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Prioritization of Oil and Gas Fields for Regional Groundwater Monitoring Based on a Preliminary Assessment of Petroleum Resource Development and Proximity to California's Groundwater Resources

Scientific Investigation Report 2018–5065
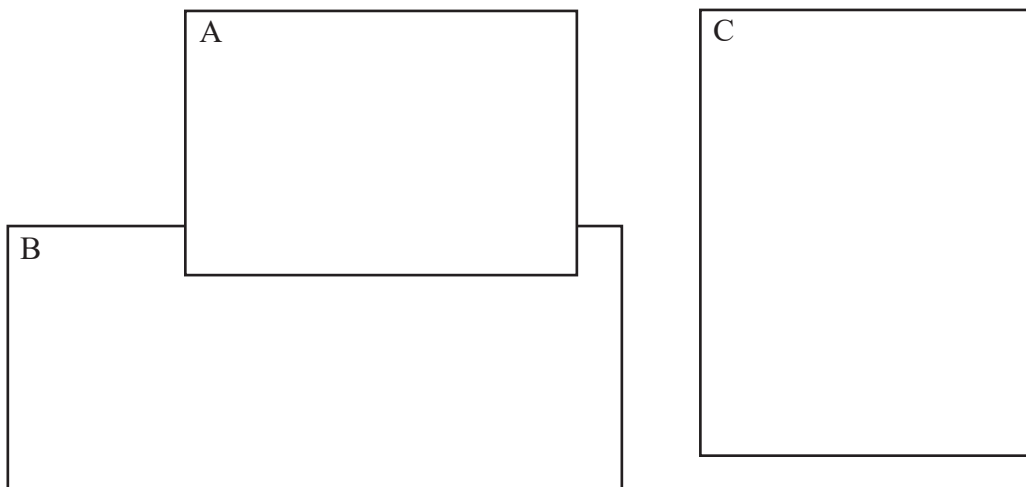
U.S. Department of the Interior
U.S. Geological Survey

Prioritization of Oil and Gas Fields for Regional Groundwater Monitoring Based on a Preliminary Assessment of Petroleum Resource Development and Proximity to California's Groundwater Resources

By Tracy A. Davis, Matthew K. Landon, and George L. Bennett

A product of the California Oil and Gas Regional Groundwater Monitoring Program

Prepared in cooperation with the California State Water Resources Control Board

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Acknowledgments

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
barrel (bbl; petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
million barrel	158,987	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
Flow rate		
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

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

Datum

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

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

Abbreviations

α	significance level
AI	air injection
BFW	base of freshwater
bls	below land surface
CalWIMS	California Well Information Management System
CCST	California Council on Science and Technology
COGG	California Oil, Gas, and Groundwater cooperative program
DDW	Division of Drinking Water (SWRCB)
DH	dry hole
DOGGR	California Division of Oil, Gas, and Geothermal Resources
DWR	California Department of Water Resources
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
GD	gas disposal
GIS	geographical information system
GS	gas storage
H	Humboldt
IQR	interquartile range
LG	liquid gas
LSE	land surface elevation
OB	observation
M	Mount Diablo
MMB	million barrels
MTRS	meridian, township, range, and section
na	not available
PLSS	Public Land Survey System
PM	pressure maintenance
RGMP	Regional Groundwater Monitoring Program
RPD	relative percent difference
S	San Bernardino
SB 4	California Senate Bill 4 of 2013
SC	cyclic steam
SF	steam flood
SWRCB	California State Water Resources Control Board

Abbreviations—Continued

TD	total depth
TDS	total dissolved solids
TOP	top of first perforated interval in a well
UIC	underground injection control
USGS	U.S. Geological Survey
WD	waste-water disposal
WS	water source

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Abstract

The California State Water Resources Control Board initiated a regional monitoring program in July 2015 to determine where and to what degree groundwater quality may be adversely impacted by oil and gas development activities. A key issue in the implementation of the regional groundwater monitoring program is that each year, detailed characterization work can be done in only a few of California's 487 onshore oil and gas fields. The first step in monitoring groundwater near petroleum development is to prioritize oil and gas fields using consistent statewide analysis of available data that indicate potential risk of groundwater to oil and gas development.

The U.S. Geological Survey compiled data for four factors that characterize the intensity of petroleum resource development and proximity to groundwater resources: petroleum-well density, volume of water injected in oil fields, vertical proximity of groundwater resources to oil and gas resource development, and water-well density. An overall priority ranking for each field was determined by computing summary metrics, analyzing statewide distributions of summary metrics for all oil and gas fields, using those distributions to define relative categories of potential risk for each factor, and combining relative risk rankings for different factors into an overall priority ranking. This preliminary assessment does not represent an evaluation of groundwater risk to oil and gas development, which needs to be based on detailed analysis and data related to development activities including well stimulation, well integrity issues, produced water ponds, and underground injection.

Based on the prioritization analysis, 22 percent (107 fields) of the total number of oil and gas fields in California were ranked as high priority, 23 percent (114 fields) as moderate priority, and 55 percent (266 fields) as low priority. These results indicate that between 100 and 200 oil fields are principal candidates for the next steps in the regional monitoring program. The land area of fields that ranked high priority accounted for 41 percent of the total field area (3,392 square miles). More than half of the high priority fields were in the southern San Joaquin Valley and the Los Angeles Basin. Some of the larger fields tended to have higher rankings because of greater intensity of petroleum development, sometimes coupled with proximity to groundwater resources.

The U.S. Geological Survey, in collaboration with the California State Water Resources Control Board and other agencies, has begun regional groundwater monitoring near oil and gas fields selected for study through the California Oil, Gas, and Groundwater cooperative program. Groundwater monitoring includes compiling, analyzing, and developing three-dimensional visualizations of existing data, including geological frameworks, salinity mapping, identification of surface features that could potentially affect groundwater quality, locations and depths of oil/gas and water wells, cataloging well-construction integrity issues, and evaluating the directions of groundwater flow. These analyses are required to determine where existing wells should be monitored and where new monitoring wells may need to be drilled.

Introduction

As required by California Senate Bill 4 of 2013 (SB 4; State of California, 2013), and detailed in "Model Criteria for Groundwater Monitoring in Areas of Oil and Gas Well Stimulation" (California State Water Resources Control Board, 2015), the California State Water Resources Control Board (SWRCB) initiated a Regional Groundwater Monitoring Program (RGMP) to protect waters designated for any beneficial use in the vicinity of oil and gas fields in California, while prioritizing the monitoring of groundwater that is or has the potential to be a source of drinking water (California State Water Resources Control Board, 2017b). Factors considered for the RGMP include well stimulation treatments and other events or activities that have the potential to contaminate groundwater, such as an oil and gas well failure or breach.

Fluids produced or introduced in the well stimulation process, underground injection control (UIC) wells, and other oil field waste management activities such as produced water ponds are examined in the RGMP as part of the process of characterizing and monitoring groundwater priority zones.

Accounting for 6 percent of total United States crude oil production in 2015, California ranks third in the nation for oil production (U.S. Energy Information Administration, 2016). Geospatial data and summaries of the nation's petroleum resources are available from the U.S. Geological Survey (USGS) Energy Resources Program National Oil and Gas Assessment interactive map (U.S. Geological Survey website, accessed March 16, 2017, at https://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment.aspx). The characteristics of oil and gas fields in California have been documented by the California Department of Conservation's Division of Oil, Gas, and Geothermal Resources (DOGGR; California Division of Oil, Gas, and Geothermal Resources, 1982, 1992, and 1998).

California, one of the most populated states in the nation, uses more groundwater (and surface water) than any other state (Maupin and others, 2014). In 2010, groundwater withdrawals in California averaged 12.7 billion gallons per day. In many parts of the State, oil and gas resources overlap with or are in lateral proximity to groundwater resources; this overlap is depicted in figure 1*A* with the olive- and mauve-colored dots representing areas with both oil and gas wells and domestic water wells (California Division of Oil, Gas, and Geothermal Resources, 2014; Johnson and Belitz, 2015). Households in some areas depend heavily on water from domestic wells; however, irrigation and public supply accounted for 69 and 22 percent (by volume), respectively, of total fresh groundwater withdrawal in California in 2010 (Brandt and others, 2014). Some counties, such as Kern, Kings, Fresno, and Los Angeles, have the greatest groundwater withdrawals in the State as well as the most productive oil fields in the State and the Nation (Gautier and others, 2004, 2012; Tennyson and others, 2012; Brandt and others, 2014; U.S. Energy Information Administration, 2016; figs. 1*B*, *C*). Reviews of groundwater resources of California are provided by the California Department of Water Resources (2003, 2016) and Planert and Williams (1995).

A key issue in the implementation of the RGMP is that the State has 487 onshore oil and gas fields, but detailed characterization work can only be done in a few fields each year. For planning purposes, a prioritization of oil and gas fields is needed for consideration in implementing regional groundwater monitoring. During 2014–16, the USGS analyzed the limited data related to petroleum resource development and proximity to groundwater resources in California. This analysis uses a consistent approach for all oil and gas fields in the State to develop a relative priority ranking (high, moderate, and low priority; shown in fig. 2). The prioritization does not represent an evaluation of groundwater risk from oil and gas development, which needs to be based on detailed data analysis from regional monitoring.

Through the California Oil, Gas, and Groundwater (COGG) program, the USGS is cooperating collaboratively with the SWRCB to implement the RGMP. The COGG program is coordinated with other agencies involved in managing groundwater and oil and gas resources, including DOGGR, the Regional Water Quality Control Boards (RWQCBs), the Bureau of Land Management, and local water agencies.

The SWRCB and nine RWQCBs (fig. 2) assist DOGGR districts to ensure operators of oil and gas wells adhere to state and federal regulations intended to protect waters designated for any beneficial use and to promote transparency to the public. The DOGGR oversees drilling, operation, maintenance, and plugging and abandonment of oil, gas, and geothermal wells in California and regulates injection of fluids into fields under the UIC program, which includes permitting, inspection, and well integrity tests (California Division of Oil, Gas, and Geothermal Resources website, accessed January 11, 2017, at http://www.conservation.ca.gov/dog). The RWQCBs have developed programs to monitor and address surface-water and groundwater issues related to oil and gas production activities, including well stimulation treatments, UIC wells, produced-water storage and disposal at the surface, and aquifer exemptions (Central Valley Regional Water Quality Control Board, 2017; Los Angeles Regional Water Quality Control Board, 2017). Records pertaining to these activities are uploaded by agencies and operators to Geotracker, the SWRCB's data management system for sites that impact or have the potential to impact groundwater (California State Water Resources Control Board, 2017a).

Purpose and Scope

The purposes of this report are to provide (1) a statewide and subordinate regional view of physical characteristics that indicate the potential risk to California's groundwater resources from oil and gas resources in the subsurface and (2) a comparative analysis of these characteristics to assign priority rankings to California oil and gas fields for regional groundwater monitoring.

This report describes which factors were considered in the prioritization of oil and gas fields and methods for compiling and synthesizing data from various sources, calculating each factor, ranking fields by each factor, and combining the rankings into an overall priority classification. Ancillary well data that were compiled in the process of assembling information on petroleum resource development were summarized in tables and include drill and abandonment dates, number of abandoned wells in each field, volume of water produced, net water or steam injection volume, and water injection and production volumes for oil and gas wells outside field boundaries. Results of statistical analyses that quantify the limitations of the statewide datasets are presented in tables and described.

A
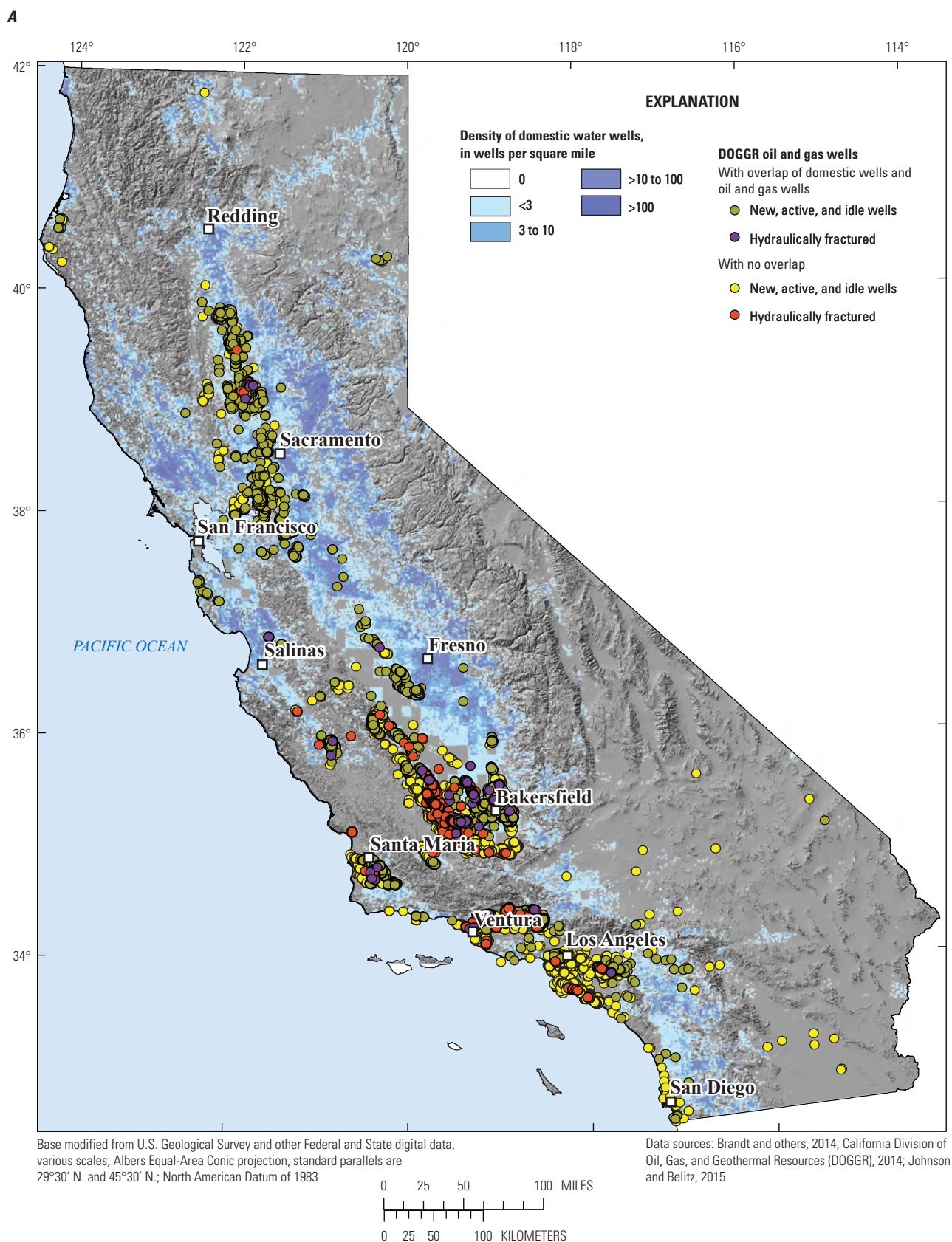
Figure 1. Groundwater supply and areas of overlap with oil and gas production in California: *A*, density of domestic water wells and locations of California Division of Oil, Gas, and Geothermal (DOGGR) oil and gas wells; *B*, 2010 groundwater withdrawal per county; and *C*, 2010 groundwater withdrawal per county in selected counties and the locations of DOGGR oil and gas wells.

Figure 1.   —Continued

c

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: Brandt and others, 2014; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014; Johnson and Belitz, 2015

0   10   20   40   MILES

0   10   20   40   KILOMETERS

EXPLANATION

2010 groundwater withdrawal by county, in million gallons per day

<25	>100 to 250	>500 to 750
25 to 100	>250 to 500	>750

DOGGR oil and gas wells

○ New, active, and idle wells

● Hydraulically fractured
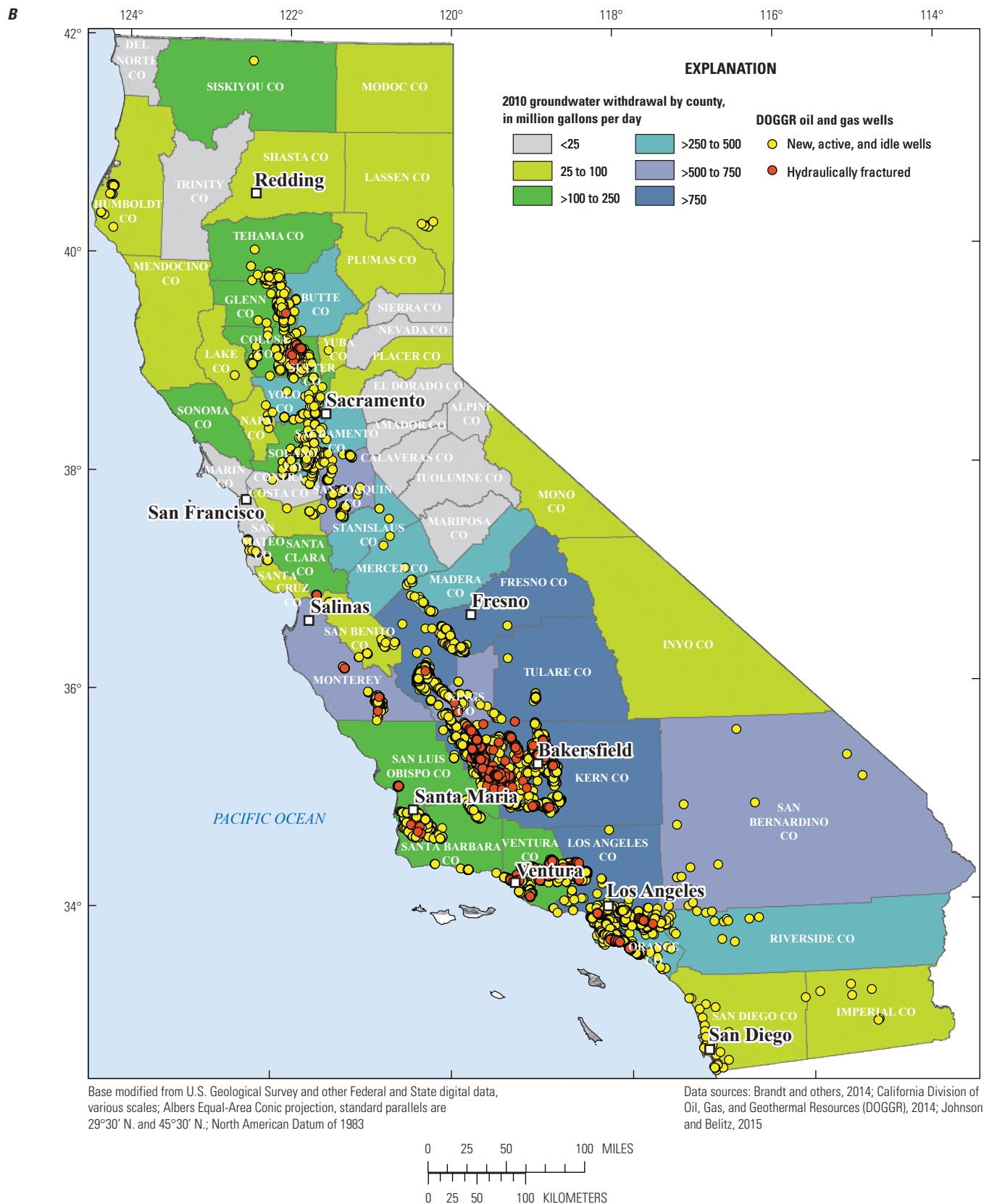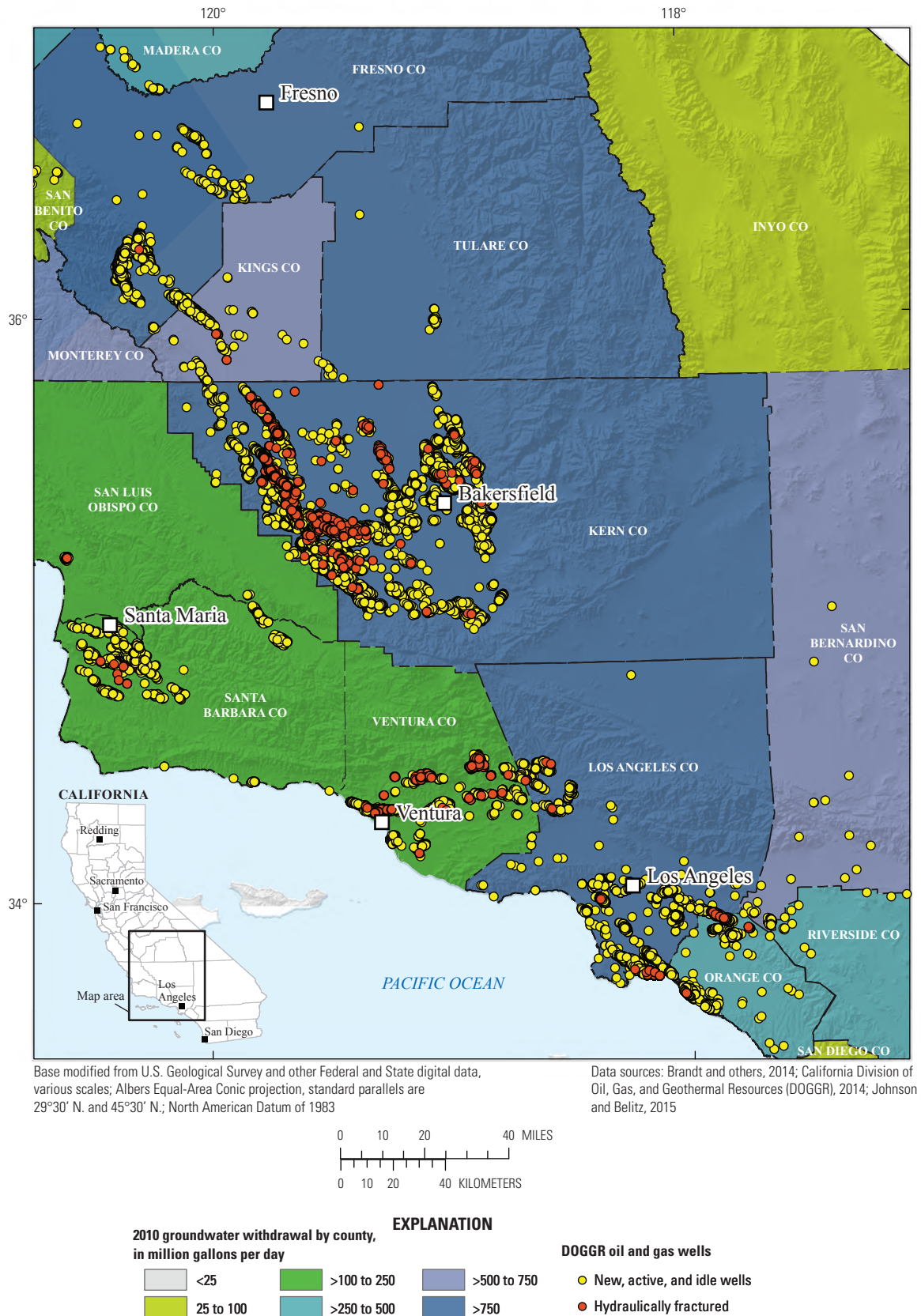
Figure 1. —Continued
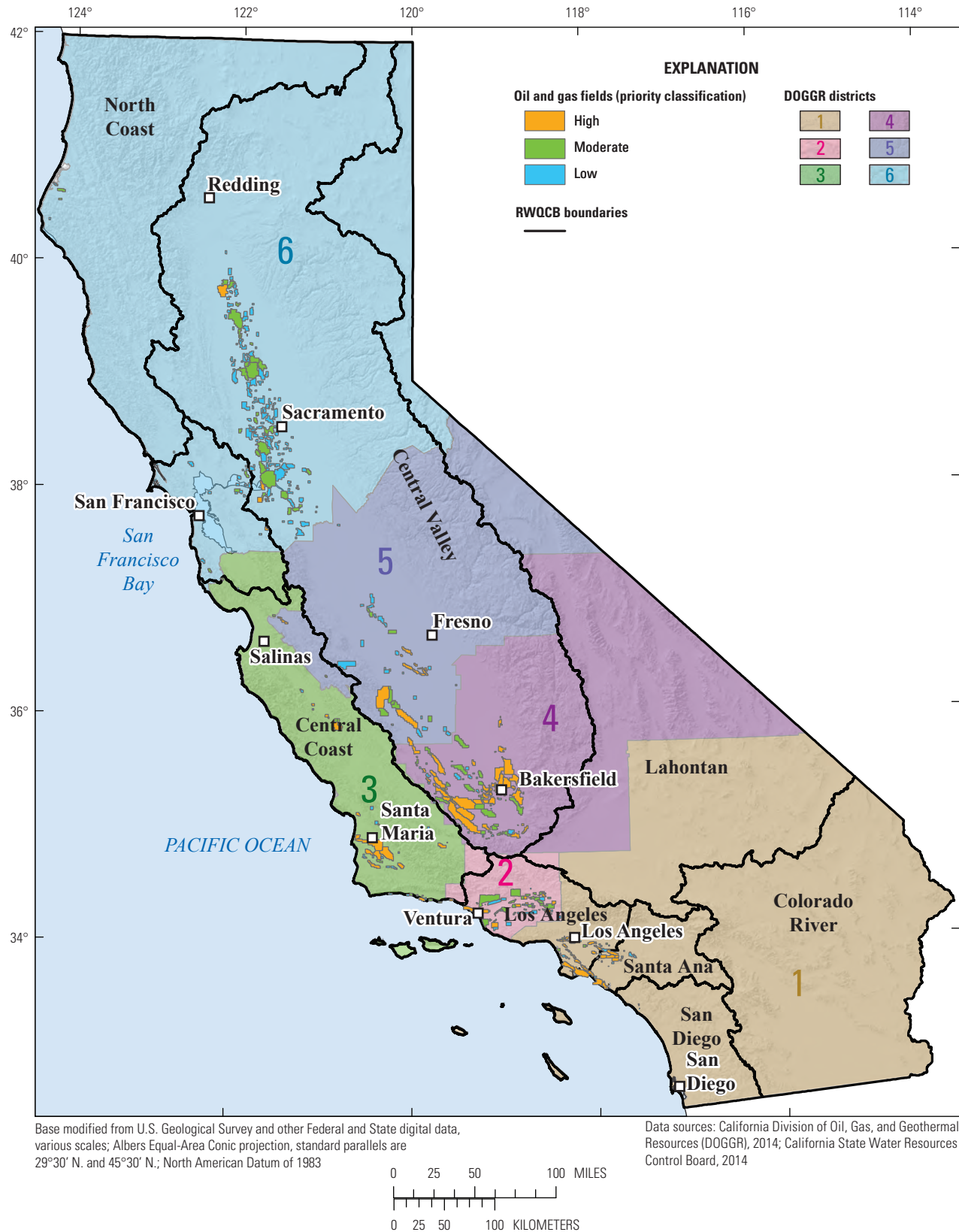
Figure 2. California Division of Oil, Gas, and Geothermal Resources (DOGGR) district boundaries, California Regional Water Quality Control Board (RWQCB) boundaries, and the location of oil and gas fields in California.

Factors discussed in this report are those used in the preliminary assessment and do not include all activities related to oil and gas development that have the potential to contaminate groundwater, such as produced-water storage and disposal at the surface. Hydraulic fracturing and acid well stimulation were not considered in the prioritization analysis described in this report because the RGMP plans to make an overall assessment of the effects of oil and gas development on groundwater resources, examining several factors in addition to those linked to well stimulation treatments. A review of the potential risks of oil and gas well stimulation in California was carried out by the California Council on Science and Technology (2014, 2015).

Conceptual Description of Factors used in Prioritization

Four factors that characterize petroleum resource development and proximity to groundwater resources were included in the preliminary assessment: petroleum-well density, volume of water injected into oil and gas fields, vertical proximity of oil and gas development to groundwater resources, and density of water wells overlying and adjacent to fields. These factors can indicate potential risk of groundwater contamination by subsurface processes and activities related to oil and gas resource development. Although the effects of high density of petroleum wells, fluid injection, and vertical and lateral proximity of oil and gas resources to groundwater resources could interact to potentially increase the risk to groundwater quality, these factors were treated as independent variables for the purpose of the prioritization analysis. The data sources and how each factor was computed are described in the "Methods" section.

Petroleum-Well Density

One factor contributing to potential groundwater risk that was available for statewide analysis is density of oil and gas wells in each field (fig. 3A). Literature on the effects of oil and gas development on groundwater quality has indicated that leaky wellbores are the predominant pathway allowing contamination (Davies and others, 2014; Dusseault and others, 2014). The petroleum-well density measurement primarily reflects that the more oil and gas wells that are present, the greater the risk that some may leak and provide potential pathways for contaminants mobilized during oil and gas development to move to groundwater. In addition, the density of injection wells was analyzed (fig. 3B) because injecting fluids and gas into the subsurface increases pressures in certain zones; this may in turn spread fluids beyond the intended injection zones. Similarly, the density of waste-disposal wells

was also analyzed (fig. 3B) because injection of oilfield wastes into the subsurface has the potential to affect groundwater quality and because waste injections generally occur above, below, or laterally displaced from the main oilfield production zones and may be closer to groundwater resources in some cases.

Volume of Injection

The volume of injection of fluids into the subsurface in or near oil fields was considered a potential risk factor to groundwater because injections have the potential to alter subsurface fluid movement towards useable groundwater and because the injected fluids are sometimes relatively poor quality water. Sources of injected waters include produced water (often brines) withdrawn along with the extracted hydrocarbons in wells withdrawing fluids from oil-bearing formations, groundwater withdrawn from non-oil-bearing formations, and imported fresh water. Some produced waters are mixed with fresh water and treated prior to injection.

Water is typically injected into formations in oil and gas fields for the purposes of subsidence control, enhanced oil recovery, and waste disposal (fig. 3B). Categories of injection for enhanced recovery include water flooding, steam flooding, and cyclic steam injection, the latter involving cyclic injection and withdrawal from a single well. Waste disposal is permitted only in formations from which no more hydrocarbons can be viably recovered and formations that are not potential sources of drinking water (U.S. Environmental Protection Agency, 2016).

Vertical Proximity

Vertical proximity of petroleum resource development to groundwater resources is a measure of the difference in depths at which the two resources occur (fig. 3C). Conceptually, the farther apart the oil and gas resources and useable groundwater are, the less likely it is constituents from oil and gas development will move to groundwater. Oil and gas resources are generally considered to be separated from groundwater resources by large vertical distances. However, in parts of California, oil and gas resources are found at shallower depths than is common in other parts of the United States (California Council on Science and Technology, 2015; Jackson and others, 2015), and consequently, at greater proximity to usable groundwater. In areas of the State where oil and gas resources are thousands of feet below groundwater resources, those groundwater resources should, all other factors being the same, be less at risk from oil and gas development than in areas where petroleum resources are close to groundwater resources.

Water-Well Density

Water-well density can be considered to be a factor influencing groundwater risk from oil field contamination. Water-well density is a surrogate measure of potential exposure of water users; more wells can indicate more water users who could be exposed should groundwater quality be degraded (fig. 3D). Additionally, the density of water wells overlying and adjacent to oil and gas fields was used to identify areas of lateral overlap of oil and gas development activities and currently used groundwater resources. There is a greater probability of the proximity of oil and gas development to private and public supplies of groundwater, as well as to human population, in or near fields with higher water-well density compared to fields with lower water-well density.

Methods

For this study, data on petroleum wells and water wells in California were compiled from various sources. The data were used to compute petroleum-well density, volume of injection, vertical proximity, and water-well density for each oil and gas field. Fields were ranked by each factor based on the distribution of data for all oil and gas fields, and the priority classifications were assigned to fields based on the relative potential risk to groundwater near each field using an algorithm that considered all available data.
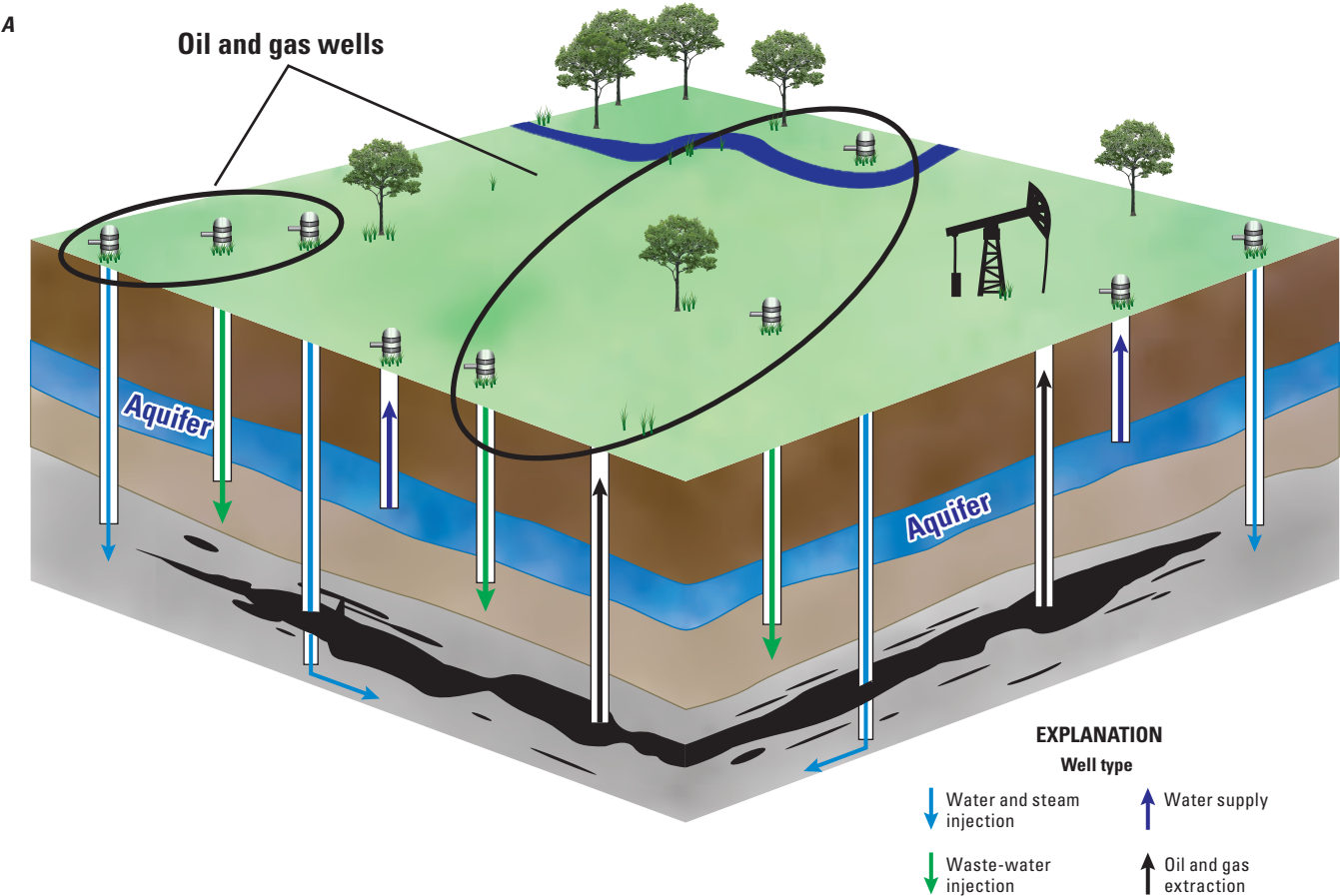
Figure 3. Factors that were assessed in the prioritization of oil and gas fields for regional groundwater monitoring: *A*, oil and gas production; *B*, injection for enhanced oil recovery and waste disposal; *C*, vertical proximity of petroleum resource development to groundwater resources; and *D*, groundwater withdrawal in and near oil and gas fields.

Figure 3.   —Continued

C

EXPLANATION

Well type

Water and steam injection

Waste-water injection

Water supply

Oil and gas extraction
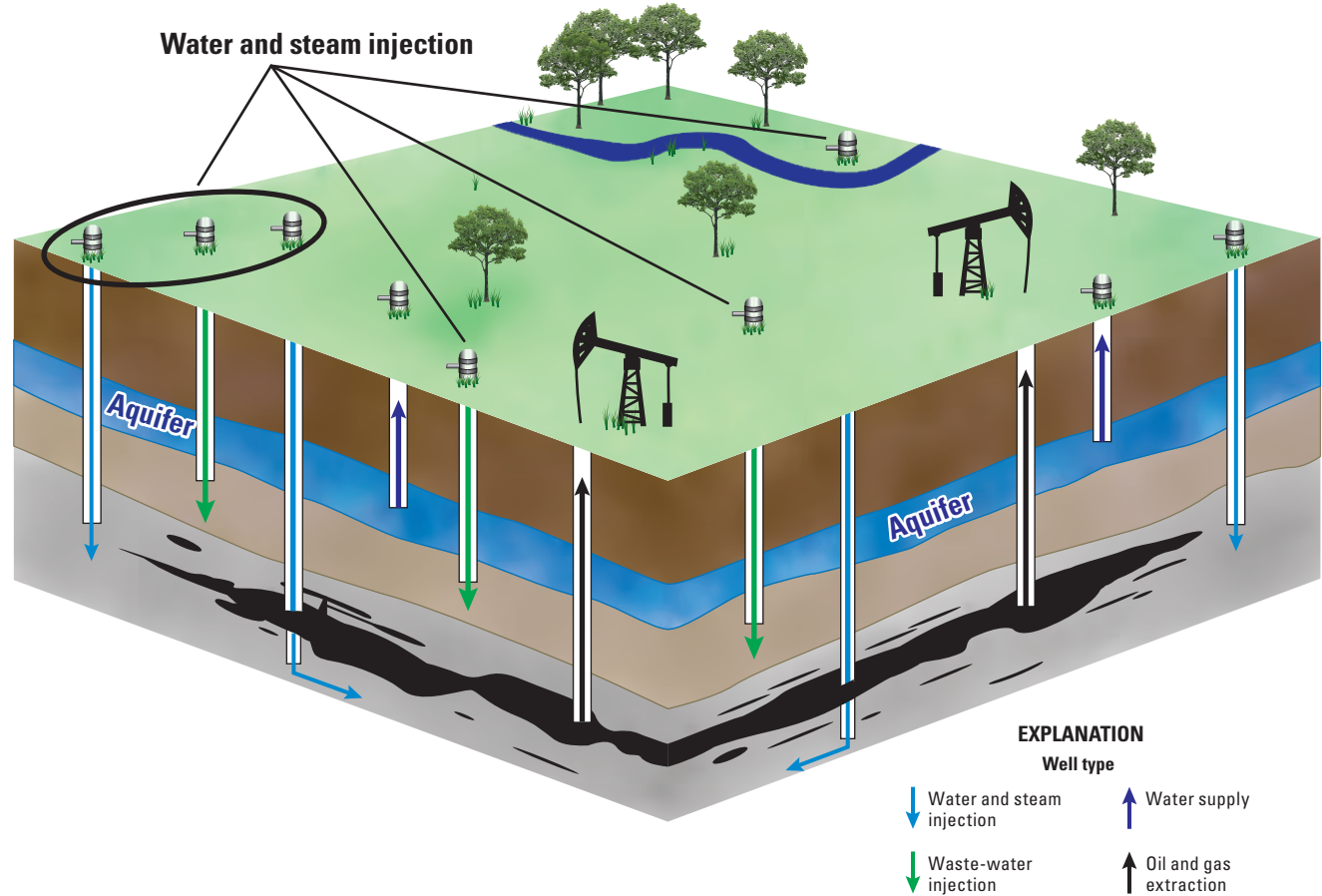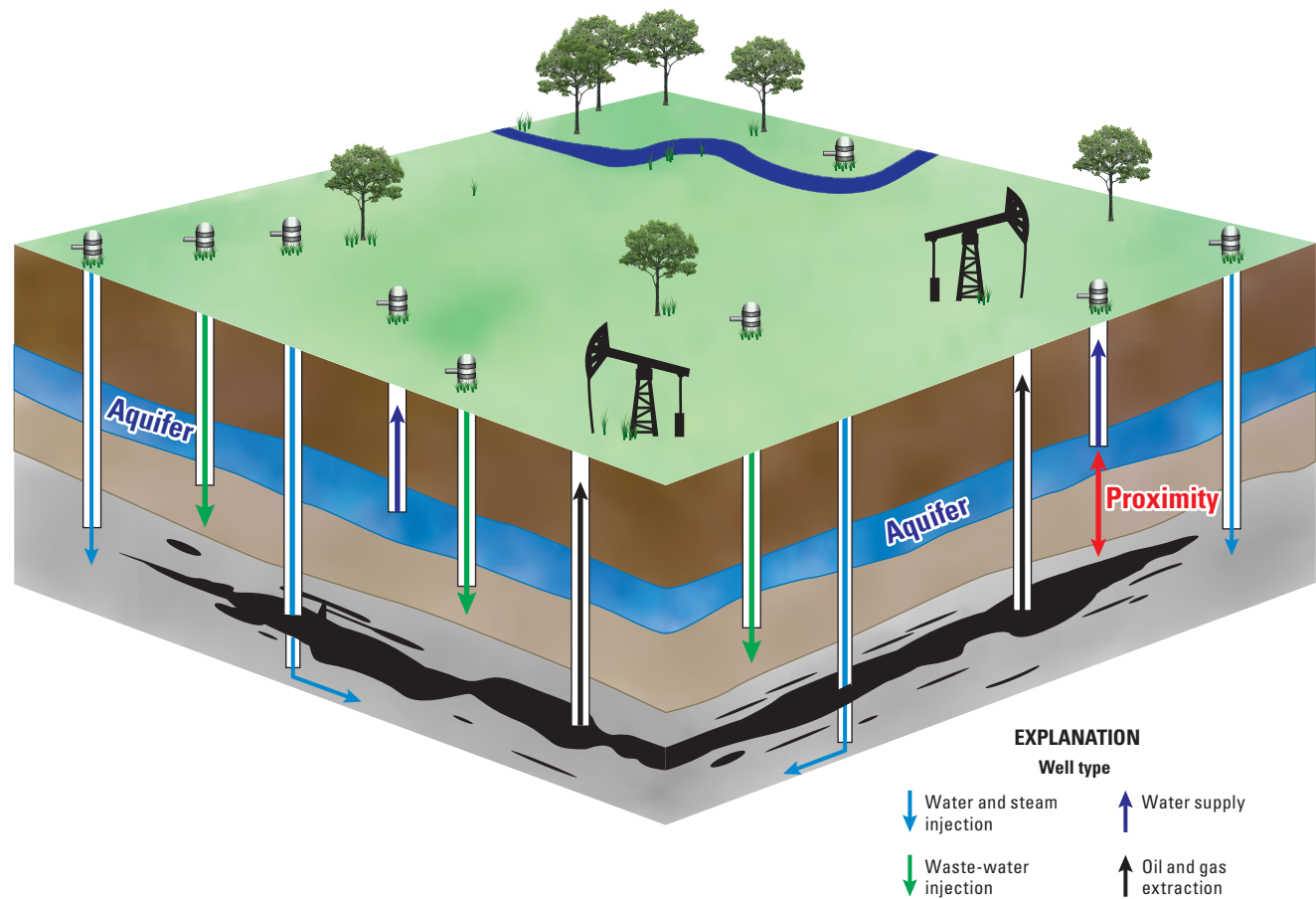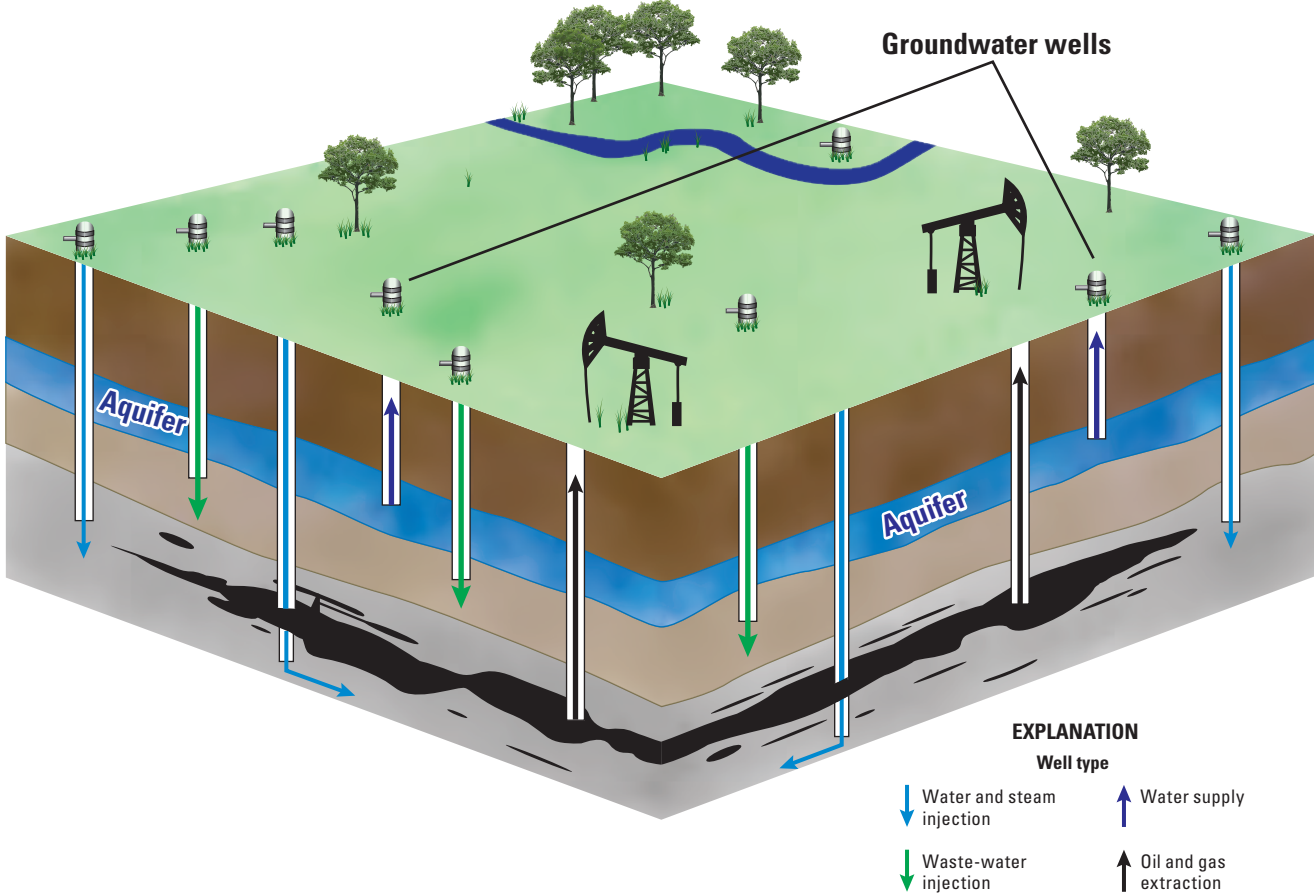
Figure 3.   —Continued

Figure 3.   —Continued

Data Available for Priority Assessment

The main sources of data available for the prioritization assessment were databases provided by DOGGR, the California Department of Water Resources (DWR), and the SWRCB's Division of Drinking Water (DDW).

Three datasets downloaded from DOGGR's geographical information system (GIS) mapping website were used for mapping locations of oil and gas wells, administrative boundaries of oil and gas fields, and DOGGR districts: All Wells, Field Boundaries, and District Boundaries (California Division of Oil, Gas, and Geothermal Resources, 2014; Davis and others, 2018). The geospatial data were downloaded December 29, 2014, from http://www.conservation.ca.gov/dog/maps/Pages/GISMapping2.aspx and are available at https://doi.org/10.5066/F7FJ2DV3. The 2014 DOGGR Field Boundaries dataset included 514 oil, gas, and geothermal fields in California. Offshore and geothermal fields were excluded from this assessment, leaving 487 onshore oil and gas fields available for analysis.

The State is divided into six DOGGR jurisdictional districts, the boundaries of which generally follow county lines (California Division of Oil, Gas, and Geothermal Resources, 2014; fig. 2). The DOGGR districts are used in this report to organize results for oil and gas fields into geographic areas and are named by district number and the primary geologic basin or region in which oil and gas fields are located: District 1—Los Angeles Basin, District 2—Ventura Basin, District 3—Central Coast, District 4—San Joaquin Basin (South), District 5—San Joaquin Basin (North/Central), and District 6—Sacramento Basin.

Water injection and production volumes were compiled from DOGGR's online injection databases available at ftp://ftp.consrv.ca.gov/pub/oil/new_database_format/. Digital records of water injection and production on a monthly basis for all wells were available for the period 1977–2015 (California Division of Oil, Gas, and Geothermal Resources, 2015). The DOGGR production and injection database also included oil produced, gas produced and injected, and surface pressures; however, these attributes are not summarized in this report.

Information about well construction was not included in the 2014 DOGGR All Wells dataset and was compiled from other sources. The well data used to calculate vertical proximity, including oil and gas well depths and water well depths, are available online at https://doi.org/10.5066/F7FJ2DV3 (Davis and others, 2018). Data sources and methods used to attribute wells with depth information are described in the metadata associated with this data release and are discussed only briefly here.

Scanned images of records for individual oil and gas wells, including geophysical logs, well history, well completion reports, and correspondences, were viewed on DOGGR's online Well Finder (http://www.conservation.ca.gov/dog/Pages/Wellfinder.aspx). For oil and gas production wells (excluding injection wells), depths to the top of perforated intervals (TOP), depths to base of freshwater (BFW), and ancillary data were extracted from these well records. For injection wells, depths to TOP and BFW were included in the data from DOGGR's California Well Information Management System (CalWIMS) database for UIC wells. The Microsoft Access database file was received from DOGGR on February 28, 2015, and included information pertaining to underground injection and well construction for 28,462 injection wells.

The depth to BFW was often reported in the DOGGR UIC database and scanned well records for individual wells on the DOGGR Well Finder. The source and methodology of the reported depth to the BFW were generally not documented. The data for depths to BFW had larger uncertainties than the other variables compiled for this analysis. The BFW is historically defined by DOGGR and the Bureau of Land Management as the depth in a well where the water in overlying aquifers has less than or equal to 3,000 milligrams per liter (mg/L or parts per million) of total dissolved solids (TDS; California Division of Oil, Gas, and Geothermal Resources, 1982, 1992, 1998; Bureau of Land Management, 2001). The depth to the BFW has generally been estimated using qualitative interpretations of borehole geophysical logs to estimate the depth to the first sandy zone where TDS is greater than overlying zones or using water-quality criteria such as the presence of high concentrations of individual constituents like boron. Some oil and gas fields have field rules that define the criteria for estimating base of freshwater, but more commonly, specific criteria for determining the BFW within fields are not apparent. Additionally, under SB 4, the U.S. Environmental Protection Agency (EPA) definition of water potentially useful for drinking water as less than 10,000 mg/L TDS has been adopted by California as the definition for groundwater that needs to be protected for beneficial uses. There are few data available on the distribution of groundwater having TDS between 3,000 and 10,000 mg/L. Despite the uncertainties in TDS value, the corresponding BFW, and how it is determined, the BFW data are an informative and widely available data source for evaluating proximity of oil and gas development to groundwater resources, if used with appropriate awareness of the limitations. It is assumed that the BFW values were determined by oil and gas geologists based on knowledge and experience. Because the level of knowledge and experience is likely to vary, BFW values in individual wells are likely to have substantial uncertainties. However, when aggregated at oil field scales, the BFW data are likely to preserve regional differences that allow comparison of the relative depths of the fresh groundwater systems between oil fields.

The DWR provided about 750,000 scanned images of drillers' logs and well completion reports for water wells in California. Using a combination of well selection methods, well construction and ancillary data were extracted from drillers' logs for about 67,000 wells and entered into a geodatabase. Well locations were approximated from the Public Land Survey System (PLSS) designation provided by DWR for each scanned log. The PLSS designation lists the meridian, township, range, and section (MTRS). The PLSS grid system in California consists of three meridians—Humboldt (H), Mount Diablo (M), and San Bernardino (S)—and baselines. Each township is identified by township and range designations: township designation indicates the location north or south of the baseline; range indicates the location east of west of the meridian. Each township is divided into 36 numbered sections, each approximately 1 square mile, which were further divided into 16 quarter-quarter sections. Wells were plotted at the center of the section or quarter-quarter section in which each was located as indicated by MTRS and location information from the well completion report. If a field boundary intersected or contained the center of a section, then the wells in that section were considered to overlie the field. The scanned images provided by DWR are not a complete inventory of all water wells statewide. However, the scanned images and the data extracted from them are considered, for this analysis, to be the best representation of existing water wells near oil and gas wells.

The DDW database of public supply wells supplemented the water well data (data available on the SWRCB's Geotracker at https://geotracker.waterboards.ca.gov/gama/datadownload). This database included well location and ancillary data for about 22,000 public supply wells in California, of which 3,672 wells were located in or within 3.1 miles (5 kilometers) of oil and gas fields (table 1). The DDW wells were included in well-density calculations but not vertical-proximity calculations because well depth information was generally not available for these wells.

Calculation of Variables

The intensity of petroleum resource development was characterized for each oil and gas field by assessing petroleum-well density and volume of injection, and the proximity of oil and gas development to groundwater resources was characterized by vertical proximity and water-well density. Multiple variables were considered for each factor (table 2). Petroleum-well density was based on three variables: density of all petroleum wells, density of injection wells, and density of waste-disposal wells. Volume of injection was based on two variables: total volume of water

or steam injection and total volume of water injection for waste disposal only. Vertical proximity was assessed by using a combination of five methods for calculating the distance separating petroleum and groundwater resources. Water-well density considered two variables: the density of water wells overlying the field and density of water wells adjacent to each oil and gas field.

Petroleum-Well Density

Density of all petroleum wells, density of injection wells, and density of waste-disposal wells were calculated as the number of wells in a field divided by the area of the field expressed in units of wells per square mile (wells/mi^2; fig. 4A). The well densities were calculated using ESRI ArcGIS tools and datasets downloaded from the DOGGR GIS Mapping website (Davis and others, 2018). The 2014 DOGGR All Wells dataset included the locations, well classification, and selected information for over 222,000 new, active, idle, or plugged petroleum wells in 3,247 sections in California. Onshore oil and gas wells from this dataset that plotted within the field boundaries were used in density calculations. There were about 13,000 petroleum wells that plotted outside of field boundaries (appendix table 1–1).

The three variables of petroleum-well density were differentiated by well type as indicated in the "GISSymbol" column of the 2014 DOGGR All Wells dataset. Major categories of wells used for oil and gas extraction or field management and the total number of wells for each category are listed in table 1. Petroleum wells were grouped in this analysis into three categories: production, injection, and other. Wells in all three categories were included in the density of all petroleum wells. Production wells were those used for oil and (or) gas extraction and included two DOGGR well types: oil and gas (OG) and dry gas (DG). Injection wells included wells used for water, steam, gas, air, and waste injection and included the following DOGGR well types: water flood (WF), steam flood (SF), cyclic steam (SC), waste-water disposal (WD), gas disposal (GD), gas storage (GS), pressure maintenance (PM), air injection (AI) and liquid petroleum gas (LG). The density of injection wells included all of these injection well types. The density of waste-disposal wells included only injection wells with the DOGGR well types WD and GD. The GD wells, which were primarily in the Midway-Sunset field and a few other fields in District 4, represented only 4 percent of the waste-disposal wells. Well types SF, WF, SC, and AI compose the enhanced oil recovery (EOR) category of injection wells. The remaining DOGGR well types, dry hole (DH), observation (OB), water source (WS), and unknown, were categorized as other.

Volume of Injection

Volume of injection was calculated by the sum of monthly injection volumes of water and steam, as reported for January 1977 through September 2015 in DOGGR's online injection databases (California Division of Oil, Gas, and Geothermal Resources, 2015). Similar to the density calculations, the two volume variables were differentiated by well type. The total volume of water and steam injection considered all wells that inject water or steam for the purposes of EOR (WF, SF, and SC wells) and waste disposal (WD wells). The total volume of water injection for waste disposal considered only WD wells. Volumes were reported by well in units of barrels, which are equal to about 42 gallons and include steam injection. Volumes calculated for each field over the approximate 39 years of record were large and are therefore presented in this report as million barrels (MMB).

Vertical Proximity

Vertical proximity was estimated by calculating the vertical separation distance between oil and gas development and groundwater resources for fields using a combination of variables and calculation methods (fig. 5). For all methods, vertical proximity is the inverse of the separation distance. That is, the smaller the distance between the resources, the greater proximity of (or closer) oil and gas production activities are to groundwater resources, and therefore, the greater potential risk to usable groundwater. Variables used to calculate separation distance were depths to TOP and BFW extracted from DOGGR well records for oil and gas wells, depths to TOP from DOGGR's UIC database, and total well depths (TD) extracted from DWR scanned images of well completion reports for water wells. Depth data for petroleum and water wells, although painstaking to compile into databases, represent best available data for estimating vertical proximity on an oil-field scale across the State. The availability of data for each of the variables used to calculate separation distance, however, varied by oil field, necessitating the use of a combination of different calculation methods. Statistical summaries of the depth data for each field are available in appendix 1 (appendix table 1–3). Statewide, the dataset of separation-distance variables included depths to TOP for 20,242 oil and gas wells (17,278 injection and 2,964 production); depths to BFW for 6,202 oil and gas wells (5,248 injection and 954 production); and TD for 16,911 water wells overlying or adjacent to oil and gas fields (Davis and others, 2018).

The five methods used to calculate separation distance for each oil and gas field are shown in figure 5. Each subsequent method introduced additional uncertainty making it less robust than the previous method; therefore, the method selected to define separation distance for each field was the first method to have five or more values for depth to TOP for petroleum wells, except where noted. Method 1 is the only method for calculating separation distance that used data available in the same well, which were comparisons of depths to TOP and BFW in individual petroleum wells (4,157 of the 20,242 wells with depth to TOP also had depth to BFW). For the four other methods, data for petroleum wells and water wells were compared using a near-neighbor scheme or aggregated at an oil-and-gas-field scale.

For method 1, separation distance for each field was calculated by taking the difference between depth to TOP and depth to BFW in the same well for all petroleum wells with data and then computing the median value:

$$SEP_{f,1} = \left(d_{TOP} - d_{BFW}\right)_M \qquad (1)$$

where
$\quad SEP_{f,1}$ is the separation distance for a field using method 1,
$\quad d_{TOP}$ is the depth to top of perforated interval for a petroleum well,
$\quad d_{BFW}$ is the depth to base of freshwater in the same petroleum well, and
$\quad M$ is the median of all values for the field.

In order to calculate separation distance using method 1, each well must be attributed with both TOP and BFW depths. This method used an imprecisely defined BFW, likely representing the depth to the deepest groundwater resources with less than 3,000 mg/L TDS. This depth does not represent the depth of currently used groundwater.

For method 2, separation distance for each field was calculated by taking the difference between depth to TOP for petroleum wells and TD of the nearest and deepest water well within 1.25 miles of the petroleum well and then computing the median value:

$$SEP_{f,2} = \left(d_{TOP} - d_{TD}\right)_M \qquad (2)$$

where
$\quad SEP_{f,2}$ is the separation distance for a field using method 2,
$\quad d_{TOP}$ is the depth to top of perforated interval for a petroleum well,
$\quad d_{TD}$ is the total well depth of a water well near the petroleum well, and
$\quad M$ is the median of all values for the field.

Petroleum wells were matched with the nearest DWR water well within 1.25 miles. Sections are not exactly 1 square mile, and the distance between their centers, which is where water wells are typically plotted, may vary slightly. Using the 1.25-mile search radius allows petroleum wells to be matched with water wells in an adjacent section even if the center of the adjacent section is greater than 1 mile away from the petroleum wells. The deepest water well in a section was chosen because the calculated separation distance will be a minimum distance and is the most protective of groundwater quality. In contrast to method 1, the depth of groundwater resources in method 2 was represented by the depths of groundwater wells in the area.

For method 3, separation distance for each field was calculated by computing the median depth to TOP for all petroleum wells in the field and the median depth to BFW and then taking the difference between the two medians:

$$SEP_{f,3} = d_{TOP,M} - d_{BFW,M} \qquad (3)$$

where

$\quad SEP_{f,3}$ is the separation distance for a field using method 3,

$\quad d_{TOP,M}$ is the median depth to top of perforated interval for all petroleum wells in a field, and

$\quad d_{BFW,M}$ is the median depth to base of freshwater for all petroleum wells in a field.

This approach has uncertainty because it compares data for petroleum wells that were potentially in different parts of an oil field with varying land surface elevation. Additional steps were taken to evaluate the effects of land-surface variations on the statistically aggregated results for the field (see appendix 1).

For method 4, vertical separation distance for each field was calculated by computing the median depth to TOP for all petroleum wells in the field and the median TD for water wells within 1.25 miles of the petroleum wells and then taking the difference between the two medians:

$$SEP_{f,4} = d_{TOP,M} - d_{TD,M} \qquad (4)$$

where

$\quad SEP_{f,4}$ is the vertical separation distance for a field using method 4,

$\quad d_{TOP,M}$ is the median depth to top of perforated interval for all petroleum wells in a field, and

$\quad d_{TD,M}$ is the median total well depth for water wells near the petroleum wells.

Only one field (Northwest Lost Hills) was attributed with vertical separation distance using method 4 (fig. 6A). If a field had an overlying water well, the well was usually within 1.25 miles of a petroleum well, and method 2 was the preferred calculation method.

For method 5, vertical separation distance for each field was calculated by computing the median depth to TOP for all petroleum wells in the field:

$$SEP_{f,5} = d_{TOP,M} \qquad (5)$$

where

$\quad SEP_{f,5}$ is the vertical separation distance for a field using method 5, and

$\quad d_{TOP,M}$ is the median depth to top of perforated interval for all petroleum wells in a field.

Method 5 used only perforation depths for petroleum wells because all other sources of depth data for groundwater resources were exhausted. This approach represents the maximum distance between groundwater and petroleum resources by assuming that freshwater overlies the fields and the depth to BFW is shallow in comparison to depths to TOP for petroleum wells.

A total of 174 oil and gas fields were attributed with separation distance using the following combination of calculation methods: 77 fields by method 1, 75 fields by method 2, 13 fields by method 3, 1 field (Northwest Lost Hills) by method 4, and 9 fields by method 5. Fields for which separation distance was attributed using method 1 were generally the larger fields throughout DOGGR districts 1, 2, and 3 (fig. 6A); fields in districts 4 and 5 that are at the center of the Central Valley or on the east side; and most of the fields that were attributed for district 6 (fig. 6B). Several fields on the west side of the Central Valley in districts 4 and 5 used methods 2 and 5, indicating data on the depths of freshwater resources in the area were generally not available.

All of the separation distance calculation methods make the assumption that the minimum depth of oil and gas resources in a particular field can be represented by a summary of the depths to TOP for petroleum wells with available data. Although there are far more oil and gas production wells than injection wells statewide, there were more perforation-depth data readily available for injection wells. Data for the two categories of wells were combined for separation distance calculations because of the lack of data available for production wells. Generally, injection wells were shallower than production wells for each field (see appendix 1 section "Comparison of Depths to Top of Perforations for Production versus Injection Petroleum Wells" for more information). Therefore, by using depths to TOP that are primarily for injection wells, the distance between oil and gas development and groundwater resources likely was smaller in some cases than if more data were available for production wells.

The separation distance calculation methods also assume that the maximum depth of usable groundwater can be represented by a summary of depth to BFW for petroleum wells or by TD for water wells. Methods 1 and 3 estimate the vertical distance between oil and gas resources and brackish groundwater, as represented by depth to BFW (assumed to be the boundary between waters less than and greater than 3,000 mg/L TDS), which is generally not currently used but could presumably be used as a water source in the future. In contrast, methods 2 and 4 estimate vertical distance between oil and gas resources and TD of water wells, which generally pump fresh groundwater. For fields that have no information about the depths of groundwater resources that can be used for beneficial uses, method 5 estimates separation distance using only the depths to TOP for petroleum wells. The use of different attributes to define the depth of groundwater resources, including depth to BFW and TD of water wells, or using only depths to TOP for petroleum wells to calculate separation distance, caused variability in the values between different methods in some cases, but did not result in different classifications of vertical proximity or the overall priority classifications for 56 of 81 fields compared (see appendix 1 section "Comparisons of Vertical Proximity Classifications using Separation-Distance Calculation Methods 1 and 2").

For 10 fields, the distance between oil and gas resources and BFW (method 1) was greater than the distance between petroleum resources and currently used groundwater (method 2), and the smaller separation values (greater proximity) calculated from method 2 were used in the prioritization analysis (appendix table 1–7). Results from methods 1 and 2 are preferred to results from methods 3, 4, and 5. The BFW values that are recorded in wells that also have TOP values permit vertical separation distance to be calculated in that well using method 1, which is not possible with any of the other separation distance calculation methods used in this report. Once these vertical separation distance values are calculated for the set of wells having both BFW and TOP for an oil and gas field, the resulting dataset likely represents one of the better-constrained estimates of vertical proximity available. For methods 3, 4, and 5, median values were used as the summary statistic of grouped data for each field. Vertical separation calculated using methods 3 and 4 may be less reliable than methods 1 and 2 because there are topographic features that result in substantial changes in land surface elevation within some fields. Comparisons of depths between wells or well types in different parts of a field may not be appropriate if land surface elevations differ substantially. More information about how the aggregation of data for each field (regardless of well type or elevation) and use of different variables (depths to TOP and BFW, and TD) for estimation of the separation of resources can cause variations in separation distance values or the vertical proximity classification for some fields is included in appendix 1.

Water-Well Density

The density of water wells overlying a field was calculated as the number of DWR wells plus DDW wells in a field divided by the area of the field (fig. 4B). The density of water wells adjacent to each oil and gas field was calculated as the number of DWR plus DDW wells within 3.1 miles (5 kilometers) of the field boundary (buffer) divided by the area of the buffer (fig. 4B). Buffers for oil and gas fields often overlap with each other; therefore, the same water well may be counted in more than one field's adjacent water-well density.

Active and idle water wells that are used to withdraw water for beneficial uses, such as municipal, domestic, irrigation, agricultural, and industrial uses, were included in the water-well density calculations. Monitoring wells, other uncategorized wells (for example, cathodic protection and unknown), and wells for which the section was unknown were excluded from the dataset. Some of the DDW wells have entries for both the raw and treated sample points; treated sample points were excluded from the dataset. A statewide count of attributed water wells overlying or adjacent to oil and gas fields (dataset available at https://doi.org/10.5066/F7FJ2DV3) is included in table 1. The DWR data included 16,911 wells overlying or adjacent (within 3.1 miles) to oil and gas fields; the DDW data consisted of 3,672 water wells overlying or adjacent to oil and gas fields. The calculation of water-well densities used the combined DWR and DDW dataset; municipal wells were excluded from the DWR data to avoid possibly double-counting municipal wells.

Field Rankings by Variable

Oil and gas fields were grouped into three relative categories (high, moderate, or low) of potential risk to groundwater resources for each variable representing petroleum-well density, volume of injection, vertical proximity, and water-well density. When describing results of the preliminary assessment, fields with vertical proximity are categorized as close, moderate, or far for high, moderate, or low (respectively) relative categories of potential risk. The boundaries between high and moderate categories and between moderate and low categories for each variable were chosen based on the statistical distribution of values for all oil and gas fields. Percentiles (0, 10th, 25th, 50th, 75th, and 90th), indicating the percent of the distribution that is equal to or below it, were calculated to summarize the distribution and group fields into the three categories for each variable. Percentiles were targeted to delineate the boundaries between categories, yet the actual bounding values used were often rounded to the nearest whole number. The range of values that defined the high, moderate, and low categories for each variable and the targeted and actual percentiles that were used to define the boundaries between each category are shown in table 2.

A

118°11'30''   117°57'30''

34°4'

33°58'

0   0.5   1   2 MILES

0   0.5   1   2 KILOMETERS

Base modified from U.S. Geological Survey and other Federal and State digital data,
various scales; Albers Equal-Area Conic projection, standard parallels are
29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources
(DOGGR), 2014; California State Water Resources Control Board, 2016

EXPLANATION

Oil and gas field

☐   Montebello field

DOGGR wells

🔵   Other

🔵   Production

🔴   Injection—enhanced oil recovery

🟡   Injection—waste disposal

Petroleum wells are all wells in the California Division of Oil, Gas, and Geothermal Resources (DOGGR) 2014 All Wells dataset. Injection wells are all injection wells for enhanced oil recovery and waste disposal (see table 1 for well types). Waste disposal wells are all injection wells used for waste-water and gas disposal.

Well density: the number of wells in the field (n) divided by the field area (*A*)

Density of all petroleum wells	Density of injection wells	Density of waste-disposal wells
n = 802 DOGGR wells	n = 97 injection wells	n = 1 waste-disposal well
A = 5.7 square miles	A = 5.7 square miles	A = 5.7 square miles
Density = 141 wells per square mile	Density = 17 wells per square mile	Density = 0.18 wells per square mile

Figure 4.   Methods for calculating petroleum and water well densities: *A*, density of all petroleum wells, injection wells, and waste-disposal wells in the field; and *B*, density of water wells overlying the field and adjacent to the field.

B

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014; California State Water Resources Control Board, 2016

EXPLANATION

Oil and gas field
□ Montebello field

3.1-mile buffer
■ Montebello buffer

□ **PLSS section**

Water wells
■ DWR well (1 or more)
△ DDW well

Water wells are beneficial-use groundwater wells (excluding public supply wells) attributed from California Department of Water Resources (DWR) well logs plus public supply wells from the California State Water Resources Control Board's Division of Drinking Water (DDW) database. DWR wells were plotted at the center of the Public Land Survey System (PLSS) section or the quarter-quarter section in which they are located.

Density of water wells overlying the field
 Number of wells overlying the field (n)
  divided by the field area (A)

  n = 7 water wells
  A = 5.7 square miles
  Density = 1.2 wells per square mile

Density of water wells adjacent to the field
 Number of water wells in the 3.1-mile buffer (n)
  divided by the buffer area (A)

  n = 147 water wells
  A = 64 square miles
  Density = 2.3 wells per square mile

Figure 4.   —Continued

Method 1

- Compares depth to top of first perforated interval in a well (TOP) and depth to base of freshwater (BFW) in the same petroleum well, then computes the median value for the field

- Most robust of the methods

- Provided vertical proximity for almost half of the 174 fields that were attributed (77 fields; 44 percent)

Method 2

- Compares depth to TOP in a petroleum well to total depth (TD) of a water well within 1.25 miles, then computes the median value for the field

- Groundwater resources are characterized by currently used resources

- Provided vertical proximity for almost half of the fields that were attributed (75 fields; 43 percent)

Method 3

- Compares the median depth to TOP for petroleum wells in the field to the median depth to BFW for petroleum wells in the field

- Because depths are grouped for the entire field prior to calculating the vertical distance, topographic features within a field may make depth comparisons between wells less reliable

- Provided vertical proximity for 13 fields (7 percent of the attributed fields)

Method 4

- Compares the median depth to TOP for petroleum wells in the field to the median TD for water wells overlying the field

- Similar to method 3, topographic features within a field may make depth comparisons between wells less reliable

- Provided vertical proximity for only 1 field, because water wells overlying fields were generally within 1.25 miles of a petroleum well

Method 5

- Computes the median depth to TOP for petroleum wells

- Least robust of the methods because the depth of groundwater resources is not taken into account

- Provided vertical proximity for 9 fields (5 percent of the fields that were attributed)

Figure 5. Methods used to calculate vertical separation distance between petroleum resource development and groundwater resources for each oil and gas field in California.

Figure 6. Location of oil and gas fields in California and the method number for calculating vertical separation distance for each field in A, California Division of Oil, Gas, and Geothermal Resources (DOGGR) districts 1–5 and B, DOGGR district 6.

B

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Calculation method for separation distance

1

2

None

DWR groundwater basins

DOGGR district boundary

County

Figure 6.   —Continued

The range of values that defined each category was chosen based on the data distribution shown in histograms (figs. 7A–D) and the occurrence of natural breaks, or inflection points, in the data. One method for dividing up the fields into three categories is to rank the fields by each variable and place the lowest ranked one-third of the fields in the low category, the middle one-third in the moderate category, and the upper one-third in the high category. Another method is to use the interquartile range for the moderate category, the lower quarter of fields for the low category, and the upper quarter of fields for the high category. However, more than half of the fields had values of zero for some variables, such as density of injection wells and total volume of water or steam injection (figs. 7A, B). These variables had left-skewed distributions with 50 percent or more of the data having the lowest values and a long right tail, for some variables exceeding a range of three or four orders of magnitude (for example, total volume of water or steam injection had a 50th percentile value of 6.7 MMB, 90th percentile of 140 MMB, and maximum of 18,178 MMB). Therefore, the targeted boundary between the low and moderate categories was shifted up from the 25th or 33rd percentile to the 50th (median) or 75th percentile, depending upon which value was closest to break points, or inflection points, where the frequency of occurrence of higher values decreased substantially. The targeted range of values defining the low-risk category was the 0th (minimum) to 50th percentile for density of all petroleum wells, density of injection wells, density of waste-disposal wells, and density of water wells overlying the field (table 2). The 50th percentile to maximum of separation distance was the targeted range of values for defining the low-risk category of inversely-proportion vertical proximity. The range of values defining the low category for total volume of water or steam injection, total volume of injection for waste disposal, and density of water wells adjacent to field was targeted as the minimum to 75th percentile. The boundary between the moderate and high categories was approximated by the 90th percentile for all variables except vertical proximity, so that the high range included only the top 10 percent of fields and the moderate range included 15–40 percent of the fields. For vertical proximity, the boundary between moderate and high risk-categories was approximated by the 25th percentile of the separation distance values, so that 25 percent of the fields would be in each of the high and moderate categories and 50 percent of the fields would be in the low category. The values that delineated the boundaries between categories were often rounded from the targeted percentiles resulting in variations in the percentages of fields in each category.

Determining Overall Priority Classifications

Oil and gas fields were ranked for each of the individual variables measuring the intensity of oil and gas development activities and proximity to groundwater resources. From these rankings, a summary classification of high, moderate, or low priority was assigned to each oil and gas field. A hierarchy based on the expected effect on the imminence of

groundwater contamination that each of the factors represents was developed to determine the order in which they were considered (fig. 8). The decision process that was used for classifying all oil and gas fields is shown in more detail in figure 8.

The ranking for the factor petroleum-well density was determined by the highest ranking assigned among the three density variables: density of all petroleum wells, density of injection wells, and density of waste-disposal wells. Similarly, the ranking for volume of injection was determined by the higher ranking assigned between the two volume variables: total volume of water or steam injection and total volume of water injection for waste disposal only. The ranking for the factor water-well density was determined by rankings for densities of water wells overlying and adjacent to fields: fields ranked high in overlying water-well density or moderate in overlying density and high in adjacent water-well density were ranked high, fields that had low overlying and adjacent water-well densities were ranked low, and all other fields were ranked moderate.

For assignment of the summary priority, vertical proximity was considered first, followed by injection volume, petroleum-well density, and lastly water-well density (fig. 8). Fields that had petroleum resource development closest to groundwater resources (vertical separation distance of 1,000 ft or less) were categorized as high priority for the purpose of identifying where regional groundwater monitoring should be implemented first. Fields that had the greatest injection volumes (top decile of all fields) were classified as high priority. For the other fields, combinations of injection volume, petroleum-well densities, and overlying and adjacent water-well densities were considered. Fields were not assigned to a lower summary priority classification than their ranking for the injection volume factor; however, some fields had lower summary priority classifications than their ranking for the petroleum-well density factor. For example, fields that ranked high for petroleum-well density and low for injection volume were classified as moderate for summary priority. This is because fields with these characteristics generally had high petroleum-well density owing to small field size but contained few oil and gas wells overall (appendix table 1–1), had no records of water injection, and vertical proximity of resources was unknown or considered low risk.

Water-well density was factored in to the classifications to determine if a field that had intermediate rankings for other factors would be moved into the low or high summary priority category. The rankings for variables measuring water-well density (densities of water wells overlying and adjacent to fields) were applied to the overall priority classifications based on the algorithm shown in figure 8. Fields ranked moderate for injection volume, moderate for petroleum-well density, and high for water-well density (either overlying or adjacent) were classified as high for summary priority because there is potentially substantial lateral overlap of resources. Fields ranked low for injection volume, moderate for petroleum-well density, and low for overlying and adjacent water-well density were classified as low for summary priority.
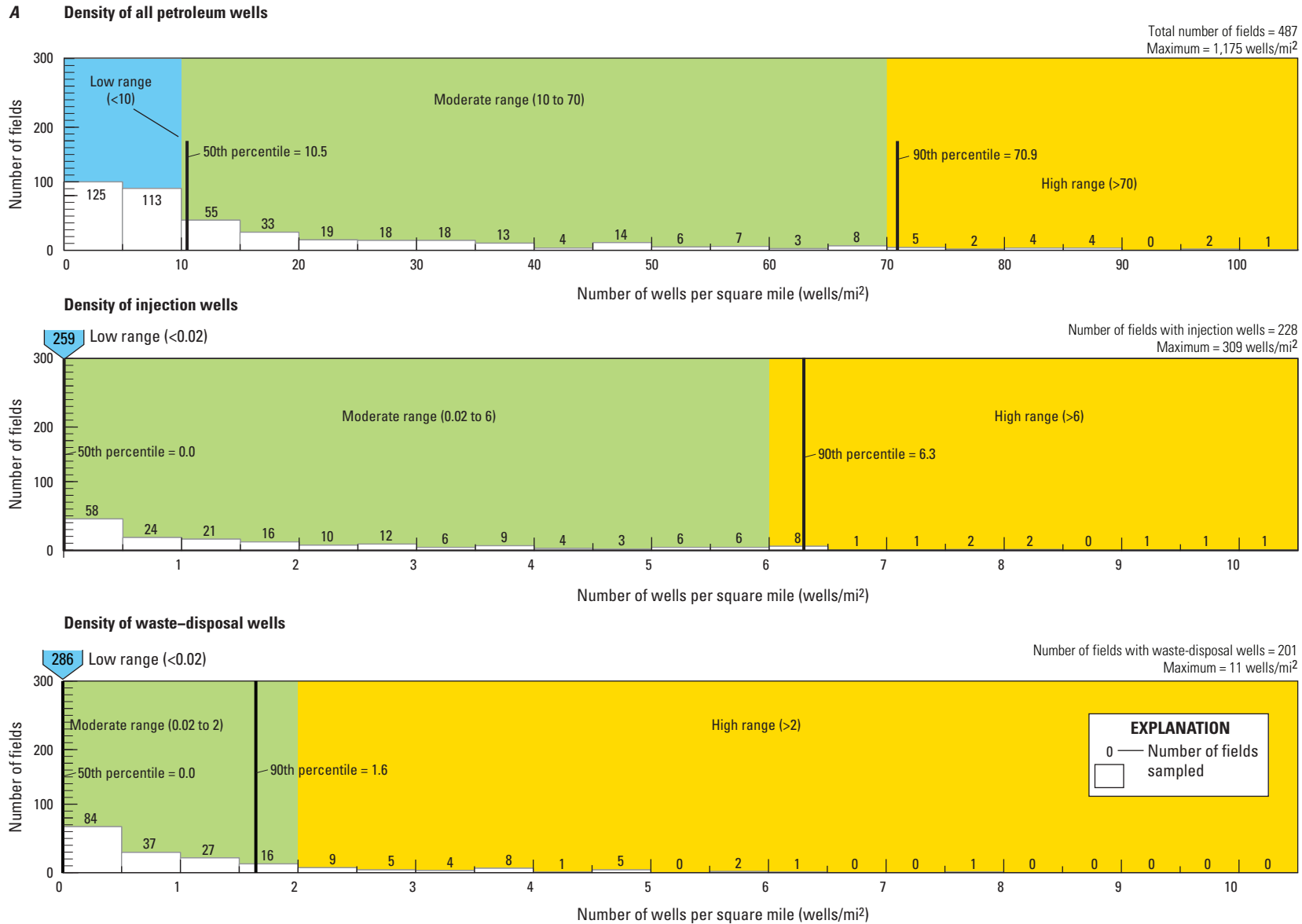
Figure 7. Distribution of data for individual variables calculated for California oil and gas fields in the preliminary assessment of petroleum resource development and proximity to groundwater resources: *A*, density of all petroleum wells, injection wells, and waste-disposal wells; *B*, total volume of water and steam injection and volume of water injection for waste-disposal; *C*, vertical proximity using combined methods, method 1, and method 2; and *D*, density of overlying water wells and adjacent water wells.

B   **Volume of total water and steam injection**
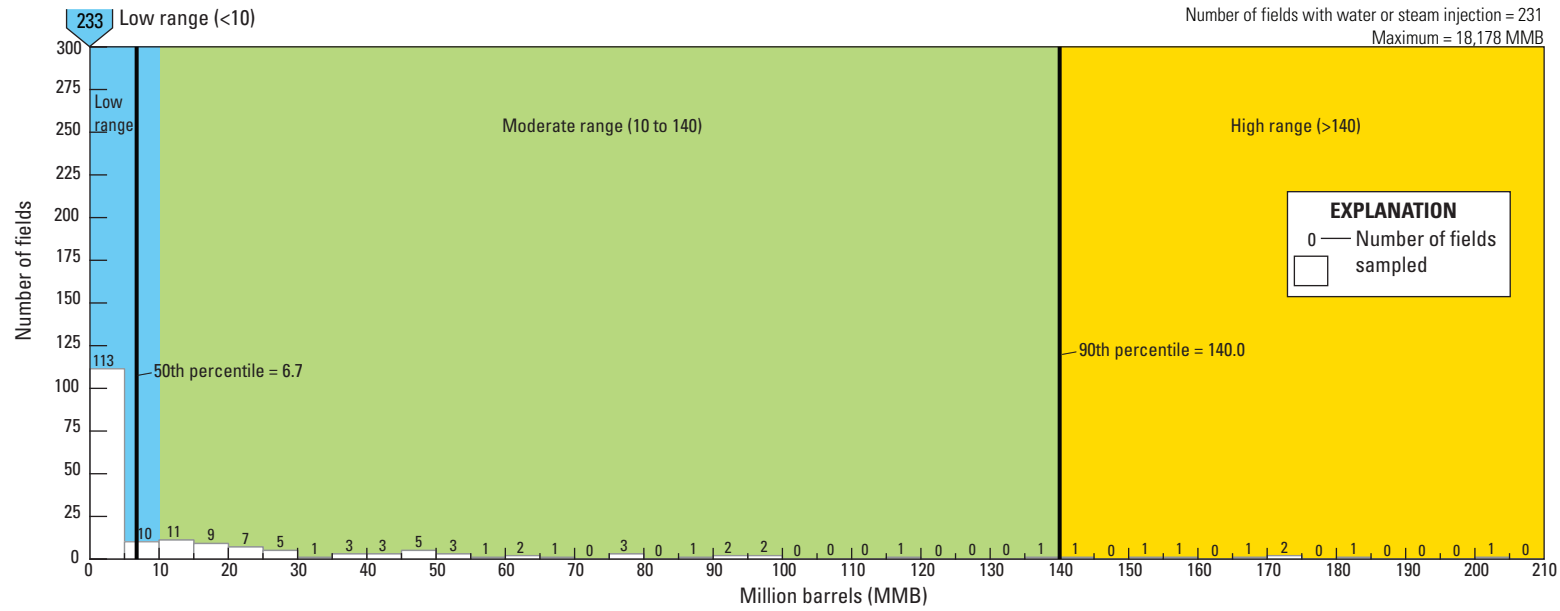
Volume of waste-water injection

Figure 7.   —Continued

c

Vertical separation distance using combined methods

Total number of fields with separation distance = 174

Vertical separation distance using method 1

Number of fields with method 1 separation distance = 87

Vertical separation distance using method 2

Number of fields with method 2 separation distance = 145

Figure 7. —Continued

Density of water wells overlying the field

Density of water wells adjacent to the field

Figure 7.   —Continued

Prioritization analysis decision tree
(Number on line indicates number of fields)

Fields were ranked by each factor into the high, moderate, and low categories for potential risk to groundwater resources using the threshold values listed in table 3. Rankings were then combined to determine the overall priority classification for each oil and gas field by using the decision process and hierarchy of factors shown in this figure.

Vertical proximity classification has an inverse relation with separation distance: smaller distances correspond to greater proximity and higher potential risk categories. The injection-volume classification was determined by the higher ranking of the two volume calculations: total volume of water or steam injection and total volume of waste-water injection. The petroleum-well density classification was determined by the highest ranking of the three well density calculations: all petroleum wells, injection wells, or waste-disposal wells. The water-well density classification was determined using a combination of rankings for overlying and adjacent water-well densities.

Figure 8. Decision process and hierarchy of factors considered as part of the prioritization analysis in which California oil and gas fields are classified as high, moderate, low priority for regional groundwater monitoring.

Results of the Preliminary Assessment of Factors for Prioritization

For each of the variables representing petroleum-well density, around 10 percent of the fields were in the high category, around 40 percent were in the moderate category, and around 50 percent were in the low category (table 2). The 90th percentile was chosen as the moderate-high boundary for the variables representing petroleum-well density because the data spanned a wide range and some fields having values greater than the 90th percentile had dramatically larger petroleum-well densities than most of the fields (fig. 7A). The 90th percentile selected as the boundary between the high and moderate categories was rounded from 6.3 wells/mi^2 to 6 wells/mi^2 for density of injection wells and rounded from 1.6 wells/mi^2 to 2 wells/mi^2 for density of waste-disposal wells. Less than half of the oil and gas fields contained injection wells; therefore, the boundary between the moderate and low categories for both the density of injection wells and density of waste-disposal wells was the smallest non-zero value (0.02 wells/mi^2), equal to the 53rd and 58th percentiles, respectively. The 50th percentile approximated a change in the frequency distribution of petroleum-well density values, with a relatively large number of fields having densities less than 10 wells/mi^2.

For each of the variables representing volume of injection, around 10 percent of the fields were in the high category, around 15 percent were in the moderate category, and around 75 percent were in the low category (table 2). The percentiles for total volume of water or steam injection and total volume of water injection for waste disposal were calculated from the 464 fields that had data. About half of the fields had water or steam injection, and total volumes of water injection per field were much greater than volumes of waste-water disposal (fig. 7B). The 23 fields that did not have any injection or production records available online were generally small (up to 3 mi^2), contained few wells, and were mostly abandoned (fields coded as "na" for injection-volume variables; appendix table 1–1); these fields were grouped into the low risk category for each of the injection-volume variables. The 75th percentile was used for the boundary between low and moderate categories for total water or steam injection and for volume of waste-water injection because it was close to a substantial change in the frequency distribution for water injection volumes by field and therefore represented a logical threshold for separating fields with lower values from those with higher injection volumes (fig. 7B).

About 36 percent of the oil and gas fields were assessed for vertical proximity (174 of the 487 fields; fig. 6) based on median vertical separation distance between petroleum resource development to groundwater resources. Separation distance was calculated for oil and gas fields with sufficient data using a combination of five methods. Separation values from each method, the principal method

used to define separation, and the resulting classification for vertical proximity for each of the 174 fields are presented in table 3. Separation distance values were positive if petroleum development activities were generally deeper than groundwater resources and negative if petroleum development activities were shallower than groundwater resources. Note that greater potential risk to groundwater resources is represented by greater values for the density and injection-volume variables, whereas greater potential risk is represented by smaller values for vertical separation (that is, less distance between petroleum resources and groundwater resources, or greater proximity). Separation distance values were generally greater as calculated from method 2 than from method 1 (fig. 7C). Values for vertical separation had a broad distribution, with the most frequently occurring values in the central part of the distribution and a longer right tail of large separation values (lowest proximity) than the left tail (greatest proximity).

The values that defined the boundaries between ranges were round numbers close to the 50th and 25th percentiles for the combination of all methods applied and for methods 1 and 2 (the primary methods that were used to define median separation distance for the fields; fig. 7C). The proportion of total number of fields with vertical proximity in each of the high-, moderate-, and low-risk categories and the proportion of total fields in each district and statewide are listed in table 4. About 23 percent of fields with oil and gas resources closest to groundwater resources (separation distance less than 1,000 feet [ft]) were classified in the high-risk category for vertical proximity, which corresponds to 8 percent of the total 487 fields (table 4). The next approximately one-third of fields with vertical separation distance between 1,000 to 3,000 ft were in the moderate-risk category, and the 44 percent of the fields with separation greater than 3,000 ft were in the low-risk category. The true threshold at which groundwater throughout California is less vulnerable to oil and gas development is unknown. A vertical distance of 3,000 ft was used in this study, classifying about half of the fields with sufficient depth data in the low-risk category for vertical proximity.

For density of water wells overlying the field, 10 percent of the fields were in the high category, 34 percent were in the moderate category, and 56 percent were in the low category (table 2). For density of water wells adjacent to the field, 12 percent of the fields were in the high category, 11 percent were in the moderate category, and 77 percent were in the low category. About two-thirds of the oil and gas fields had at least one overlying water well and nearly all fields had at least one adjacent water well within 3.1 miles of field administrative boundaries (fig. 7D). Densities of overlying water wells were generally greater than densities of adjacent water wells. This difference was likely not because of greater water use within field boundaries compared to just outside the fields, but because water wells were plotted at the center of the section in which they are located (see "Methods" section titled "Calculation of Variables").

A buffer may contain part of a section, but the wells in that section were not included in the well-density calculation unless the buffer passed through the center of the section. Conversely, administrative boundaries for oil and gas fields often traced along section boundaries or bisected a section, resulting in more water wells being included in the well density overlying the field. Water-well densities spanned a relatively narrow range of values compared to the petroleum-well densities (fig. 7D). Values near the 90th percentiles were selected as the boundary between the moderate and high categories for density of overlying water wells and density of adjacent water wells because use of the 90th percentiles resulted in a clear separation of fields having substantially higher well densities. For overlying water-well density, the 50th percentile approximated the boundary between low and moderate categories, above which the frequency of occurrence of values gradually declined. In contrast, the 75th percentile approximated the boundary between low and moderate categories for adjacent water-well density, because it was an approximate inflection point in the frequency distribution of adjacent well-density values.

Results of the Prioritization Analysis

The prioritization analysis is a statewide reconnaissance assessment of potential risk to groundwater from oil and gas development using existing data for the purpose of identifying where regional monitoring should be implemented first. A preliminary analysis of petroleum resource development and the proximity to California's groundwater resources was followed by classification of oil and gas fields into overall priority classes.

Petroleum resource development and proximity to groundwater resources were assessed for oil and gas fields using a combination of rankings of calculated values for variables delineating petroleum-well density, volume of injection, vertical proximity, and water-well density. Based on variable-specific rankings for density of all petroleum wells (fig. 9A), injection wells (fig. 9B), and waste-disposal wells (fig. 9C), 84 fields had high petroleum-well density, 218 fields had moderate petroleum-well density, and 185 fields had low petroleum-well density (table 5). Based on variable-specific rankings for total volume of water and steam injection (fig. 9D) and total volume of waste-water injection (fig. 9E), 62 fields were classified in the high category for volume of injection, 75 fields had moderate volume of injection, and 350 fields had low volume of injection. Of the 174 fields with vertical separation distance values, 39 fields were classified in the high-risk category for vertical proximity of oil and gas resource development to groundwater resources (greatest proximity), 58 fields were in the moderate-risk category, and 77 fields were in the low-risk category (table 4; fig. 11).

Based on rankings for density of water wells overlying the field (fig. 9F) and density of water wells adjacent to the field (fig. 9G), 67 fields had high water-well density, 158 fields had moderate water-well density, and 262 fields had low water-well density. Only four fields had no overlying or adjacent water wells; two of these fields were categorized as high priority based on high petroleum-well density and moderate volume of injection. Calculated values for the individual variables and the rankings for factors used in the prioritization analysis are listed in tables 6A–C.

The prioritization of fields for regional groundwater monitoring resulted in 107 fields classified as high overall priority, 114 fields as moderate priority, and 266 fields as low priority (table 5; fig. 10). On an area-weighted basis, 41 percent of the aggregated field area ranked high priority, 30 percent ranked moderate, and 29 percent ranked low. Of the 107 high priority fields, 39 fields (36 percent) were classified as high priority based on vertical proximity, 42 fields were classified as high priority based on high volume of injection, and the other 26 fields classified as high priority had moderate volume of injection coupled with high petroleum-well density or had a combination of moderate and high risk classifications for petroleum-well density and water-well density (table 6A; fig. 8). Often, fields that had petroleum resource development vertically closest to groundwater resources also had high petroleum-well density: 28 of 39 of the fields that had the greatest vertical proximity also had high petroleum-well density or high volume of injection.

Fields were classified as having overall moderate or low priority primarily based on a combination of moderate and low rankings for three of the major factors considered: volume of injection, petroleum-well density, and water-well density (table 6B, C; fig. 8). A total of 43 fields that had moderate injection volume were classified as moderate priority (table 6B). For the 337 remaining fields that had low injection volume, overall priority classifications were based on rankings for well densities: 71 fields were classified as moderate priority based on a synthesis of rankings for petroleum-well density and water-well density; 183 fields that had low petroleum-well density were classified as low priority (table 6C); and 83 fields that had moderate petroleum-well density and low water-well density were classified as low priority. Whereas petroleum resource development and vertical proximity often co-occurred, high water-well density was generally not in areas with greatest density of oil and gas production activities. Only 13 fields had high water-well density and also were ranked high for either volume of injection or petroleum-well density. On average, low priority fields presented the least amount of risk to groundwater resources based on low volume of injection and low or moderate petroleum-well density (table 6C). Results of the prioritization analysis, including maps of fields, their priority classification, and rankings for each factor, are summarized in more detail by DOGGR district.
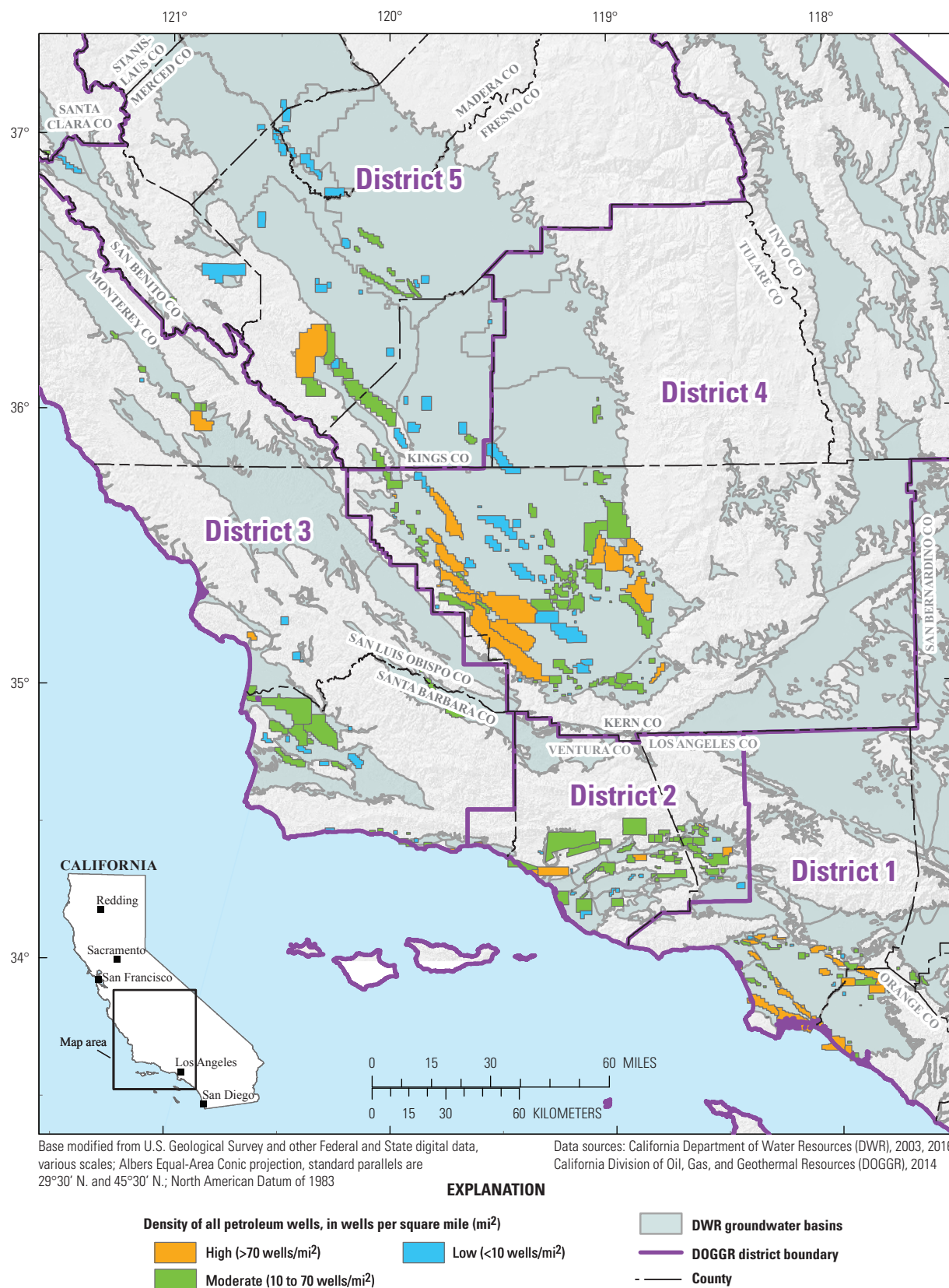
Figure 9. California oil and gas fields showing rankings for each of the variables: *A*, density of all petroleum wells; *B*, density of injection wells; *C*, density of waste-disposal wells; *D*, total volume of water and steam injection; *E*, total volume of water injection for waste disposal; *F*, density of water wells overlying the field; and *G*, density of water wells adjacent to the field.

A—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Density of all petroleum wells, in wells per square mile (mi²)

- Moderate (10 to 70 wells/mi²)
- Low (>10 wells/mi²)

- DWR groundwater basins
- DOGGR district boundary
- County

Figure 9.   —Continued

B

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Density of injection wells, in wells per square mile (mi²)

- High (>6 wells/mi²)
- Low (<0.02 wells/mi²)
- Moderate (0.02 to 6 wells/mi²)

- DWR groundwater basins
- DOGGR district boundary
- County

Figure 9.   —Continued

B—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Density of injection wells, in wells per square mile (mi²)

High (>6 wells/mi²)

Moderate (0.02 to 6 wells/mi²)

Low (<0.02 wells/mi²)

DWR groundwater basins

DOGGR district boundary

County

Figure 9.   —Continued

c

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Density of waste-disposal wells, in wells per square mile (mi²)

High (>2 wells/mi²)   Low (<0.02 wells/mi²)

Moderate (0.02 to 2 wells/mi²)

DWR groundwater basins

DOGGR district boundary

County

Figure 9.   —Continued

C—Continued

Figure 9. —Continued

D

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Total volume of water and steam injection, in million barrels (MMB)

- High (>140 MMB)
- Low (<10 MMB)
- Moderate (10 to 140 MMB)
- DWR groundwater basins
- DOGGR district boundary
- County

Figure 9.   —Continued

D—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Total volume of water and steam injection

Moderate (10 to 140 MMB)   Low (<10 MMB)

DWR groundwater basins

DOGGR district boundary

County

Figure 9.   —Continued

Figure 9. —Continued

E—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Total volume of water injection for waste disposal, in million barrels (MMB)

High (>25 MMB)

Moderate (2.5 to 25 MMB)

Low (<2.5 MMB)

DWR groundwater basins

DOGGR district boundary

County

Figure 9.   —Continued

F

EXPLANATION

Density of water wells overlying the field, in wells per square mile (mi²)

High (>8 wells/mi²)

Low (<1 well/mi²)

Moderate (1 to 8 wells/mi²)

DWR groundwater basins

DOGGR district boundary

County

Figure 9.   —Continued

F—Continued

Figure 9. —Continued

G
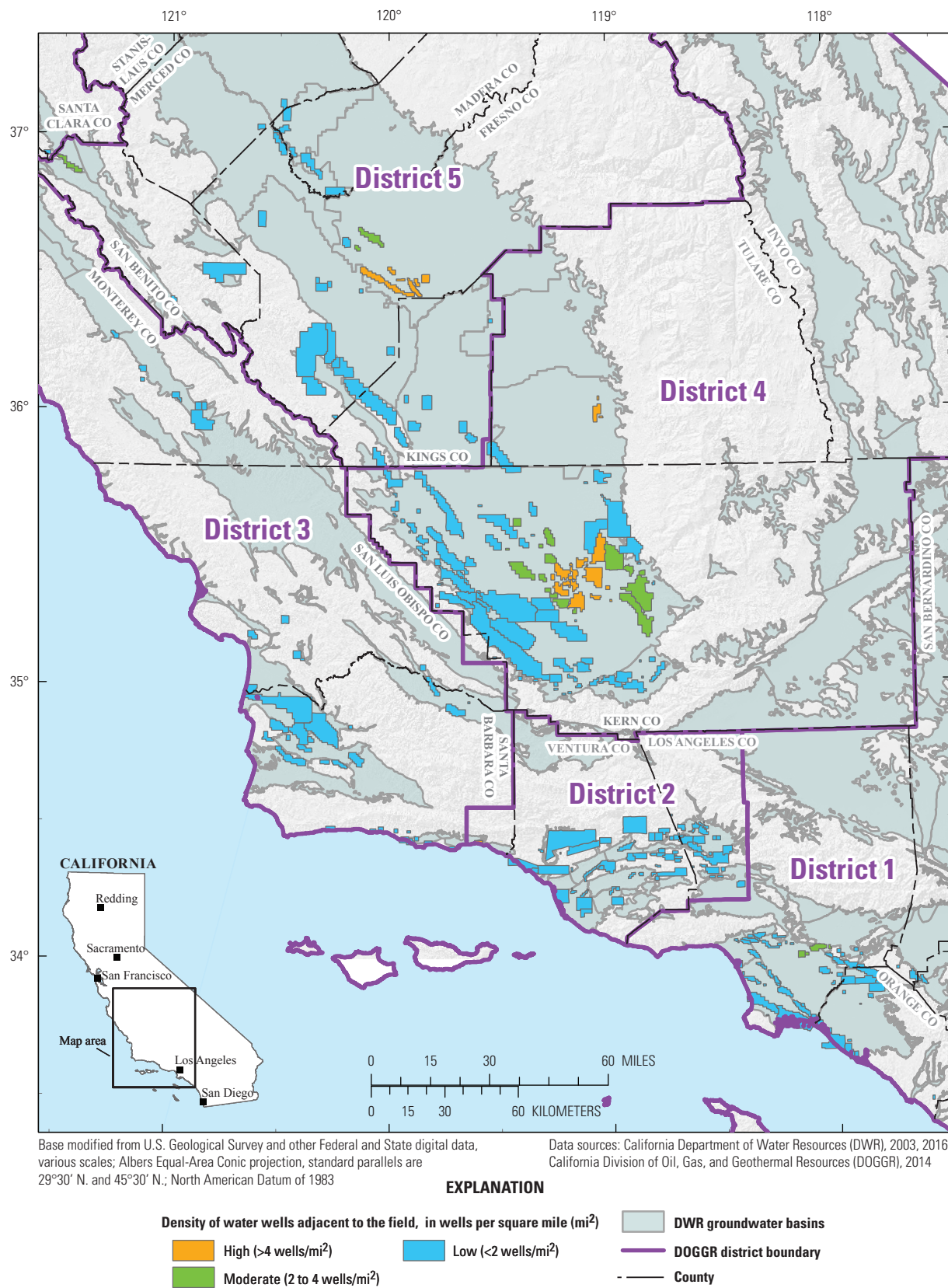
Figure 9. —Continued

G—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data,
various scales; Albers Equal-Area Conic projection, standard parallels are
29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016;
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014
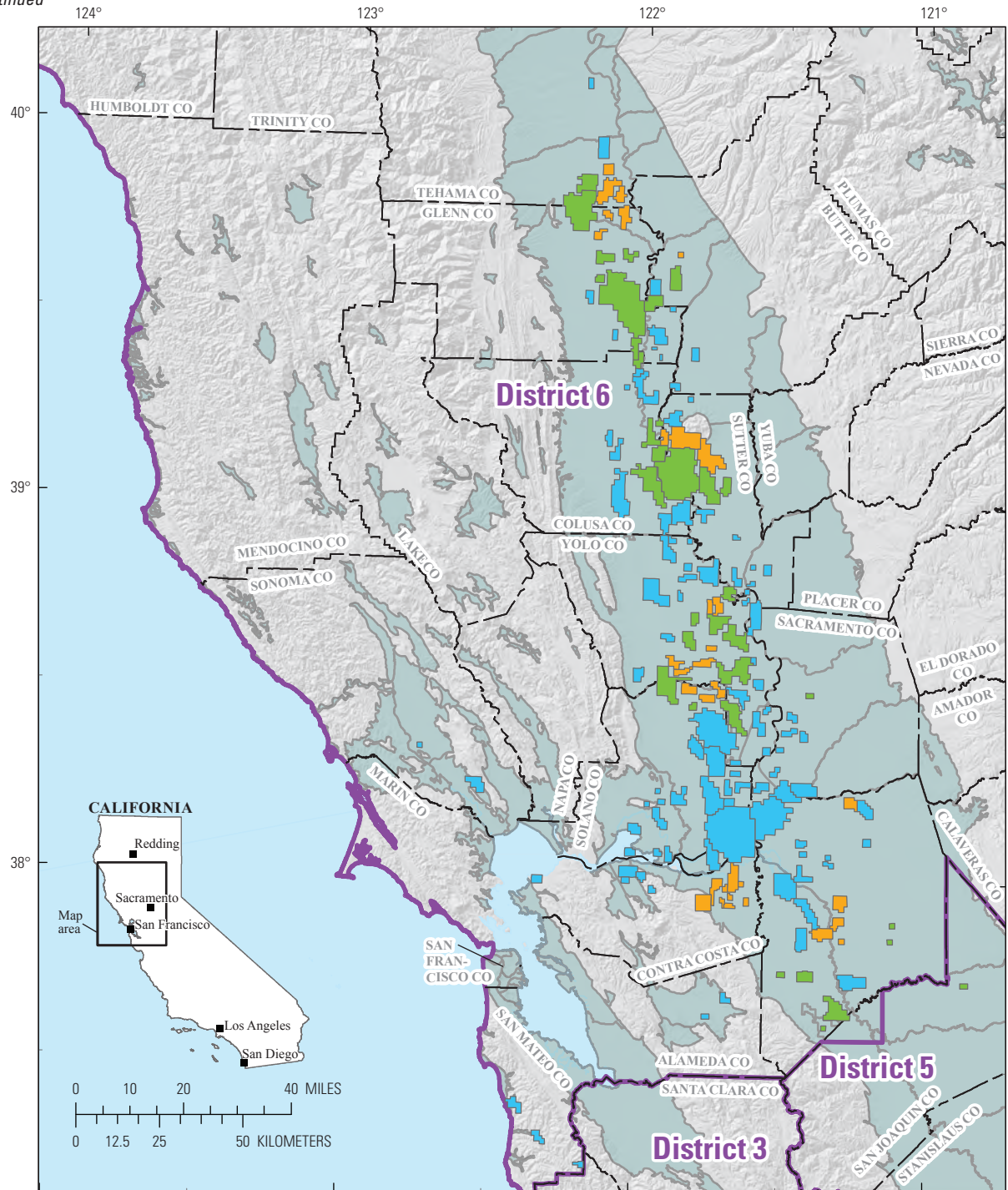
EXPLANATION

Density of water wells adjacent to the field, in wells per square mile (mi²)

High (>4 wells/mi²)   Low (<2 wells/mi²)

Moderate (2 to 4 wells/mi²)

DWR groundwater basins

DOGGR district boundary

County

Figure 9. —Continued

A
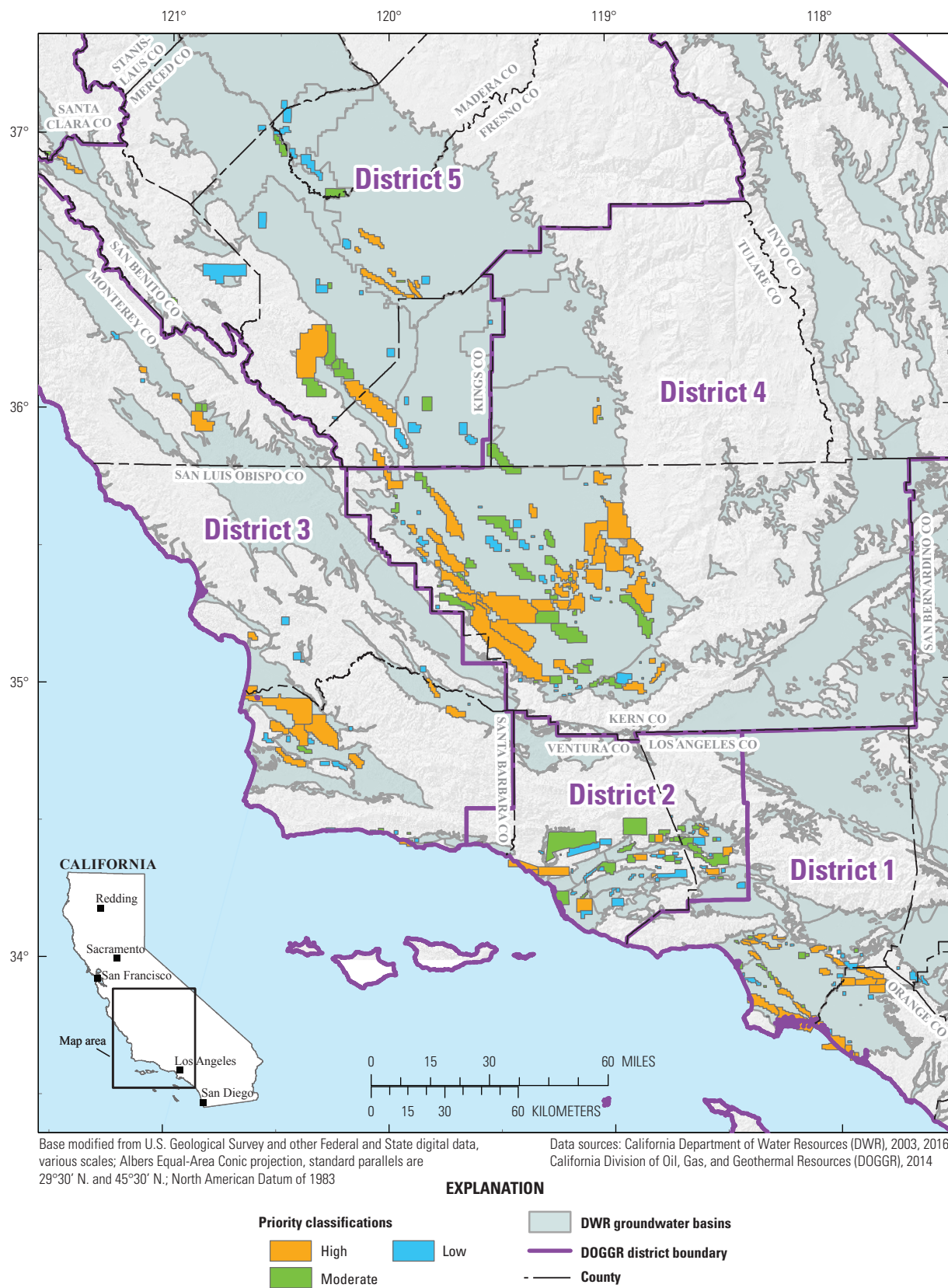
Figure 10.   Overall priority classification for oil and gas fields in *A*, California Division of Oil, Gas, and Geothermal Resources (DOGGR) districts 1–5 and *B*, DOGGR district 6.

B

CALIFORNIA

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014; California Department of Water Resources (DWR), 2003; California State Water Resources Control Board, 2016; Davis and others, 2017

EXPLANATION

Priority classifications

High
Moderate
Low

DWR groundwater basins
DOGGR district boundary
County

Figure 10. —Continued

Figure 11.   Vertical separation distance values calculated using a combination of methods for each oil and gas field with sufficient data by California Division of Oil, Gas, and Geothermal Resources (DOGGR) district: *A*, district 1; *B*, district 2; *C*, district 3; *D*, district 4; *E*, district 5; and *F*, district 6.
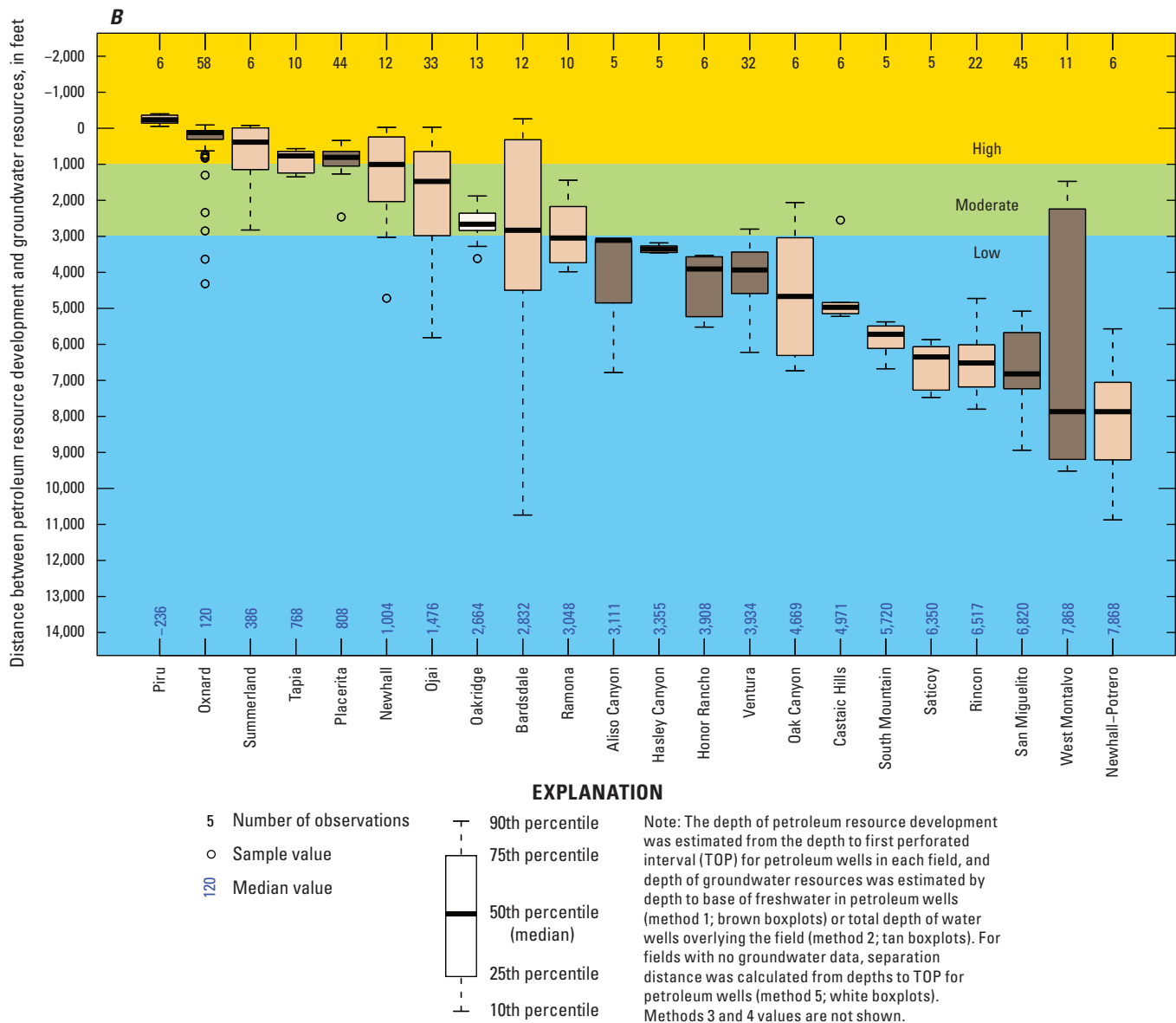
Figure 11.   —Continued
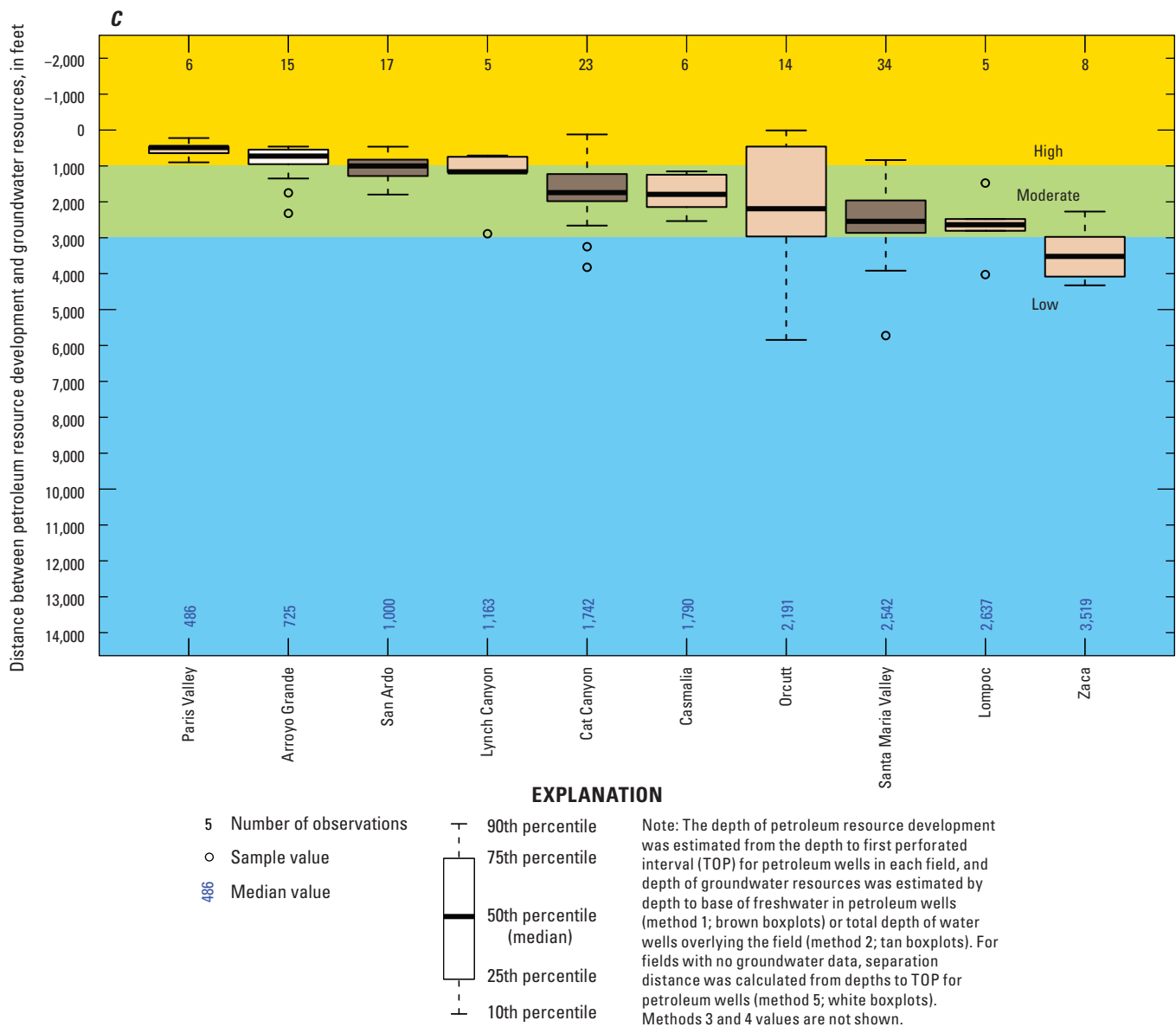
Figure 11.   —Continued
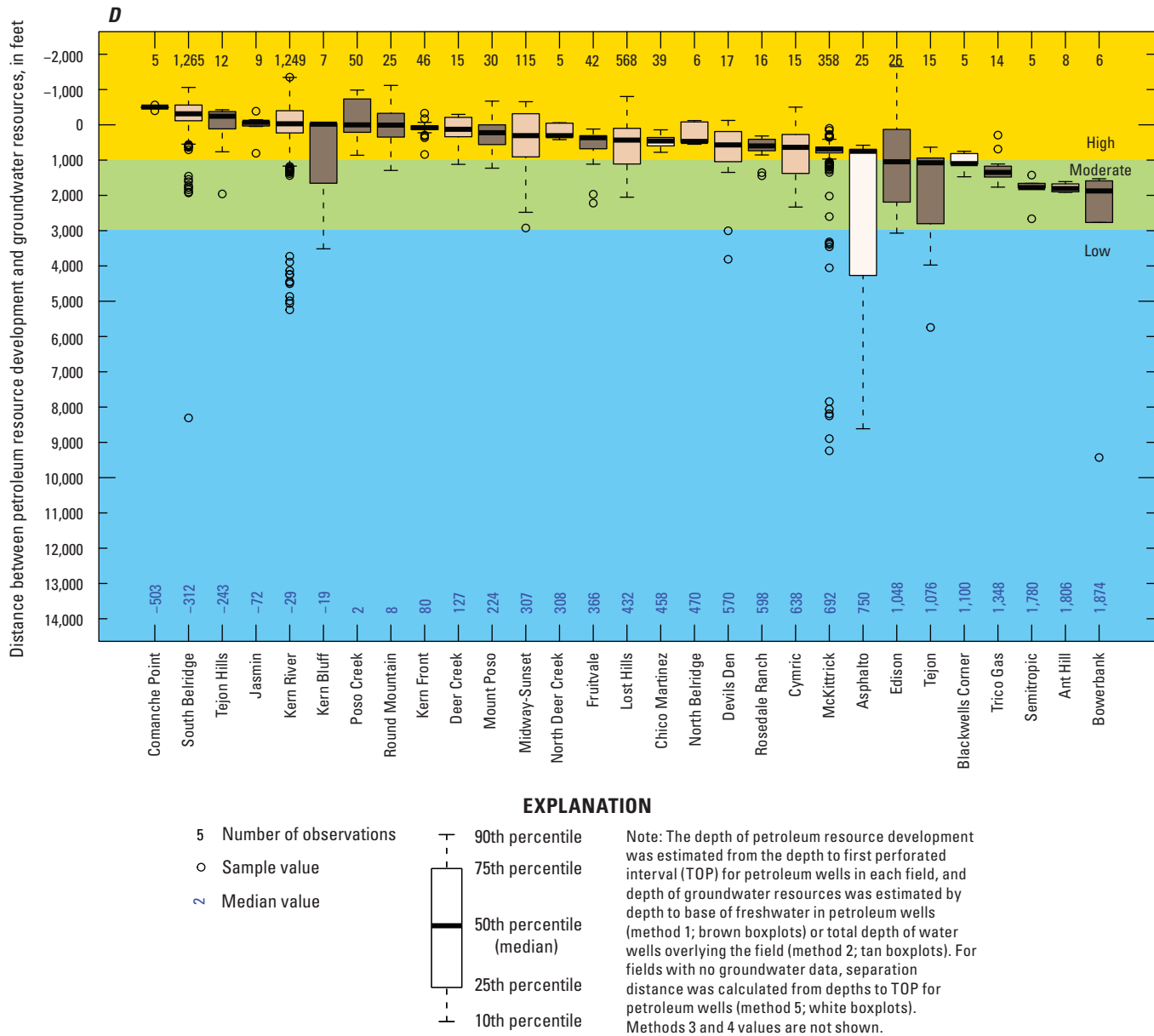
Figure 11. —Continued
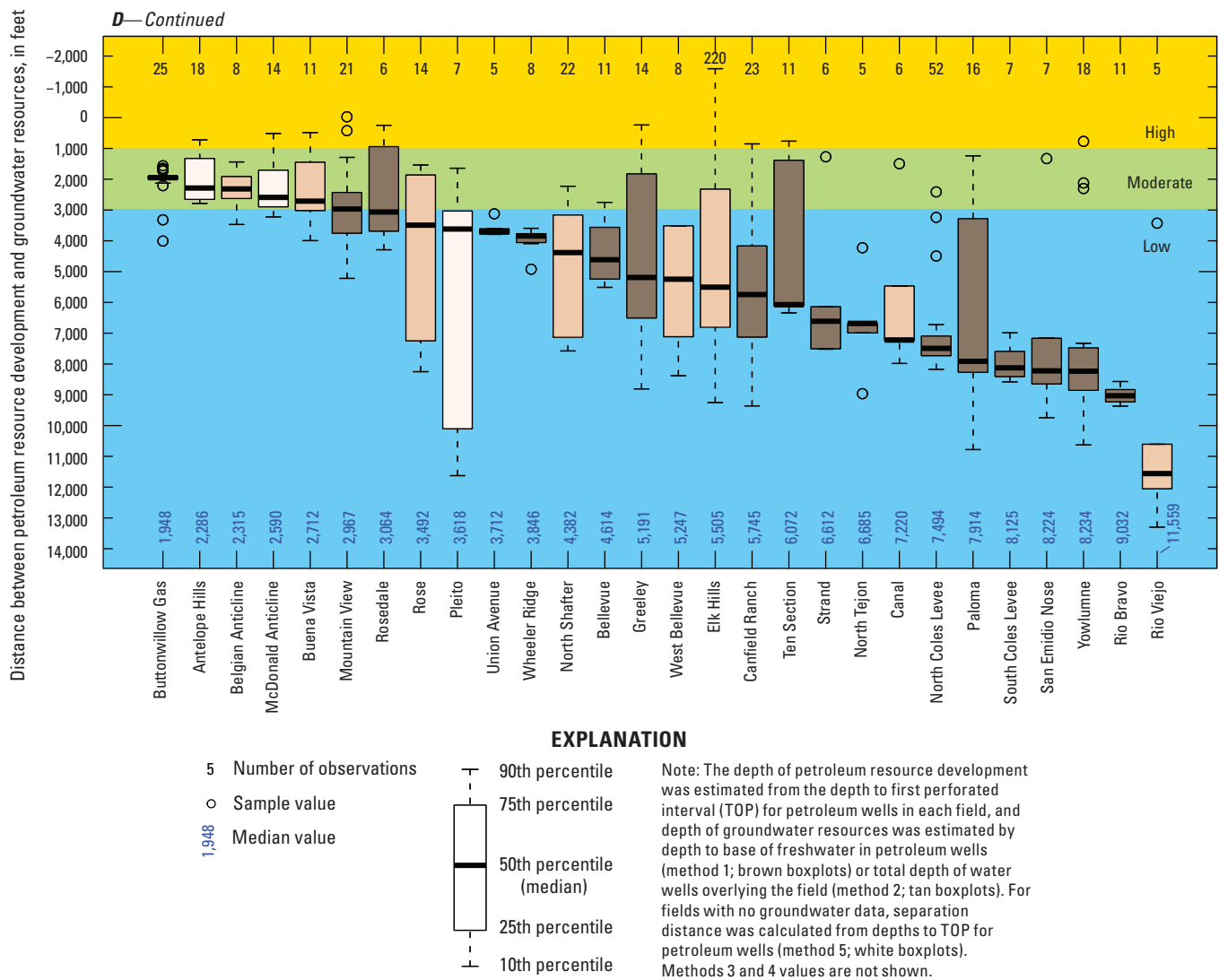
Figure 11.   —Continued
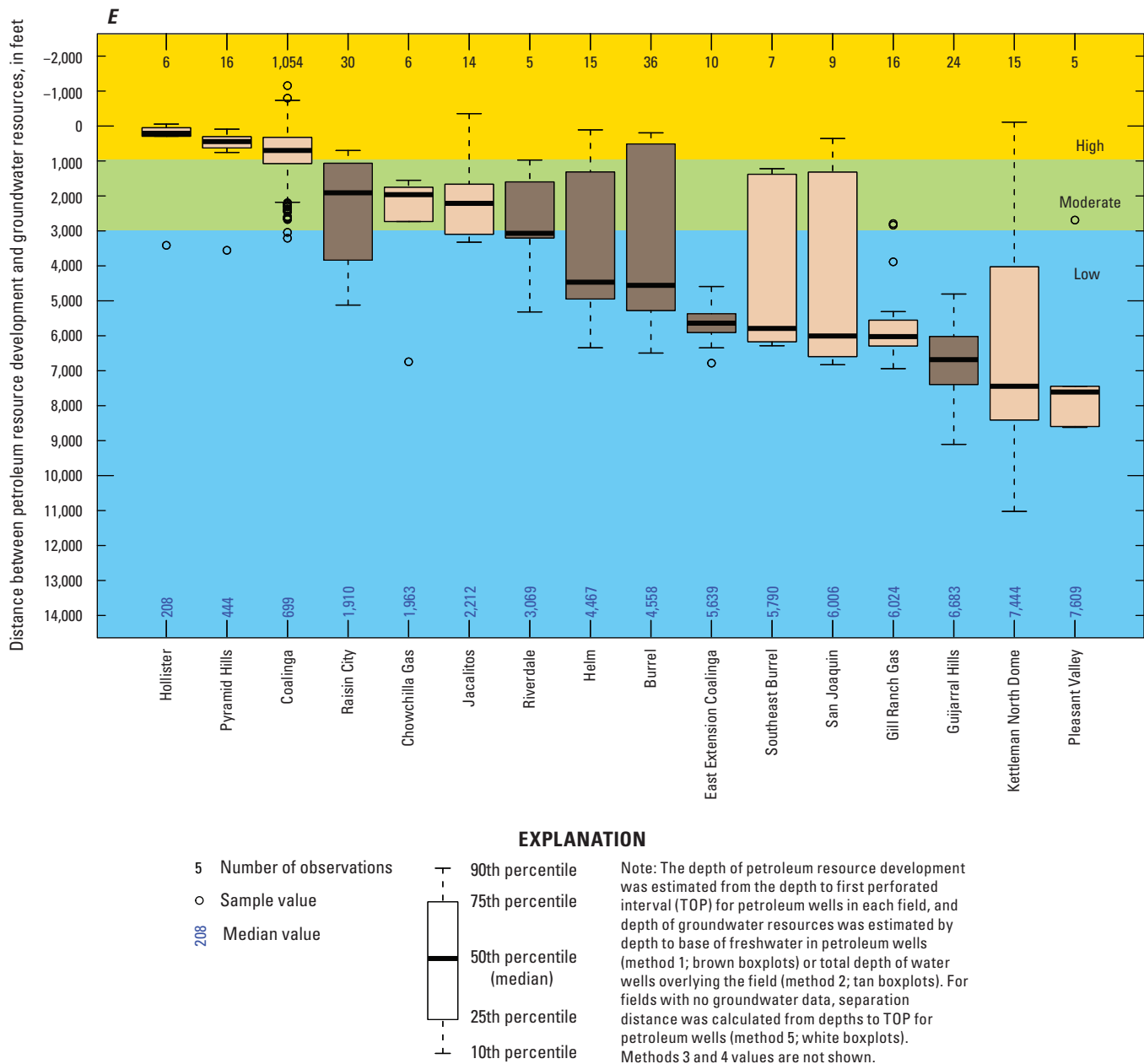
Figure 11. —Continued
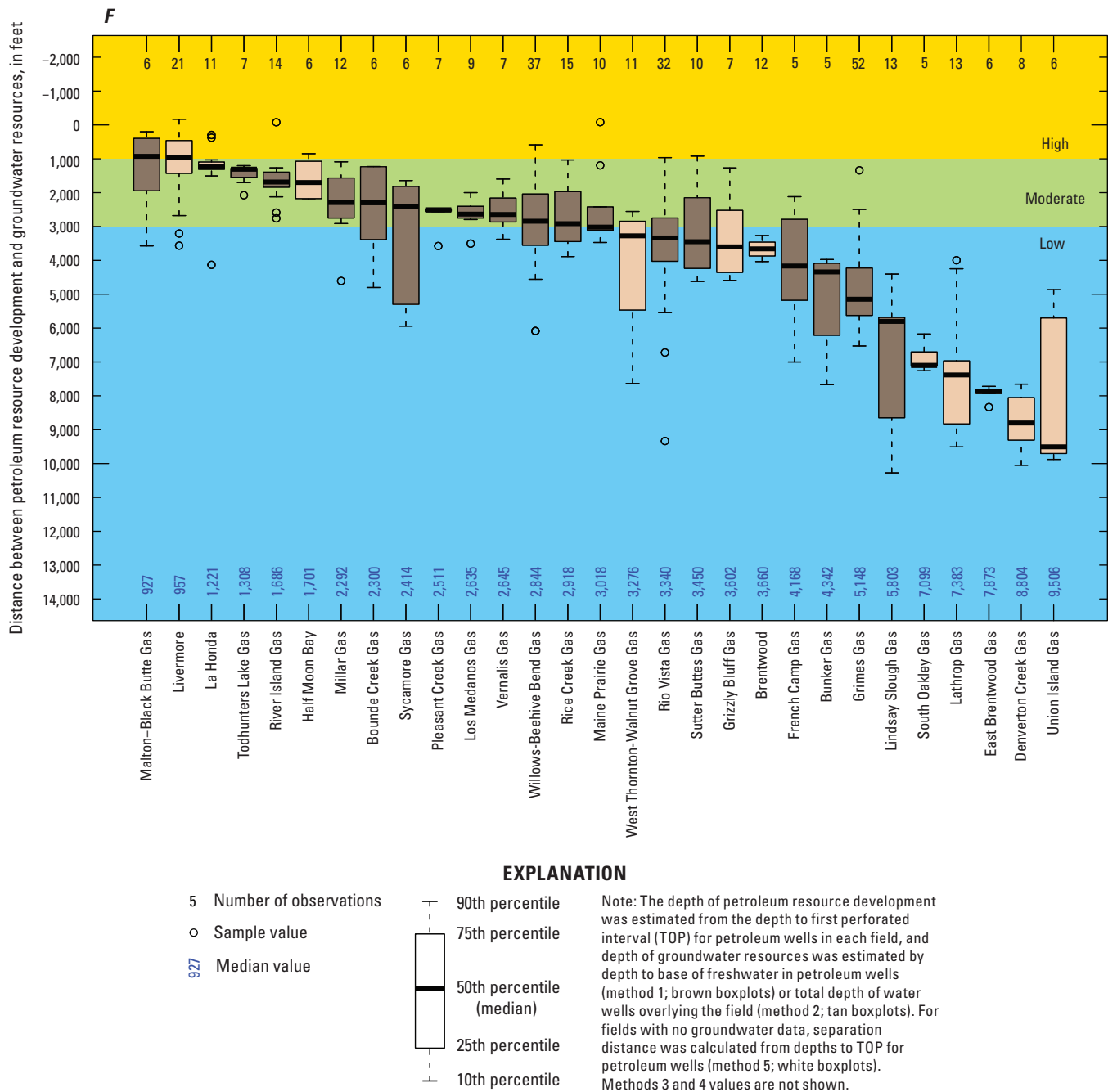
Figure 11.   —Continued

District 1 (Los Angeles Basin)

District 1 covers the southern end of California from the international boundary to San Bernardino County (fig. 12A). The 67 oil and gas fields in district 1 represent the smallest aggregated field area of the districts (214 mi²; table 5) and are primarily within the coastal plain of Los Angeles and Orange Counties. The Los Angeles Basin is centered on a northwest-trending syncline bordered by the Newport-Inglewood fault zone in the southwest and the Whittier fault zone in the northeast (Beyer, 1995). There is a long history of intensive oil and gas development in the Los Angeles Basin. Gautier and others (2012) estimated a mean of 3.2 billion barrels of remaining oil in the most productive oil fields in the Los Angeles Basin. Enhanced oil recovery techniques have been used in many of these fields to recover remaining oil. The Los Angeles Basin coincides with the Coastal Plain of Los Angeles and Coastal Plain of Orange County groundwater basins, which are separated by the Los Angeles-Orange County line (California Department of Water Resources, 2016). The northeastern parts of these coastal groundwater basins are considered to have higher recharge to underlying deposits, and the central and western parts of the groundwater basins are areas in which groundwater percolation is impeded by lower permeability deposits and groundwater is confined (California Department of Water Resources, 2015). Eleven district 1 fields are in or near the San Gabriel Valley groundwater basin and Upper Santa Ana Valley groundwater basin in San Bernardino and Riverside Counties (fig. 12A).

For district 1, 37 percent of the fields (25 fields) were classified as high priority, 19 percent (13 fields) were moderate, and 43 percent (29 fields) were low (table 5). High overall priority classification was primarily based on high intensity of petroleum resource development and, for a few fields, vertical proximity to groundwater resources. Of the 25 fields in district 1 classified as high overall priority, 24 fields had high petroleum-well density and moderate or high volume of injection, 4 fields had close vertical proximity of resources, and none had high water-well density (table 6A; figs. 12A–E). For fields with high volume of injection, oil field injection volumes were predominantly for the purposes of enhanced oil recovery. High-priority fields were generally the largest fields that accounted for the majority of the district's field area. By area, 79 percent of the total area of district 1 oil and gas fields was classified as high priority, 7 percent was moderate, and 14 percent was low (table 5). Otherwise, fields had physical characteristics that indicated moderate to low risk to groundwater resources. Vertical proximity of petroleum resource development to groundwater resources was most frequently moderate and low. Water-well density was typically low in and near oil and gas fields, particularly at fields along the edges of the groundwater basins.

Petroleum resource development in district 1 was relatively far from groundwater resources compared to oil and gas fields in other districts. Of the 67 fields in district

1, 4 fields were classified in the high-risk category based on vertical proximity, 16 fields were in the moderate category, 13 fields were in the low category, and 34 fields had insufficient data to evaluate this factor (table 4; fig. 12D). Median vertical separation distances for district 1 fields were typically between 1,000 and 8,500 ft (fig. 11). Many of the smaller fields had insufficient data to evaluate vertical proximity and had low intensity of petroleum resource development based on low petroleum-well density and little or no water injection compared with larger fields. The availability of depth to BFW data was greater in district 1 than in most other districts (except district 6): vertical separation distance for almost half of the fields was calculated using BFW data, and these fields were mostly in the moderate risk category for vertical proximity (figs. 6 and 11). Water-well density for the fields was most frequently low (fig. 12E); water wells were primarily public supply wells located in the central part of the Coastal Plain of Los Angeles and Coastal Plain of Orange County groundwater basins, whereas oil and gas fields are located along the edges of the groundwater basins. High overall priority classification for district 1 fields was based on the intensity of oil and gas development, and with the exception of a few fields with close vertical proximity to groundwater resources, these fields were not classified as high risk based on proximity to groundwater resources.

District 2 (Ventura Basin)

District 2 encompasses Ventura County and the western part of Los Angeles County in southern California. The 70 fields in district 2 have an aggregated field area of 309 mi² in the coastal valley and surrounding foothills of the western Transverse Ranges between the Topatopa Mountains in the north and the Santa Monica Mountains in the south (fig. 13A). The Ventura Basin is the main structural downwarp that formed in the major fold and thrust belt system, trapping oil accumulations along several anticlinal structures that have varying degrees of deformation (Keller, 1995). Cumulative production in Ventura Basin through 1990 was approximately 2,640 million barrels of oil, 4.64 trillion cubic feet of gas, and 160 million barrels of total natural gas liquids. District 2 fields are primarily in or near the Santa Clara River Valley, a few fields are in Ventura River Valley, Los Posas Valley, San Fernando Valley, Simi Valley, Conejo, Pleasant Valley, Ojai Valley, and Upper Ojai Valley groundwater basins, and two fields are in Montecito and Carpinteria groundwater basins in Santa Barbara County. The other oil and gas fields in the Santa Barbara coastal plain are part of the Ventura Basin but are within the boundary of district 3. The most productive groundwater aquifers of the Santa Clara River Valley generally consist of layers of alluvium deposited between the Pliocene and Holocene epochs with groundwater present under unconfined, semi-confined, and confined conditions (California Department of Water Resources, 2015).

For district 2, 19 percent of the fields (13 fields) were classified as high priority, 30 percent (21 fields) were moderate, and 51 percent (36 fields) were low (table 5; fig. 13A). High overall priority classification was primarily based on high petroleum-well density, including some of the highest densities of injection wells and waste-disposal wells in the state. Eleven of the 13 high-priority fields in the district had high petroleum-well density and high or moderate volume of injection wells (table 6A; figs. 13B, C). Densities of injection and waste-disposal wells in the State were up to 43 wells/mi^2 (San Miguelito field) and 11 wells/mi^2 (Placerita field), respectively. Other than injection wells used for EOR or waste disposal, district 2 contained about 35 percent of the gas storage wells and more than half of the dry hole wells in California. Although well densities were high for some fields in the district, fields were more frequently classified as moderate and low overall priority. By area, 23 percent of the total area of district 2 oil and gas fields was ranked as high priority, 52 percent was moderate, and 24 percent was low. The percentage of moderate-priority fields (by count and by area) in district 2 was greater than for other districts. Moderate overall priority classification was characterized by moderate petroleum-well density, moderate and low volume of injection, moderate and low vertical proximity of resources, and low water-well density. This combination may indicate that most fields in district 2 were small, produced little petroleum, and did not have petroleum resource development near where groundwater resources are currently used.

Median vertical separation distances for fields varied throughout district 2, but most oil and gas fields in the district were deep and had large vertical distances from groundwater (fig. 13D). Of the fields in district 2, 5 fields were classified in the high-risk category for vertical proximity, 6 fields were in the moderate category, 15 were in the low category, and 44 fields had insufficient data to evaluate vertical proximity (table 4). Median vertical separation distance (shown in fig. 11) varied from a potential overlap of resources to 7,900 ft separation. Water-well density was low for most fields throughout the district (fig. 13E). Many of the groundwater wells were in the alluvial groundwater basins in the center of the valleys, whereas oil and gas fields were more often in the mountainous regions outside or at the edges of the groundwater basins.

District 3 (Central Coast)

District 3 includes counties along the central coast of California from Santa Barbara to Santa Clara County (fig. 10A). The 39 fields in the district have an aggregated field area of 264 mi^2 (table 5). There were about 12,600 DOGGR oil and gas wells in the district, including 11,000 production wells and 1,350 injection wells (table 1). Injection wells are primarily steam injection, water flood, and waste disposal. District 3 fields are primarily in the Santa Maria Basin (Stanley, 1995) that coincides with the Santa Maria, San Antonio Creek Valley, and Santa Ynez River Valley

groundwater basins; in the Cuyama Basin (Tennyson, 1995) that coincides with the Cuyama Valley groundwater basin; and in the Salinas Basin (Stanley, 1995) that coincides with the Salinas Valley groundwater basin in the north portion of the district (California Department of Water Resources, 2016). There are a few fields along the Santa Barbara coastal plain, some of which are gas fields or used for gas storage. Much of the petroleum that has been produced is from reservoirs in Miocene sandstones, and indications of oil and gas at the surface, such as tar sands and seeps, are known in certain areas. In the Santa Maria Basin, oil accumulations are generally heavy and from reservoirs in the Miocene Monterey Formation trapped in anticlines or by an unconformity and from Pliocene sandstone reservoirs above an unconformity (Tennyson, 1996). In the Salinas Basin, fields such as San Ardo, Paris Valley, and King City fields have oil trapped in anticlines; the other fields in the Salinas Basin have stratigraphic petroleum traps (Stanley, 1995). The source rock for petroleum in the Salinas Basin is believed to be the Monterey Formation, from which heavy oil, minor amounts of gas, and large volumes of water have been produced.

For district 3, 36 percent of the oil and gas fields (14 fields) were classified as high priority, 21 percent (8 fields) were moderate, and 44 percent (17 fields) were low (table 5; fig. 14A). District 3 contains the fewest number of fields among all the districts, but some fields are larger, giving an aggregated field area (264 mi^2) that is greater than the 67 fields in district 1 (214 mi^2). By area, 80 percent of the total area of district 3 oil and gas fields ranked as high priority, 7 percent was moderate, and 13 percent was low. High priority fields in district 3 were generally characterized as large fields with moderate to high petroleum-well density. Because the fields were larger (up to 60 mi^2) and had moderate to high density of injection wells, fields also tended to have high water injection volumes (total and waste-disposal). Twelve of the fourteen high priority fields were in the high risk category for water injection volumes and included fields with some of the highest waste-water disposal volumes in the State (table 6A). The rest of the 25 fields classified as moderate and low priority were small compared to other fields in the district (field areas less than 5 mi^2) and mostly had moderate to low petroleum-well density, low volume of injection, unknown vertical proximity, and moderate to low water-well density (tables 6A–B).

Of the fields in district 3, 2 fields were classified as high risk based on vertical proximity, 7 fields were moderate, 1 field was low, and 29 fields had insufficient data to evaluate this factor (table 5; fig. 14D). District 3 fields had mostly low water-well density (26 fields), some fields had moderate density (13 fields), and no fields in the district had high water-well density (fig. 14E). There were a couple fields (Santa Maria Valley and Cat Canyon) in the middle of the Santa Maria groundwater basins that had several overlying water wells, yet had low or moderate water-well density and moderate risk from vertical proximity; these fields were classified as high priority based on high volume of injection rather than proximity of petroleum resource development to groundwater resources.

A

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Priority classifications

High   Moderate   Low

Numbers in priority classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
012	Alondra	316	Howard Townsite	440	Mahala	666	Santa Fe Springs
014	Anaheim	320	Huntington Beach	478	Montebello	674	San Vicente
034	Bandini	322	Hyperion	496	Newgate	682	Sawtelle
054	Beverly Hills	324	Inglewood	502	Newport	688	Seal Beach
068	Boyle Heights	360	Kraemer	504	Newport, West	704	Sherman
070	Brea-Olinda	362	Kraemer, Northeast	522	Olive	728	Sunset Beach
076	Buena Park, East	364	Kraemer, West	554	Playa Del Rey	740	Talbert
078	Buena Park, West	376	La Mirada	568	Potrero	782	Torrance
134	Cheney Ranch Gas	378	Lapworth	572	Prado-Corona	796	Turnbull
136	Cheviot Hills	382	Las Cienegas	598	Richfield	804	Union Station
142	Chino-Soquel	394	Lawndale	618	Rosecrans	820	Walnut
178	Coyote, East	396	Leffingwell	620	Rosecrans, East	836	Whittier
180	Coyote, West	412	Long Beach	622	Rosecrans, South	838	Whittier Heights, North
208	Dominguez	414	Long Beach Airport	630	Rowland	849	Wilmington
232	El Segundo	422	Los Angeles City	640	Salt Lake	856	Yorba Linda
240	Esperanza	424	Los Angeles Downtown	642	Salt Lake, South		
258	Gaffey	426	Los Angeles, East	660	Sansinena		

Figure 12.   Oil and gas fields in district 1, Los Angeles Basin, showing classifications for *A*, overall priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

B

District 1

CALIFORNIA

Redding

Sacramento
San Francisco

Los Angeles
Map area
San Diego

SAN FERNANDO VALLEY

RAYMOND

SAN GABRIEL VALLEY

UPPER SANTA ANA VALLEY

COASTAL PLAIN OF LOS ANGELES

COASTAL PLAIN OF ORANGE COUNTY

SAN JUAN VALLEY

LOS ANGELES CO / SAN BERNARDINO CO

RIVERSIDE CO

LOS ANGELES CO / ORANGE CO

0   2.5   5   10 MILES
0   2.5   5   10 KILOMETERS

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Petroleum-well density

High   Moderate   Low

DWR groundwater basins

DWR groundwater subbasins

County

Numbers in petroleum-well density classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
012	Alondra	316	Howard Townsite	440	Mahala	666	Santa Fe Springs
014	Anaheim	320	Huntington Beach	478	Montebello	674	San Vicente
034	Bandini	322	Hyperion	496	Newgate	682	Sawtelle
054	Beverly Hills	324	Inglewood	502	Newport	688	Seal Beach
068	Boyle Heights	360	Kraemer	504	Newport, West	704	Sherman
070	Brea-Olinda	362	Kraemer, Northeast	522	Olive	728	Sunset Beach
076	Buena Park, East	364	Kraemer, West	554	Playa Del Rey	740	Talbert
078	Buena Park, West	376	La Mirada	568	Potrero	782	Torrance
134	Cheney Ranch Gas	378	Lapworth	572	Prado-Corona	796	Turnbull
136	Cheviot Hills	382	Las Cienegas	598	Richfield	804	Union Station
142	Chino-Soquel	394	Lawndale	618	Rosecrans	820	Walnut
178	Coyote, East	396	Leffingwell	620	Rosecrans, East	836	Whittier
180	Coyote, West	412	Long Beach	622	Rosecrans, South	838	Whittier Heights, North
208	Dominguez	414	Long Beach Airport	630	Rowland	849	Wilmington
232	El Segundo	422	Los Angeles City	640	Salt Lake	856	Yorba Linda
240	Esperanza	424	Los Angeles Downtown	642	Salt Lake, South		
258	Gaffey	426	Los Angeles, East	660	Sansinena		

Figure 12.   —Continued

c

Base modified from U.S. Geological Survey and other Federal and State digital data,
various scales; Albers Equal-Area Conic projection, standard parallels are
29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016;
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Volume of injection

High   Moderate   Low

Numbers in volume of injection classifications indicate the field codes

DWR groundwater basins
DWR groundwater subbasins
County

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
012	Alondra	316	Howard Townsite	440	Mahala	666	Santa Fe Springs		
014	Anaheim	320	Huntington Beach	478	Montebello	674	San Vicente		
034	Bandini	322	Hyperion	496	Newgate	682	Sawtelle		
054	Beverly Hills	324	Inglewood	502	Newport	688	Seal Beach		
068	Boyle Heights	360	Kraemer	504	Newport, West	704	Sherman		
070	Brea-Olinda	362	Kraemer, Northeast	522	Olive	728	Sunset Beach		
076	Buena Park, East	364	Kraemer, West	554	Playa Del Rey	740	Talbert		
078	Buena Park, West	376	La Mirada	568	Potrero	782	Torrance		
134	Cheney Ranch Gas	378	Lapworth	572	Prado-Corona	796	Turnbull		
136	Cheviot Hills	382	Las Cienegas	598	Richfield	804	Union Station		
142	Chino-Soquel	394	Lawndale	618	Rosecrans	820	Walnut		
178	Coyote, East	396	Leffingwell	620	Rosecrans, East	836	Whittier		
180	Coyote, West	412	Long Beach	622	Rosecrans, South	838	Whittier Heights, North		
208	Dominguez	414	Long Beach Airport	630	Rowland	849	Wilmington		
232	El Segundo	422	Los Angeles City	640	Salt Lake	856	Yorba Linda		
240	Esperanza	424	Los Angeles Downtown	642	Salt Lake, South				
258	Gaffey	426	Los Angeles, East	660	Sansinena				

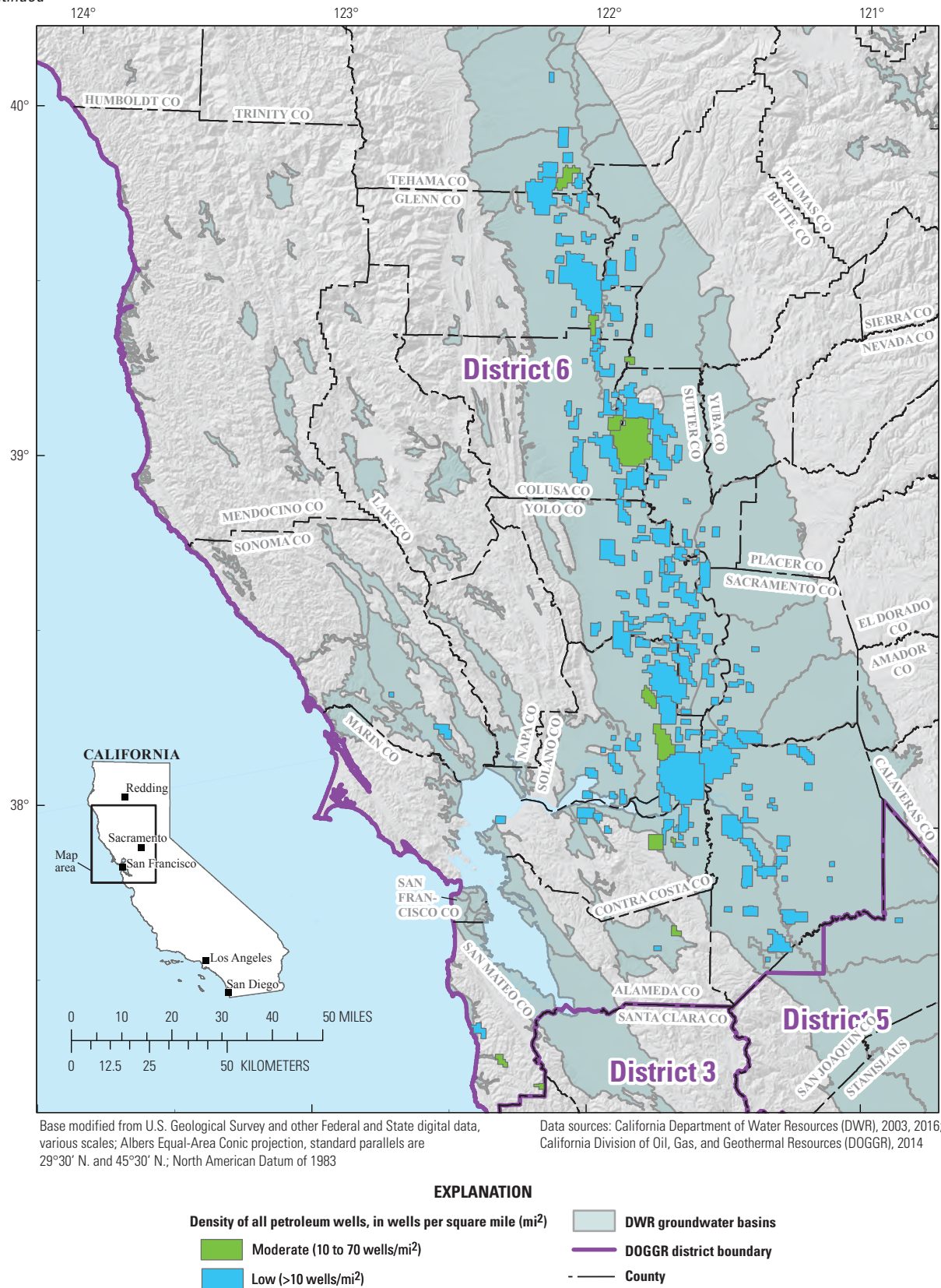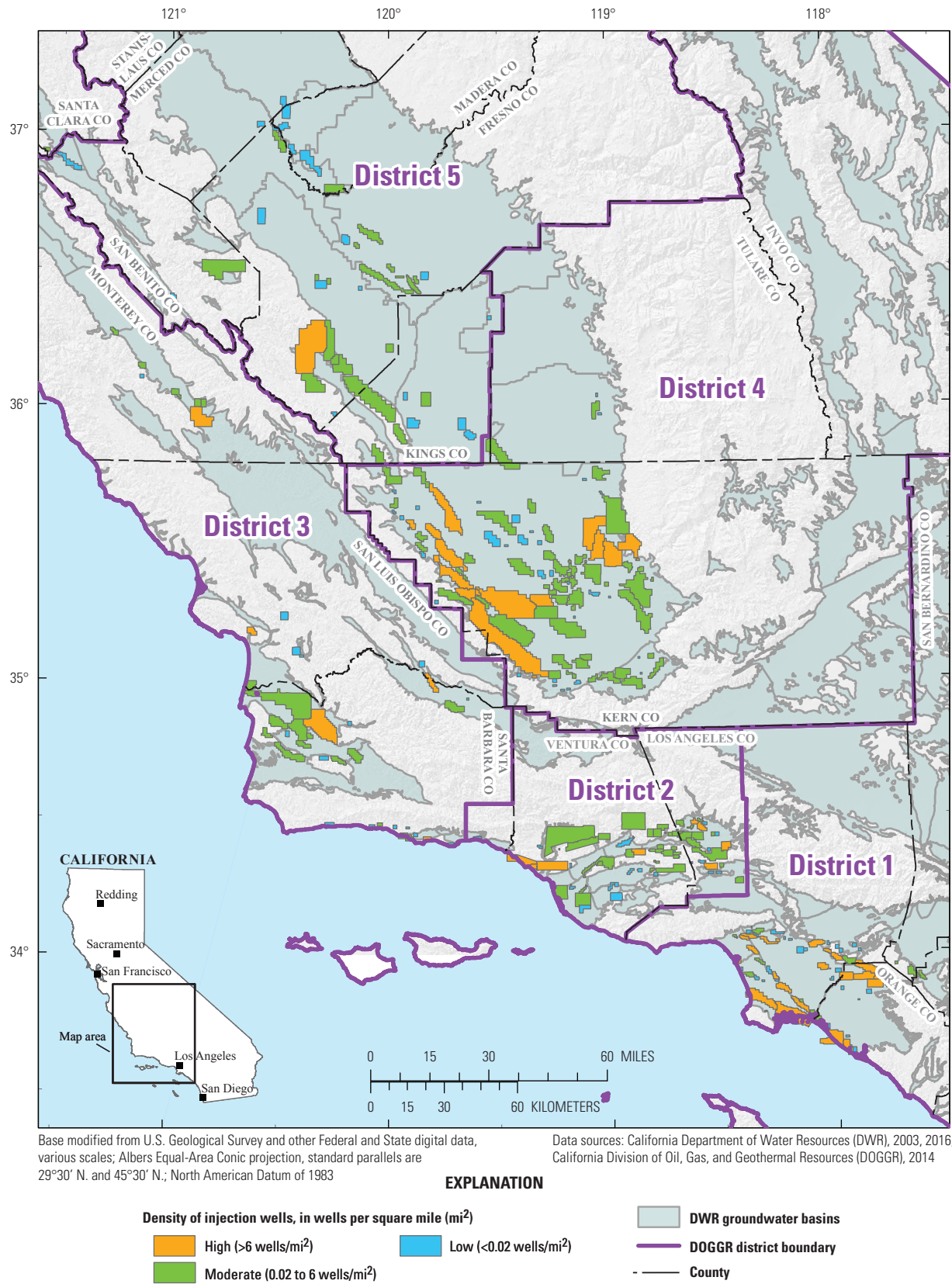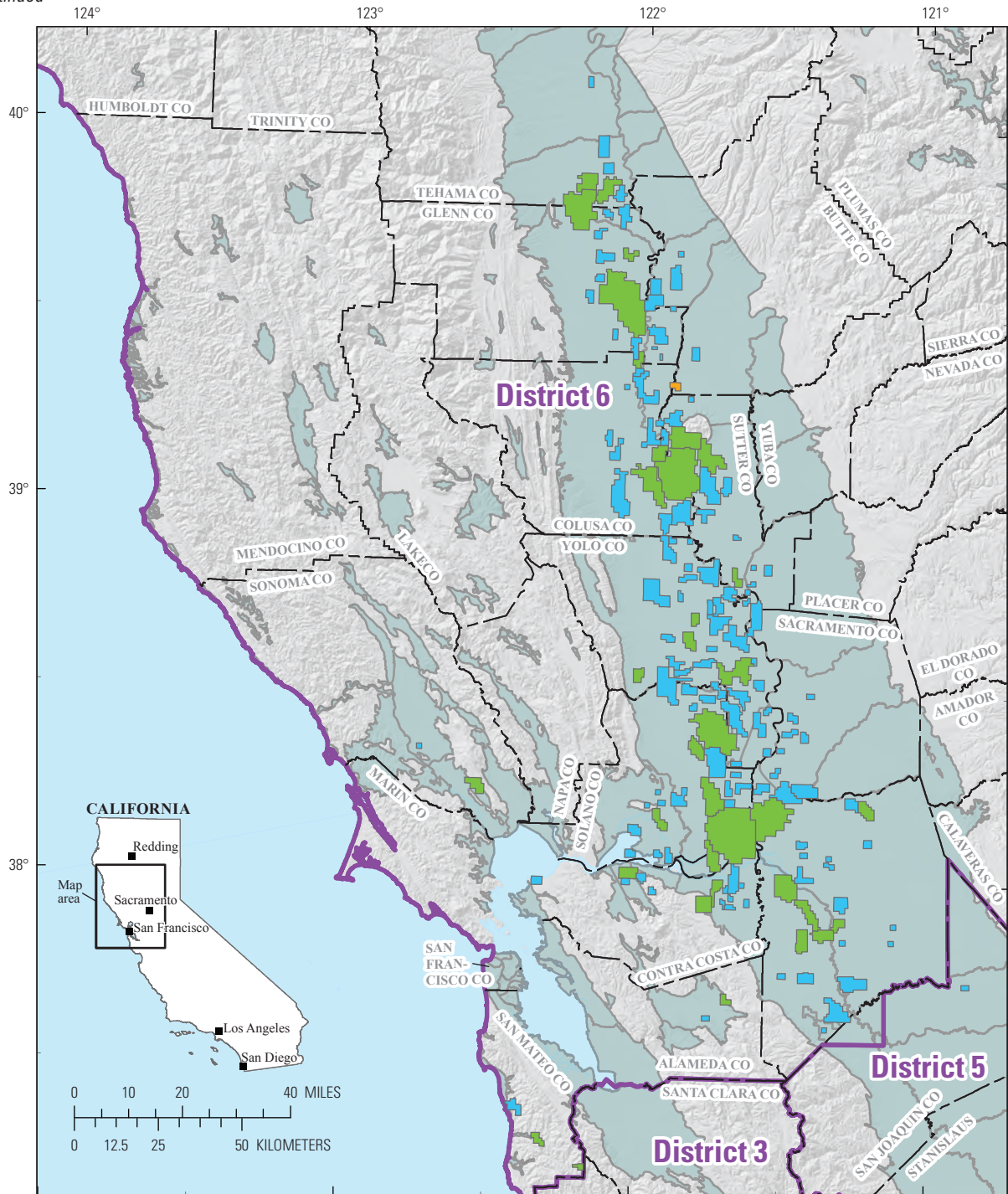**Figure 12.**   —Continued

D

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Vertical Proximity

Close   Moderate   Far   Unknown

Numbers in vertical proximity classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
012	Alondra	316	Howard Townsite	440	Mahala	666	Santa Fe Springs
014	Anaheim	320	Huntington Beach	478	Montebello	674	San Vicente
034	Bandini	322	Hyperion	496	Newgate	682	Sawtelle
054	Beverly Hills	324	Inglewood	502	Newport	688	Seal Beach
068	Boyle Heights	360	Kraemer	504	Newport, West	704	Sherman
070	Brea-Olinda	362	Kraemer, Northeast	522	Olive	728	Sunset Beach
076	Buena Park, East	364	Kraemer, West	554	Playa Del Rey	740	Talbert
078	Buena Park, West	376	La Mirada	568	Potrero	782	Torrance
134	Cheney Ranch Gas	378	Lapworth	572	Prado-Corona	796	Turnbull
136	Cheviot Hills	382	Las Cienegas	598	Richfield	804	Union Station
142	Chino-Soquel	394	Lawndale	618	Rosecrans	820	Walnut
178	Coyote, East	396	Leffingwell	620	Rosecrans, East	836	Whittier
180	Coyote, West	412	Long Beach	622	Rosecrans, South	838	Whittier Heights, North
208	Dominguez	414	Long Beach Airport	630	Rowland	849	Wilmington
232	El Segundo	422	Los Angeles City	640	Salt Lake	856	Yorba Linda
240	Esperanza	424	Los Angeles Downtown	642	Salt Lake, South		
258	Gaffey	426	Los Angeles, East	660	Sansinena		

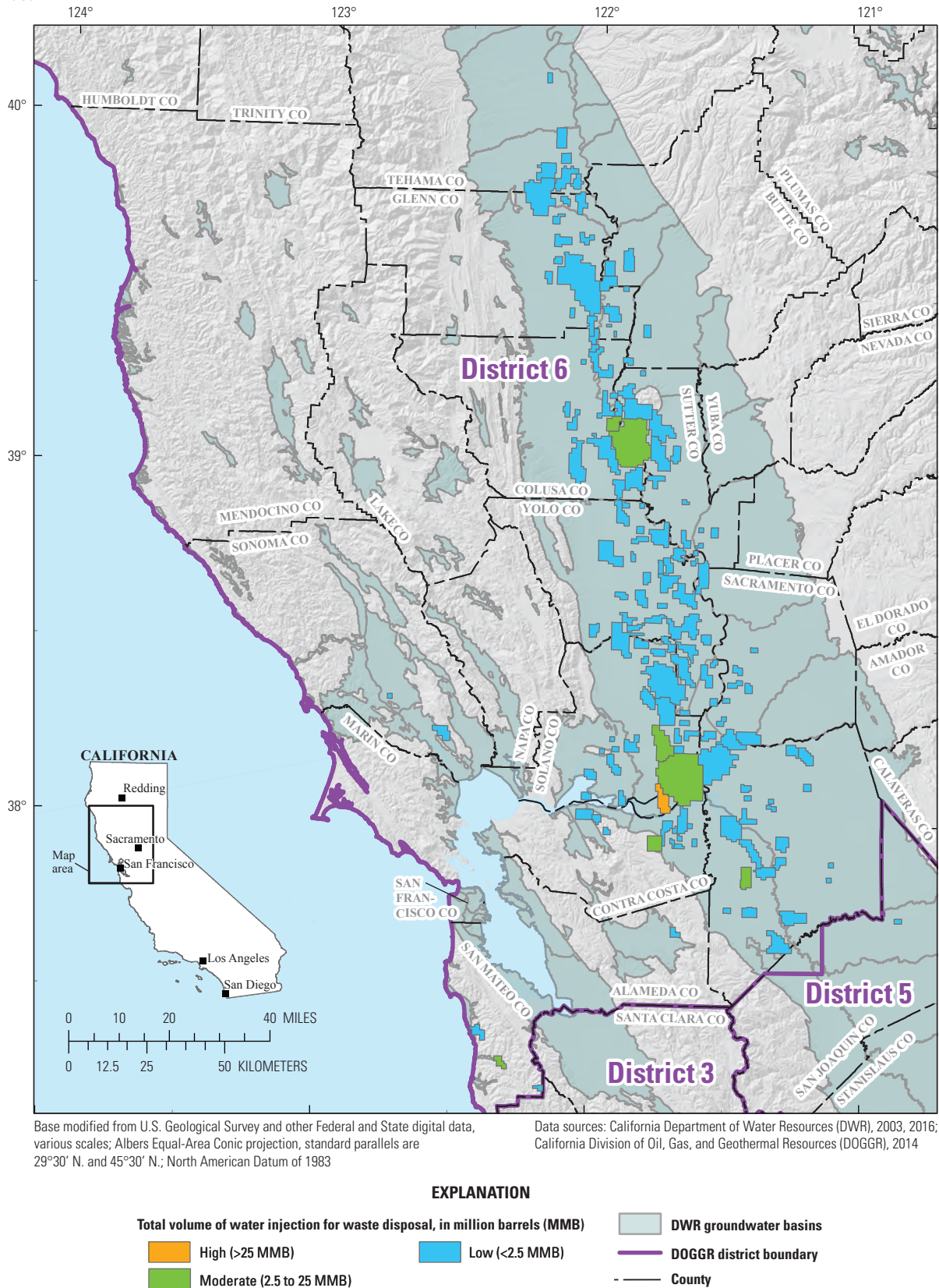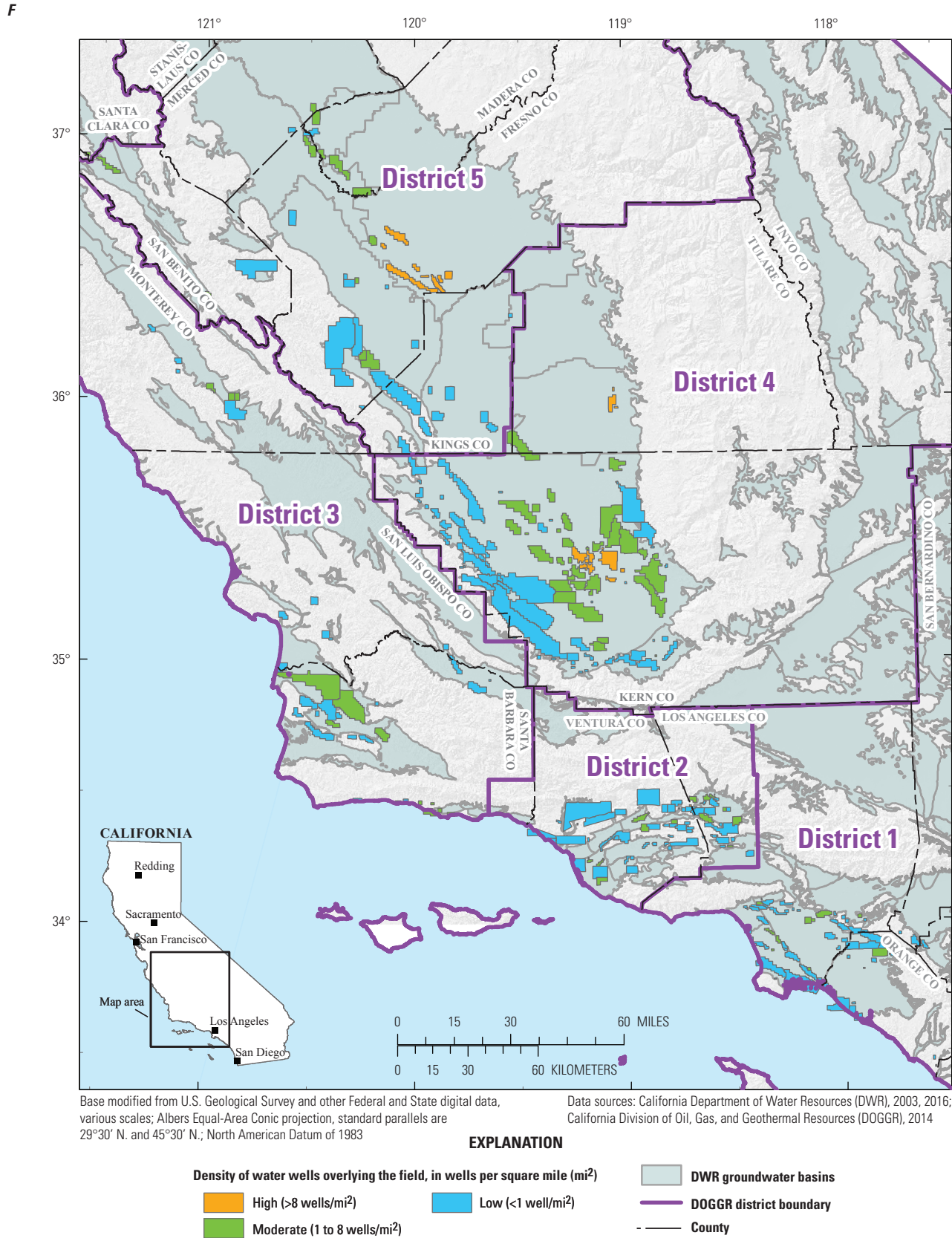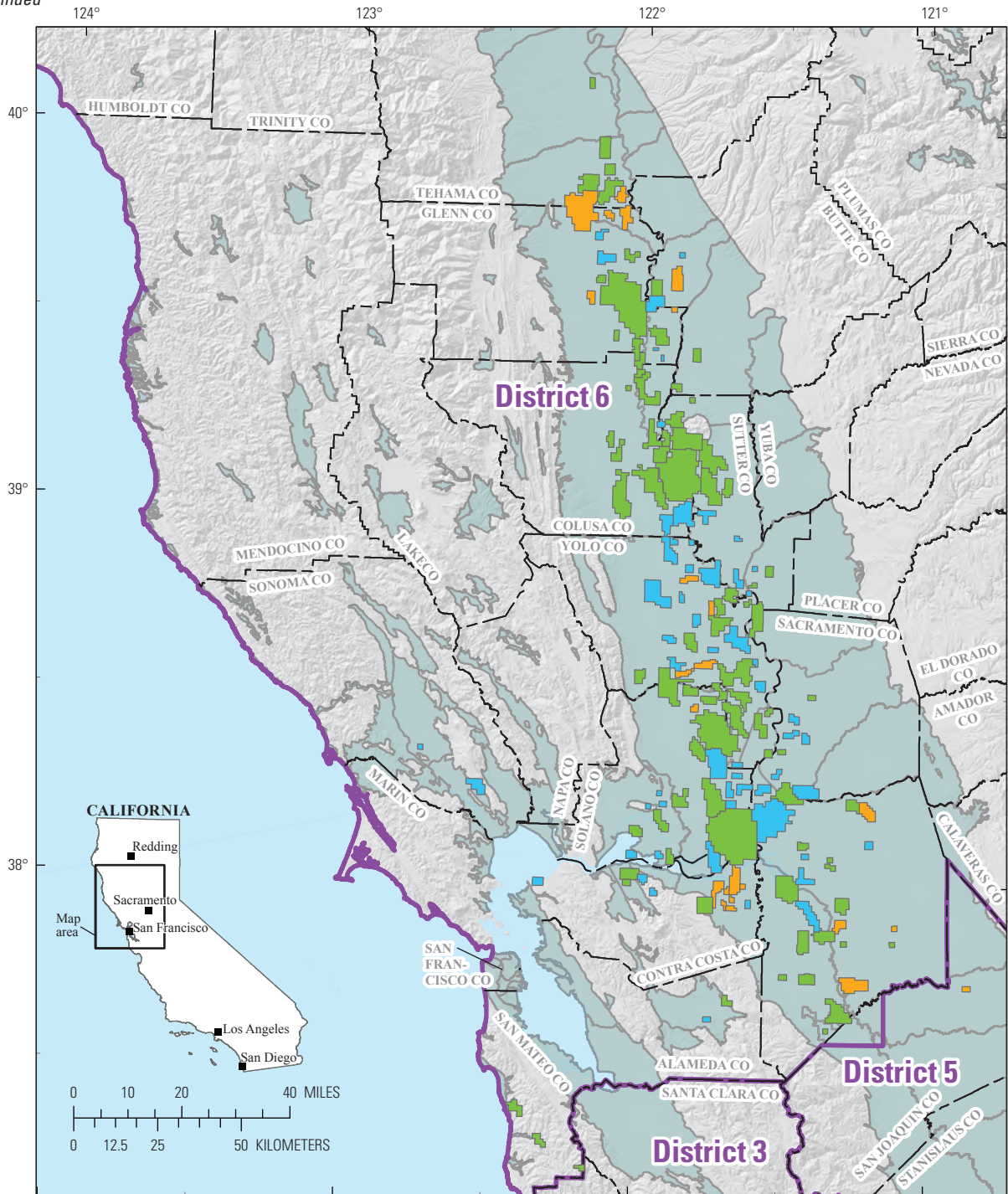**Figure 12.**   —Continued

E

Base modified from U.S. Geological Survey and other Federal and State digital data,
various scales; Albers Equal-Area Conic projection, standard parallels are
29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016;
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Water-well density

High   Moderate   Low

Numbers in water-well density classifications indicate the field codes

DWR groundwater basins
DWR groundwater subbasins
County

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
012	Alondra	316	Howard Townsite	440	Mahala	666	Santa Fe Springs
014	Anaheim	320	Huntington Beach	478	Montebello	674	San Vicente
034	Bandini	322	Hyperion	496	Newgate	682	Sawtelle
054	Beverly Hills	324	Inglewood	502	Newport	688	Seal Beach
068	Boyle Heights	360	Kraemer	504	Newport, West	704	Sherman
070	Brea-Olinda	362	Kraemer, Northeast	522	Olive	728	Sunset Beach
076	Buena Park, East	364	Kraemer, West	554	Playa Del Rey	740	Talbert
078	Buena Park, West	376	La Mirada	568	Potrero	782	Torrance
134	Cheney Ranch Gas	378	Lapworth	572	Prado-Corona	796	Turnbull
136	Cheviot Hills	382	Las Cienegas	598	Richfield	804	Union Station
142	Chino-Soquel	394	Lawndale	618	Rosecrans	820	Walnut
178	Coyote, East	396	Leffingwell	620	Rosecrans, East	836	Whittier
180	Coyote, West	412	Long Beach	622	Rosecrans, South	838	Whittier Heights, North
208	Dominguez	414	Long Beach Airport	630	Rowland	849	Wilmington
232	El Segundo	422	Los Angeles City	640	Salt Lake	856	Yorba Linda
240	Esperanza	424	Los Angeles Downtown	642	Salt Lake, South		
258	Gaffey	426	Los Angeles, East	660	Sansinena		

Figure 12. —Continued

A

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Priority classifications

High   Moderate   Low

Numbers in priority classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
010	Aliso Canyon	298	Hasley Canyon	516	Oakview	680	Saugus
036	Bardsdale	304	Holser	519	Oat Mountain	682	Sawtelle
054	Beverly Hills	308	Honor Rancho	520	Ojai	694	Sespe
056	Big Mountain	310	Hopper Canyon	530	Oxnard	704	Sherman
064	Bouquet Canyon	312	Horse Meadows	531	Pacoima	708	Shiells Canyon
091	Cabrillo	322	Hyperion	546	Piru	710	Simi
102	Canada Larga	324	Inglewood	548	Piru Creek	712	Somis
110	Canton Creek	384	Las Llajas	550	Placerita	714	South Mountain
120	Cascade	386	Las Posas	554	Playa Del Rey	724	Summerland
124	Castaic Hills	416	Long Canyon	586	Ramona	742	Tapia
126	Castaic Junction	438	Lyon Canyon	588	Ramona, North	744	Tapo, North
130	Chaffee Canyon	468	Mission	600	Rincon	746	Tapo Canyon, South
132	Charlie Canyon	476	Montalvo, West	601	Rincon Creek	748	Tapo Ridge
136	Cheviot Hills	484	Moorpark	640	Salt Lake	764	Temescal
170	Conejo	485	Moorpark West	658	San Miguelito	774	Timber Canyon
198	Del Valle	498	Newhall	662	Santa Clara Avenue	784	Torrey Canyon
230	El Rio	500	Newhall-Potrero	670	Santa Paula	814	Ventura
232	El Segundo	508	Oak Canyon	672	Santa Susana	824	Wayside Canyon
242	Eureka Canyon	512	Oak Park	674	San Vicente	830	West Mountain
246	Fillmore	514	Oakridge	678	Saticoy		

Figure 13.   Oil and gas fields in district 2, Ventura Basin, showing classifications for *A*, overall priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

Figure 13.   —Continued

B

District 3
District 2
District 1

CALIFORNIA

Redding
Sacramento
San Francisco
Los Angeles
Map area
San Diego

0   2.5   5   10 MILES
0   2.5 5   10 KILOMETERS

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29° 30′ and 45° 30′; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Petroleum-well density

High   Moderate   Low

DWR groundwater basins

DWR groundwater subbasins

- County

DOGGR district boundary

Numbers in petroleum-well density classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
010	Aliso Canyon	298	Hasley Canyon	516	Oakview	680	Saugus
036	Bardsdale	304	Holser	519	Oat Mountain	682	Sawtelle
054	Beverly Hills	308	Honor Rancho	520	Ojai	694	Sespe
056	Big Mountain	310	Hopper Canyon	530	Oxnard	704	Sherman
064	Bouquet Canyon	312	Horse Meadows	531	Pacoima	708	Shiells Canyon
091	Cabrillo	322	Hyperion	546	Piru	710	Simi
102	Canada Larga	324	Inglewood	548	Piru Creek	712	Somis
110	Canton Creek	384	Las Llajas	550	Placerita	714	South Mountain
120	Cascade	386	Las Posas	554	Playa Del Rey	724	Summerland
124	Castaic Hills	416	Long Canyon	586	Ramona	742	Tapia
126	Castaic Junction	438	Lyon Canyon	588	Ramona, North	744	Tapo, North
130	Chaffee Canyon	468	Mission	600	Rincon	746	Tapo Canyon, South
132	Charlie Canyon	476	Montalvo, West	601	Rincon Creek	748	Tapo Ridge
136	Cheviot Hills	484	Moorpark	640	Salt Lake	764	Temescal
170	Conejo	485	Moorpark West	658	San Miguelito	774	Timber Canyon
198	Del Valle	498	Newhall	662	Santa Clara Avenue	784	Torrey Canyon
230	El Rio	500	Newhall-Potrero	670	Santa Paula	814	Ventura
232	El Segundo	508	Oak Canyon	672	Santa Susana	824	Wayside Canyon
242	Eureka Canyon	512	Oak Park	674	San Vicente	830	West Mountain
246	Fillmore	514	Oakridge	678	Saticoy		

c

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29° 30' and 45° 30'; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Volume of injection

High	Moderate	Low

DWR groundwater basins — County

DWR groundwater subbasins — DOGGR district boundary

Numbers in injection classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
010	Aliso Canyon	298	Hasley Canyon	516	Oakview	680	Saugus
036	Bardsdale	304	Holser	519	Oat Mountain	682	Sawtelle
054	Beverly Hills	308	Honor Rancho	520	Ojai	694	Sespe
056	Big Mountain	310	Hopper Canyon	530	Oxnard	704	Sherman
064	Bouquet Canyon	312	Horse Meadows	531	Pacoima	708	Shiells Canyon
091	Cabrillo	322	Hyperion	546	Piru	710	Simi
102	Canada Larga	324	Inglewood	548	Piru Creek	712	Somis
110	Canton Creek	384	Las Llajas	550	Placerita	714	South Mountain
120	Cascade	386	Las Posas	554	Playa Del Rey	724	Summerland
124	Castaic Hills	416	Long Canyon	586	Ramona	742	Tapia
126	Castaic Junction	438	Lyon Canyon	588	Ramona, North	744	Tapo, North
130	Chaffee Canyon	468	Mission	600	Rincon	746	Tapo Canyon, South
132	Charlie Canyon	476	Montalvo, West	601	Rincon Creek	748	Tapo Ridge
136	Cheviot Hills	484	Moorpark	640	Salt Lake	764	Temescal
170	Conejo	485	Moorpark West	658	San Miguelito	774	Timber Canyon
198	Del Valle	498	Newhall	662	Santa Clara Avenue	784	Torrey Canyon
230	El Rio	500	Newhall-Potrero	670	Santa Susana	814	Ventura
232	El Segundo	508	Oak Canyon	672	Santa Susana	824	Wayside Canyon
242	Eureka Canyon	512	Oak Park	674	San Vicente	830	West Mountain
246	Fillmore	514	Oakridge	678	Saticoy		

Figure 13.   —Continued

D

Base modified from U.S. Geological Survey and other Federal and State digital data,
various scales; Albers Equal-Area Conic projection, standard parallels are
29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016;
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Vertical proximity

High   Moderate   Far   Unknown

Numbers in vertical proximity classifications indicate the field codes

DWR groundwater basins
DWR groundwater subbasins

County
DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
010	Aliso Canyon	298	Hasley Canyon	516	Oakview	680	Saugus
036	Bardsdale	304	Holser	519	Oat Mountain	682	Sawtelle
054	Beverly Hills	308	Honor Rancho	520	Ojai	694	Sespe
056	Big Mountain	310	Hopper Canyon	530	Oxnard	704	Sherman
064	Bouquet Canyon	312	Horse Meadows	531	Pacoima	708	Shiells Canyon
091	Cabrillo	322	Hyperion	546	Piru	710	Simi
102	Canada Larga	324	Inglewood	548	Piru Creek	712	Somis
110	Canton Creek	384	Las Llajas	550	Placerita	714	South Mountain
120	Cascade	386	Las Posas	554	Playa Del Rey	724	Summerland
124	Castaic Hills	416	Long Canyon	586	Ramona	742	Tapia
126	Castaic Junction	438	Lyon Canyon	588	Ramona, North	744	Tapo, North
130	Chaffee Canyon	468	Mission	600	Rincon	746	Tapo Canyon, South
132	Charlie Canyon	476	Montalvo, West	601	Rincon Creek	748	Tapo Ridge
136	Cheviot Hills	484	Moorpark	640	Salt Lake	764	Temescal
170	Conejo	485	Moorpark West	658	San Miguelito	774	Timber Canyon
198	Del Valle	498	Newhall	662	Santa Clara Avenue	784	Torrey Canyon
230	El Rio	500	Newhall-Potrero	670	Santa Paula	814	Ventura
232	El Segundo	508	Oak Canyon	672	Santa Susana	824	Wayside Canyon
242	Eureka Canyon	512	Oak Park	674	San Vicente	830	West Mountain
246	Fillmore	514	Oakridge	678	Saticoy		

Figure 13.   —Continued

E

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Water-well density

High	Moderate	Low

Numbers in water-well density classifications indicate the field codes

- DWR groundwater basins — County
- DWR groundwater subbasins — DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
010	Aliso Canyon	298	Hasley Canyon	516	Oakview	680	Saugus
036	Bardsdale	304	Holser	519	Oat Mountain	682	Sawtelle
054	Beverly Hills	308	Honor Rancho	520	Ojai	694	Sespe
056	Big Mountain	310	Hopper Canyon	530	Oxnard	704	Sherman
064	Bouquet Canyon	322	Hyperion	531	Pacoima	708	Shiells Canyon
091	Cabrillo	324	Inglewood	546	Piru	710	Simi
102	Canada Larga	384	Las Llajas	548	Piru Creek	712	Somis
110	Canton Creek	386	Las Posas	550	Placerita	714	South Mountain
120	Cascade	416	Long Canyon	554	Playa Del Rey	724	Summerland
124	Castaic Hills	438	Lyon Canyon	586	Ramona	742	Tapia
126	Castaic Junction	468	Mission	588	Ramona, North	744	Tapo, North
130	Chaffee Canyon	476	Montalvo, West	600	Rincon	746	Tapo Canyon, South
132	Charlie Canyon	484	Moorpark	601	Rincon Creek	748	Tapo Ridge
136	Cheviot Hills	485	Moorpark West	640	Salt Lake	764	Temescal
170	Conejo	498	Newhall	658	San Miguelito	774	Timber Canyon
198	Del Valle	500	Newhall-Potrero	662	Santa Clara Avenue	784	Torrey Canyon
230	El Rio	508	Oak Canyon	670	Santa Paula	814	Ventura
232	El Segundo	512	Oak Park	672	Santa Susana	824	Wayside Canyon
242	Eureka Canyon	514	Oakridge	674	San Vicente	830	West Mountain
246	Fillmore			678	Saticoy		

Figure 13. —Continued

A

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Priority classifications

High   Moderate   Low

Numbers in priority classifications indicate the field codes

DWR groundwater basins   - - - County
DWR groundwater subbasins   —— DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
006	Alegria	122	Casmalia	286	Guadalupe	486	Morales Canyon
028	Arroyo Grande	128	Cat Canyon	295	Harris Canyon, NV	524	Orcutt
032	Asphalto	186	Cuyama, Central	318	Huasna	594	Refugio Cove Gas
038	Barham Ranch	188	Cuyama, South	334	Jesus Maria	601	Rincon Creek
042	Belgian Anticline	228	Elk Hills	368	La Goleta Gas	632	Russell Ranch
080	Buena Vista	234	Elwood	388	Las Varas Canyon	668	Santa Maria Valley
102	Canada Larga	250	Four Deer	410	Lompoc	711	Sisquoc Ranch
114	Capitan Oil	268	Glen Annie Gas	418	Lopez Canyon	724	Summerland
115	Capitola Park	270	Goleta	420	Los Alamos	760	Temblor Hills
116	Careaga Canyon	272	Gonyer Anticline	462	Mesa	860	Zaca

Figure 14.   Oil and gas fields in district 3, Central Coast, showing classifications for *A*, overall priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

A—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Priority classifications

High	Moderate	Low

Numbers in priority classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
058	Bitterwater	288	Guijarral Hills	436	Lynch Canyon	580	Quinado Canyon
112	Cantua Creek	326	Jacalitos	448	Merritt Gas	644	San Ardo
113	Cantua Nueva	348	Kettleman North Dome	474	Monroe Swell	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	806	Vallecitos
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley		

Figure 14.   —Continued

B

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Petroleum-well density

| High | Moderate | Low |

Numbers in petroleum-well density classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
006	Alegria	122	Casmalia	286	Guadalupe	486	Morales Canyon
028	Arroyo Grande	128	Cat Canyon	295	Harris Canyon, NW	524	Orcutt
032	Asphalto	186	Cuyama, Central	318	Huasna	594	Refugio Cove Gas
038	Barham Ranch	188	Cuyama, South	334	Jesus Maria	601	Rincon Creek
042	Belgian Anticline	228	Elk Hills	368	La Goleta Gas	632	Russell Ranch
080	Buena Vista	234	Elwood	388	Las Varas Canyon	668	Santa Maria Valley
102	Canada Larga	250	Four Deer	410	Lompoc	711	Sisquoc Ranch
114	Capitan Oil	268	Glen Annie Gas	418	Lopez Canyon	724	Summerland
115	Capitola Park	270	Goleta	420	Los Alamos	760	Temblor Hills
116	Careaga Canyon	272	Gonyer Anticline	462	Mesa	860	Zaca

Figure 14.   —Continued

B—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Petroleum-well density

High   Moderate   Low

DWR groundwater basins

DWR groundwater subbasins

- ——— County

—— DOGGR district boundary

Numbers in petroleum-well density classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
058	Bitterwater	288	Guijarral Hills	436	Lynch Canyon	580	Quinado Canyon
112	Cantua Creek	326	Jacalitos	448	McCool Ranch	644	San Ardo
113	Cantua Nueva	348	Kettleman North Dome	474	Monroe Swell	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	806	Vallecitos
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley		

Figure 14.   —Continued

c

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Volume of injection

High   Moderate   Low

Numbers in volume of injection classifications indicate the field codes

DWR groundwater basins
County
DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
006	Alegria	122	Casmalia	286	Guadalupe	486	Morales Canyon
028	Arroyo Grande	128	Cat Canyon	295	Harris Canyon, NV	524	Orcutt
032	Asphalto	186	Cuyama, Central	318	Huasna	594	Refugio Cove Gas
038	Barham Ranch	188	Cuyama, South	334	Jesus Maria	601	Rincon Creek
042	Belgian Anticline	228	Elk Hills	368	La Goleta Gas	632	Russell Ranch
080	Buena Vista	234	Elwood	388	Las Varas Canyon	668	Santa Maria Valley
102	Canada Larga	250	Four Deer	410	Lompoc	711	Sisquoc Ranch
114	Capitan Oil	268	Glen Annie Gas	420	Los Alamos	724	Summerland
115	Capitola Park	270	Goleta	462	Mesa	760	Temblor Hills
116	Careaga Canyon	272	Gonyer Anticline			860	Zaca

Figure 14.   —Continued

C—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Volume of injection
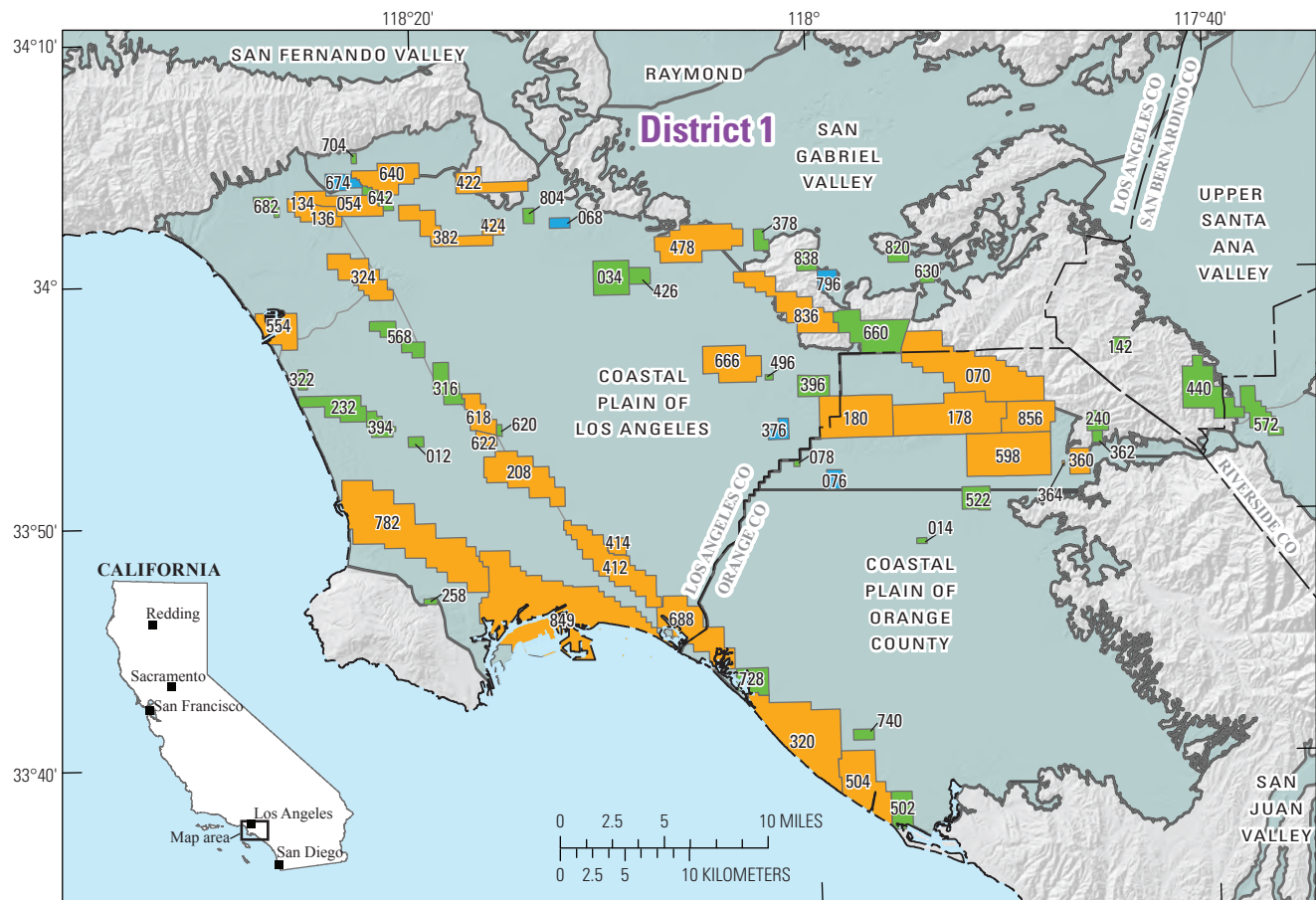
High   Moderate   Low

Numbers in volume of injection classifications indicate the field codes

DWR groundwater basins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
058	Bitterwater	288	Guijarral Hills	436	Lynch Canyon	580	Quinado Canyon
112	Cantua Creek	326	Jacalitos	448	McCool Ranch	644	San Ardo
113	Cantua Nueva	348	Kettleman North Dome	474	Monroe Swell	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	806	Vallecitos
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley		

Figure 14.   —Continued

D

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Vertical proximity

Close	Moderate	Far	Unknown	

DWR groundwater basins — — — County

DWR groundwater subbasins —— DOGGR district boundary

Numbers in vertical proximity classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
006	Alegria	122	Casmalia	286	Guadalupe	486	Morales Canyon
028	Arroyo Grande	128	Cat Canyon	295	Harris Canyon, NW	524	Orcutt
032	Asphalto	186	Cuyama, Central	318	Huasna	594	Refugio Cove Gas
038	Barham Ranch	188	Cuyama, South	334	Jesus Maria	601	Rincon Creek
042	Belgian Anticline	228	Elk Hills	368	La Goleta Gas	632	Russell Ranch
080	Buena Vista	234	Elwood	388	Las Varas Canyon	668	Santa Maria Valley
102	Canada Larga	250	Four Deer	410	Lompoc	711	Sisquoc Ranch
114	Capitan Oil	268	Glen Annie Gas	418	Lopez Canyon	724	Summerland
115	Capitola Park	270	Goleta	420	Los Alamos	760	Temblor Hills
116	Careaga Canyon	272	Gonyer Anticline	462	Mesa	860	Zaca

Figure 14.   —Continued

D—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014
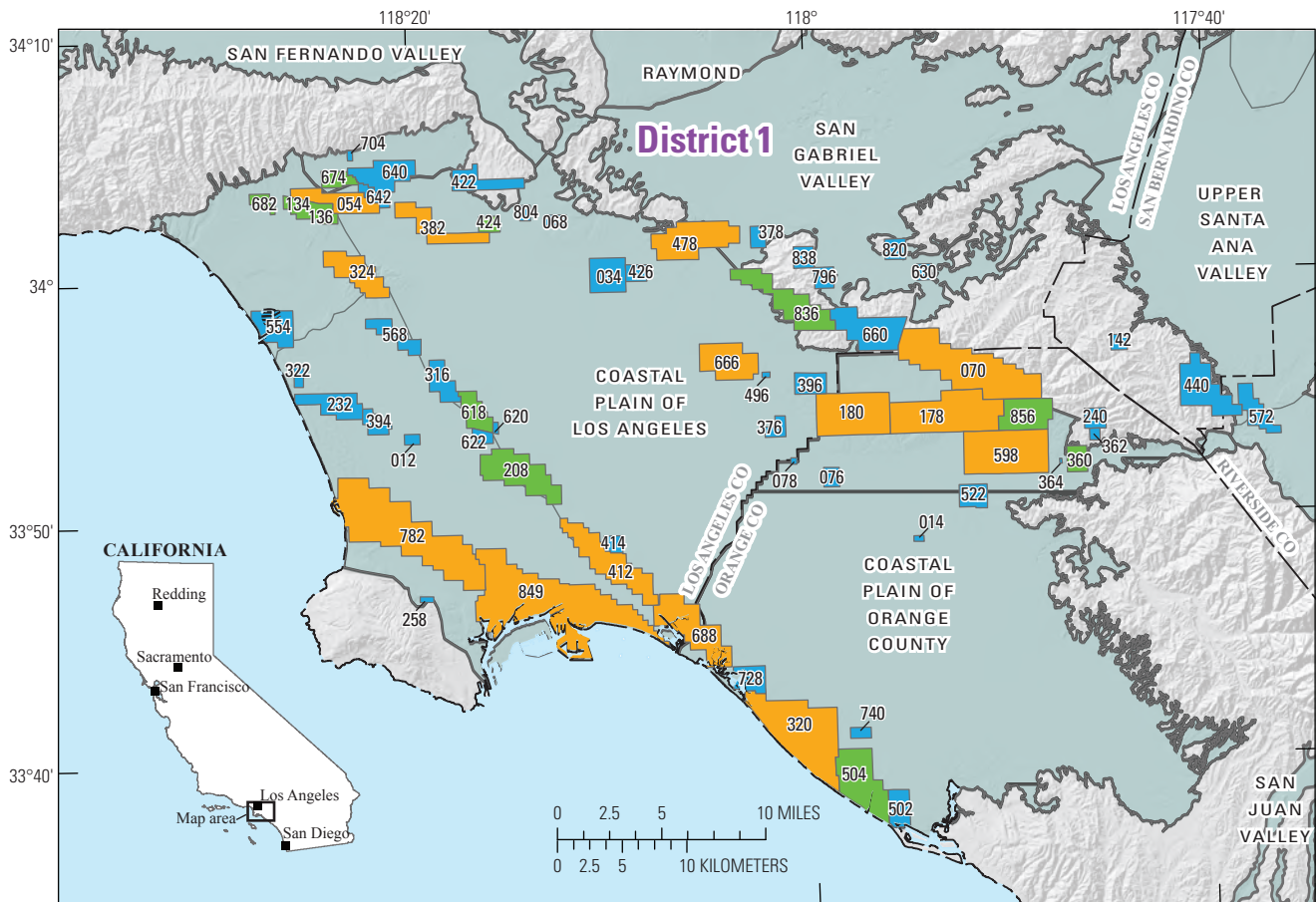
EXPLANATION

Vertical proximity

Close   Moderate   Far   Unknown

Numbers in vertical proximity classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
058	Bitterwater	288	Guijarral Hills	436	Lynch Canyon	580	Quinado Canyon
112	Cantua Creek	326	Jacalitos	448	McCool Ranch	644	San Ardo
113	Cantua Nueva	348	Kettleman North Dome	474	Monroe Swell	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	806	Vallecitos
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley		

Figure 14.   —Continued

Base modified from U.S. Geological Survey and other Federal and State digital data,
various scales; Albers Equal-Area Conic projection, standard parallels are
29°30' N. and 45°30' N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016;
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Water-well density

Moderate   Low

DWR groundwater basins

County

DOGGR district boundary

DWR groundwater subbasins

Numbers in water-well density classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
006	Alegria	122	Casmalia	286	Guadalupe	486	Morales Canyon
028	Arroyo Grande	128	Cat Canyon	295	Harris Canyon, NV	524	Orcutt
032	Asphalto	186	Cuyama, Central	318	Huasna	594	Refugio Cove Gas
038	Barham Ranch	188	Cuyama, South	334	Jesus Maria	601	Rincon Creek
042	Belgian Anticline	228	Elk Hills	368	La Goleta Gas	632	Russell Ranch
080	Buena Vista	234	Elwood	388	Las Varas Canyon	668	Santa Maria Valley
102	Canada Larga	250	Four Deer	410	Lompoc	711	Sisquoc Ranch
114	Capitan Oil	268	Glen Annie Gas	418	Lopez Canyon	724	Summerland
115	Capitola Park	270	Goleta	420	Los Alamos	760	Temblor Hills
116	Careaga Canyon	272	Gonyer Anticline	462	Mesa	860	Zaca

Figure 14. —Continued

E—Continued

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

EXPLANATION

Water-well density

Moderate   Low

DWR groundwater basins   County

DWR groundwater subbasins   DOGGR district boundary

Numbers in water-well density classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
058	Bitterwater	288	Guijarral Hills	436	Lynch Canyon	580	Quinado Canyon
112	Cantua Creek	326	Jacalitos	448	McCool Ranch	644	San Ardo
113	Cantua Nueva	348	Kettleman North Done	474	Monroe Swell	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	806	Vallecitos
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley		

Figure 14.   —Continued

District 4 (South San Joaquin Basin)

District 4 encompasses the south zone of the San Joaquin Basin in central California that is bounded by the Temblor Range in the west and by the Sierra Nevada in the east (for description of south, central, and north zones, see Hosford Scheirer, 2007). The boundary within the San Joaquin Basin between district 4 and district 5 is defined by the Kern-Kings County line and Tulare-Fresno County line (fig. 10A). The 102 fields of district 4 have an aggregated field area of 962 mi² (table 5). District 4 fields are within the southern part of the San Joaquin Valley groundwater basin (fig. 15A; California Department of Water Resources, 2016). The southern San Joaquin Valley groundwater basin is composed of eroded materials from the surrounding mountains that deposited into the valley, primarily Coast Range alluvium underlain by the Corcoran Clay confining unit on the western side of the valley and alluvium from the Sierra Nevada on the east side (Faunt, 2009; California Department of Water Resources, 2015). Other alluvial deposits include flood-basin deposits along the axis of the valley and buried-river channel deposits of Pleistocene age.

For district 4, 40 percent of the fields (41 fields) were classified as high priority, 28 percent (29 fields) were moderate, and 31 percent (32 fields) were low (table 5; fig. 15A). District 4 contained almost half of the fields that had high overall priority classifications for the state, and these fields accounted for a majority of the aggregated field area. By area, 70 percent of the total area of district 4 oil and gas fields ranked as high priority, 24 percent was moderate, and 6 percent was low. High overall priority classification in the district was characterized by commonly co-occurring high petroleum-well density, high injection volume, and high vertical proximity of petroleum resource development to groundwater resources (figs. 15B–D). District 4 also had the most fields with high water-well density (fig. 15E), next to district 6. Some areas within the district, such as the center of the groundwater basins, had fields classified as high priority based on moderate petroleum-well density and high water-well density. Fields that had small vertical separation distance between petroleum and groundwater resources were located along the western and eastern edges of the San Joaquin Valley, and fields that had moderate and great separation distances were located on the valley floor where groundwater use was the highest.

Vertical proximity of petroleum resources to groundwater resources in district 4 was classified as close for 23 fields, moderate for 14 fields, far for 23 fields, and 42 fields had insufficient data to evaluate vertical proximity (table 4; fig. 15D). There were seven fields in the State that had median vertical separation distance less than 0 ft, indicating potential overlap of oil and gas resources and groundwater resources; six of these fields were located in district 4 (the other field is Piru in district 2; table 6A), and with the exception of one field

(South Belridge), are located along the east side of the Kern County groundwater basin (fig. 15D). Some fields in which hydraulic fracturing and well stimulation have been used (California Council on Science and Technology, 2015) were among the fields in the high risk category based on vertical proximity. For example, median vertical separation distances for North Belridge, South Belridge, and Lost Hills fields were 470 ft, –312 ft (overlap), and 432 ft, respectively (fig. 11). In contrast, separation distance for Elk Hills field was greater: median distance between petroleum resource development and groundwater resources was 5,505 ft. The EOR injection wells in the Elk Hills field were deeper (6,300 ft median depth to TOP) than in the other district 4 fields; however, perforation depths for waste-disposal wells were much shallower (608 ft median depth to TOP; appendix table 1–3). The proportion of fields (with available data) in the high-risk category for vertical proximity was 20 percent or less for each district, with the exception of district 4, where 38 percent of the fields were classified in the high-risk category for vertical proximity (table 4). Small separation distances between petroleum resource development and groundwater resources, in combination with high petroleum-well density and injection volume, resulted in district 4 having the highest percentage of fields classified as high priorities for consideration for regional monitoring than any of the other districts.

District 5 (North/Central San Joaquin Basin)

District 5 encompasses the north and central zones of the San Joaquin Basin from Kings County to Stanislaus County (fig. 10A). There are 41 oil and gas fields in the district; these fields have an aggregated area of 425 mi² (table 5). There are about 14,000 DOGGR new, active, idle, and plugged oil and gas wells in the district, of which about 12,000 are oil and gas production wells and about 1,500 are injection wells (table 1). In the north zone of the of the San Joaquin Basin, fields in Madera, Merced, and Stanislaus Counties and a few fields in Fresno County produce nonassociated gas from Cretaceous, Eocene, and Miocene sandstones (Hosford Scheirer, 2007). In the central zone of the basin, oil and gas fields are located in Fresno, Kings, and San Benito Counties. District 5 fields are within the San Joaquin Valley groundwater basin and in nearby basins to the west, such as the Gilroy-Hollister Valley and Kettleman Plain groundwater basins (California Department of Water Resources, 2015; fig. 16A). The north zone coincides with the Delta-Mendota, Madera, Chowchilla, Merced, Turlock, and Modesto subbasins, which compose part of the San Joaquin River hydrologic region. The Tulare Lake, Westside, and Kings groundwater subbasins, along with the Kern County, Tule, and Kaweah subbasins included in district 4 (fig. 15A), compose part of the Tulare Lake hydrologic region and account for about 38 percent of average annual groundwater extraction in the State (California Department of Water Resources, 2015).

For district 5, 24 percent of the fields (10 fields) were classified as high priority, 24 percent were moderate (10 fields), and 51 percent were low (21 fields; table 5; fig. 16*A*). Fields that had high overall priority classification accounted for almost half of the aggregated field area for the district. By area, 46 percent of the total area of district 5 oil and gas fields was ranked as high priority, 22 percent was moderate, and 32 percent was low. High overall priority classification was primarily based on either high volume of injection or high vertical proximity of resources, and these fields were located in the central zone of the San Joaquin Basin (exception is the Hollister field, which is outside the basin boundary). Although most injection wells were water flood and steam injection (table 1), injection volumes were predominantly waste-water disposal (tables 6*A–C*); exceptions were Coalinga, East Extension of Coalinga, and North Tejon, which had injection for both EOR and waste disposal. For a few fields in the western region of Kings groundwater subbasin, high priority classifications were based on moderate petroleum-well density in an area with high water-well density. Fields in district 5 were more frequently characterized by moderate or low petroleum-well density (39 of 41 fields) and low volume of injection (30 fields; figs. 16*B*, *C*). Eleven of the 13 gas fields in the district and located in the north zone of the San Joaquin Basin were classified as low priority based on low intensity of petroleum resource development with almost no water injection and moderate to low water-well density (table 6*C*).

Vertical proximity of petroleum resource development to groundwater resources in district 5 was classified as close for 3 fields, moderate for 3 fields, far for 10 fields, and 25 fields had insufficient data to evaluate (table 4; fig. 16*D*). Two of the fields that ranked in the high-risk category for vertical proximity (Hollister and Pyramid Hills) were classified in the low and moderate categories for all of the other factors (table 6*A*). The third field in the high-risk category, Coalinga, also had high petroleum-well density and volume of injection. One of the high-priority fields in the district, Kettleman North Dome, was classified in low category for vertical proximity (7,444 ft median separation distance) and in the high category for total volume of waste-water disposal (39 MMB). However, vertical separation distance was calculated using mostly production well data for which median depth to TOP was 8,300 ft, whereas median depth to TOP for waste-disposal wells was much shallower at about 1,100 ft (appendix table 1–3). Results from preliminary assessment of petroleum resource development at Kettleman North Dome suggest there may be few injection wells injecting large volumes of waste-water and at shallower depths than reflected in the vertical proximity assessment. This comparison of TOP-depths by well type exemplifies how the vertical proximity analysis does not represent separation distance of groundwater from all petroleum development activities within a field and further investigation is necessary on a field scale for evaluating vulnerability of groundwater to oil and gas development.

District 6 (Sacramento Basin)

District 6 covers the northern part of California, bounded in the west by the Pacific Ocean and in the north and east by the State boundaries (fig. 2). The boundary in central California between district 5 and district 6 is roughly defined by the Stanislaus-San Joaquin County line. District 6 also borders the northern end of district 3 near the San Francisco Bay region. Collectively, the 168 oil and gas fields in district 6 represent the largest area of any district (1,216 mi^2). District 6 fields are primarily within the Sacramento Basin and are generally used for developing natural gas resources; 11 fields are outside of the basin and in or near the coastal valleys to the west of the basin. Hosford Scheirer and others (2007) estimated a mean of 534 billion cubic feet of natural gas and 323 thousand barrels of natural gas liquids in the Sacramento Basin that are recoverable; more than 80 percent of the natural gas is contained in the Upper Cretaceous rocks of the Dobbins-Forbes and Winters-Domengine petroleum systems. More than 9 trillion cubic feet of natural gas have already been produced in the basin. The Sacramento Basin coincides with the Sacramento Valley groundwater basin and the northern subbasins of the San Joaquin Valley groundwater basin (fig. 17*A*; California Department of Water Resources, 2016). Primary groundwater producing formations in the Sacramento Valley groundwater basin are composed of alluvial fan deposits and volcanic flow deposits derived from erosion of the Coast Ranges and Klamath Mountains to the northwest and west, Lassen Peak to the northeast, and the Sierra Nevada to the east (California Department of Water Resources, 2015). The few fields outside of the Sacramento Basin are within the boundaries of the coastal Eureka Plain and Eel River Valley groundwater basins of Humboldt County, and in or near Santa Rosa Valley, Suisun-Fairfield Valley, Petaluma Valley, Clayton Valley, Pittsburg Plain, Livermore Valley, and Half Moon Bay Terrace groundwater basins surrounding the San Francisco Bay region (California Department of Water Resources, 2015).

For district 6, 2 percent of the fields (4 fields) were classified as high priority, 20 percent (33 fields) were moderate, and 78 percent (131 fields) were low (table 5; fig. 17*A*). District 6 had the most oil and gas fields of the districts by count and area, but these fields are mostly used for gas extraction and have comparatively less intense petroleum resource development, characterized by moderate to low petroleum-well density (fig. 17*B*), virtually no injection for enhanced oil recovery, and comparatively low injection volume for waste-water disposal (fig. 17*C*). By area, 5 percent of the total area of district 6 oil and gas fields ranked as high priority, 40 percent was moderate, and 55 percent was low. High overall priority classification was based on vertical proximity (two fields), water-injection volume (one field), or moderate petroleum-well density in areas with high water-well density (one field; table 6*A*). More than half of the fields in the state with high water-well density were in district 6, and the majority of these fields were classified as low priority based on low volume of injection and low petroleum-well density.

Fields in which there were injection activities (gas storage or waste disposal) were classified as high or moderate priority, based on lateral proximity to currently used groundwater resources. In general, injection volumes in the district were low relative to other districts: only 8 district-6 fields were classified as high or moderate for injection volumes.

For district 6 oil and gas fields, 2 fields were classified in the high-risk category for vertical proximity, 12 were in the moderate-risk category, 15 were in the low-risk category, and 139 had insufficient data to evaluate (table 4; fig. 17D). Few fields in district 6 were attributed with vertical proximity, because fields generally consisted of oil and gas production wells, for which there was a lack of available depth data (table 1; appendix table 1–3). Where known, petroleum resource development was generally thousands of feet deeper than groundwater resources: median vertical separation distance ranged from 927 ft to 9,506 ft (fig. 11).

Whereas district 6 fields generally had moderate to low potential risk to groundwater sources based on volume of injection, petroleum-well density, and vertical proximity,

the majority of fields (131 of 168 fields) were characterized by moderate to high water-well density (table 5; fig. 17E). Fields in California that had high density of overlying or adjacent water wells were located in the Sacramento and San Joaquin Valleys (figs. 11F, G), and more than half of the fields classified in the high-risk category for water-well density were in district 6. Because water wells were generally present throughout the State (fig. 1A), and all potentially beneficial-use waters adjacent to oil fields have protected-groundwater status in California, water-well density was only a deciding factor in the overall priority classification for fields that had intermediate rankings for other factors. As a result, 27 of the 37 fields in district 6 that had high water-well density were low priority for regional monitoring based on low volume of injection and low petroleum-well density (tables 5 and 6C). However, 32 fields were classified as moderate priority because they had moderate petroleum-well density (sometimes coupled with moderate injection volume) and moderate to high water-well density (table 6B).
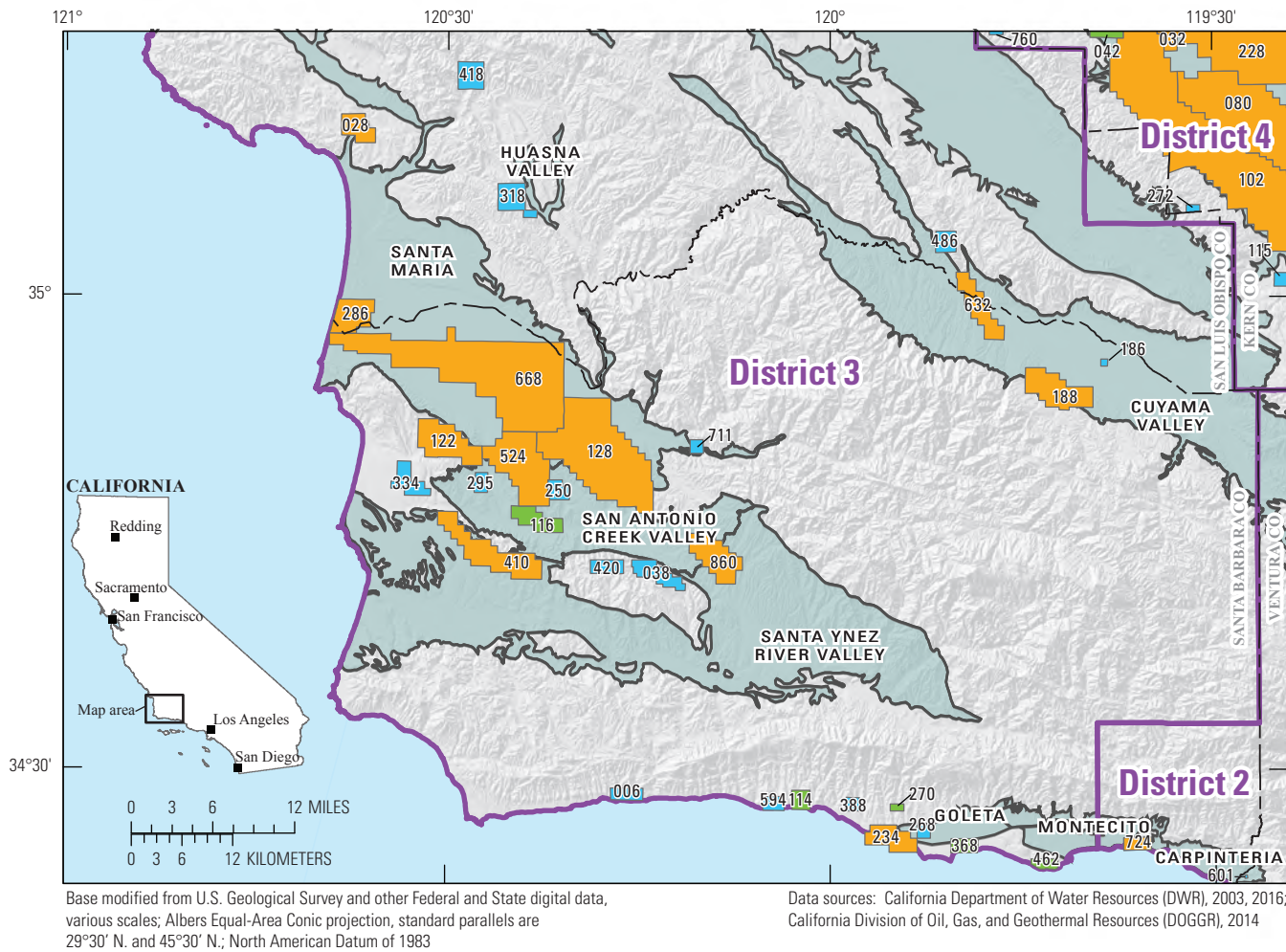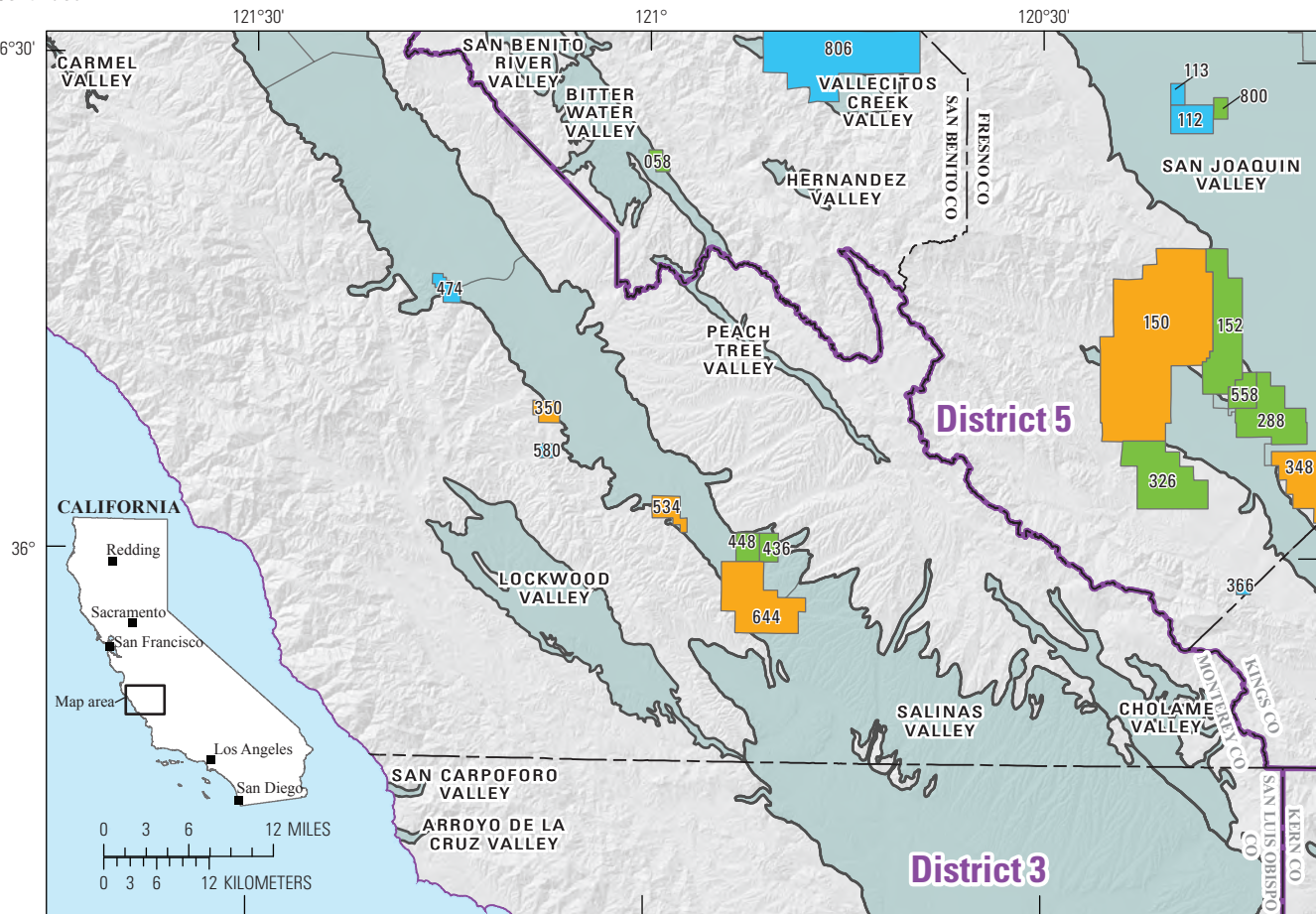
Figure 15.   Oil and gas fields in district 4, San Joaquin Basin—South, showing classifications for *A*, priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

EXPLANATION

Priority classifications

[ ] High   [ ] Moderate   [ ] Low

[ ] DWR groundwater basins   - — County
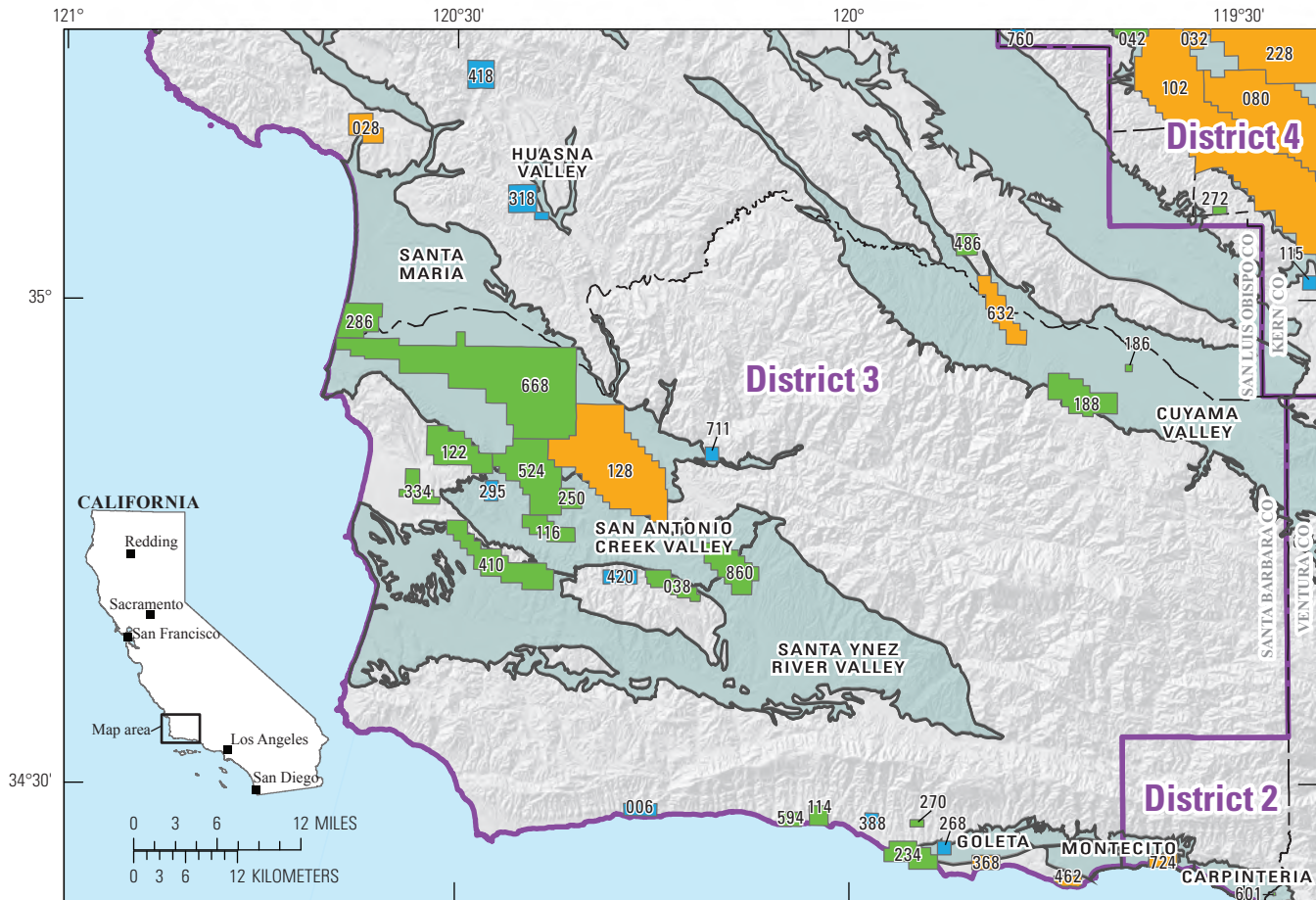
—— DWR groundwater subbasins   —— DOGGR district boundary

Numbers in priority classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
018	Ant Hill	188	Cuyama, South	372	Lakeside	690	Semitropic
020	Antelope Hills	190	Cymric	374	Lakeside, South	696	Seventh Standard
022	Antelope Hills, North	194	Deer Creek	375	Landslide	697	Shafter
024	Antelope Plains Gas	196	Deer Creek, North	428	Los Lobos	698	Shafter, Southeast Gas
032	Asphalto	204	Devils Den	432	Lost Hills	699	Shafter, North
038	Barham Ranch	210	Dudley Ridge Gas	434	Lost Hills, Northwest	700	Shale Flats Gas
040	Beer Nose	220	Dyer Creek	446	McClung	702	Shale Point Gas
042	Belgian Anticline	221	Eagle Rest	450	McDonald Anticline	711	Sisquoc Ranch
044	Bellevue	222	Edison	454	McKittrick	716	Rose
046	Bellevue, West	224	Edison, Northeast	479	Monument Junction	720	Rosecrans, East
050	Belridge, North	228	Elk Hills	486	Morales Canyon	752	Tejon
052	Belridge, South	238	English Colony	488	Mount Poso	754	Tejon Flats
060	Blackwells Corner	256	Fruitvale	490	Mountain View	756	Tejon Hills
066	Bowerbank	260	Garrison City Gas	532	Paloma	758	Tejon, North
080	Buena Vista	272	Gonyer Anticline	544	Pioneer	759	Temblor East
092	Buttonwillow Gas	274	Goosloo	558	Pleasant Valley	760	Temblor Hills
095	Cal Canal Gas	280	Greeley	560	Pleito	762	Temblor Ranch
096	Calders Corner	288	Guijarral Hills	566	Poso Creek	766	Ten Section
102	Capitola Park	296	Harvester Gas	578	Pyramid Hills	768	Terra Bella
104	Canal	328	Jasmin	582	Railroad Gap	790	Trico Gas
106	Canfield Ranch	330	Jasmin, West	602	Rio Bravo	792	Trico Gas, Northwest
115	Capitola Park	332	Jerry Slough	608	Rio Viejo	794	Tulare Lake
117	Carneros Creek	336	Kern Bluff	617	Rose	798	Union Avenue
140	Chico Martinez	338	Kern Front	624	Rosedale	808	Valpredo
146	Cienaga Canyon	340	Kern River	626	Rosedale Ranch	822	Wasco
156	Coles Levee, North	342	Kernsumner	628	Round Mountain	826	Welcome Valley
158	Coles Levee, South	344	Kettleman City	632	Russell Ranch	832	Wheeler Ridge
160	Comanche Point	346	Kettleman Middle Dome	648	San Emidio Nose	834	White Wolf
186	Cuyama, Central	348	Kettleman North Dome	650	San Emidio	858	Yowlumne
				652	San Emidio Creek	860	Zaca

Figure 15.   —Continued

Figure 15. —Continued

EXPLANATION

Petroleum-well density

High   Moderate   Low

☐ DWR groundwater basins

─── DWR groundwater subbasins

- ─── County

━━━ DOGGR district boundary

Numbers in petroleum-well density classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
018	Ant Hill	188	Cuyama, South	372	Lakeside	690	Semitropic
020	Antelope Hills	190	Cymric	374	Lakeside, South	696	Seventh Standard
022	Antelope Hills, North	194	Deer Creek	375	Landslide	697	Shafter
024	Antelope Plains Gas	196	Deer Creek, North	428	Los Lobos	698	Shafter, Southeast Gas
032	Asphalto	204	Devils Den	432	Lost Hills	699	Shafter, North
038	Barham Ranch	210	Dudley Ridge Gas	434	Lost Hills, Northwest	700	Shale Flats Gas
040	Beer Nose	220	Dyer Creek	446	McClung	702	Shale Point Gas
042	Belgian Anticline	221	Eagle Rest	450	McDonald Anticline	711	Sisquoc Ranch
044	Bellevue	222	Edison	454	McKittrick	716	Rose
046	Bellevue, West	224	Edison, Northeast	479	Monument Junction	720	Rosecrans, East
050	Belridge, North	228	Elk Hills	486	Morales Canyon	752	Tejon
052	Belridge, South	238	English Colony	488	Mount Poso	754	Tejon Flats
060	Blackwells Corner	256	Fruitvale	490	Mountain View	756	Tejon Hills
066	Bowerbank	260	Garrison City Gas	532	Paloma	758	Tejon, North
080	Buena Vista	272	Gonyer Anticline	544	Pioneer	759	Temblor East
092	Buttonwillow Gas	274	Goosloo	558	Pleasant Valley	760	Temblor Hills
095	Cal Canal Gas	280	Greeley	560	Pleito	762	Temblor Ranch
096	Calders Corner	288	Guijarral Hills	566	Poso Creek	766	Ten Section
102	Capitola Park	296	Harvester Gas	578	Pyramid Hills	768	Terra Bella
104	Canal	328	Jasmin	582	Railroad Gap	790	Trico Gas
106	Canfield Ranch	330	Jasmin, West	602	Rio Bravo	792	Trico Gas, Northwest
115	Capitola Park	332	Jerry Slough	608	Rio Viejo	794	Tulare Lake
117	Carneros Creek	336	Kern Bluff	617	Rose	798	Union Avenue
140	Chico Martinez	338	Kern Front	624	Rosedale	808	Valpredo
146	Cienaga Canyon	340	Kern River	626	Rosedale Ranch	822	Wasco
156	Coles Levee, North	342	Kernsumner	628	Round Mountain	826	Welcome Valley
158	Coles Levee, South	344	Kettleman City	632	Russell Ranch	832	Wheeler Ridge
160	Comanche Point	346	Kettleman Middle Dome	648	San Emidio Nose	834	White Wolf
186	Cuyama, Central	348	Kettleman North Dome	650	San Emidio	858	Yowlumne
				652	San Emidio Creek	860	Zaca

Figure 15. —Continued

Figure 15. —Continued

EXPLANATION

Volume of injection				DWR groundwater basins	- County
High	Moderate	Low		DWR groundwater subbasins	DOGGR district boundary

Numbers in volume of injection indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
018	Ant Hill	188	Cuyama, South	372	Lakeside	690	Semitropic
020	Antelope Hills	190	Cymric	374	Lakeside, South	696	Seventh Standard
022	Antelope Hills, North	194	Deer Creek	375	Landslide	697	Shafter
024	Antelope Plains Gas	196	Deer Creek, North	428	Los Lobos	698	Shafter, Southeast Gas
032	Asphalto	204	Devils Den	432	Lost Hills	699	Shafter, North
038	Barham Ranch	210	Dudley Ridge Gas	434	Lost Hills, Northwest	700	Shale Flats Gas
040	Beer Nose	220	Dyer Creek	446	McClung	702	Shale Point Gas
042	Belgian Anticline	221	Eagle Rest	450	McDonald Anticline	711	Sisquoc Ranch
044	Bellevue	222	Edison	454	McKittrick	716	Rose
046	Bellevue, West	224	Edison, Northeast	479	Monument Junction	720	Rosecrans, East
050	Belridge, North	228	Elk Hills	486	Morales Canyon	752	Tejon
052	Belridge, South	238	English Colony	488	Mount Poso	754	Tejon Flats
060	Blackwells Corner	256	Fruitvale	490	Mountain View	756	Tejon Hills
066	Bowerbank	260	Garrison City Gas	532	Paloma	758	Tejon, North
080	Buena Vista	272	Gonyer Anticline	544	Pioneer	759	Temblor East
092	Buttonwillow Gas	274	Goosloo	558	Pleasant Valley	760	Temblor Hills
095	Cal Canal Gas	280	Greeley	560	Pleito	762	Temblor Ranch
096	Calders Corner	288	Guijarral Hills	566	Poso Creek	766	Ten Section
102	Capitola Park	296	Harvester Gas	578	Pyramid Hills	768	Terra Bella
104	Canal	328	Jasmin	582	Railroad Gap	790	Trico Gas
106	Canfield Ranch	330	Jasmin, West	602	Rio Bravo	792	Trico Gas, Northwest
115	Capitola Park	332	Jerry Slough	608	Rio Viejo	794	Tulare Lake
117	Carneros Creek	336	Kern Bluff	617	Rose	798	Union Avenue
140	Chico Martinez	338	Kern Front	624	Rosedale	808	Valpredo
146	Cienaga Canyon	340	Kern River	626	Rosedale Ranch	822	Wasco
156	Coles Levee, North	342	Kernsumner	628	Round Mountain	826	Welcome Valley
158	Coles Levee, South	344	Kettleman City	632	Russell Ranch	832	Wheeler Ridge
160	Comanche Point	346	Kettleman Middle Dome	648	San Emidio Nose	834	White Wolf
186	Cuyama, Central	348	Kettleman North Dome	650	San Emidio	858	Yowlumne
				652	San Emidio Creek	860	Zaca

Figure 15.   —Continued

Figure 15.   —Continued

EXPLANATION

Vertical proximity

Close   Far

Moderate   Unknown

Numbers in vertical proximity indicate the field codes

DWR groundwater basins   County

DWR groundwater subbasins   DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
018	Ant Hill	188	Cuyama, South	372	Lakeside	690	Semitropic
020	Antelope Hills	190	Cymric	374	Lakeside, South	696	Seventh Standard
022	Antelope Hills, North	194	Deer Creek	375	Landslide	697	Shafter
024	Antelope Plains Gas	196	Deer Creek, North	428	Los Lobos	698	Shafter, Southeast Gas
032	Asphalto	204	Devils Den	432	Lost Hills	699	Shafter, North
038	Barham Ranch	210	Dudley Ridge Gas	434	Lost Hills, Northwest	700	Shale Flats Gas
040	Beer Nose	220	Dyer Creek	446	McClung	702	Shale Point Gas
042	Belgian Anticline	221	Eagle Rest	450	McDonald Anticline	711	Sisquoc Ranch
044	Bellevue	222	Edison	454	McKittrick	716	Rose
046	Bellevue, West	224	Edison, Northeast	479	Monument Junction	720	Rosecrans, East
050	Belridge, North	228	Elk Hills	486	Morales Canyon	752	Tejon
052	Belridge, South	238	English Colony	488	Mount Poso	754	Tejon Flats
060	Blackwells Corner	256	Fruitvale	490	Mountain View	756	Tejon Hills
066	Bowerbank	260	Garrison City Gas	532	Paloma	758	Tejon, North
080	Buena Vista	272	Gonyer Anticline	544	Pioneer	759	Temblor East
092	Buttonwillow Gas	274	Goosloo	558	Pleasant Valley	760	Temblor Hills
095	Cal Canal Gas	280	Greeley	560	Pleito	762	Temblor Ranch
096	Calders Corner	288	Guijarral Hills	566	Poso Creek	766	Ten Section
102	Capitola Park	296	Harvester Gas	578	Pyramid Hills	768	Terra Bella
104	Canal	328	Jasmin	582	Railroad Gap	790	Trico Gas
106	Canfield Ranch	330	Jasmin, West	602	Rio Bravo	792	Trico Gas, Northwest
115	Capitola Park	332	Jerry Slough	608	Rio Viejo	794	Tulare Lake
117	Carneros Creek	336	Kern Bluff	617	Rose	798	Union Avenue
140	Chico Martinez	338	Kern Front	624	Rosedale	808	Valpredo
146	Cienaga Canyon	340	Kern River	626	Rosedale Ranch	822	Wasco
156	Coles Levee, North	342	Kernsumner	628	Round Mountain	826	Welcome Valley
158	Coles Levee, South	344	Kettleman City	632	Russell Ranch	832	Wheeler Ridge
160	Comanche Point	346	Kettleman Middle Dome	648	San Emidio Nose	834	White Wolf
186	Cuyama, Central	348	Kettleman North Dome	650	San Emidio	858	Yowlumne
				652	San Emidio Creek	860	Zaca

Figure 15. —Continued

Figure 15.   —Continued

EXPLANATION

Water-well density

High   Moderate   Low

Numbers in water-well density indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

- —— County

—— DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
018	Ant Hill	188	Cuyama, South	372	Lakeside	690	Semitropic
020	Antelope Hills	190	Cymric	374	Lakeside, South	696	Seventh Standard
022	Antelope Hills, North	194	Deer Creek	375	Landslide	697	Shafter
024	Antelope Plains Gas	196	Deer Creek, North	428	Los Lobos	698	Shafter, Southeast Gas
032	Asphalto	204	Devils Den	432	Lost Hills	699	Shafter, North
038	Barham Ranch	210	Dudley Ridge Gas	434	Lost Hills, Northwest	700	Shale Flats Gas
040	Beer Nose	220	Dyer Creek	446	McClung	702	Shale Point Gas
042	Belgian Anticline	221	Eagle Rest	450	McDonald Anticline	711	Sisquoc Ranch
044	Bellevue	222	Edison	454	McKittrick	716	Rose
046	Bellevue, West	224	Edison, Northeast	479	Monument Junction	720	Rosecrans, East
050	Belridge, North	228	Elk Hills	486	Morales Canyon	752	Tejon
052	Belridge, South	238	English Colony	488	Mount Poso	754	Tejon Flats
060	Blackwells Corner	256	Fruitvale	490	Mountain View	756	Tejon Hills
066	Bowerbank	260	Garrison City Gas	532	Paloma	758	Tejon, North
080	Buena Vista	272	Gonyer Anticline	544	Pioneer	759	Temblor East
092	Buttonwillow Gas	274	Goosloo	558	Pleasant Valley	760	Temblor Hills
095	Cal Canal Gas	280	Greeley	560	Pleito	762	Temblor Ranch
096	Calders Corner	288	Guijarral Hills	566	Poso Creek	766	Ten Section
102	Capitola Park	296	Harvester Gas	578	Pyramid Hills	768	Terra Bella
104	Canal	328	Jasmin	582	Railroad Gap	790	Trico Gas
106	Canfield Ranch	330	Jasmin, West	602	Rio Bravo	792	Trico Gas, Northwest
115	Capitola Park	332	Jerry Slough	608	Rio Viejo	794	Tulare Lake
117	Carneros Creek	336	Kern Bluff	617	Rose	798	Union Avenue
140	Chico Martinez	338	Kern Front	624	Rosedale	808	Valpredo
146	Cienaga Canyon	340	Kern River	626	Rosedale Ranch	822	Wasco
156	Coles Levee, North	342	Kernsumner	628	Round Mountain	826	Welcome Valley
158	Coles Levee, South	344	Kettleman City	632	Russell Ranch	832	Wheeler Ridge
160	Comanche Point	346	Kettleman Middle Dome	648	San Emidio Nose	834	White Wolf
186	Cuyama, Central	348	Kettleman North Dome	650	San Emidio	858	Yowlumne
				652	San Emidio Creek	860	Zaca

Figure 15. —Continued

Figure 16.   Oil and gas fields in district 5, San Joaquin Basin—North/Central, showing classifications for *A*, priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

EXPLANATION

Priority classifications

High   Moderate   Low

Numbers in priority classifications indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
051	Ash Slough Gas	288	Guijarral Hills	434	Lost Hills, Northwest	644	San Ardo
058	Bitterwater	292	Hanford	436	Lynch Canyon	654	San Joaquin
084	Burrel	296	Harvester Gas	448	McCool Ranch	656	San Joaquin Gas, Northwest
086	Burrel, Southeast	300	Helm	456	McMullin Ranch Gas	676	Sargent
100	Camden	302	Hollister	457	Merrill Avenue Gas	786	Tracy Gas
112	Cantua Creek	314	Hospital Nose Gas	459	Merrill Avenue, Southeast, Gas	787	Tracy, West, Gas
113	Cantua Nueva	326	Jacalitos	467	Mint Road Gas	790	Trico Gas
134	Cheney Ranch Gas	344	Kettleman North Dome	470	Moffat Ranch Gas	792	Trico Gas, Northwest
144	Chowchilla Gas	346	Kettleman Middle Dome	474	Monroe Swell	794	Tulare Lake
149	Collegeville, East	348	Deer Creek	513	Oakdale Gas	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	802	Union Island Gas
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley	806	Vallecitos
204	Devils Den	390	Lathrop Gas	578	Pyramid Hills	809	Van Ness Slough
210	Dudley Ridge Gas	392	Lathrop Southeast Gas	580	Quinado Canyon	816	Vernalis Gas
248	Five Points	404	Livermore	584	Raisin City	818	Vernalis, Southwest Gas
254	French Camp Gas	413	Lone Tree Creek Gas	614	Riverdale	826	Welcome Valley
266	Gill Ranch Gas	432	Lost Hills	616	Roberts Island Gas	831	Westhaven

Figure 16.   —Continued

B

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

Figure 16.   —Continued

EXPLANATION

Petroleum-well density

| | High | | Low | | DWR groundwater basins | | County |
| | Moderate | | | | DWR groundwater subbasins | | DOGGR district boundary |

Numbers in petroleum-well density indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
051	Ash Slough Gas	288	Guijarral Hills	434	Lost Hills, Northwest	644	San Ardo
058	Bitterwater	292	Hanford	436	Lynch Canyon	654	San Joaquin
084	Burrel	296	Harvester Gas	448	McCool Ranch	656	San Joaquin Gas, Northwest
086	Burrel, Southeast	300	Helm	456	McMullin Ranch Gas	676	Sargent
100	Camden	302	Hollister	457	Merrill Avenue Gas	786	Tracy Gas
112	Cantua Creek	314	Hospital Nose Gas	459	Merrill Avenue, Southeast, Gas	787	Tracy, West, Gas
113	Cantua Nueva	326	Jacalitos	467	Mint Road Gas	790	Trico Gas
134	Cheney Ranch Gas	344	Kettleman North Dome	470	Moffat Ranch Gas	792	Trico Gas, Northwest
144	Chowchilla Gas	346	Kettleman Middle Dome	474	Monroe Swell	794	Tulare Lake
149	Collegeville, East	348	Deer Creek	513	Oakdale Gas	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	802	Union Island Gas
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley	806	Vallecitos
204	Devils Den	390	Lathrop Gas	578	Pyramid Hills	809	Van Ness Slough
210	Dudley Ridge Gas	392	Lathrop Southeast Gas	580	Quinado Canyon	816	Vernalis Gas
248	Five Points	404	Livermore	584	Raisin City	818	Vernalis, Southwest Gas
254	French Camp Gas	413	Lone Tree Creek Gas	614	Riverdale	826	Welcome Valley
266	Gill Ranch Gas	432	Lost Hills	616	Roberts Island Gas	831	Westhaven

Figure 16.   —Continued

Figure 16.   —Continued

EXPLANATION

Volume of injection

☐ High   ☐ Low

☐ Moderate

Numbers in volume of injection indicate the field codes

☐ DWR groundwater basins   - — County

—— DWR groundwater subbasins   —— DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
051	Ash Slough Gas	288	Guijarral Hills	434	Lost Hills, Northwest	644	San Ardo
058	Bitterwater	292	Hanford	436	Lynch Canyon	654	San Joaquin
084	Burrel	296	Harvester Gas	448	McCool Ranch	656	San Joaquin Gas, Northwest
086	Burrel, Southeast	300	Helm	456	McMullin Ranch Gas	676	Sargent
100	Camden	302	Hollister	457	Merrill Avenue Gas	786	Tracy Gas
112	Cantua Creek	314	Hospital Nose Gas	459	Merrill Avenue, Southeast, Gas	787	Tracy, West, Gas
113	Cantua Nueva	326	Jacalitos	467	Mint Road Gas	790	Trico Gas
134	Cheney Ranch Gas	344	Kettleman North Dome	470	Moffat Ranch Gas	792	Trico Gas, Northwest
144	Chowchilla Gas	346	Kettleman Middle Dome	474	Monroe Swell	794	Tulare Lake
149	Collegeville, East	348	Deer Creek	513	Oakdale Gas	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	802	Union Island Gas
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley	806	Vallecitos
204	Devils Den	390	Lathrop Gas	578	Pyramid Hills	809	Van Ness Slough
210	Dudley Ridge Gas	392	Lathrop Southeast Gas	580	Quinado Canyon	816	Vernalis Gas
248	Five Points	404	Livermore	584	Raisin City	818	Vernalis, Southwest Gas
254	French Camp Gas	413	Lone Tree Creek Gas	614	Riverdale	826	Welcome Valley
266	Gill Ranch Gas	432	Lost Hills	616	Roberts Island Gas	831	Westhaven

Figure 16.   —Continued

Figure 16.   —Continued

EXPLANATION

Vertical proximity

Close

Far

Moderate

Unknown

Numbers in vertical proximity indicate the field codes

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
051	Ash Slough Gas	288	Guijarral Hills	434	Lost Hills, Northwest	644	San Ardo
058	Bitterwater	292	Hanford	436	Lynch Canyon	654	San Joaquin
084	Burrel	296	Harvester Gas	448	McCool Ranch	656	San Joaquin Gas, Northwest
086	Burrel, Southeast	300	Helm	456	McMullin Ranch Gas	676	Sargent
100	Camden	302	Hollister	457	Merrill Avenue Gas	786	Tracy Gas
112	Cantua Creek	314	Hospital Nose Gas	459	Merrill Avenue, Southeast, Gas	787	Tracy, West, Gas
113	Cantua Nueva	326	Jacalitos	467	Mint Road Gas	790	Trico Gas
134	Cheney Ranch Gas	344	Kettleman North Dome	470	Moffat Ranch Gas	792	Trico Gas, Northwest
144	Chowchilla Gas	346	Kettleman Middle Dome	474	Monroe Swell	794	Tulare Lake
149	Collegeville, East	348	Deer Creek	513	Oakdale Gas	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	802	Union Island Gas
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley	806	Vallecitos
204	Devils Den	390	Lathrop Gas	578	Pyramid Hills	809	Van Ness Slough
210	Dudley Ridge Gas	392	Lathrop Southeast Gas	580	Quinado Canyon	816	Vernalis Gas
248	Five Points	404	Livermore	584	Raisin City	818	Vernalis, Southwest Gas
254	French Camp Gas	413	Lone Tree Creek Gas	614	Riverdale	826	Welcome Valley
266	Gill Ranch Gas	432	Lost Hills	616	Roberts Island Gas	831	Westhaven

Figure 16.   —Continued

E

Base modified from U.S. Geological Survey and other Federal and
State digital data, various scales; Albers Equal-Area Conic projection,
standard parallels are 29°30′ N. and 45°30′ N.; North American
Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016;
California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014

Figure 16.   —Continued

EXPLANATION

Water-well density

High   Moderate   Low

Numbers in water-well density indicate the field codes

DWR groundwater basins   - —— County

—— DWR groundwater subbasins   —— DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
051	Ash Slough Gas	288	Guijarral Hills	434	Lost Hills, Northwest	644	San Ardo
058	Bitterwater	292	Hanford	436	Lynch Canyon	654	San Joaquin
084	Burrel	296	Harvester Gas	448	McCool Ranch	656	San Joaquin Gas, Northwest
086	Burrel, Southeast	300	Helm	456	McMullin Ranch Gas	676	Sargent
100	Camden	302	Hollister	457	Merrill Avenue Gas	786	Tracy Gas
112	Cantua Creek	314	Hospital Nose Gas	459	Merrill Avenue, Southeast, Gas	787	Tracy, West, Gas
113	Cantua Nueva	326	Jacalitos	467	Mint Road Gas	790	Trico Gas
134	Cheney Ranch Gas	344	Kettleman North Dome	470	Moffat Ranch Gas	792	Trico Gas, Northwest
144	Chowchilla Gas	346	Kettleman Middle Dome	474	Monroe Swell	794	Tulare Lake
149	Collegeville, East	348	Deer Creek	513	Oakdale Gas	800	Turk Anticline
150	Coalinga	350	King City	534	Paris Valley	802	Union Island Gas
152	Coalinga, East Extension	366	Kreyenhagen	558	Pleasant Valley	806	Vallecitos
204	Devils Den	390	Lathrop Gas	578	Pyramid Hills	809	Van Ness Slough
210	Dudley Ridge Gas	392	Lathrop Southeast Gas	580	Quinado Canyon	816	Vernalis Gas
248	Five Points	404	Livermore	584	Raisin City	818	Vernalis, Southwest Gas
254	French Camp Gas	413	Lone Tree Creek Gas	614	Riverdale	826	Welcome Valley
266	Gill Ranch Gas	432	Lost Hills	616	Roberts Island Gas	831	Westhaven

Figure 16.   —Continued

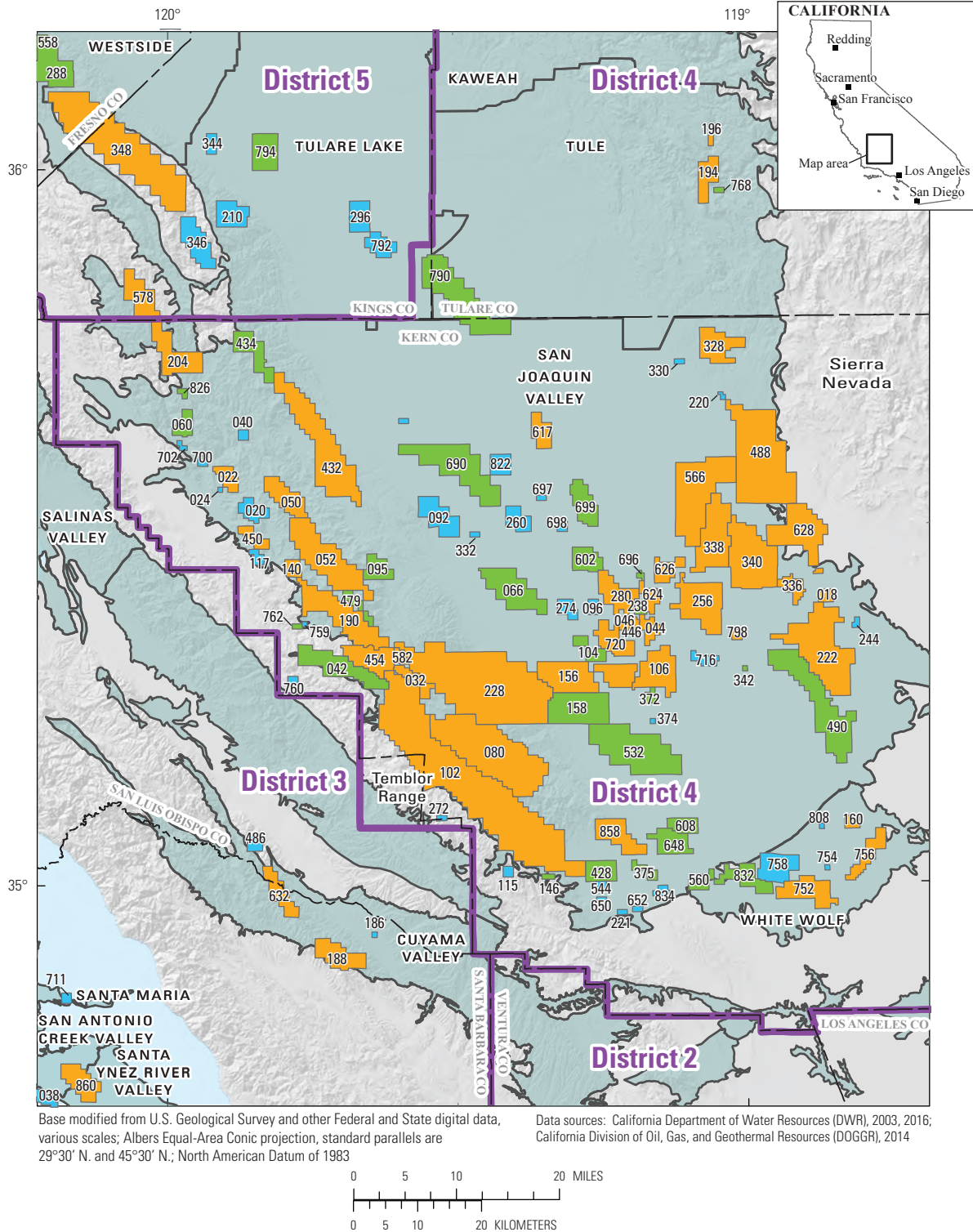**Figure 17.** Oil and gas fields in district 6, Sacramento Valley, showing classifications for *A*, priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.
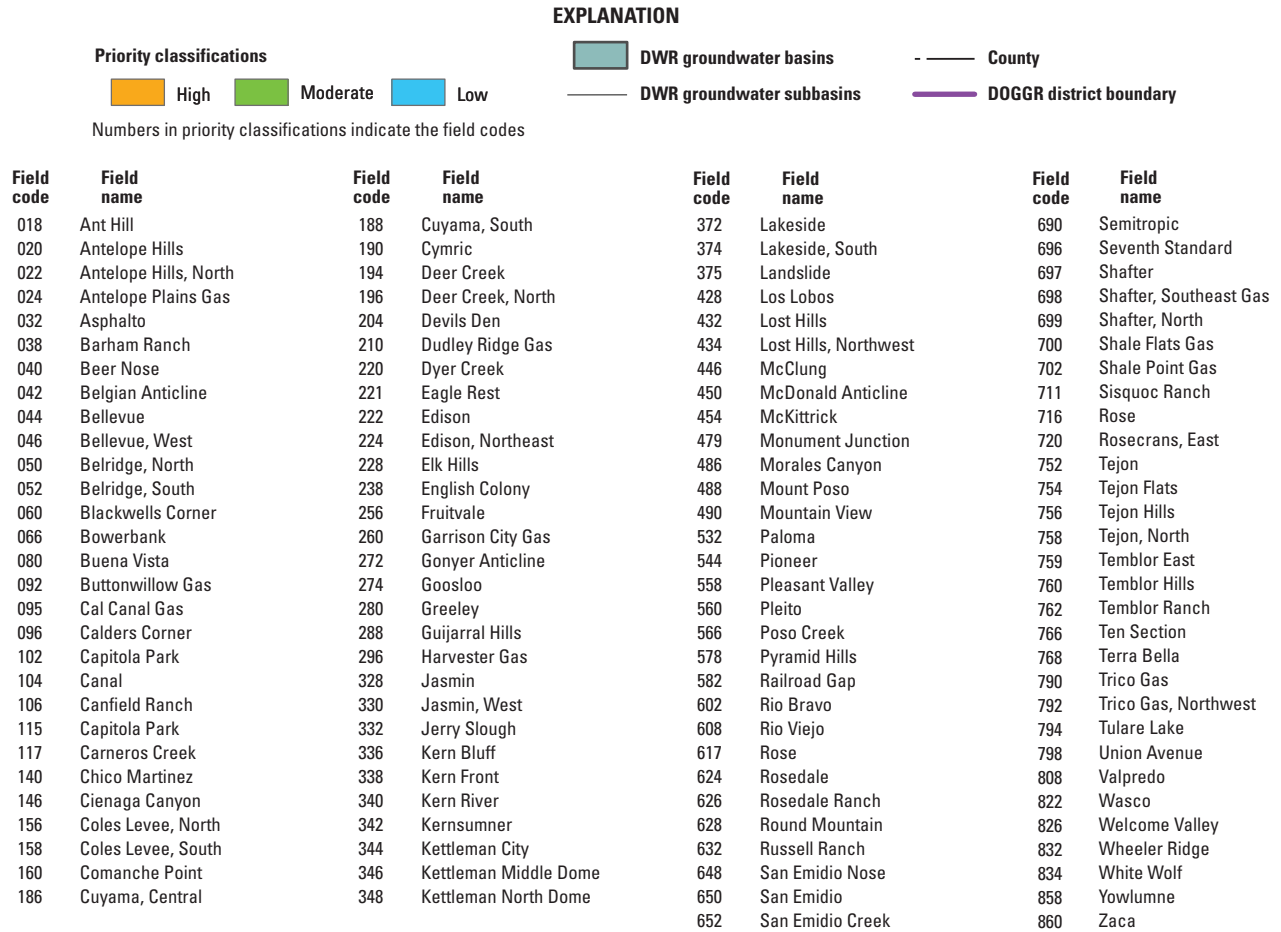
EXPLANATION

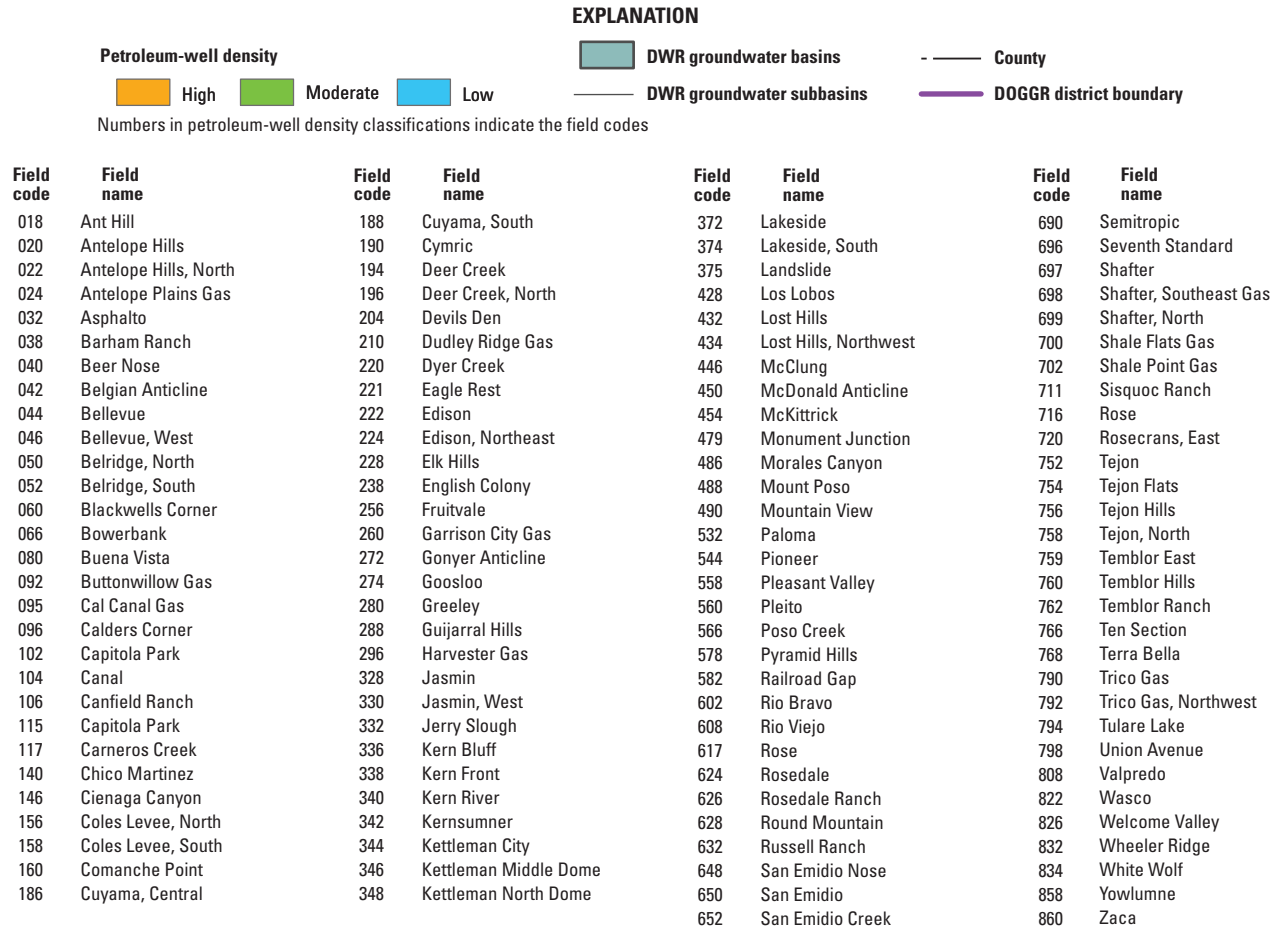**Priority classifications**

High

Moderate

Low

DWR groundwater basins

DWR groundwater subbasins

County

DOGGR district boundary

Numbers in priority classifications indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
002	Afton Gas	244	Fairfield Knolls Gas	430	Los Medanos Gas	659	Sand Mound Slough Gas
004	Afton Gas, South	249	Florin Gas	442	Maine Prairie Gas	684	Saxon Gas
016	Angel Slough Gas	252	Freeport Gas	444	Malton-Black Butte Gas	686	Schohr Ranch Gas
026	Arbuckle Gas	253	Fremont Landing Gas	452	McDonald Island Gas	706	Sherman Island Gas
030	Artois Gas	254	French Camp Gas	455	Medora Lake Gas	709	Snodgrass Slough Gas
059	Bixler Gas	264	Galt Gas	456	McMullin Ranch Gas	713	Greenwood Gas, South
062	Bounde Creek Gas	276	Grand Island Gas	458	Merritt Gas	715	Stegeman Gas
072	Brentwood	278	Greens Lake Gas	460	Merritt Island Gas	717	Oakley Gas, South
073	Brentwood, East Gas	281	Greenwood Gas	466	Millar Gas	718	Stone Lake Gas
074	Buckeye Gas	282	Grimes Gas	482	Moon Bend Gas	719	Stockton Gas
079	Bullock Bend Gas	284	Grimes, West Gas	492	Mulligan Hill Gas	721	Sugarfield Gas
082	Bunker Gas	290	Half Moon Bay	506	Nicolas Gas	722	Suisun Bay Gas
088	Butte Sink Gas	292	Hanford	510	Oakley Gas	730	Sutter Buttes Gas
090	Butte Slough Gas	293	Harlan Ranch Gas	513	Oakdale Gas	732	Sutter City Gas
093	Cache Creek Gas	294	Harte Gas	518	Oil Creek	734	Sycamore Gas
094	Cache Slough Gas	306	Honker Gas	526	Ord Bend Gas	736	Sycamore Slough Gas
138	Chico Gas	314	Hospital Nose Gas	528	Orland Gas	770	Thornton Gas
148	Clarksburg Gas	317	Howells Point Gas	535	Peace Valley Gas	772	Thornton, West-Walnut Grove Gas
149	Collegeville, East	335	Karnak Gas	536	Perkins Lake Gas	776	Tisdale Gas
162	Compton Landing Gas	351	King Island Gas	538	Petaluma Gas	778	Todhunters Lake Gas
164	Compton Landing, South Gas	352	Kirby Hill Gas	541	Pierce Road Gas	786	Tracy Gas
168	Concord Gas	354	Kirby Hill Gas, North	542	Pinole Point	787	Tracy, West, Gas
172	Conway Ranch Gas	356	Kirk Gas	552	Madison Gas	788	Tremont Gas
174	Corning Gas	358	Kirkwood Gas	556	Pleasant Creek Gas	802	Union Island Gas
176	Corning Gas, South	359	Knightsen Gas	564	Poppy Ridge Gas	810	Van Sickle Island Gas
177	Cotati Gas	361	Knights Landing Gas	574	Princeton Gas	816	Vernalis Gas
183	Crossroads Gas	370	La Honda	576	Putah Sink Gas	818	Vernalis, Southwest Gas
192	Davis Southeast Gas	380	Larkin, West Gas	590	Rancho Capay Gas	821	Verona Gas
200	Denverton Gas	390	Lathrop Gas	592	Red Bank Creek Gas	828	West Butte Gas
202	Denverton Creek Gas	392	Lathrop Southeast Gas	596	Rice Creek Gas	840	Wild Goose Gas
206	Dixon Gas	398	Liberty Cut Gas	597	Rice Creek, East Gas	841	Williams Gas
207	Dixon Gas, East	400	Liberty Island Gas	603	Rindge Tract Gas	842	Willow Pass Gas
209	Dry Slough Gas	402	Lindsey Slough Gas	604	Rio Jesus Gas	844	Willow Slough Gas
212	Dufour Gas	403	Little Butte Creek Gas	606	Rio Vista Gas	846	Willows-Beehive Bend Gas
214	Dunnigan Hills Gas	404	Livermore	610	River Break Gas	847	Wilson Creek Gas
216	Durham Gas	406	Llano Seco Gas	612	River Island Gas	850	Winchester Lake Gas
218	Dutch Slough Gas	408	Lodi Gas	615	Robbins Gas	852	Winters Gas
225	East Islands Gas	409	Lodi Airport Gas	616	Roberts Island Gas	854	Woodland Gas
227	El Dorado Bend Gas	411	Lodi, Southeast Gas	634	Ryer Island Gas	862	Zamora Gas
229	Elkhorn Slough Gas	413	Lone Tree Creek Gas	636	Sacramento Airport Gas	864	Zamora Gas, North
243	Everglade Gas	415	Lone Star Gas	638	Sacramento By-Pass Gas		

Figure 17.   —Continued

B

Figure 17.   —Continued

EXPLANATION

Petroleum-well density   DWR groundwater basins   - ——— County

High   Low   ——— DWR groundwater subbasins   ——— DOGGR district boundary

Moderate

Numbers in petroleum-well density indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
002	Afton Gas	244	Fairfield Knolls Gas	430	Los Medanos Gas	659	Sand Mound Slough Gas
004	Afton Gas, South	249	Florin Gas	442	Maine Prairie Gas	684	Saxon Gas
016	Angel Slough Gas	252	Freeport Gas	444	Malton-Black Butte Gas	686	Schohr Ranch Gas
026	Arbuckle Gas	253	Fremont Landing Gas	452	McDonald Island Gas	706	Sherman Island Gas
030	Artois Gas	254	French Camp Gas	455	Medora Lake Gas	709	Snodgrass Slough Gas
059	Bixler Gas	264	Galt Gas	456	McMullin Ranch Gas	713	Greenwood Gas, South
062	Bounde Creek Gas	276	Grand Island Gas	458	Merritt Gas	715	Stegeman Gas
072	Brentwood	278	Greens Lake Gas	460	Merritt Island Gas	717	Oakley Gas, South
073	Brentwood, East Gas	281	Greenwood Gas	466	Millar Gas	718	Stone Lake Gas
074	Buckeye Gas	282	Grimes Gas	482	Moon Bend Gas	719	Stockton Gas
079	Bullock Bend Gas	284	Grimes, West Gas	492	Mulligan Hill Gas	721	Sugarfield Gas
082	Bunker Gas	290	Half Moon Bay	506	Nicolas Gas	722	Suisun Bay Gas
088	Butte Sink Gas	292	Hanford	510	Oakley Gas	730	Sutter Buttes Gas
090	Butte Slough Gas	293	Harlan Ranch Gas	513	Oakdale Gas	732	Sutter City Gas
093	Cache Creek Gas	294	Harte Gas	518	Oil Creek	734	Sycamore Gas
094	Cache Slough Gas	306	Honker Gas	526	Ord Bend Gas	736	Sycamore Slough Gas
138	Chico Gas	314	Hospital Nose Gas	528	Orland Gas	770	Thornton Gas
148	Clarksburg Gas	317	Howells Point Gas	535	Peace Valley Gas	772	Thornton, West-Walnut Grove Gas
149	Collegeville, East	335	Karnak Gas	536	Perkins Lake Gas	776	Tisdale Gas
162	Compton Landing Gas	351	King Island Gas	538	Petaluma Gas	778	Todhunters Lake Gas
164	Compton Landing, South Gas	352	Kirby Hill Gas	541	Pierce Road Gas	786	Tracy Gas
168	Concord Gas	354	Kirby Hill Gas, North	542	Pinole Point	787	Tracy, West, Gas
172	Conway Ranch Gas	356	Kirk Gas	552	Madison Gas	788	Tremont Gas
174	Corning Gas	358	Kirkwood Gas	556	Pleasant Creek Gas	802	Union Island Gas
176	Corning Gas, South	359	Knightsen Gas	564	Poppy Ridge Gas	810	Van Sickle Island Gas
177	Cotati Gas	361	Knights Landing Gas	574	Princeton Gas	816	Vernalis Gas
183	Crossroads Gas	370	La Honda	576	Putah Sink Gas	818	Vernalis, Southwest Gas
192	Davis Southeast Gas	380	Larkin, West Gas	590	Rancho Capay Gas	821	Verona Gas
200	Denverton Gas	390	Lathrop Gas	592	Red Bank Creek Gas	828	West Butte Gas
202	Denverton Creek Gas	392	Lathrop Southeast Gas	596	Rice Creek Gas	840	Wild Goose Gas
206	Dixon Gas	398	Liberty Cut Gas	597	Rice Creek, East Gas	841	Williams Gas
207	Dixon Gas, East	400	Liberty Island Gas	603	Rindge Tract Gas	842	Willow Pass Gas
209	Dry Slough Gas	402	Lindsey Slough Gas	604	Rio Jesus Gas	844	Willow Slough Gas
212	Dufour Gas	403	Little Butte Creek Gas	606	Rio Vista Gas	846	Willows-Beehive Bend Gas
214	Dunnigan Hills Gas	404	Livermore	610	River Break Gas	847	Wilson Creek Gas
216	Durham Gas	406	Llano Seco Gas	612	River Island Gas	850	Winchester Lake Gas
218	Dutch Slough Gas	408	Lodi Gas	615	Robbins Gas	852	Winters Gas
225	East Islands Gas	409	Lodi Airport Gas	616	Roberts Island Gas	854	Woodland Gas
227	El Dorado Bend Gas	411	Lodi, Southeast Gas	634	Ryer Island Gas	862	Zamora Gas
229	Elkhorn Slough Gas	413	Lone Tree Creek Gas	636	Sacramento Airport Gas	864	Zamora Gas, North
243	Everglade Gas	415	Lone Star Gas	638	Sacramento By-Pass Gas		

Figure 17.   —Continued

Figure 17. —Continued

EXPLANATION

Volume of injection

| | High | | Low |

DWR groundwater basins

- County

| | Moderate |

DWR groundwater subbasins

DOGGR district boundary

Numbers in volume of injection indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
002	Afton Gas	244	Fairfield Knolls Gas	430	Los Medanos Gas	659	Sand Mound Slough Gas
004	Afton Gas, South	249	Florin Gas	442	Maine Prairie Gas	684	Saxon Gas
016	Angel Slough Gas	252	Freeport Gas	444	Malton-Black Butte Gas	686	Schohr Ranch Gas
026	Arbuckle Gas	253	Fremont Landing Gas	452	McDonald Island Gas	706	Sherman Island Gas
030	Artois Gas	254	French Camp Gas	455	Medora Lake Gas	709	Snodgrass Slough Gas
059	Bixler Gas	264	Galt Gas	456	McMullin Ranch Gas	713	Greenwood Gas, South
062	Bounde Creek Gas	276	Grand Island Gas	458	Merritt Gas	715	Stegeman Gas
072	Brentwood	278	Greens Lake Gas	460	Merritt Island Gas	717	Oakley Gas, South
073	Brentwood, East Gas	281	Greenwood Gas	466	Millar Gas	718	Stone Lake Gas
074	Buckeye Gas	282	Grimes Gas	482	Moon Bend Gas	719	Stockton Gas
079	Bullock Bend Gas	284	Grimes, West Gas	492	Mulligan Hill Gas	721	Sugarfield Gas
082	Bunker Gas	290	Half Moon Bay	506	Nicolas Gas	722	Suisun Bay Gas
088	Butte Sink Gas	292	Hanford	510	Oakley Gas	730	Sutter Buttes Gas
090	Butte Slough Gas	293	Harlan Ranch Gas	513	Oakdale Gas	732	Sutter City Gas
093	Cache Creek Gas	294	Harte Gas	518	Oil Creek	734	Sycamore Gas
094	Cache Slough Gas	306	Honker Gas	526	Ord Bend Gas	736	Sycamore Slough Gas
138	Chico Gas	314	Hospital Nose Gas	528	Orland Gas	770	Thornton Gas
148	Clarksburg Gas	317	Howells Point Gas	535	Peace Valley Gas	772	Thornton, West-Walnut Grove Gas
149	Collegeville, East	335	Karnak Gas	536	Perkins Lake Gas	776	Tisdale Gas
162	Compton Landing Gas	351	King Island Gas	538	Petaluma Gas	778	Todhunters Lake Gas
164	Compton Landing, South Gas	352	Kirby Hill Gas	541	Pierce Road Gas	786	Tracy Gas
168	Concord Gas	354	Kirby Hill Gas, North	542	Pinole Point	787	Tracy, West, Gas
172	Conway Ranch Gas	356	Kirk Gas	552	Madison Gas	788	Tremont Gas
174	Corning Gas	358	Kirkwood Gas	556	Pleasant Creek Gas	802	Union Island Gas
176	Corning Gas, South	359	Knightsen Gas	564	Poppy Ridge Gas	810	Van Sickle Island Gas
177	Cotati Gas	361	Knights Landing Gas	574	Princeton Gas	816	Vernalis Gas
183	Crossroads Gas	370	La Honda	576	Putah Sink Gas	818	Vernalis, Southwest Gas
192	Davis Southeast Gas	380	Larkin, West Gas	590	Rancho Capay Gas	821	Verona Gas
200	Denverton Gas	390	Lathrop Gas	592	Red Bank Creek Gas	828	West Butte Gas
202	Denverton Creek Gas	392	Lathrop Southeast Gas	596	Rice Creek Gas	840	Wild Goose Gas
206	Dixon Gas	398	Liberty Cut Gas	597	Rice Creek, East Gas	841	Williams Gas
207	Dixon Gas, East	400	Liberty Island Gas	603	Rindge Tract Gas	842	Willow Pass Gas
209	Dry Slough Gas	402	Lindsey Slough Gas	604	Rio Jesus Gas	844	Willow Slough Gas
212	Dufour Gas	403	Little Butte Creek Gas	606	Rio Vista Gas	846	Willows-Beehive Bend Gas
214	Dunnigan Hills Gas	404	Livermore	610	River Break Gas	847	Wilson Creek Gas
216	Durham Gas	406	Llano Seco Gas	612	River Island Gas	850	Winchester Lake Gas
218	Dutch Slough Gas	408	Lodi Gas	615	Robbins Gas	852	Winters Gas
225	East Islands Gas	409	Lodi Airport Gas	616	Roberts Island Gas	854	Woodland Gas
227	El Dorado Bend Gas	411	Lodi, Southeast Gas	634	Ryer Island Gas	862	Zamora Gas
229	Elkhorn Slough Gas	413	Lone Tree Creek Gas	636	Sacramento Airport Gas	864	Zamora Gas, North
243	Everglade Gas	415	Lone Star Gas	638	Sacramento By-Pass Gas		

Figure 17.   —Continued

D

Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983

Data sources: California Department of Water Resources (DWR), 2003, 2016; California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014
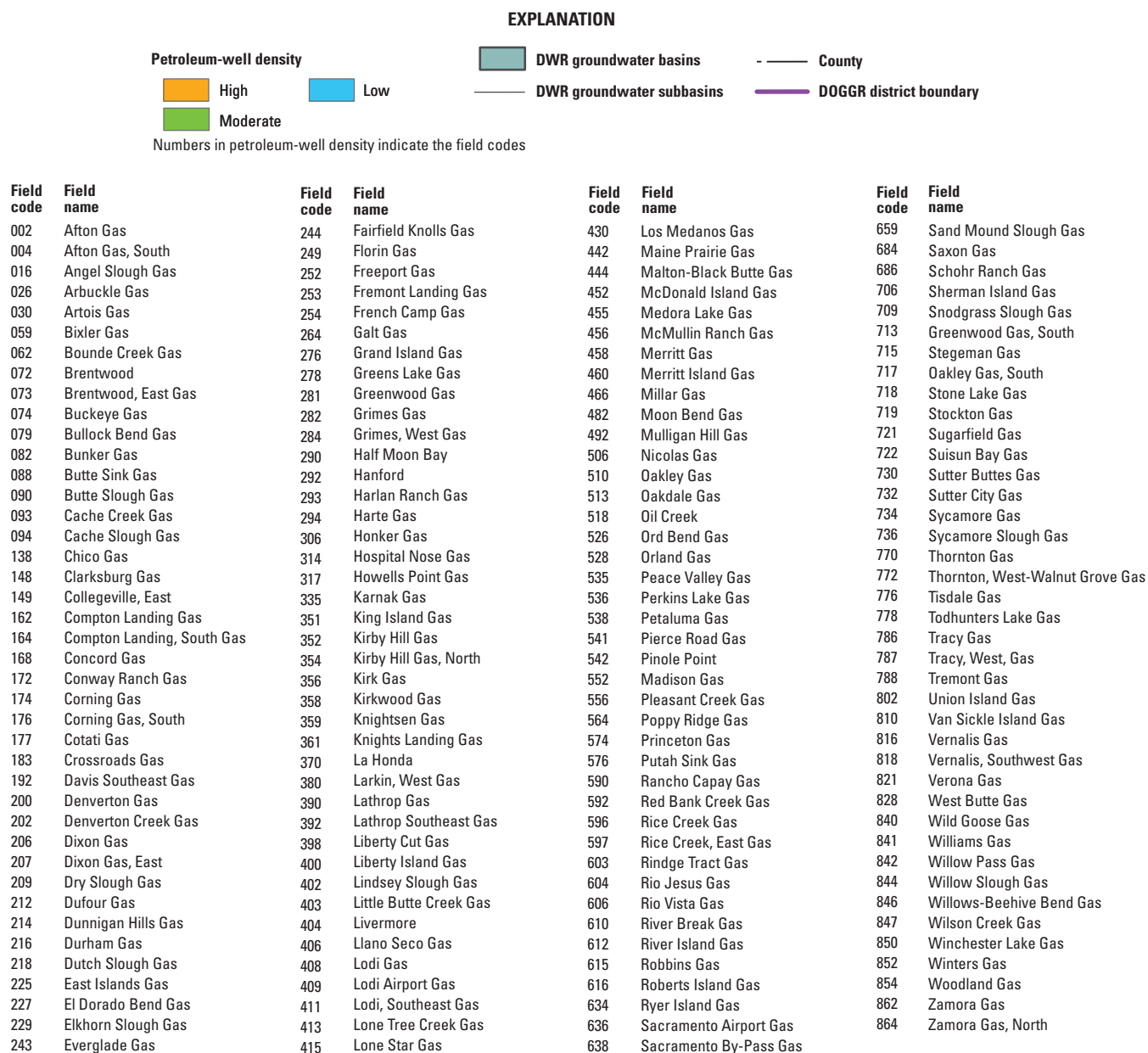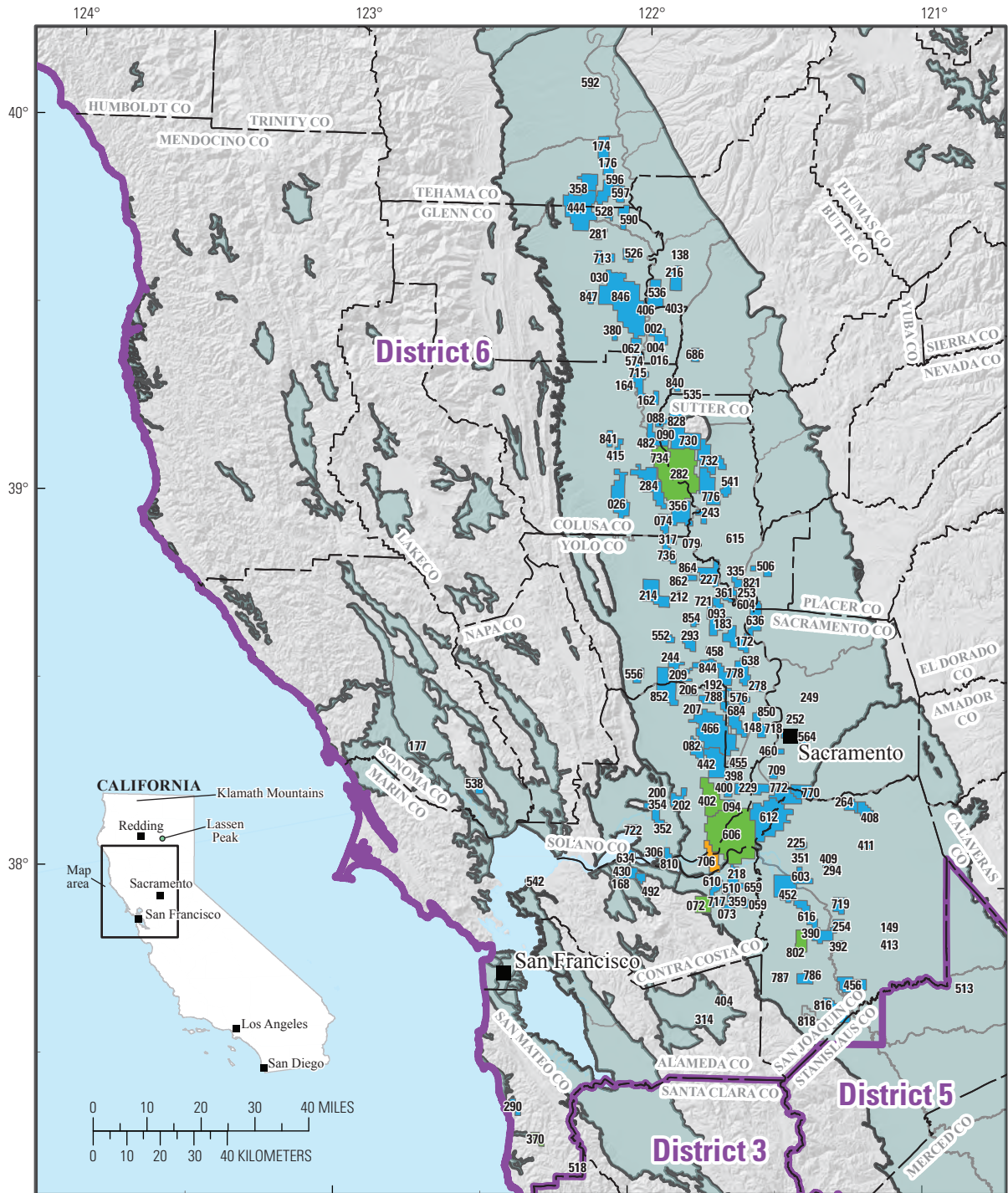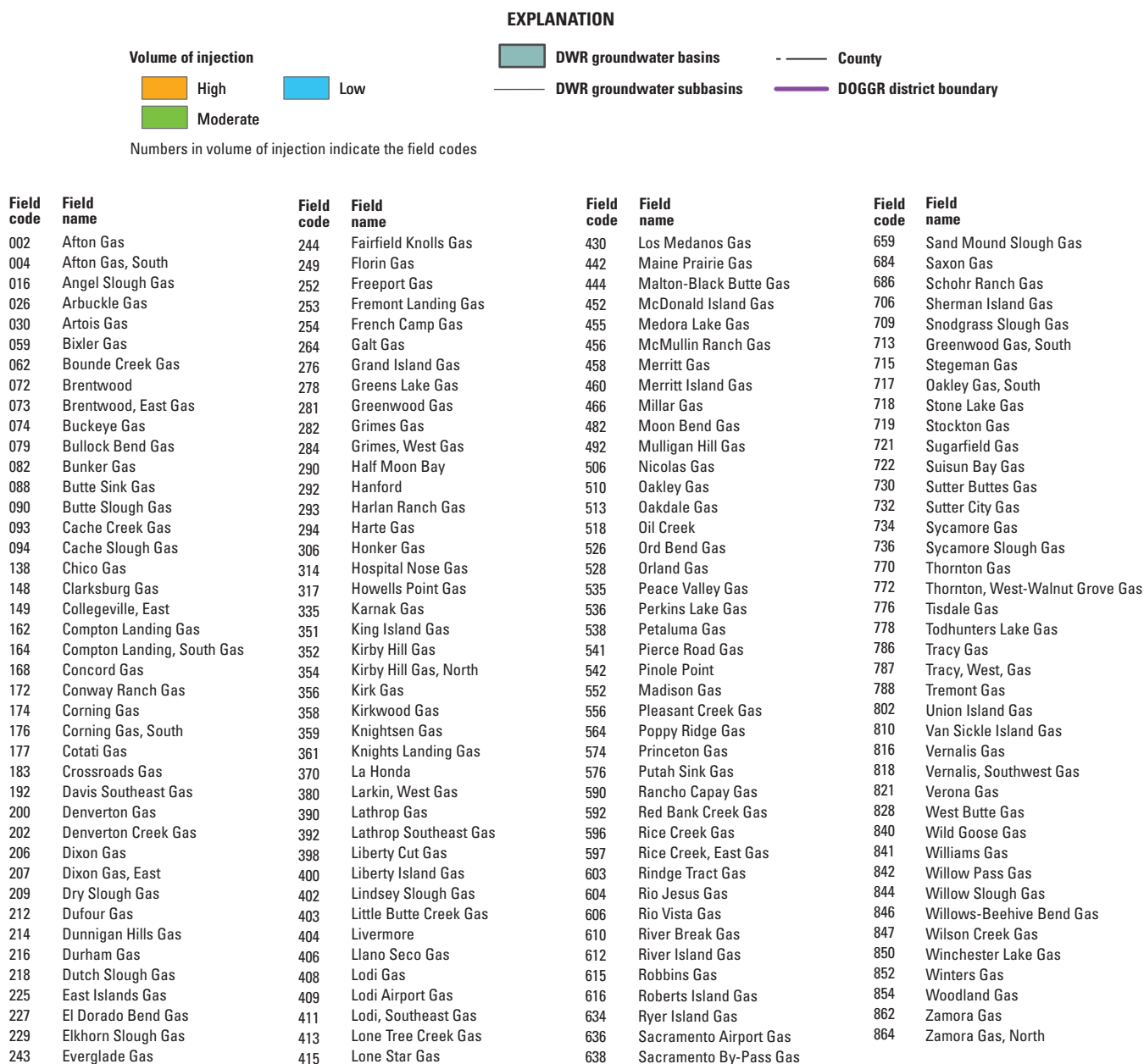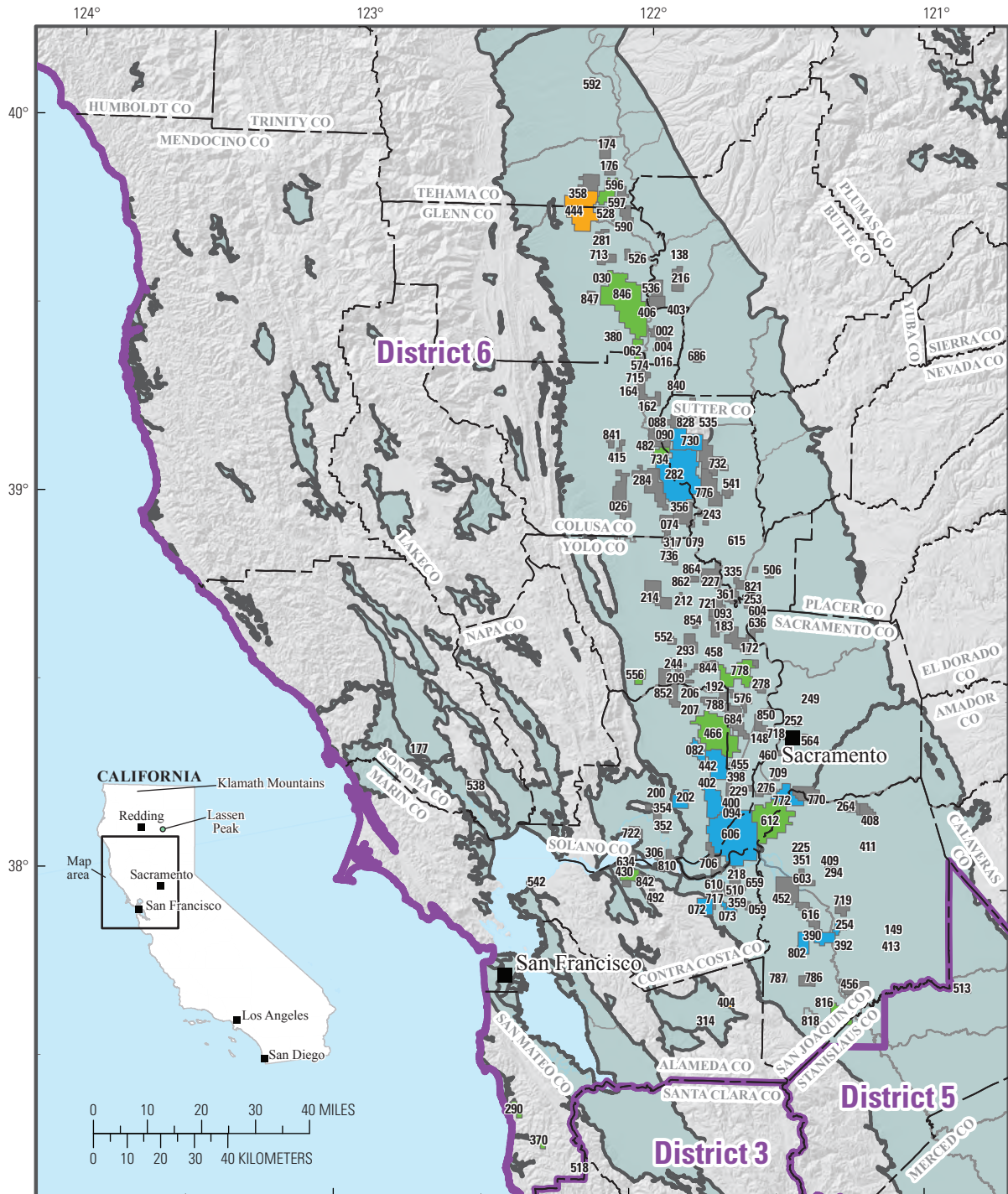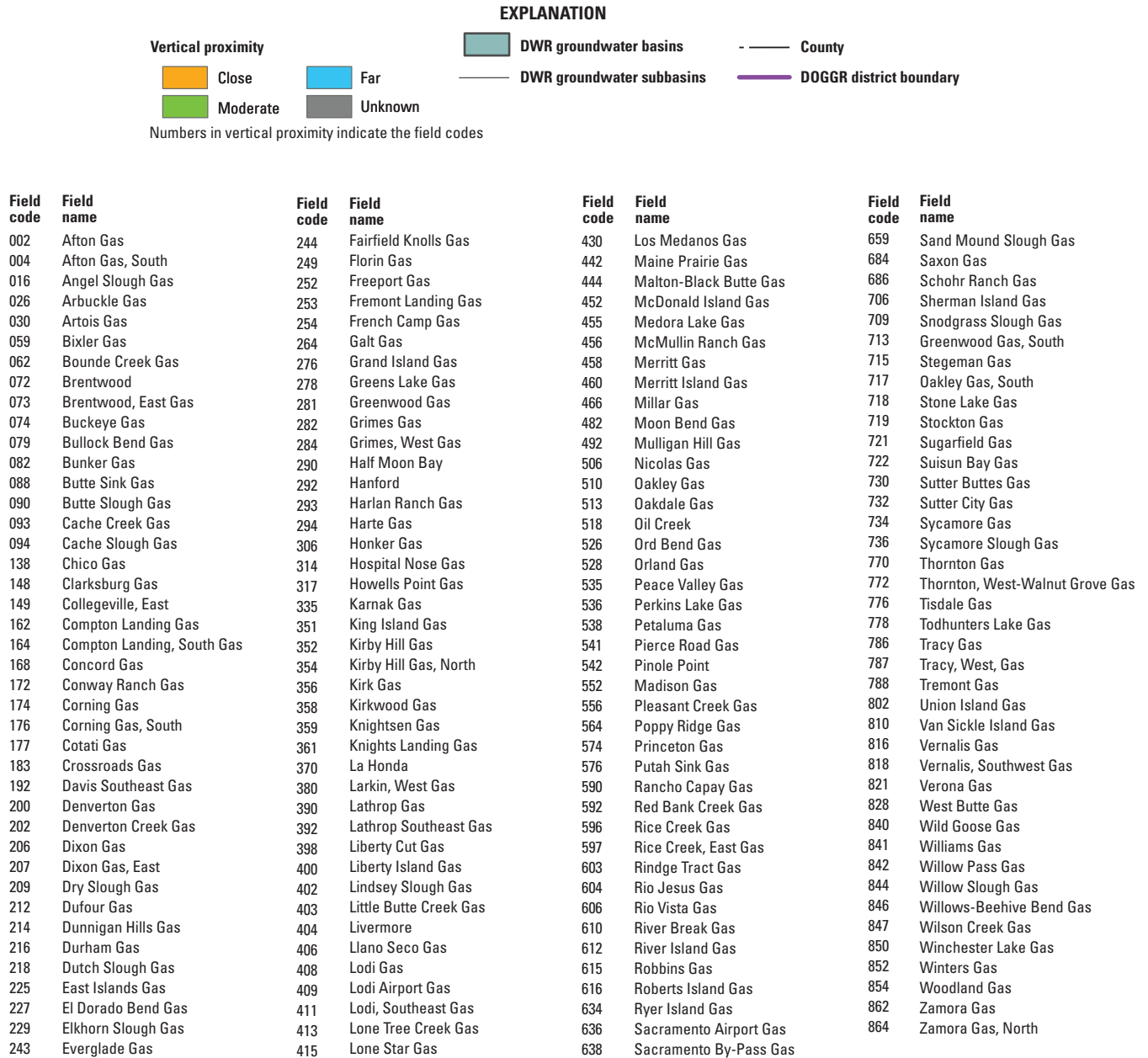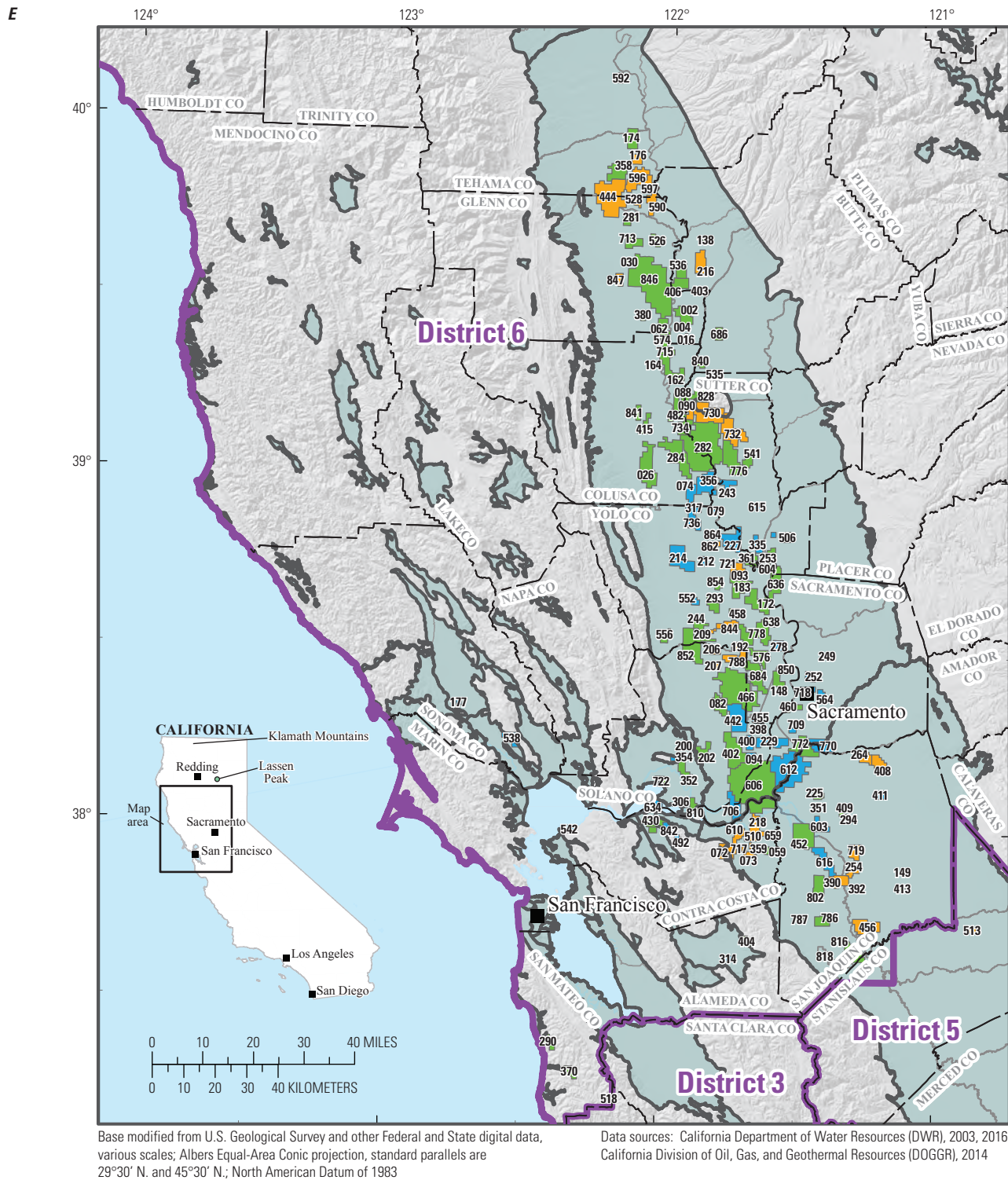
Figure 17.   —Continued

EXPLANATION

Vertical proximity

	Close		Far	
	Moderate		Unknown	

DWR groundwater basins
DWR groundwater subbasins

County
DOGGR district boundary

Numbers in vertical proximity indicate the field codes

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
002	Afton Gas	244	Fairfield Knolls Gas	430	Los Medanos Gas	659	Sand Mound Slough Gas
004	Afton Gas, South	249	Florin Gas	442	Maine Prairie Gas	684	Saxon Gas
016	Angel Slough Gas	252	Freeport Gas	444	Malton-Black Butte Gas	686	Schohr Ranch Gas
026	Arbuckle Gas	253	Fremont Landing Gas	452	McDonald Island Gas	706	Sherman Island Gas
030	Artois Gas	254	French Camp Gas	455	Medora Lake Gas	709	Snodgrass Slough Gas
059	Bixler Gas	264	Galt Gas	456	McMullin Ranch Gas	713	Greenwood Gas, South
062	Bounde Creek Gas	276	Grand Island Gas	458	Merritt Gas	715	Stegeman Gas
072	Brentwood	278	Greens Lake Gas	460	Merritt Island Gas	717	Oakley Gas, South
073	Brentwood, East Gas	281	Greenwood Gas	466	Millar Gas	718	Stone Lake Gas
074	Buckeye Gas	282	Grimes Gas	482	Moon Bend Gas	719	Stockton Gas
079	Bullock Bend Gas	284	Grimes, West Gas	492	Mulligan Hill Gas	721	Sugarfield Gas
082	Bunker Gas	290	Half Moon Bay	506	Nicolas Gas	722	Suisun Bay Gas
088	Butte Sink Gas	292	Hanford	510	Oakley Gas	730	Sutter Buttes Gas
090	Butte Slough Gas	293	Harlan Ranch Gas	513	Oakdale Gas	732	Sutter City Gas
093	Cache Creek Gas	294	Harte Gas	518	Oil Creek	734	Sycamore Gas
094	Cache Slough Gas	306	Honker Gas	526	Ord Bend Gas	736	Sycamore Slough Gas
138	Chico Gas	314	Hospital Nose Gas	528	Orland Gas	770	Thornton Gas
148	Clarksburg Gas	317	Howells Point Gas	535	Peace Valley Gas	772	Thornton, West-Walnut Grove Gas
149	Collegeville, East	335	Karnak Gas	536	Perkins Lake Gas	776	Tisdale Gas
162	Compton Landing Gas	351	King Island Gas	538	Petaluma Gas	778	Todhunters Lake Gas
164	Compton Landing, South Gas	352	Kirby Hill Gas	541	Pierce Road Gas	786	Tracy Gas
168	Concord Gas	354	Kirby Hill Gas, North	542	Pinole Point	787	Tracy, West, Gas
172	Conway Ranch Gas	356	Kirk Gas	552	Madison Gas	788	Tremont Gas
174	Corning Gas	358	Kirkwood Gas	556	Pleasant Creek Gas	802	Union Island Gas
176	Corning Gas, South	359	Knightsen Gas	564	Poppy Ridge Gas	810	Van Sickle Island Gas
177	Cotati Gas	361	Knights Landing Gas	574	Princeton Gas	816	Vernalis Gas
183	Crossroads Gas	370	La Honda	576	Putah Sink Gas	818	Vernalis, Southwest Gas
192	Davis Southeast Gas	380	Larkin, West Gas	590	Rancho Capay Gas	821	Verona Gas
200	Denverton Gas	390	Lathrop Gas	592	Red Bank Creek Gas	828	West Butte Gas
202	Denverton Creek Gas	392	Lathrop Southeast Gas	596	Rice Creek Gas	840	Wild Goose Gas
206	Dixon Gas	398	Liberty Cut Gas	597	Rice Creek, East Gas	841	Williams Gas
207	Dixon Gas, East	400	Liberty Island Gas	603	Rindge Tract Gas	842	Willow Pass Gas
209	Dry Slough Gas	402	Lindsey Slough Gas	604	Rio Jesus Gas	844	Willow Slough Gas
212	Dufour Gas	403	Little Butte Creek Gas	606	Rio Vista Gas	846	Willows-Beehive Bend Gas
214	Dunnigan Hills Gas	404	Livermore	610	River Break Gas	847	Wilson Creek Gas
216	Durham Gas	406	Llano Seco Gas	612	River Island Gas	850	Winchester Lake Gas
218	Dutch Slough Gas	408	Lodi Gas	615	Robbins Gas	852	Winters Gas
225	East Islands Gas	409	Lodi Airport Gas	616	Roberts Island Gas	854	Woodland Gas
227	El Dorado Bend Gas	411	Lodi, Southeast Gas	634	Ryer Island Gas	862	Zamora Gas
229	Elkhorn Slough Gas	413	Lone Tree Creek Gas	636	Sacramento Airport Gas	864	Zamora Gas, North
243	Everglade Gas	415	Lone Star Gas	638	Sacramento By-Pass Gas		

Figure 17. —Continued

Figure 17.   —Continued

EXPLANATION

Water-well density

☐ High

☐ Low

☐ Moderate

Numbers in vertical proximity indicate the field codes

☐ DWR groundwater basins

— — DWR groundwater subbasins

- —— County

—— DOGGR district boundary

Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
002	Afton Gas	244	Fairfield Knolls Gas	442	Maine Prairie Gas	636	Sacramento Airport Gas
004	Afton Gas, South	249	Florin Gas	444	Malton-Black Butte Gas	638	Sacramento By-Pass Gas
016	Angel Slough Gas	252	Freeport Gas	452	McDonald Island Gas	659	Sand Mound Slough Gas
026	Arbuckle Gas	253	Fremont Landing Gas	455	Medora Lake Gas	684	Saxon Gas
030	Artois Gas	254	French Camp Gas	456	McMullin Ranch Gas	686	Schohr Ranch Gas
062	Bounde Creek Gas	264	Galt Gas	458	Merritt Gas	706	Sherman Island Gas
072	Brentwood	278	Greens Lake Gas	460	Merritt Island Gas	709	Snodgrass Slough Gas
073	Brentwood, East Gas	281	Greenwood Gas	466	Millar Gas	713	Greenwood Gas, South
074	Buckeye Gas	282	Grimes Gas	482	Moon Bend Gas	715	Stegeman Gas
079	Bullock Bend Gas	284	Grimes, West Gas	492	Mulligan Hill Gas	717	Oakley Gas, South
082	Bunker Gas	290	Half Moon Bay	506	Nicolas Gas	718	Stone Lake Gas
088	Butte Sink Gas	292	Hanford	510	Oakley Gas	719	Stockton Gas
090	Butte Slough Gas	293	Harlan Ranch Gas	513	Oakdale Gas	721	Sugarfield Gas
093	Cache Creek Gas	294	Harte Gas	518	Oil Creek	722	Suisun Bay Gas
094	Cache Slough Gas	306	Honker Gas	526	Ord Bend Gas	730	Sutter Buttes Gas
138	Chico Gas	314	Hospital Nose Gas	528	Orland Gas	732	Sutter City Gas
148	Clarksburg Gas	317	Howells Point Gas	535	Peace Valley Gas	734	Sycamore Gas
149	Collegeville, East	335	Karnak Gas	536	Perkins Lake Gas	736	Sycamore Slough Gas
162	Compton Landing Gas	351	King Island Gas	538	Petaluma Gas	770	Thornton Gas
164	Compton Landing, South Gas	352	Kirby Hill Gas	541	Pierce Road Gas	772	Thornton, West-Walnut Grove Gas
168	Concord Gas	354	Kirby Hill Gas, North	542	Pinole Point	776	Tisdale Gas
172	Conway Ranch Gas	356	Kirk Gas	552	Madison Gas	778	Todhunters Lake Gas
174	Corning Gas	358	Kirkwood Gas	556	Pleasant Creek Gas	786	Tracy Gas
176	Corning Gas, South	359	Knightsen Gas	564	Poppy Ridge Gas	787	Tracy, West, Gas
177	Cotati Gas	361	Knights Landing Gas	574	Princeton Gas	788	Tremont Gas
183	Crossroads Gas	370	La Honda	576	Putah Sink Gas	802	Union Island Gas
192	Davis Southeast Gas	380	Larkin, West Gas	590	Rancho Capay Gas	810	Van Sickle Island Gas
200	Denverton Gas	390	Lathrop Gas	592	Red Bank Creek Gas	816	Vernalis Gas
202	Denverton Creek Gas	392	Lathrop Southeast Gas	596	Rice Creek Gas	818	Vernalis, Southwest Gas
206	Dixon Gas	398	Liberty Cut Gas	597	Rice Creek, East Gas	828	West Butte Gas
207	Dixon Gas, East	400	Liberty Island Gas	603	Rindge Tract Gas	840	Wild Goose Gas
209	Dry Slough Gas	402	Lindsey Slough Gas	604	Rio Jesus Gas	841	Williams Gas
212	Dufour Gas	403	Little Butte Creek Gas	606	Rio Vista Gas	842	Willow Pass Gas
214	Dunnigan Hills Gas	404	Livermore	610	River Break Gas	844	Willow Slough Gas
216	Durham Gas	406	Llano Seco Gas	612	River Island Gas	846	Willows-Beehive Bend Gas
218	Dutch Slough Gas	408	Lodi Gas	615	Robbins Gas	847	Wilson Creek Gas
225	East Islands Gas	409	Lodi Airport Gas	616	Roberts Island Gas	850	Winchester Lake Gas
227	El Dorado Bend Gas	411	Lodi, Southeast Gas	634	Ryer Island Gas	852	Winters Gas
229	Elkhorn Slough Gas	413	Lone Tree Creek Gas			854	Woodland Gas
243	Everglade Gas	415	Lone Star Gas			862	Zamora Gas
		430	Los Medanos Gas			864	Zamora Gas, North

Figure 17. —Continued

Summary

The California State Water Resources Control Board (SWRCB) initiated a Regional Groundwater Monitoring Program (RGMP) to protect waters designated for any beneficial use in the vicinity of oil and gas fields in California, while prioritizing the monitoring of groundwater that is or has the potential to be a source of drinking water. The pace of implementation of the RGMP across the 487 onshore oil and gas fields has been limited in that detailed characterization work can only be done in a few fields each year. For program planning purposes, a prioritization of oil and gas fields is needed for consideration in implementing regional groundwater monitoring. In cooperation with the SWRCB, the USGS characterized, assessed, and classified oil and gas fields (1) individually with respect to key factors contributing to the potential risk to California's groundwater resources from oil and gas resources in the subsurface, and (2) comparatively assigning overall prioritization rankings to California oil and gas fields for regional groundwater monitoring.

California's 487 onshore oil and gas fields, covering an aggregated field area of 3,392 square miles, were prioritized for regional groundwater monitoring using a statewide systematic analysis of the relative intensity of petroleum development and proximity to groundwater resources. High priority was assigned to fields with the greatest intensity of oil and gas development measured by petroleum-well density and volume of injection, often coupled with proximity to groundwater resources as measured by vertical proximity of petroleum resources to groundwater resources and by water-well density overlying and adjacent to the field. The prioritization of fields for regional groundwater monitoring resulted in 107 fields (22 percent) classified as high overall priority, 114 fields (23 percent) as moderate priority, and 266 fields (55 percent) as low priority (table 5; fig. 10). On an area-weighted basis, 41 percent of the aggregated field area ranked high priority, indicating that the largest fields tend to have the most oil and gas development activities. More than half of the high priority fields were in the southern San Joaquin Valley and the Los Angeles Basin. Moderate-priority fields (30 percent of aggregated field area) generally had intermediate characteristics and further analysis of each of these fields is needed to determine if they would be better classified as low or high priority for regional groundwater monitoring. The 266 low-priority fields accounted for 29 percent of the aggregated field area, indicating the smallest fields generally did not have high intensity of petroleum resources. About half of the low priority fields (131 of 266 fields) were located in district 6, which is the largest of the districts and contains mostly gas fields. Low priority is based on low to moderate intensity of oil and gas activities, and low to moderate horizontal or vertical proximity to groundwater resources.

The prioritization does not represent an assessment of groundwater risk from oil and gas development, which needs to be based on detailed analysis of data from regional groundwater monitoring near the oil fields selected for study in the future. Rather, this analysis identifies between 100 and 200 oil fields that are principal candidates for the next steps in the regional groundwater monitoring program. The next steps can include compiling, analyzing, and developing three-dimensional visualizations of existing data, including geological frameworks, salinity mapping, identification of surface features that could potentially affect groundwater quality, locations and depths of petroleum and water wells, cataloging well-construction integrity issues, and evaluating groundwater-flow directions. These analyses and data are required to determine where existing wells should be monitored and where new monitoring wells may need to be drilled. The U.S. Geological Survey, in collaboration with the State Water Resources Control Board and other agencies, has begun the next steps of the regional groundwater monitoring through the California Oil, Gas, and Groundwater cooperative program.

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Appendix 1. Statistical Summaries of Data used to Calculate Factors

In the preliminary assessment of petroleum resource development and proximity to groundwater resources, data and supporting information related to the variables measuring petroleum-well density, volume of injection, and vertical proximity were compiled for reference and to evaluate results of the assessment. Data were compiled from databases available during 2014–15 from the California Division of Oil, Gas, and Geothermal Resources (DOGGR). Raw data (with the exception of injection volumes) are available in the U.S. Geological Survey data release at https://doi.org/10.5066/F7FJ2DV3.

Petroleum-Well Density

Data related to petroleum-well density that were summarized for each oil and gas field were the total number of petroleum wells by well type, number of abandoned wells, and age of wells as reported in the 2014 DOGGR All Wells dataset (appendix table 1–1). The minimum and maximum well spud dates (marking the beginning of well drilling) or completion dates and well abandonment dates were calculated for petroleum wells for each oil and gas field. Dates were not available for every well; therefore, the dates represent estimates of well ages.

Petroleum wells outside field boundaries were assigned to the nearest oil and gas field. Total wells nearby each oil and gas field and the maximum distance of the wells from the nearest field's boundary are listed in appendix table 1–1. Wells outside field boundaries were not included in calculations of petroleum-well density.

Generally, the well type listed in the "GISSymbol" column of the 2014 DOGGR All Wells dataset were used to classify each well (see table 1 for well types). Wells that did not have a specified well type were classified as unknown; well types may be found on the DOGGR Well Finder website at http://maps.conservation.ca.gov/doggr/. Wells can have more than one well type or the well type changes over time. For example, a cyclic steam (SC) well is a type of oil and gas extraction well that uses cycles of steam injection followed by production to increase productivity and may be coded as SC or oil and gas production (OG). Production wells that have been converted to injection wells were coded as OG wells or as an injection well, such as water flood or waste disposal. Therefore, injection in a field may not be evident in current well counts and densities, but would likely be evident in the volumes of injection.

Volume of Injection

Volumes of water and steam injection for each oil and gas field were compiled, along with the years of injection for each field, and information on injection for petroleum wells outside field boundaries (appendix tables 1–1 and 1–2). Injection and production volumes were compiled from DOGGR's online injection and production databases (California Division of Oil, Gas, and Geothermal Resources, 2015). Although volume of water produced in each field was not part of the prioritization analysis, total water production volumes were presented in the ancillary dataset and include water production volumes for wells outside field boundaries. The years of recorded production and injection correspond to the minimum and maximum year of any recorded volume for that field.

Water production and injection records are not released to the public for wells with confidential status and consequently were not available for inclusion in the production and injection volume calculations. Petroleum wells that meet the criteria for confidentiality are exploratory wells or wells for which there are extenuating circumstances preventing the well operator from having the competitive advantage of using information obtained from the well. At the time of this study, there were 180 confidential wells located throughout the State, and they were primarily active and new production wells drilled for exploratory purposes or using new technology (confidential well list accessed December 16, 2015, at ftp://ftp.consrv.ca.gov/pub/oil/new_database_format/).

Some wells outside field boundaries had production and injection records for 1977–2015; maximum distance of production and injection from nearest field boundary was 8 miles and 12 miles, respectively. Wells outside field boundaries were included in calculations for total injection volumes for the nearest field (appendix tables 1–1 and 1–2).

About 57 injection wells had recorded water injection outside oil and gas fields, and they plotted near the boundaries of 14 fields (appendix table 1–2). Total water injected outside field boundaries during 1977–2015 is 583 million barrels (MMB), which is less than 1 percent of the total water and steam injected in the State (about 85 billion barrels). Recorded injection was primarily for waste-water disposal wells, yet enhanced oil recovery wells near five fields (Arroyo Grande, Casmalia, Edison, Raisin City, and San Ardo) had recorded injection. Of the total waste-water disposal outside field boundaries, 345 MMB were injected within 2 miles of the Lost Hills field, and 172 MMB were injected within 8 miles of the San Ardo field.

There was reported water production from about 75 production wells that plotted nearby 98 fields. Total water produced outside field boundaries during 1977–2015 was 95 MMB, which was less than 0.1 percent of the total water produced in the State (about 96 billion barrels). Of the total water production outside fields, about 91 MMB were produced within 2 miles of the Lost Hills field, and 3 MMB were produced within 2 miles of the Raisin City field.

Vertical Proximity

Variables included in the calculations of vertical proximity were depth to top of perforated intervals (TOP) for petroleum wells, depth to base of freshwater (BFW) for petroleum wells, and total well depth (TD) for water wells. The availability of depth data varied between fields and between categories of wells (production versus injection, for petroleum wells), and required combining depth data and calculation methods to estimate vertical proximity for oil and gas fields. The depth of oil and gas development may vary within a field, in which case compilation and averaging of depths on a field scale may not represent vertical proximity for the entire field. Perforation depths depend on several factors, including the use of each well and regional geology. Samples of depth data for wells were tested for statistical differences based on well categories for oil and gas fields with sufficient data (5 or more data points for each group compared). Differences in the availability of data for variables, perforation depths based on well category, and land surface elevations were evaluated for potential biases when assessing vertical proximity for fields. Percentiles and number of available depth data for petroleum and water wells are presented in appendix table 1–3. Summary statistics were presented for all water wells and petroleum wells with depth data, and depth to TOP data for petroleum wells were divided into categories: production, injection, and the sub-categories of injection (waste-disposal wells versus all other injection types "non-waste-disposal wells").

The Wilcoxon rank-sum test (equivalent to the Mann-Whitney test) was used to evaluate the differences between two groups of data (Helsel and Hirsch, 2002). Nonparametric rank-based methods were used for statistical analysis because these techniques are generally not affected by outliers and do not require that the data follow a normal distribution (Helsel and Hirsch, 2002). The significance level (p) used for hypothesis testing was compared to a threshold value (α) of 5 percent ($\alpha=0.05$) to evaluate whether the relation was statistically significant ($p\leq\alpha$). All statistical analyses were done using R, version 3.1.2 (The R Foundation for Statistical Computing). For fields that had $p\leq0.05$, the relative percent difference (RPD) of the median values for the two groups was calculated. The RPD is defined as the difference between the two values divided by the mean of the values and expressed as a percentage. RPD was used to identify the fields with greatest differences between the two groups of data compared. A positive RPD between the two groups of data compared indicates the median value for the first group was greater than the median value for the second group, and a negative RPD indicates the first group had a smaller median value. Variability in TOP-depth values within a field was estimated using the interquartile range (IQR), defined as the 75th percentile minus the 25th percentile (Helsel and Hirsch, 2002).

Land surface elevations (LSEs) were attributed for all petroleum and water wells in each field using the California National Elevation Dataset and ESRI ArcGIS software, and summary statistics are presented in appendix table 1–4. Differences in well elevations within a field and between well categories can indicate differences in regional geology, which were considered in the evaluation of grouping depth data by field to calculate vertical separation distance. For instance, vertical separation may be inaccurate as calculated when comparing the depth to TOP for a petroleum well located in the mountains with depth to BFW for a petroleum well or total well depth for a water well located in a valley. Water wells did not have exact well locations and were plotted at the center of the section in which they were located as indicated by the location information in well completion reports. Multiple water wells within a field often had the same elevation attributed. Initial results of Wilcoxon rank-sum tests were significant for even the slightest differences in land surface elevation between the water wells and petroleum wells, and therefore are not presented in this report. Results of statistical tests comparing LSE for petroleum wells with depth to TOP versus petroleum wells with depth to BFW are also not presented. Most fields for which vertical separation distance was calculated by pooling TOP-depth and BFW-depth data (method 3) did not have sufficient data to run statistical tests. Variability in LSEs, as measured by the IQR, between wells in a field for categories of wells (water wells and petroleum wells) are included in appendix table 1–4. The measured variability in LSEs for water wells in a field may be less than if LSE was attributed to water wells using more precise well locations.

Comparison of Depths to Top of Perforations for Production versus Injection Petroleum Wells

For the assessment of vertical proximity in each field, the depth at which petroleum resource development is prevalent in each field was estimated using depths to TOP for both production wells and injection wells. Whereas the injection well depths are almost a complete record of injection depths in each field, the production well depths are a randomly-selected and spatially-distributed sample of depths for all production wells. As a result, 84 percent of the 174 fields with sufficient data to assess vertical proximity had at least one injection well with depth to TOP, compared to only 47 percent of the total 487 oil and gas fields having contained injection wells. Because there were more injection well TOP-depths readily available for the assessment of vertical proximity, vertical proximity of injection activities to groundwater resources was predominate in the calculation of median vertical separation distance.

Statewide, the total number of TOP-depths for injection wells greatly exceeded the number for production wells; however, more fields had a greater number of TOP-depths for production wells than for injection wells. Of the 174 fields assessed for vertical proximity, 96 fields had more production well TOP-depths, 74 fields had more injection well TOP-depths, and 4 fields were equal (appendix table 1–3). The fields with more TOP-depth data for injection wells than for production wells had a total of about 16,800 depths and the majority of these data are concentrated in a few fields. Fields that accounted for about 67 percent of the injection well data in the state are South Belridge (4,002 TOP-depths), Midway-Sunset (2,611 TOP-depths), Lost Hills (1,559 TOP-depths), Kern River (1,275 TOP-depths), Coalinga (1,162 TOP-depths), and Wilmington (1,044 TOP-depths).

For a field-scale estimate of vertical proximity based on median separation distance, vertical proximity is largely dependent on well perforation depths for the well category with more data. Statistical tests comparing well perforation depths for injection and production wells for fields with sufficient data indicated that well perforation depths were statistically different ($p \leq 0.05$) between the two well categories for about half (37 fields) of the 71 fields tested (appendix table 1–5). Of the 37 fields, TOP-depths were deeper for production wells than for injection wells (RPD>0) in 26 fields, and TOP-depths were shallower for production wells than for injection wells (RPD<0) in 11 fields. Examples of fields that had the greatest absolute RPD between median depths are Asphalto (RPD=164 percent), Kettleman North Dome (RPD=153 percent), Ojai (RPD=−110 percent), Helm (RPD=108 percent), Oxnard (RPD=107 percent), Edison (RPD=101 percent), and Rose (RPD=100 percent) fields. On average, these fields had deeper perforation depths for production wells than for injection wells except for the Ojai field; median depth to TOP at Ojai was 948 feet (ft) for production wells and 3,285 ft for injection wells.

For a few fields that had statistically different depths to TOP for production and injection wells, the depth of petroleum resource development as characterized by median depth to TOP for injection and production wells may be biased towards the well category with more depth data. For 33 of the 37 fields with statistically different samples of data ($p \leq 0.05$), median TOP-depth for petroleum wells was closer to median TOP-depth for the well category with more depth data (appendix table 1–5). As an example, the Asphalto field has median depth to TOP of 720 ft for injection wells, median depth to TOP of 7,354 ft for production wells, and median depth to TOP of 750 ft for the combination of well categories. There were more depths to TOP values available for injection wells (19 values) in this field than for production wells (6 values), and consequently vertical proximity of injection activities to groundwater resources was predominate in the calculation of median vertical separation distance (−750 ft). In contrast, the Ten Section field had more depth data available for injection wells than production wells, yet median TOP-depth of all petroleum wells (7,790 ft) was closer to median TOP-depth of production wells (8,076 ft) than to median TOP-depth of injection wells (3,087 ft). The interquartile range of TOP-depths for injection wells showed relatively large variability in the data (IQR=5,262 ft; appendix table 1–3). Variability in well perforation depths for injection wells suggests multiple injection zones at different depths within the field. Variability in depths may also indicate differences in land surface elevations, but in the Ten Section field, LSE only varied by about 20 ft for injection wells (appendix table 1–4).

Comparison of Depths to Top of Perforations for Waste-Disposal versus Non-Waste-Disposal Wells

Additional comparisons of TOP-depths for waste-disposal wells and all other types of injection wells (non-waste-disposal), indicated that for fields with production, injection for enhanced oil recovery, and injection for waste disposal, the calculated median separation distance for a field may not characterize the proximity of groundwater resources to each of these activities. Well perforation depths for waste-disposal wells (including waste-water disposal, WD, and gas disposal, GD, well types) and non-waste-disposal injection wells (including WF, SF, SC, GS, and LG well types) were statistically different ($p \leq 0.05$) for most of the fields tested (25 of the 29 fields; appendix table 1–6). Of the 25 fields with different depths, median TOP-depth was deeper for waste-disposal wells than for non-waste-disposal wells (RPD>0) in 14 fields, and median TOP-depth was shallower for waste-disposal wells than for non-waste-disposal wells (RPD<0) in 11 fields. In general, there more depths to TOP for non-waste-disposal wells than for waste-disposal wells (23 of the 29 fields compared; appendix table 1–6), and were predominate in calculation of median depth to TOP for injection wells in each field.

Examples of fields that had the greatest absolute RPD between median depths for waste-disposal wells and non-waste-disposal wells are Elk Hills (RPD=−165 percent), Edison (RPD=115 percent), North Belridge (RPD=−113 percent), South Mountain (RPD=103 percent), and Ten Section (RPD=−102 percent) fields. In the example of the Ten Section field in which there was variability in TOP-depths for wells in the injection well category, grouping wells into the sub-categories resulted in greater precision of average well depths. There was a large spread of perforations depths for injection wells at Ten Section (IQR=5,262 ft), yet variability for TOP-depths in each of the sub-categories was comparatively small: median depth to TOP was 2,540 ft for waste-disposal wells (IQR=197 ft) and 7,796 ft for other injection wells (IQR=51 ft; appendix table 1–3). Even though there were more depths to TOP for waste-disposal wells than non-waste-disposal injection wells and more depths to TOP for injection wells than production wells at this field, the depths of waste-disposal wells were outweighed in the combination of depths for injection wells and production wells (median TOP-depth for production wells was 8,076 ft). Median vertical separation distance for the Ten Section field (6,072 ft separation, appendix table 1–5) was biased to non-waste-disposal injection activities and production activities in zones deeper than average TOP-depths for waste-disposal wells.

Comparisons of Vertical Proximity Classifications using Separation-Distance Calculation Methods 1 and 2

Separation distance values and vertical proximity classifications were compared between calculation methods 1 and 2, which were considered the most robust of the methods and provided median separation distance values for the most fields (see "Methods" section "Calculation of Variables" for a description of the five methods used to calculate vertical proximity). Of the 81 fields that had separation distance values calculated from both method 1 and method 2 and for which a comparison could be made, 25 fields were classified into different categories (close, moderate, and far) for vertical proximity depending on the calculation method. A comparison of the separation distance values between methods 1 and 2 showed that more fields would be classified as "far" for vertical proximity of petroleum and groundwater resources based on method 2 calculations, and fewer fields would be classified as "moderate" and "close." The vertical separation

distance determined from calculation method 1 was used in the prioritization analysis in most cases. For fields that had different vertical proximity classifications based on varying values between the two methods, the classification representing greater potential risk to groundwater resources was used in the overall prioritization analysis. The overall priority classification for fields rarely changed by differing vertical proximity classifications between the two methods.

Generally, median separation distance calculated from method 1 for each field was less than the median distance calculated from method 2 (72 out of 81 fields compared; appendix table 1–7). Of the 25 fields with differing vertical proximity classifications between the two methods, 22 fields had a higher ranking (less distance between resources) using vertical separation values determined from method 1 than from method 2. Most often the higher ranking for method 1 was moderate (16 fields), and the other 6 fields were ranked high using method 1. The vertical separation distance between petroleum and groundwater resources would be expected to be smaller as calculated from method 1 than from method 2, because method 1 uses depths to BFW to characterize the depth of groundwater resources, and depths to BFW are typically deeper than the TD of groundwater wells used in method 2 (fig. 5). Variations in separation distance values between the two methods can also be attributed to differences in the depths to TOP that were included in each calculation method. More depths to BFW were available for injection wells than for production wells, and in effect, greater weight was given to injection wells in method 1 calculations than in method 2 calculations.

Only the three fields Coalinga, Livermore, and Orcutt had a lower ranking for vertical proximity (greater distance between resources) using separation distance values determined from method 1 than from method 2 (appendix table 1–7). In the example of the Coalinga field, median TD of water wells overlying the field was 600 ft (calculated from data for 47 water wells), whereas the median depth to BFW was 270 ft (calculated from data for 586 petroleum wells; appendix table 1–3). One explanation for the depth to BFW being shallower than water well depths is that depths to BFW reported in well records were sometimes a single value applied to petroleum wells throughout the field rather than values determined from each well's geophysical logs. For these three fields, the vertical proximity classification for method 2 was used in the prioritization analysis so that values that are most protective of groundwater quality are used in the prioritization of oil fields.

The overall priority classification of a field was only affected by the vertical proximity ranking for fields with petroleum resource development closest to groundwater resources (fig. 8). The variability in results from each calculation method mostly affected the overall priority classification of fields that had separation distance values near the boundary between close and moderate classifications (1,000 ft median separation distance; table 2). Vertical proximity classifications varied between close and moderate between the two methods for eight fields: Coalinga, Fruitvale, Jasmin, Livermore, Malton-Black Butte Gas, Poso Creek, Rosedale Ranch, Round Mountain (appendix table 1–7). Several of the fields that had median separation distance near the classification boundary were ranked high for petroleum-well density and volume of water injection and would be classified as high overall priority based on rankings for factors other than vertical proximity. Only the Jasmin, Livermore, and Malton-Black Butte Gas fields would have a different overall priority classification based on differing vertical proximity classifications for method 1 and method 2; these fields would be classified as moderate priority if the lower ranking classification for vertical proximity had been used in the prioritization analysis. These three fields had moderate petroleum-well density, low to moderate volume of injection, and moderate to high water-well density (table 6). Of the 81 fields compared, 31 percent had differing vertical proximity classifications between method 1 and method 2, and using the higher ranking of the two classifications in the prioritization analysis resulted in high overall priority classifications than would have been assigned based on the other factors assessed for less than 4 percent of the compared fields.

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