

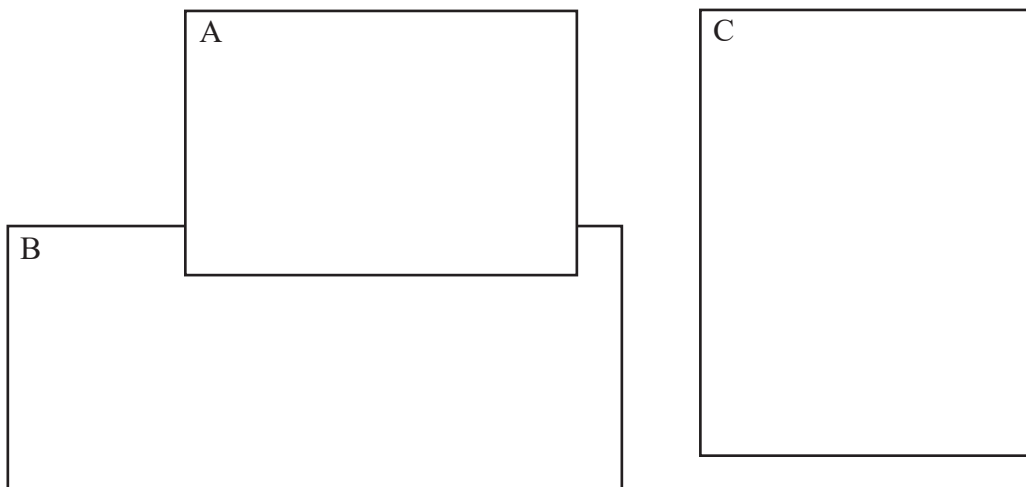
Prepared in cooperation with the California State Water Resources Control Board
A product of the California Oil and Gas Regional Groundwater Monitoring Program

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





Cover photographs:

Front cover: *A*, Kern River adjacent to oil and gas field near Bakersfield, California (Photograph taken by David Dillon, U.S. Geological Survey).

B, Oil and gas field in southern San Joaquin Valley, California (Photograph taken by Jessica Teunis, U.S. Geological Survey).

Back cover: *C*, Oil well at sunset in southern San Joaquin Valley, California (Photograph taken by Jessica Teunis, U.S. Geological Survey).

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

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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

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

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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.

2 Prioritization of Oil and Gas Fields for Regional Groundwater Monitoring

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 1A](#) 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. 1B, 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.

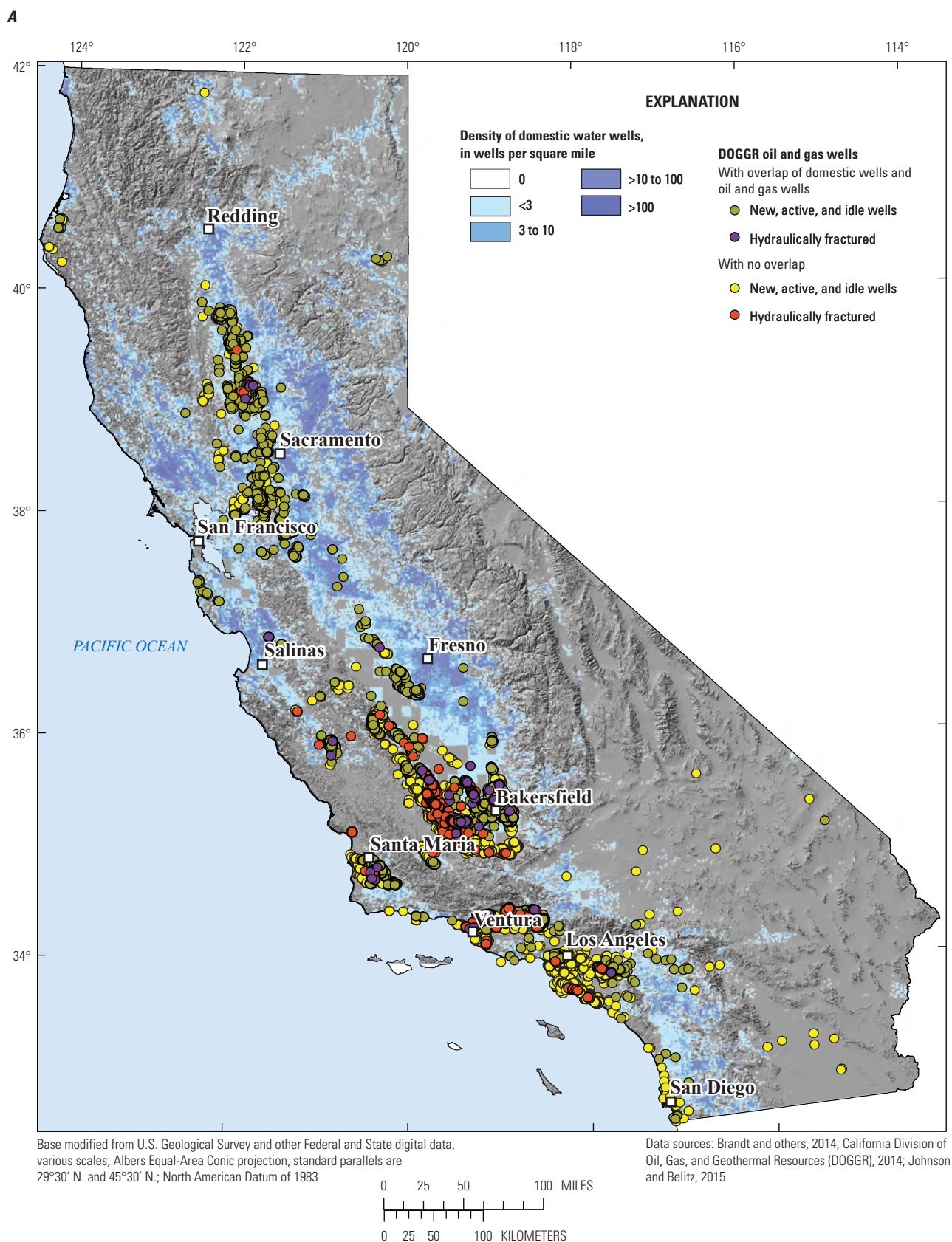


Figure 1. Groundwater supply and areas of overlap with oil and gas production in California: *A*, density of domestic water wells and locations of California Division of Oil, Gas, and Geothermal (DOGGR) oil and gas wells; *B*, 2010 groundwater withdrawal per county; and *C*, 2010 groundwater withdrawal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

4 Prioritization of Oil and Gas Fields for Regional Groundwater Monitoring

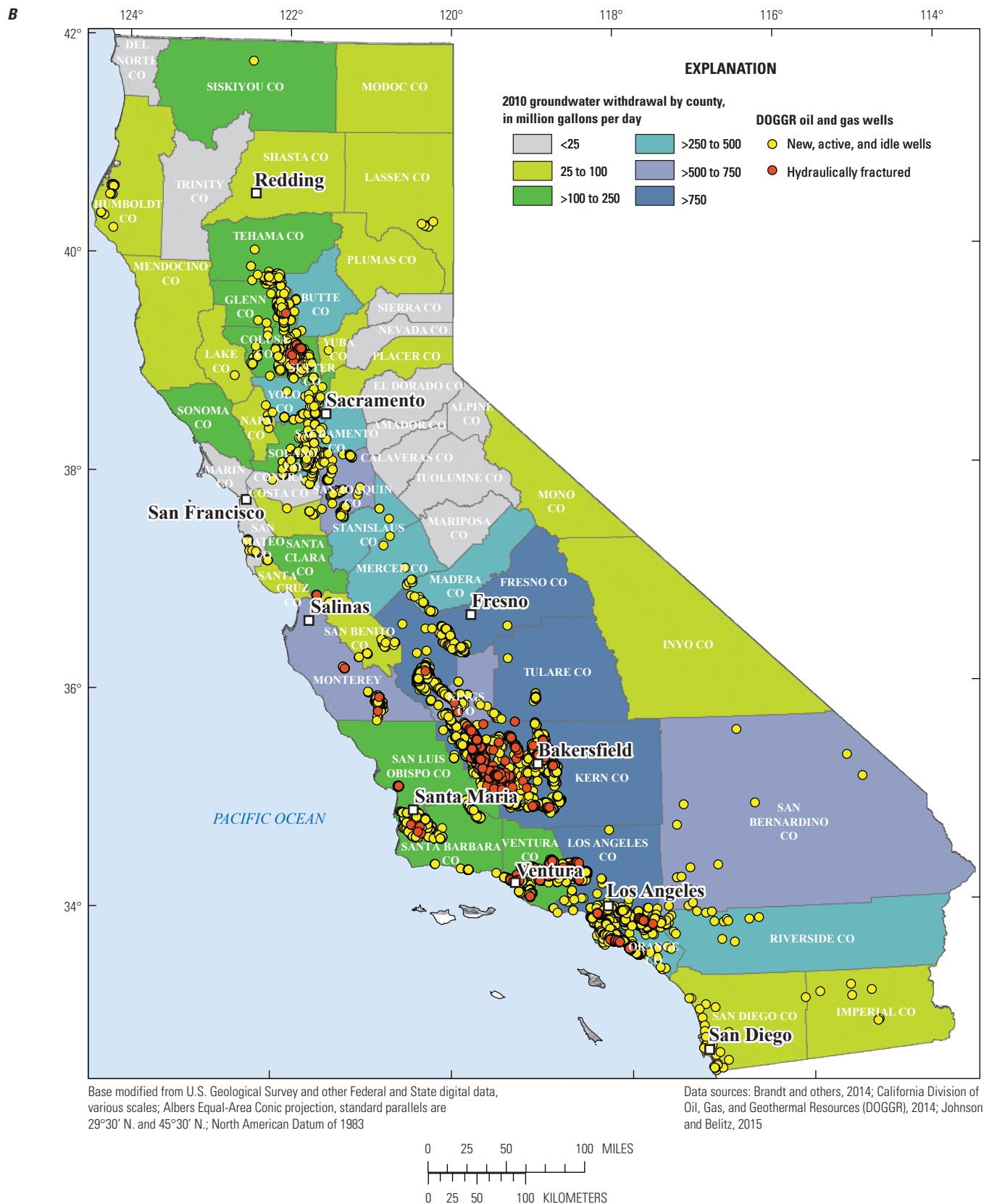


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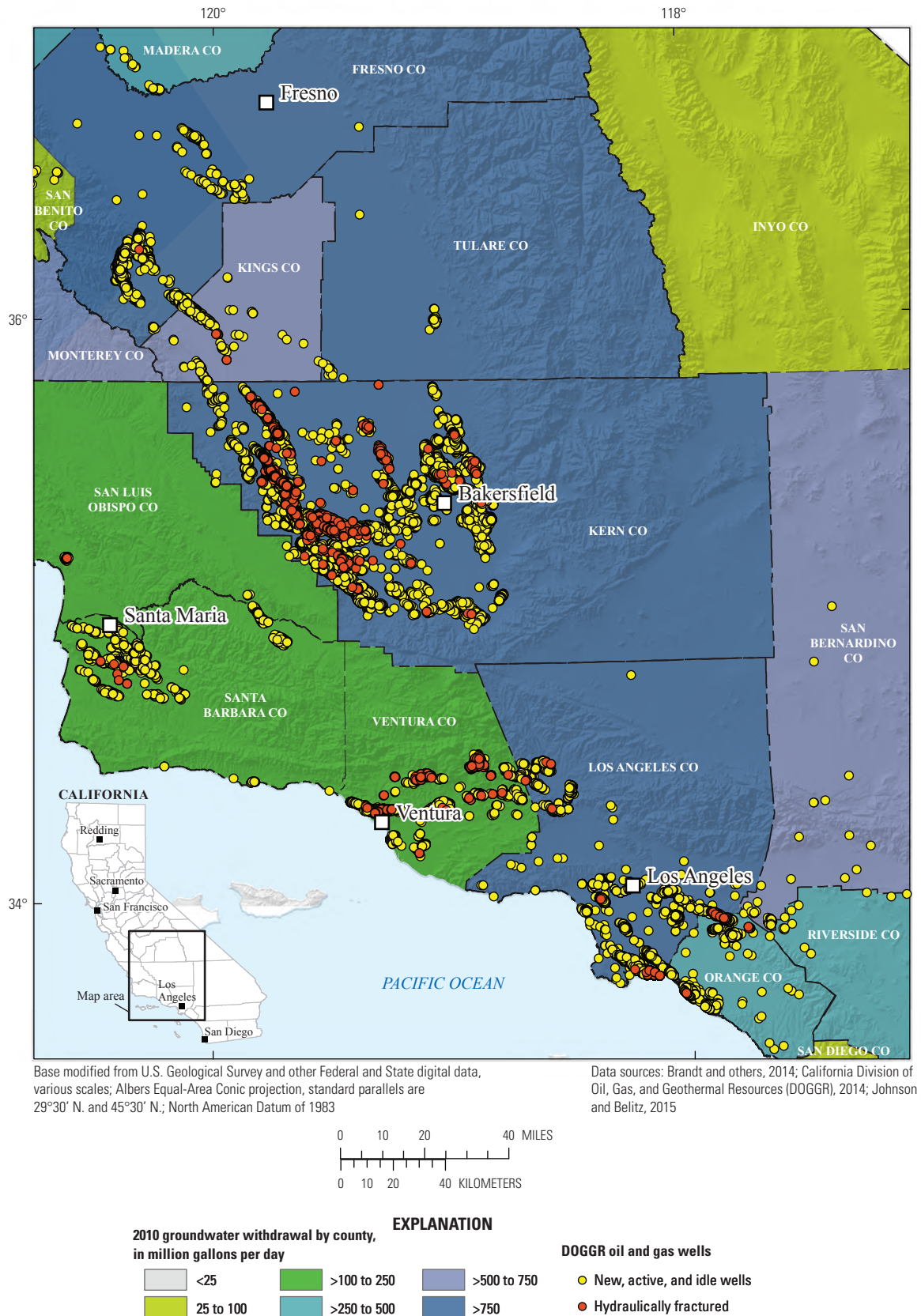


Figure 1. —Continued

6 Prioritization of Oil and Gas Fields for Regional Groundwater Monitoring

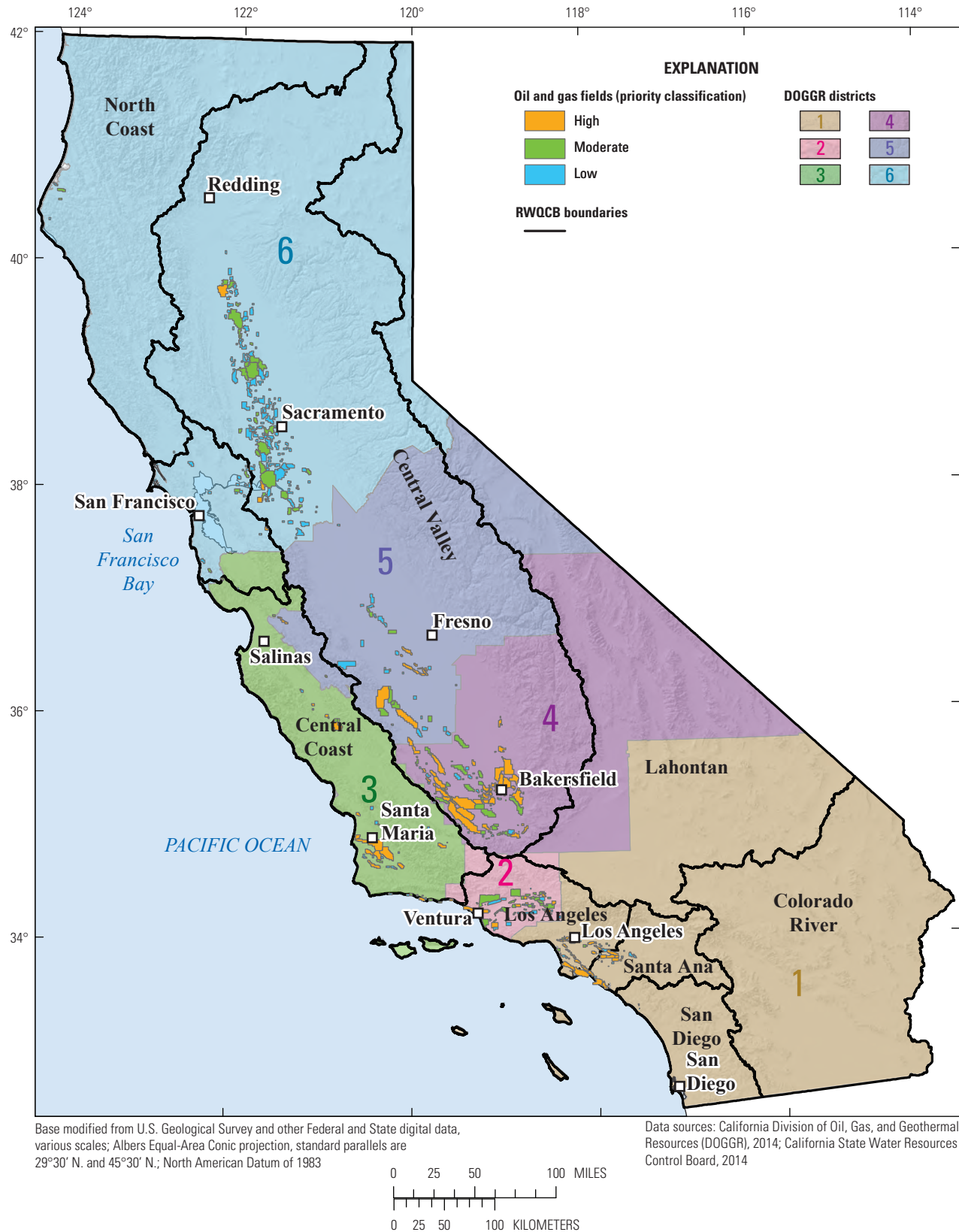


Figure 2. California Division of Oil, Gas, and Geothermal Resources (DOGGR) district boundaries, California Regional Water Quality Control Board (RWQCB) boundaries, and the location of oil and gas fields in California.

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.

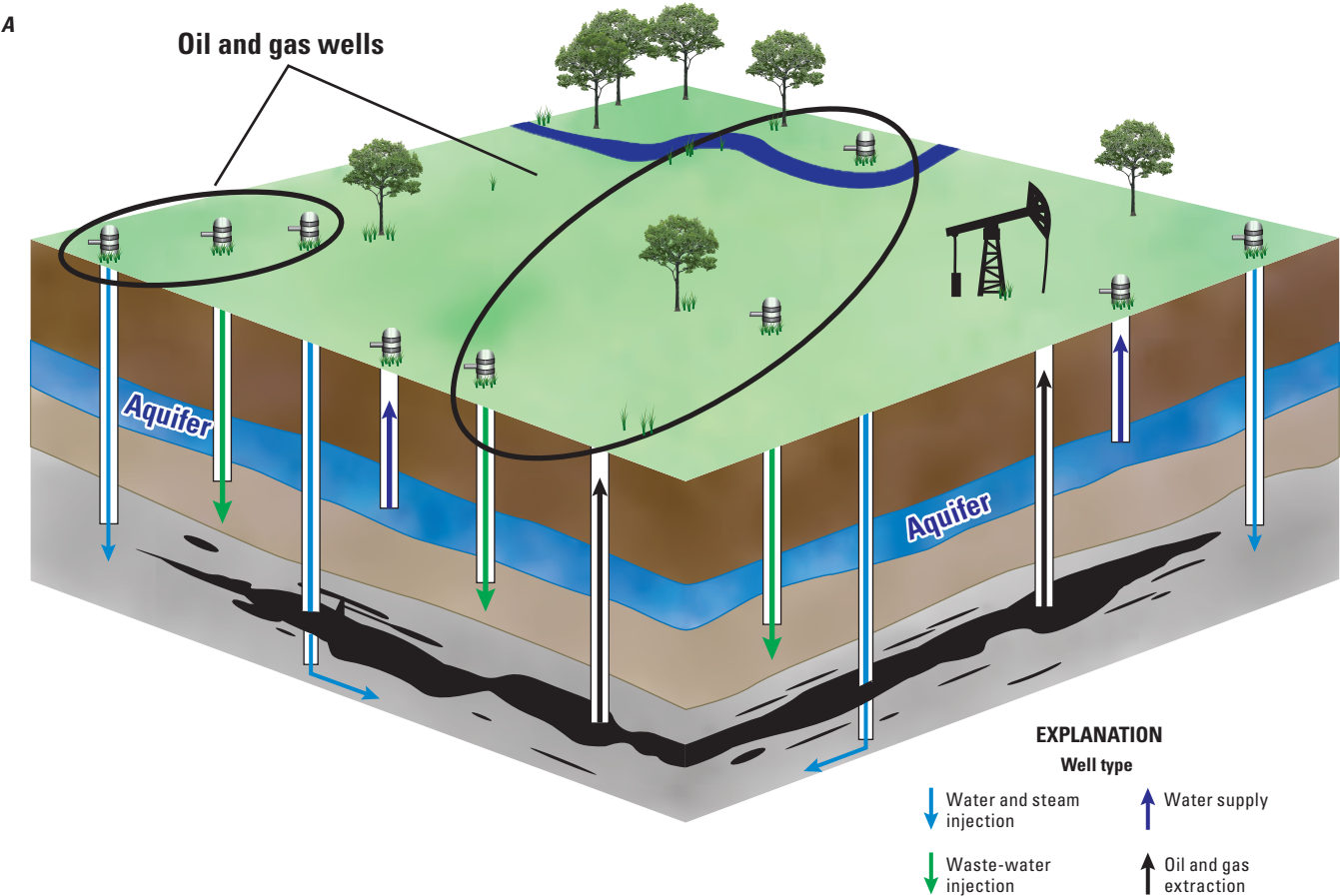


Figure 3. Factors that were assessed in the prioritization of oil and gas fields for regional groundwater monitoring: A, oil and gas production; B, injection for enhanced oil recovery and waste disposal; C, vertical proximity of petroleum resource development to groundwater resources; and D, groundwater withdrawal in and near oil and gas fields.

B

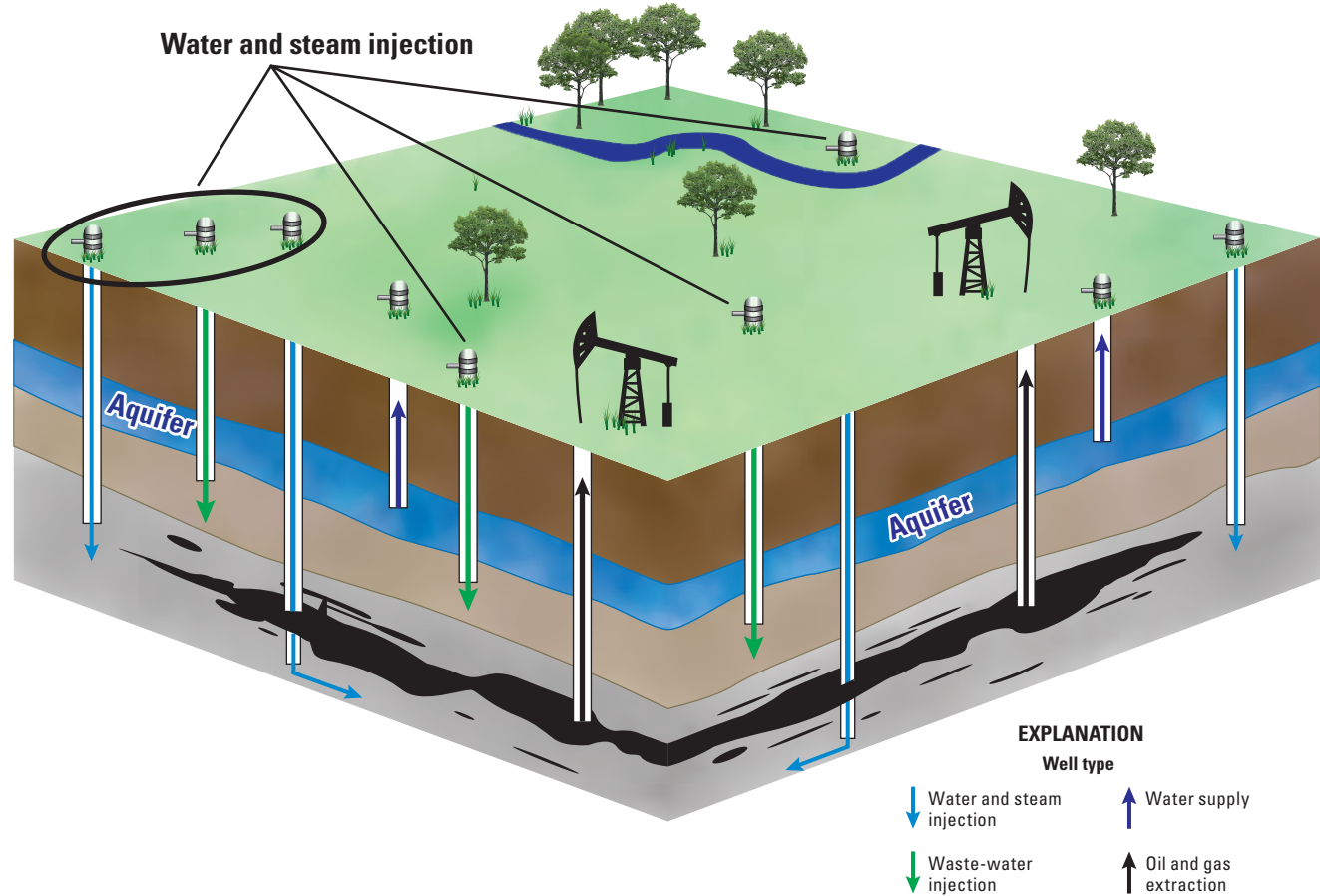


Figure 3. —Continued

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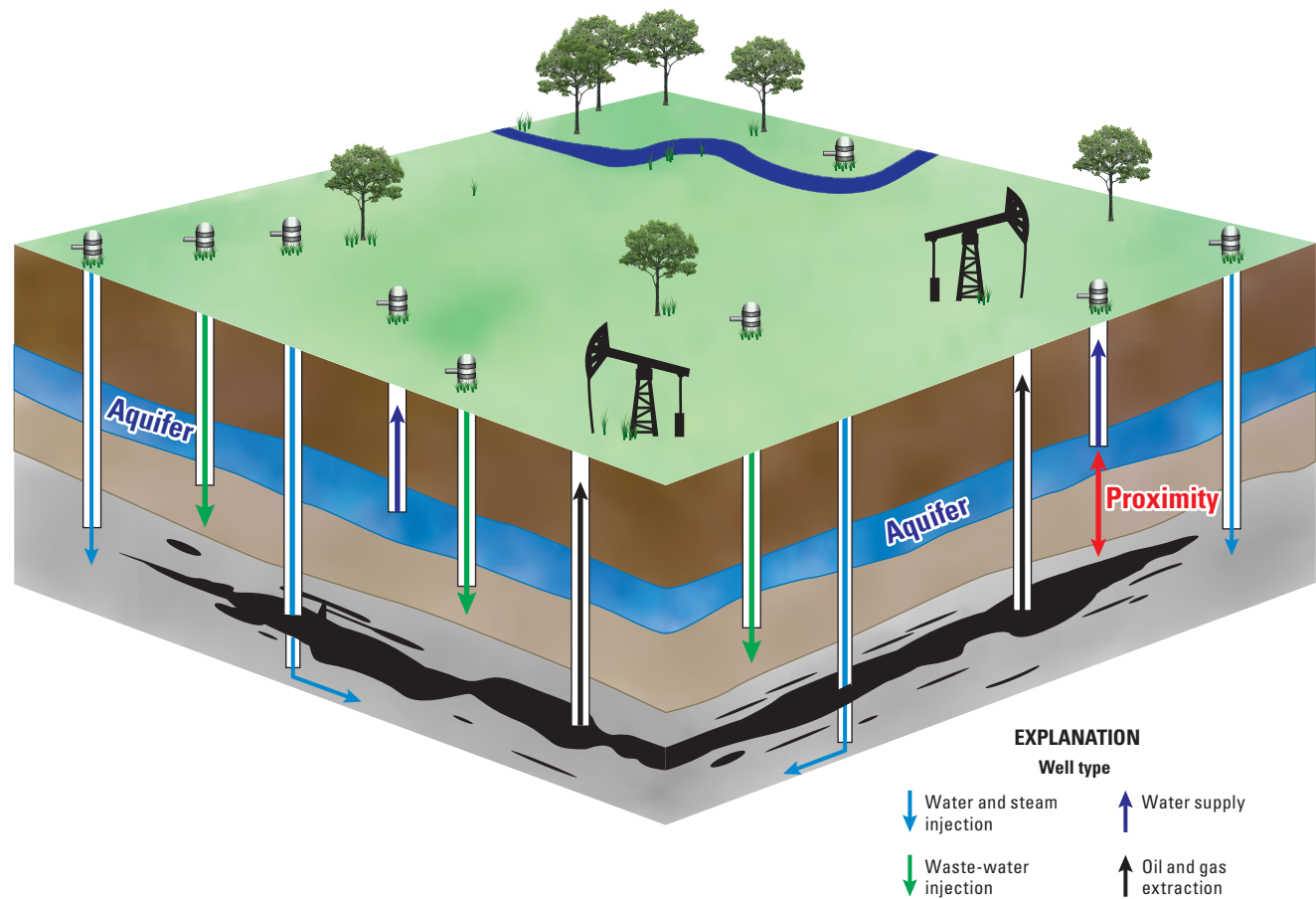


Figure 3. —Continued

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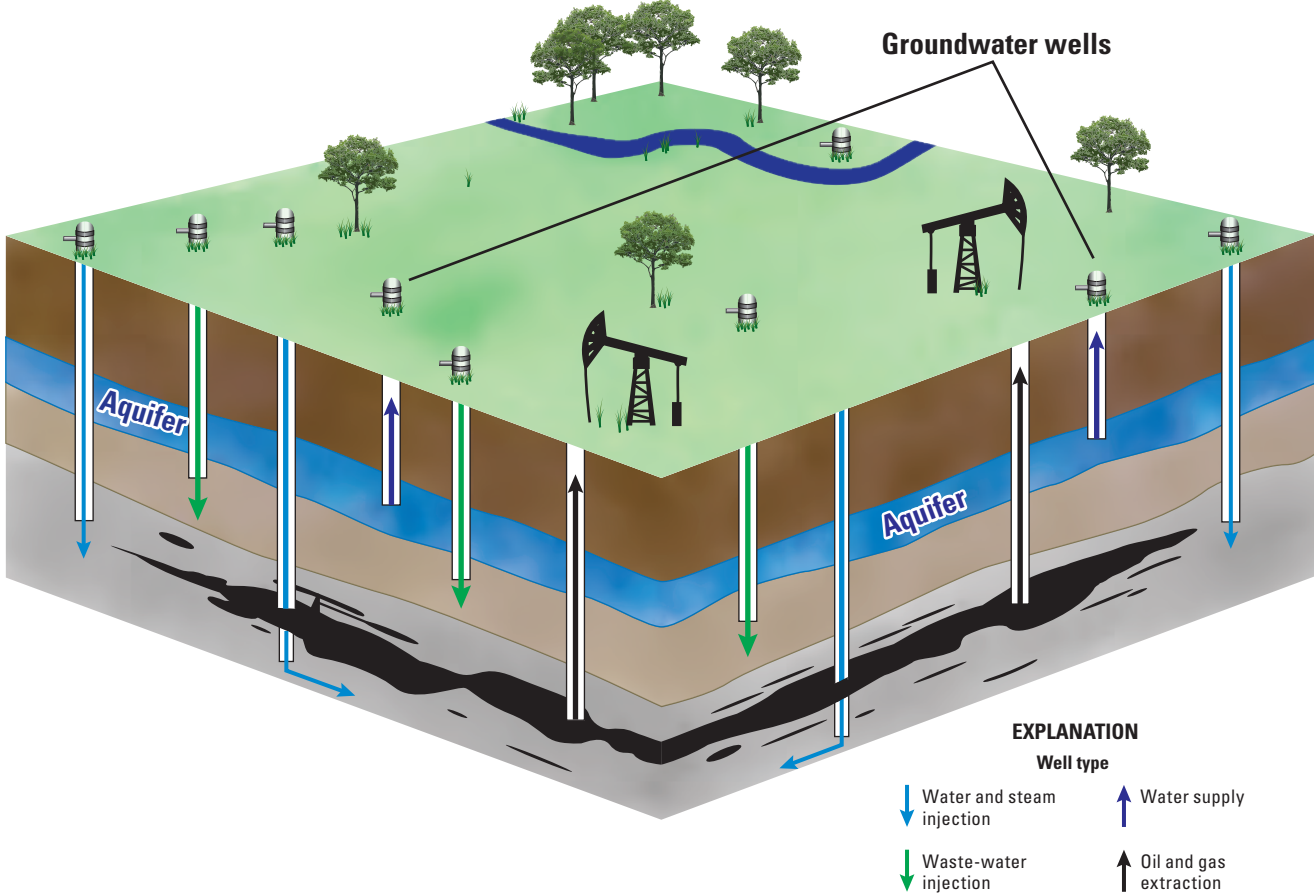


Figure 3. —Continued

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 or 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/mi²; fig. 4.4). 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:

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

where

$SEP_{f,1}$	is the separation distance for a field using method 1,
d_{TOP}	is the depth to top of perforated interval for a petroleum well,
d_{BFW}	is the depth to base of freshwater in the same petroleum well, and
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:

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

where

$SEP_{f,2}$	is the separation distance for a field using method 2,
d_{TOP}	is the depth to top of perforated interval for a petroleum well,
d_{TD}	is the total well depth of a water well near the petroleum well, and
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:

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

where

- $SEP_{f,3}$ is the separation distance for a field using method 3,
- $d_{TOP,M}$ is the median depth to top of perforated interval for all petroleum wells in a field, and
- $d_{BFW,M}$ 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:

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

where

- $SEP_{f,4}$ is the vertical separation distance for a field using method 4,
- $d_{TOP,M}$ is the median depth to top of perforated interval for all petroleum wells in a field, and
- $d_{TD,M}$ 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:

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

where

- $SEP_{f,5}$ is the vertical separation distance for a field using method 5, and
- $d_{TOP,M}$ 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](#).

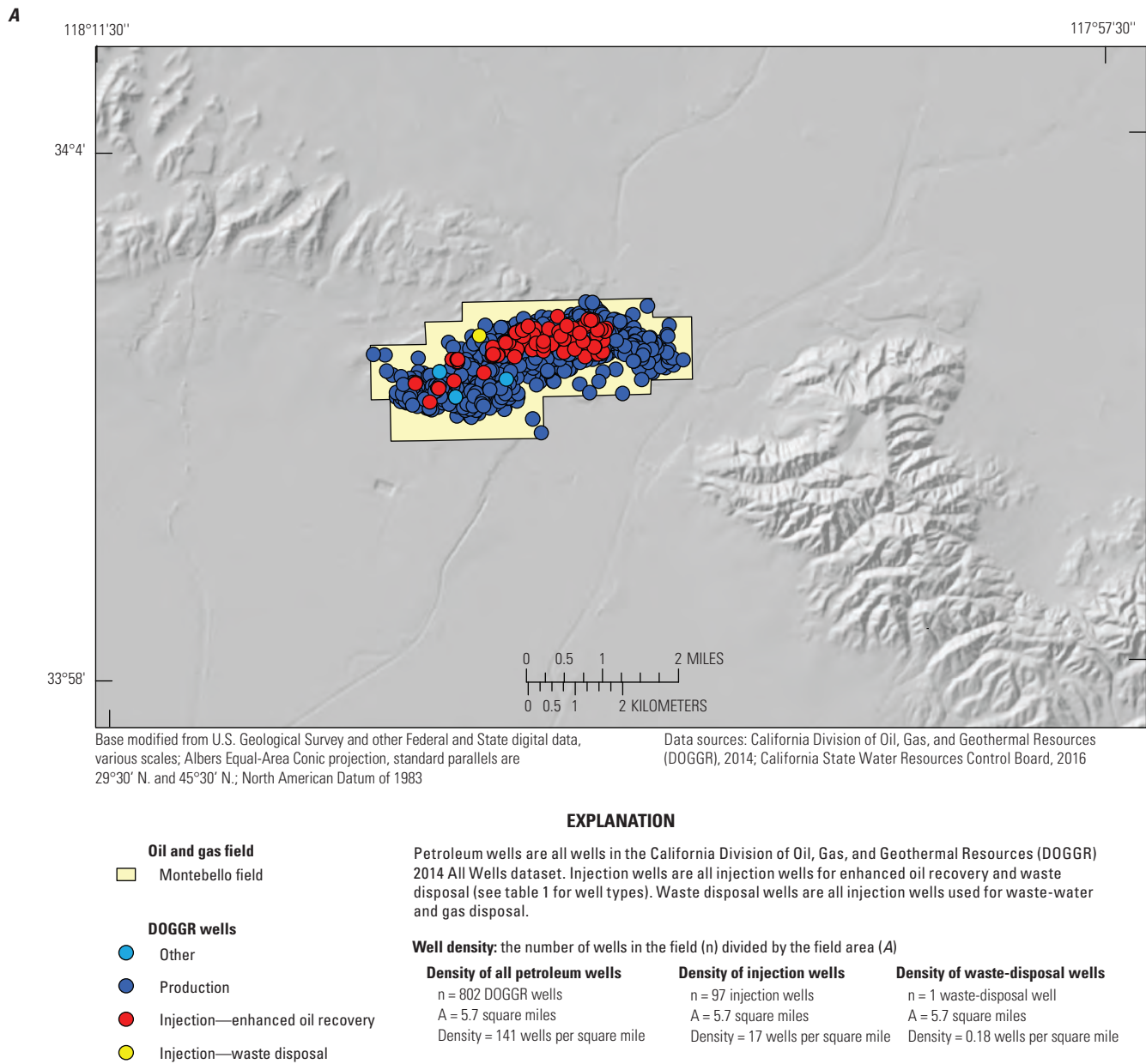


Figure 4. Methods for calculating petroleum and water well densities: *A*, density of all petroleum wells, injection wells, and waste-disposal wells in the field; and *B*, density of water wells overlying the field and adjacent to the field.

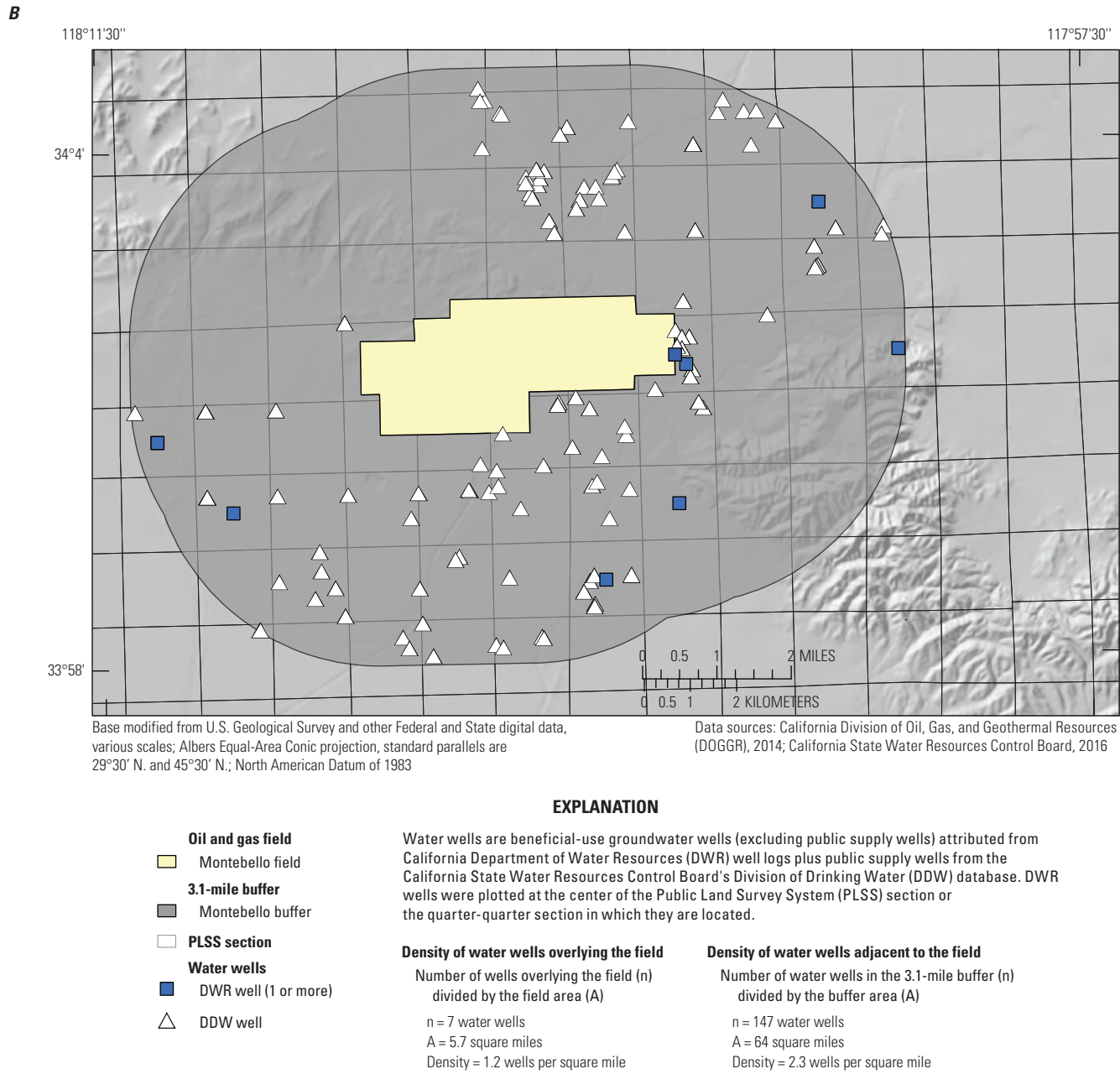


Figure 4. —Continued

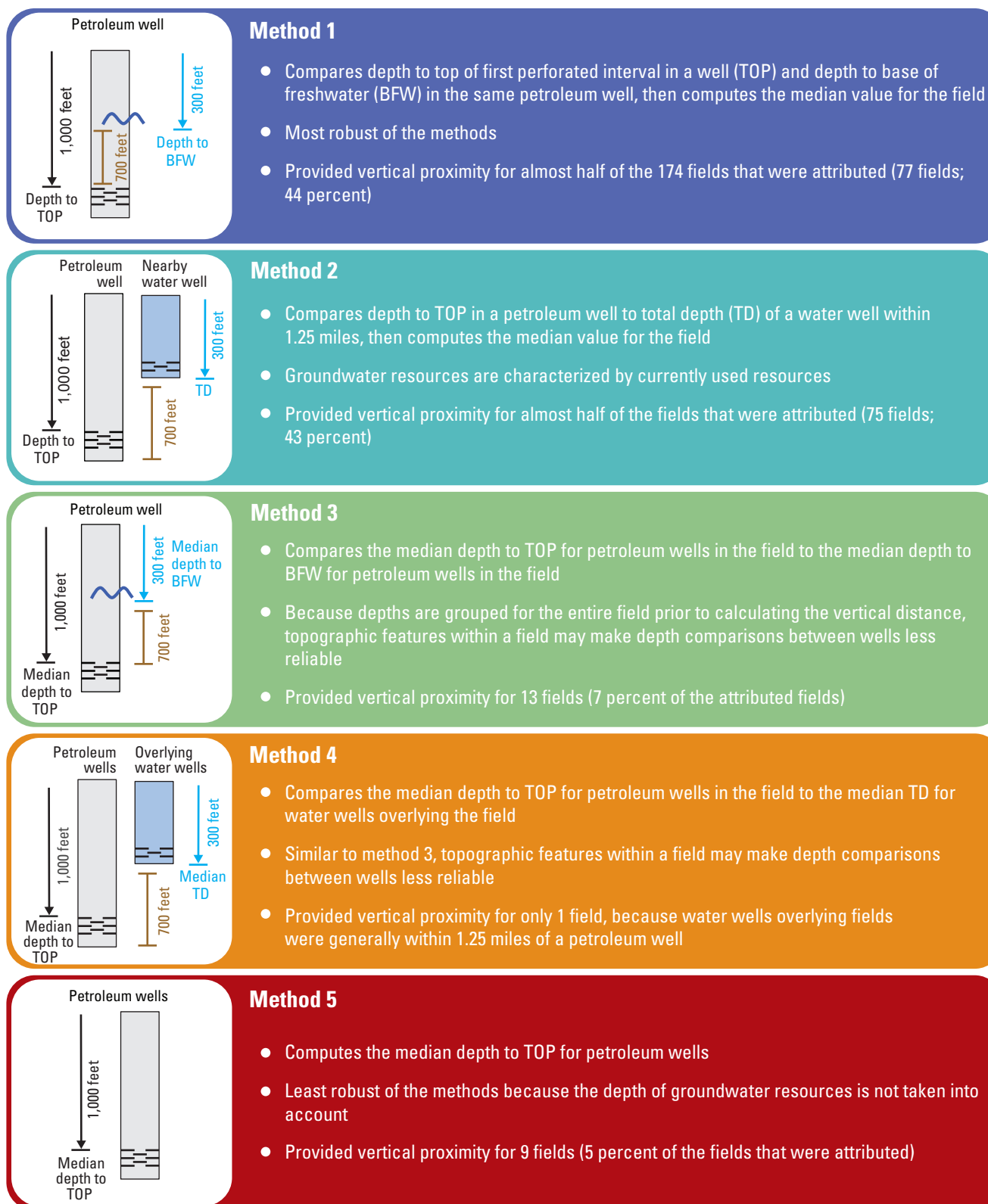


Figure 5. Methods used to calculate vertical separation distance between petroleum resource development and groundwater resources for each oil and gas field in California.

A

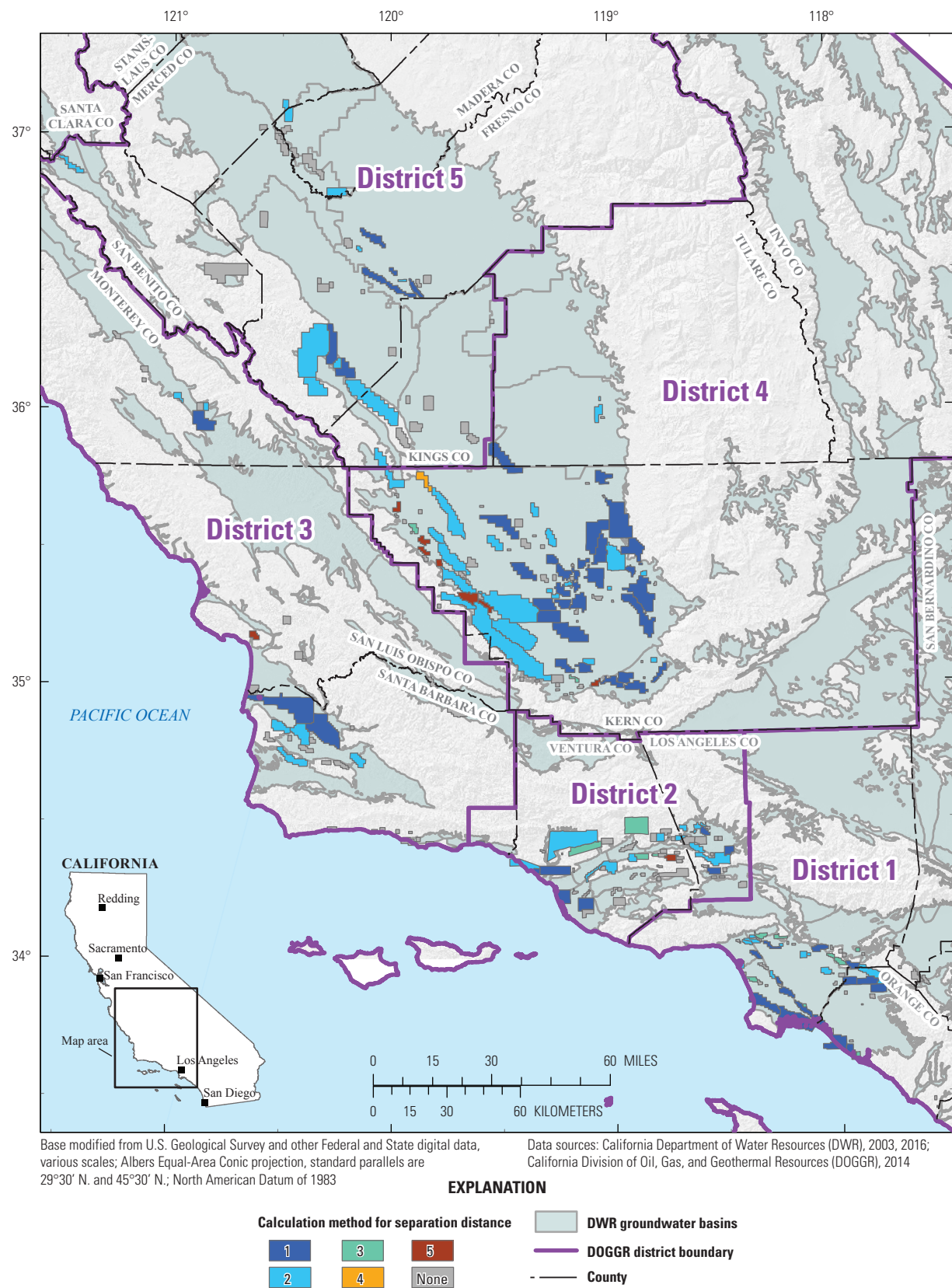


Figure 6. Location of oil and gas fields in California and the method number for calculating vertical separation distance for each field in A, California Division of Oil, Gas, and Geothermal Resources (DOGGR) districts 1–5 and B, DOGGR district 6.

B

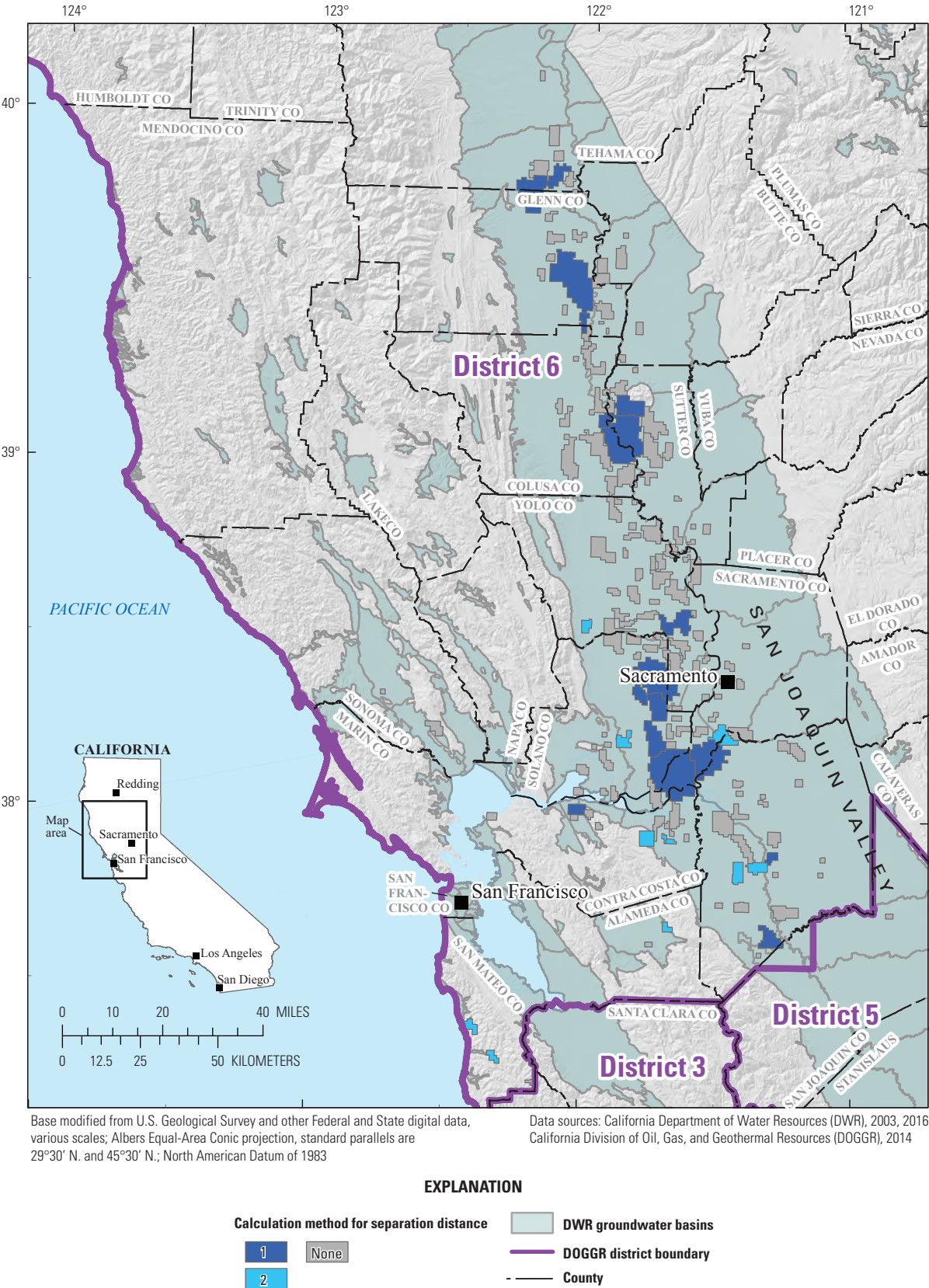


Figure 6. —Continued

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.

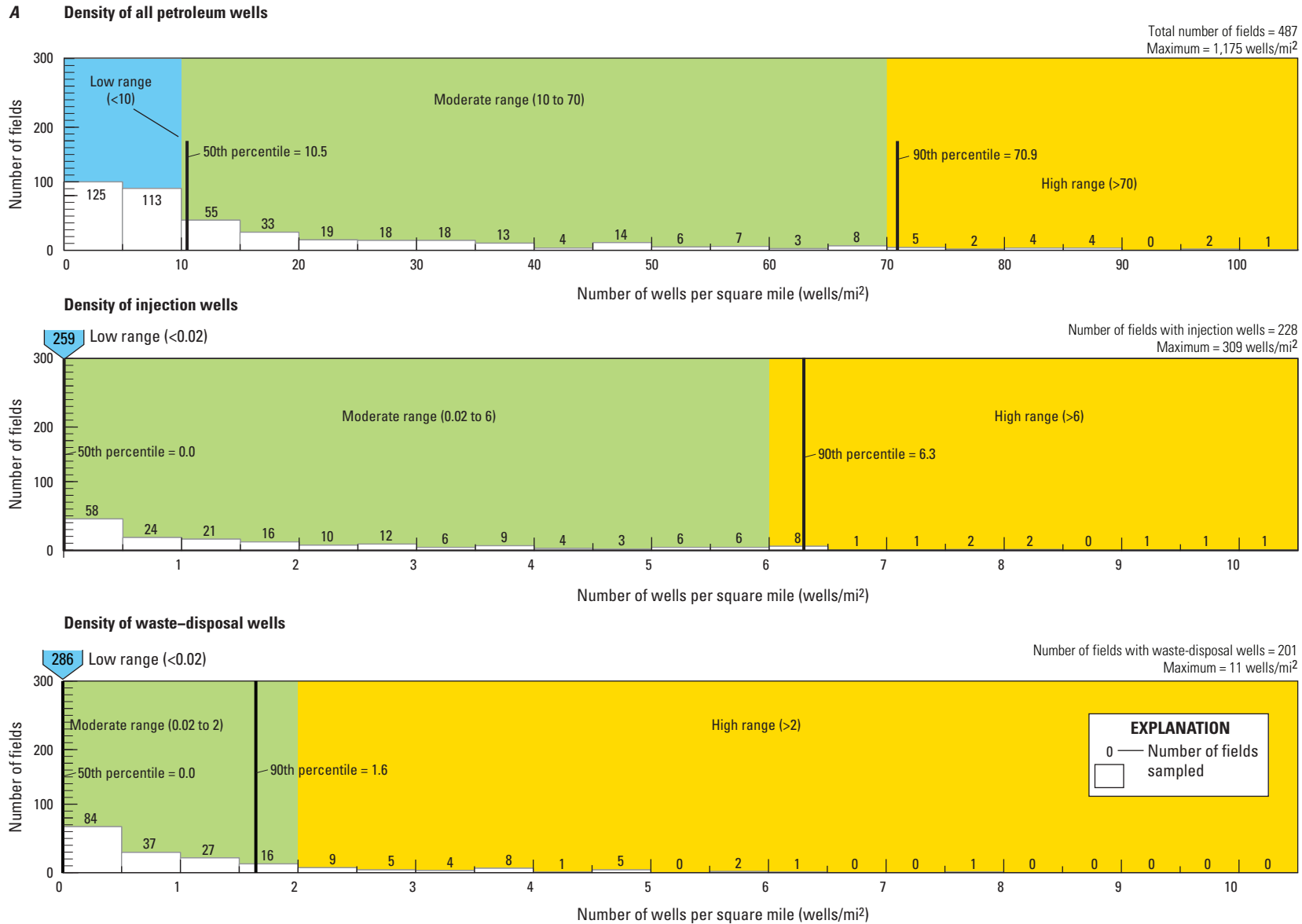
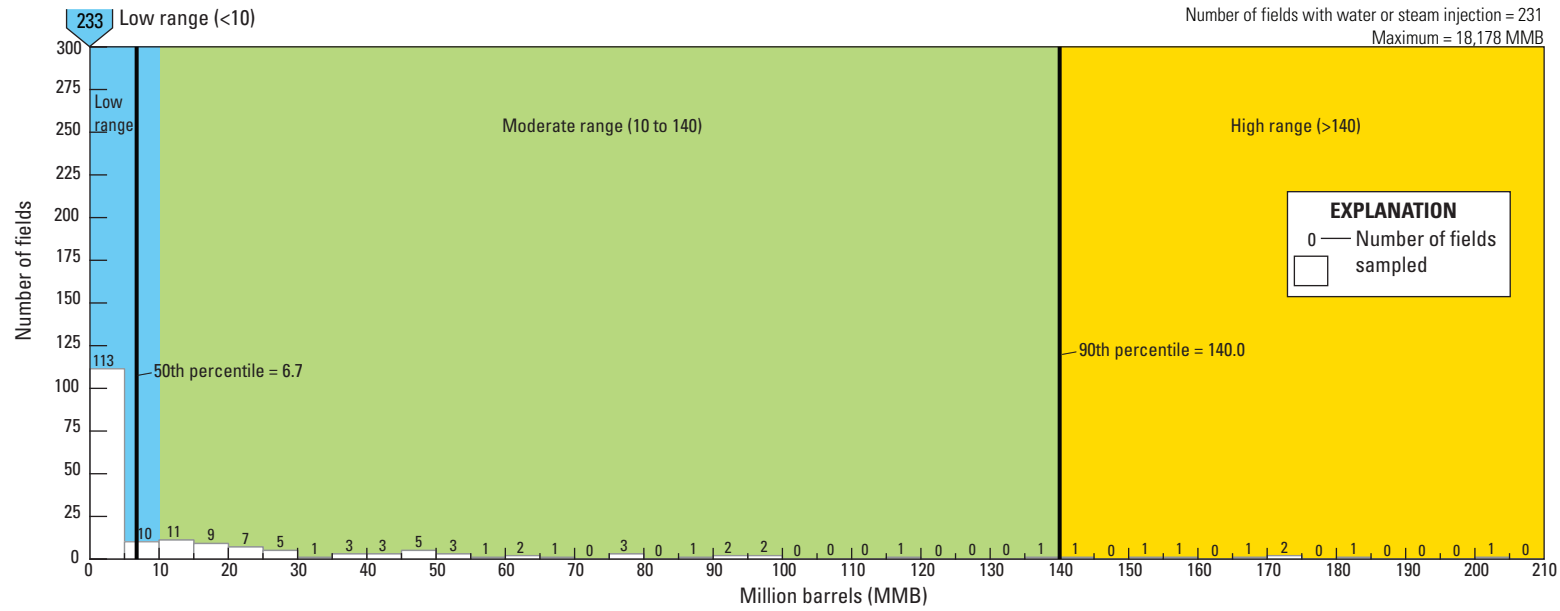


Figure 7. Distribution of data for individual variables calculated for California oil and gas fields in the preliminary assessment of petroleum resource development and proximity to groundwater resources: *A*, density of all petroleum wells, injection wells, and waste-disposal wells; *B*, total volume 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

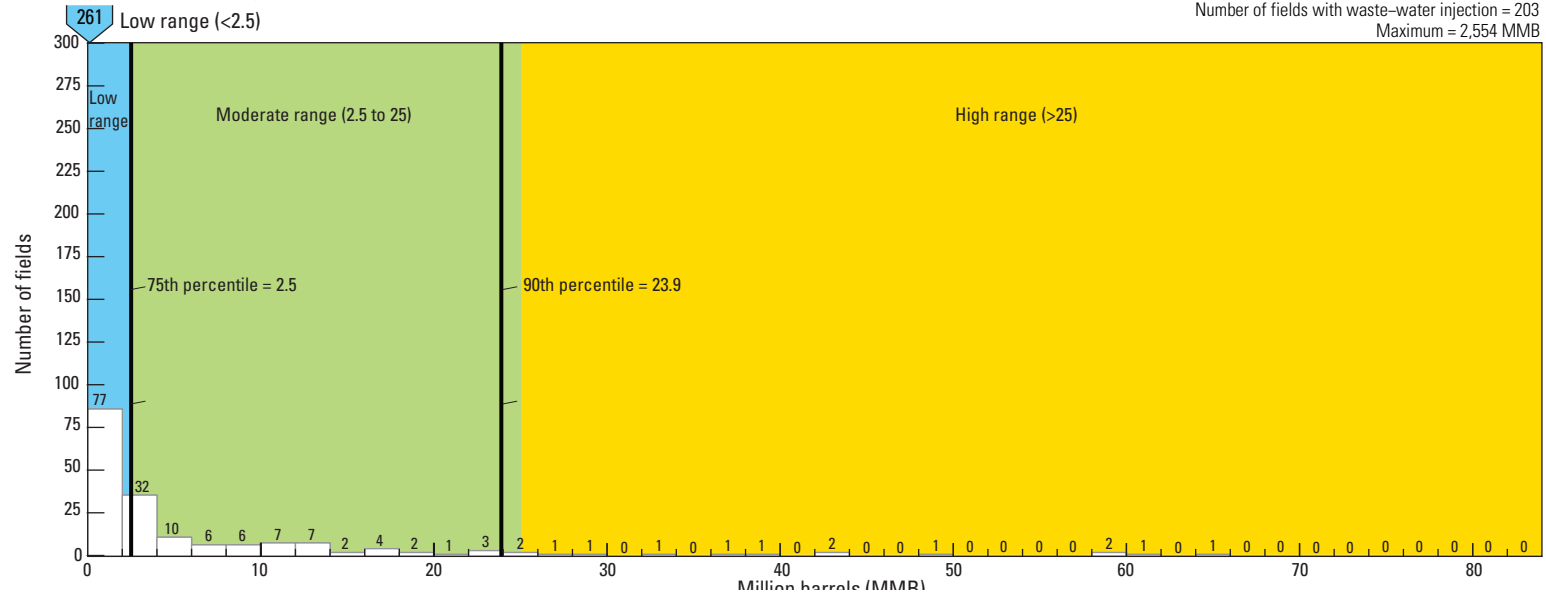


Figure 7. —Continued

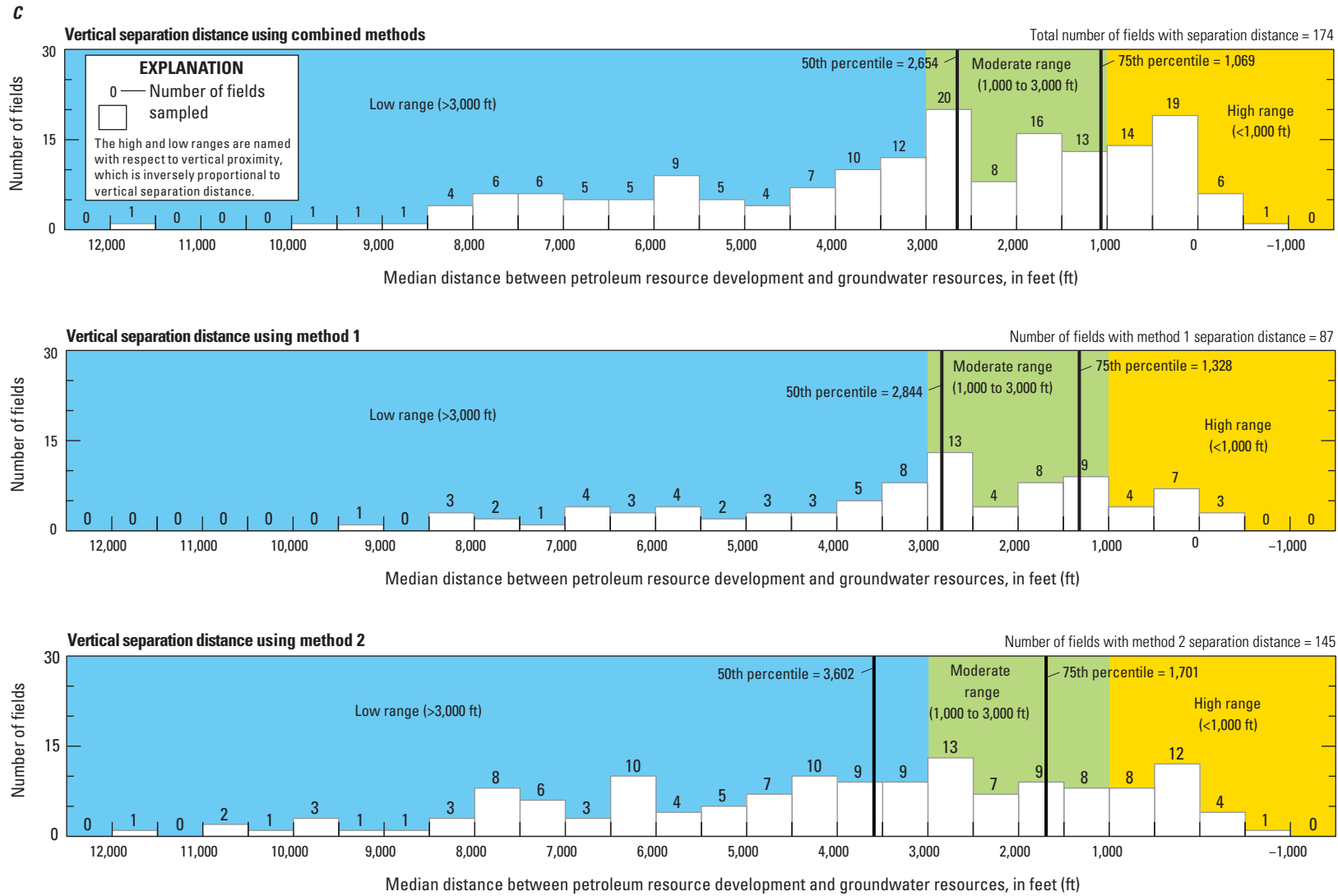


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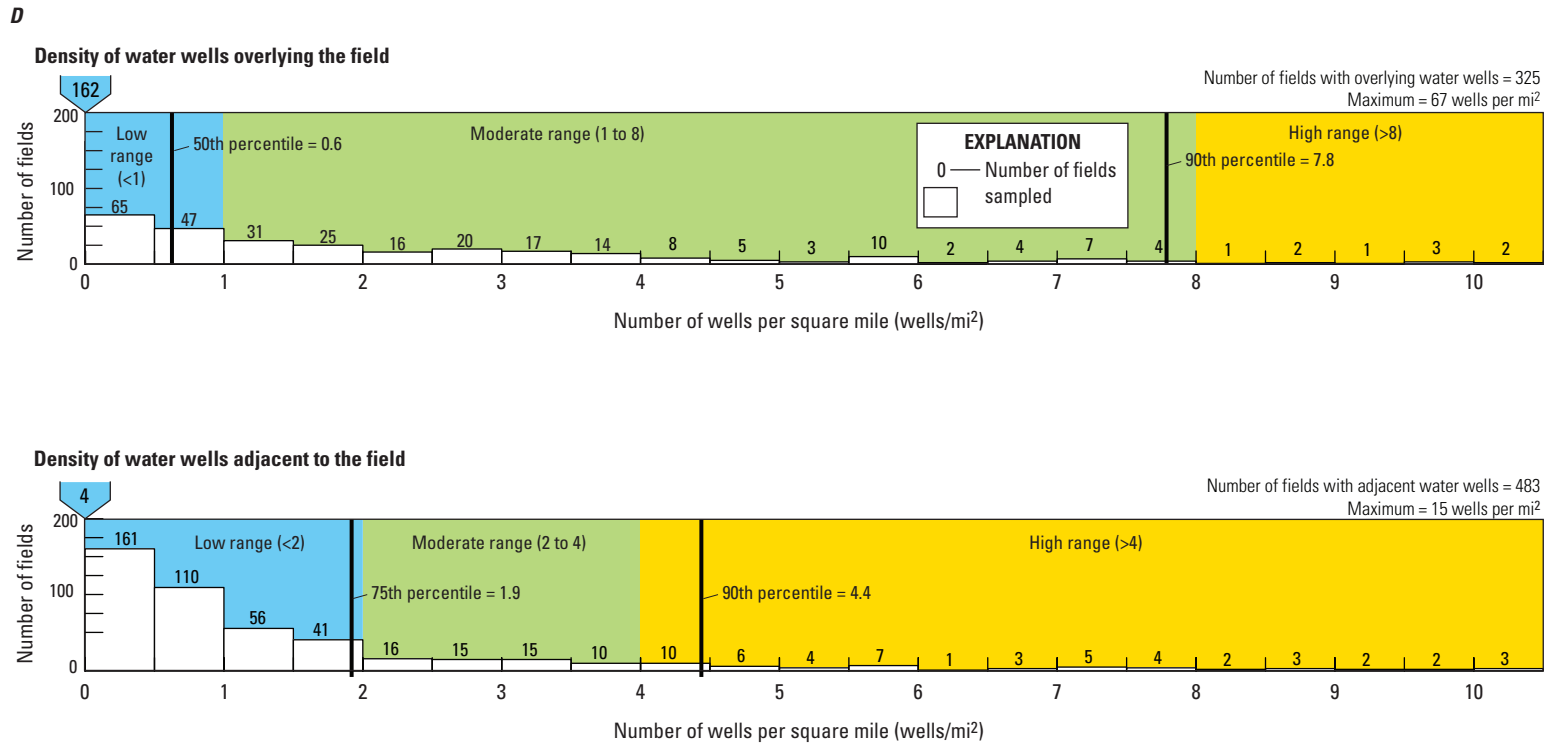


Figure 7. —Continued

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.

Prioritization analysis decision tree

(Number on line indicates number of fields)

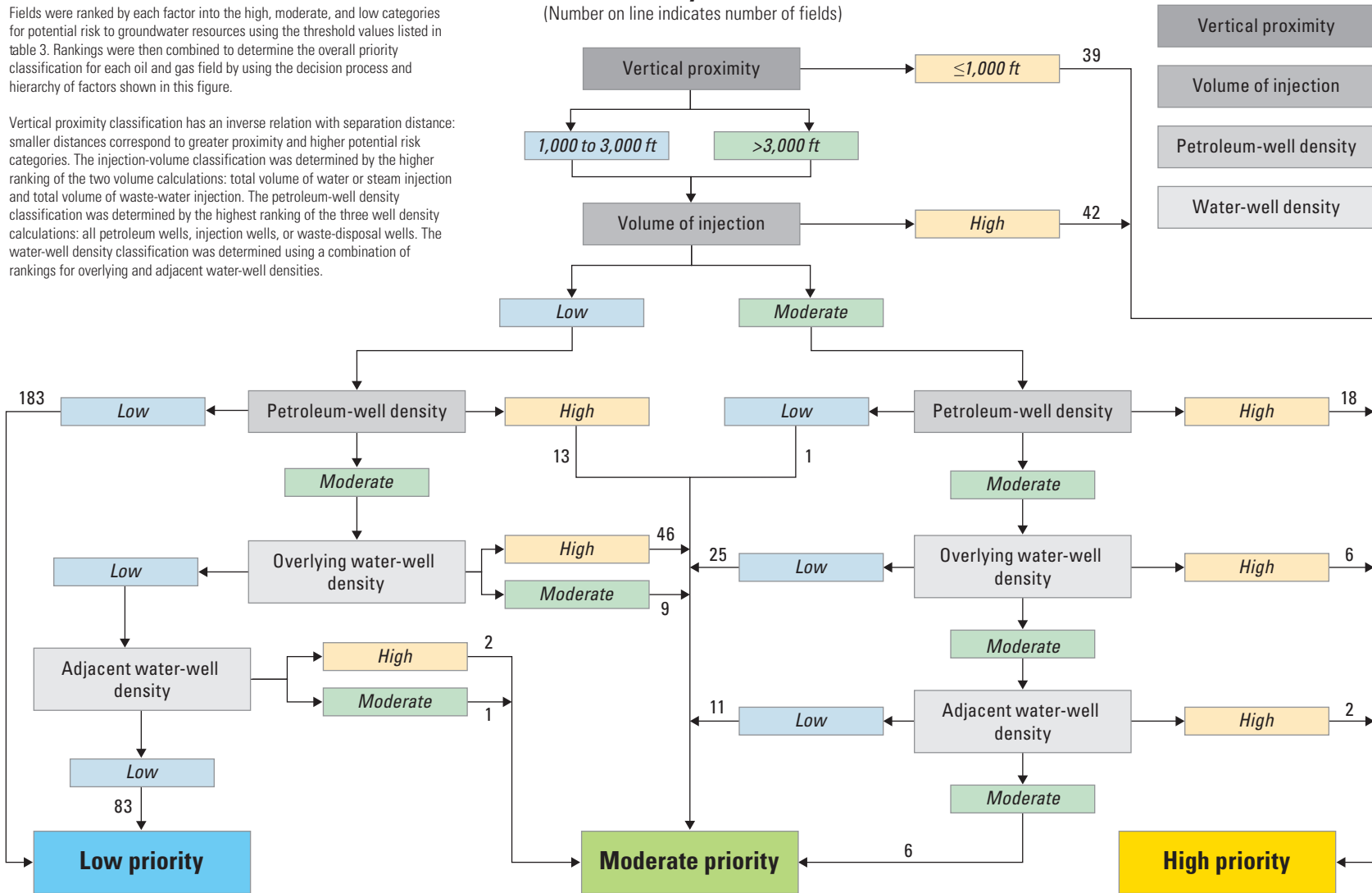


Figure 8. Decision process and hierarchy of factors considered as part of the prioritization analysis in which California oil and gas fields are classified as high, moderate, low priority for regional groundwater monitoring.

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/mi² to 6 wells/mi² for density of injection wells and rounded from 1.6 wells/mi² to 2 wells/mi² 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/mi²), 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/mi².

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 mi²), 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.

A

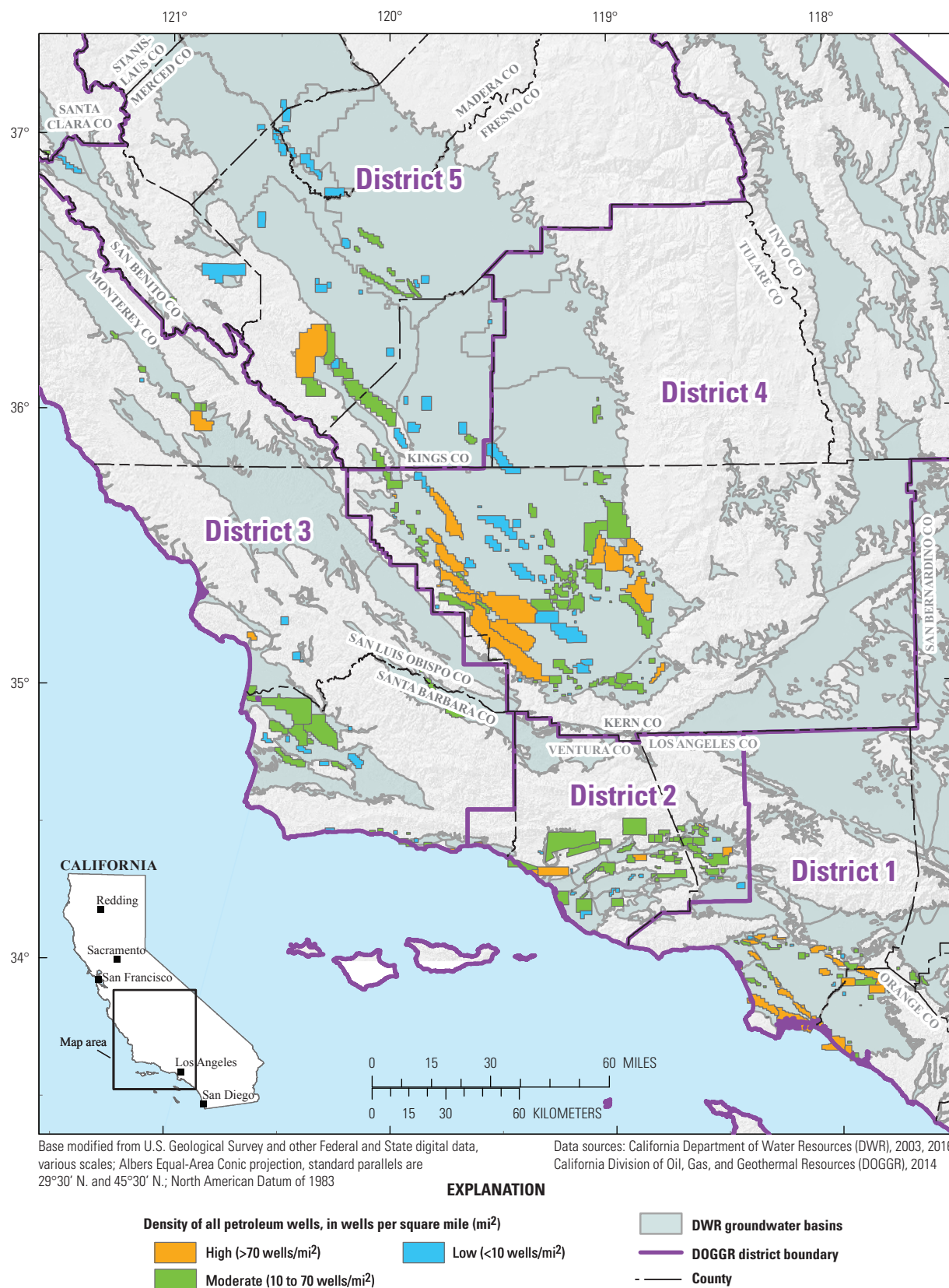
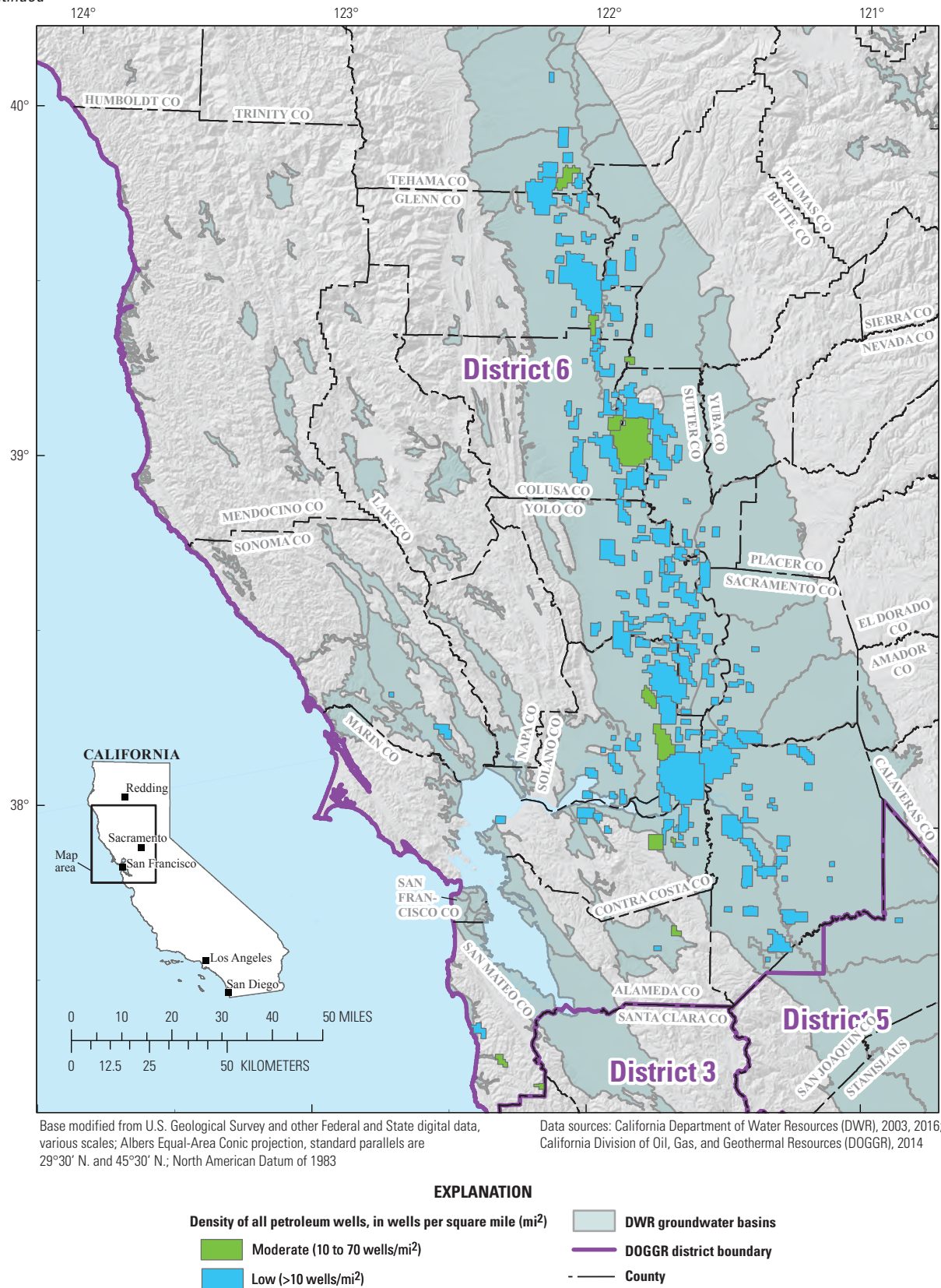


Figure 9. California oil and gas fields showing rankings for each of the variables: *A*, density of all petroleum wells; *B*, density of injection wells; *C*, density of waste-disposal wells; *D*, total volume of water and steam injection; *E*, total volume of water injection for waste disposal; *F*, 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

Figure 9. —Continued

B

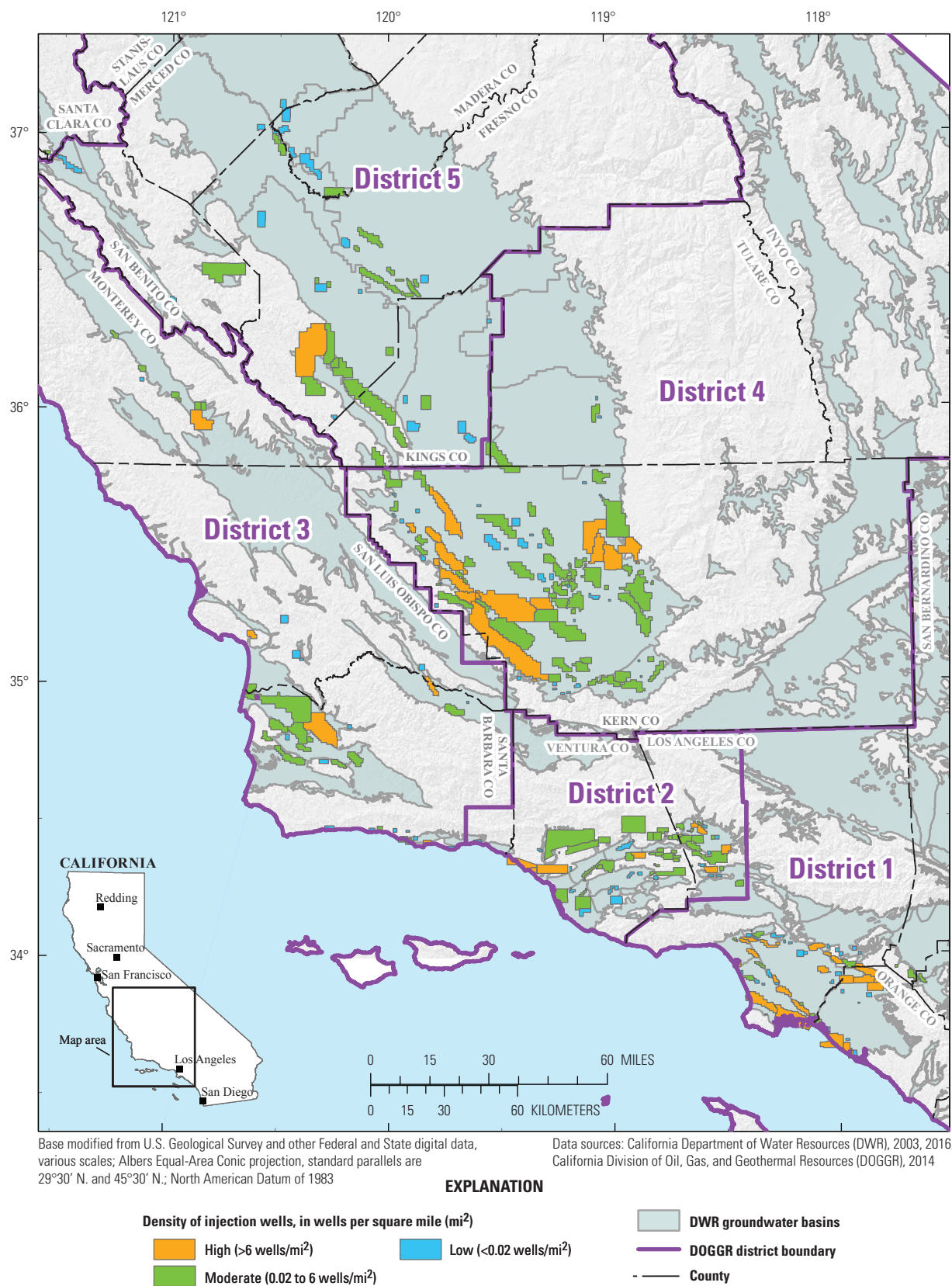


Figure 9. —Continued

B—Continued

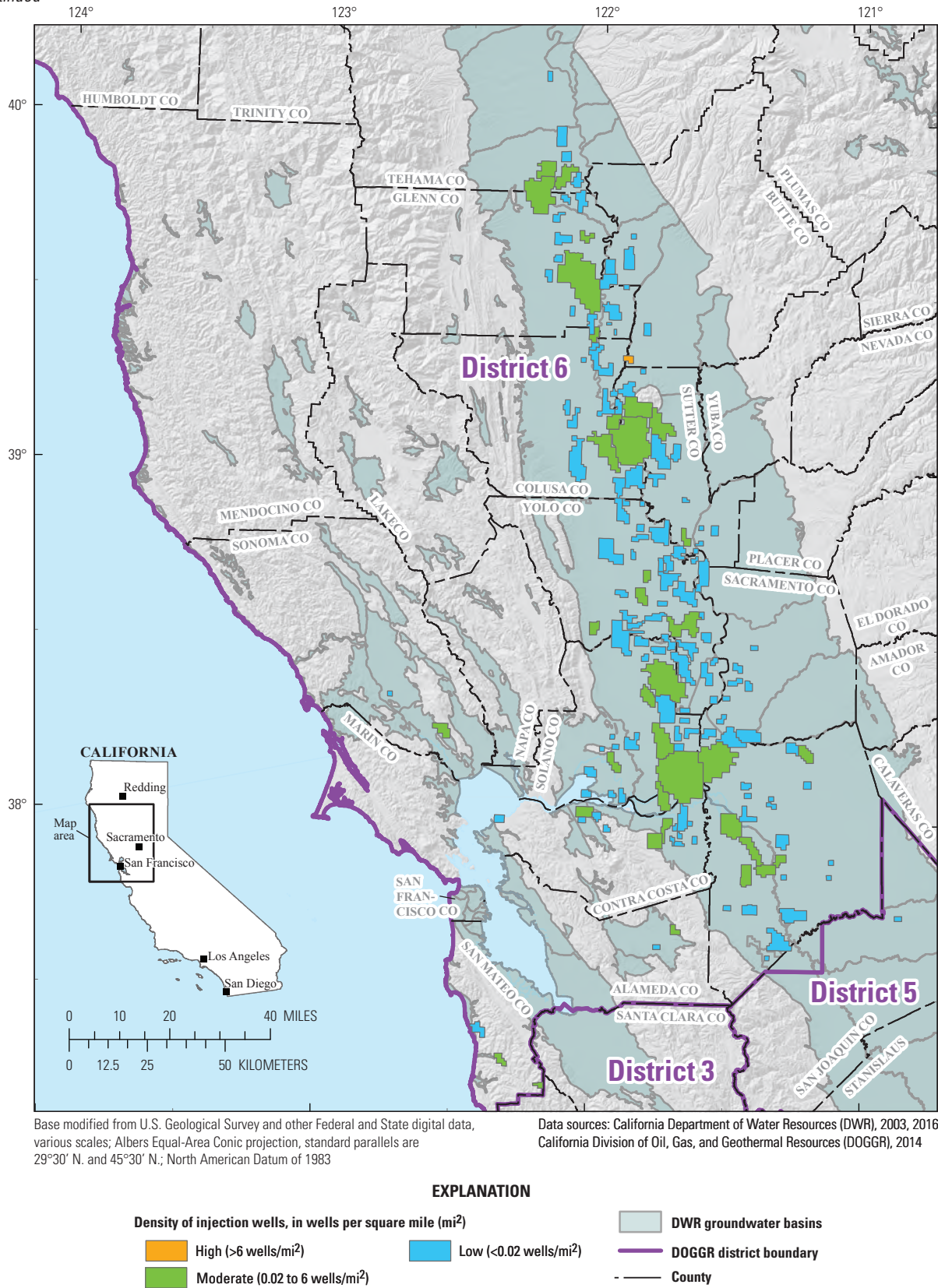


Figure 9. —Continued

c

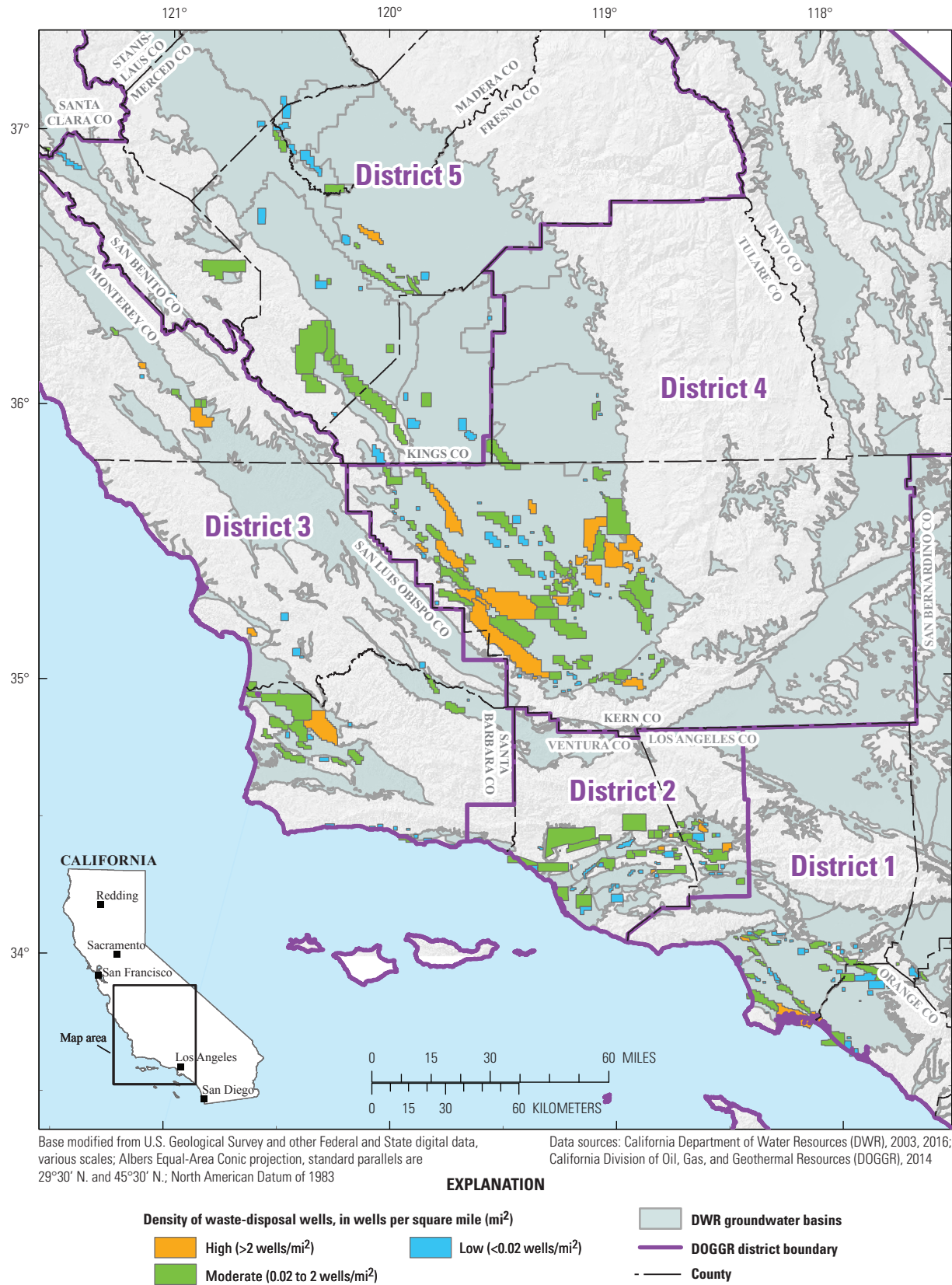


Figure 9. —Continued

C—Continued

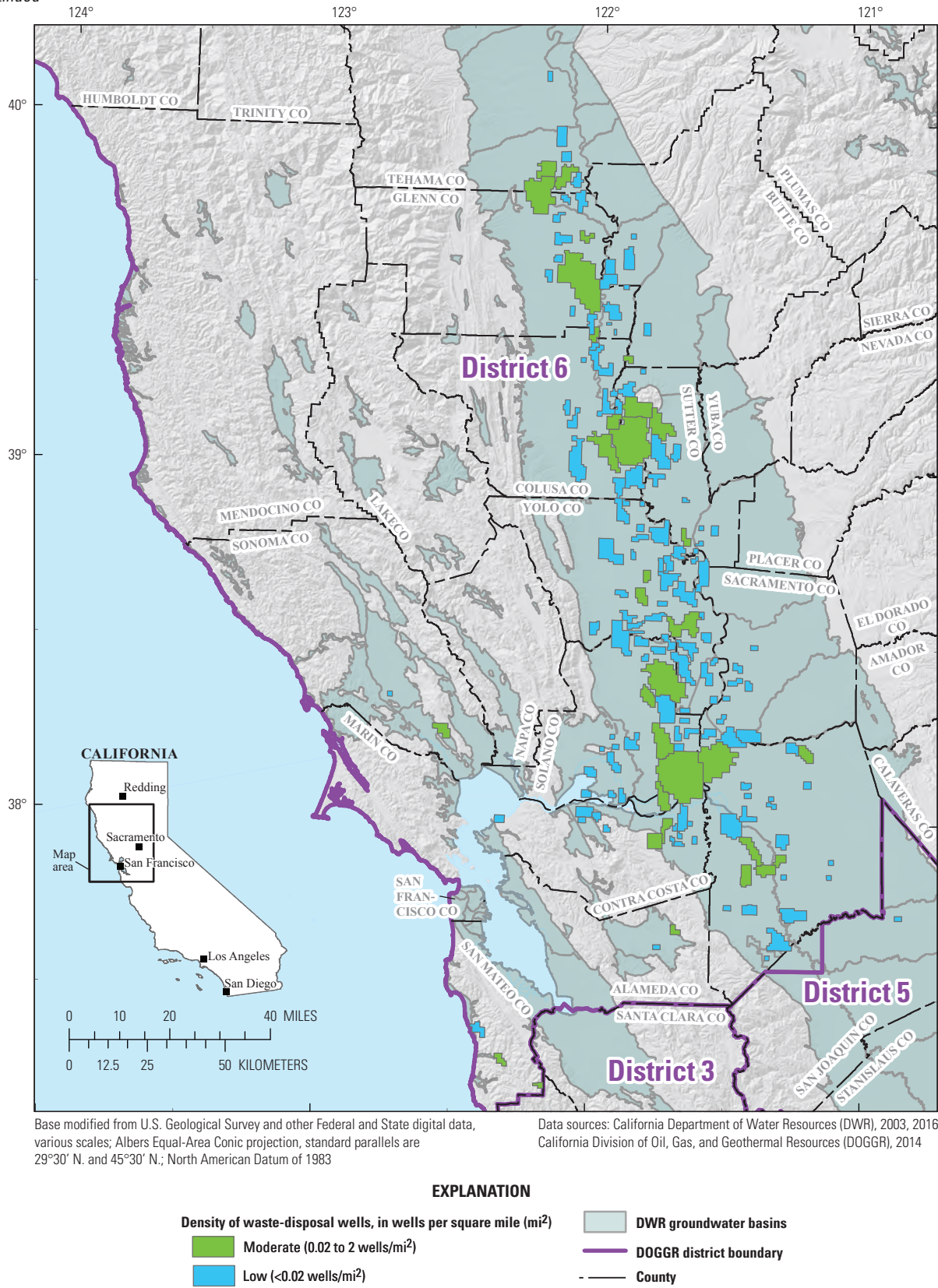


Figure 9. —Continued

D



Figure 9. —Continued

D—Continued

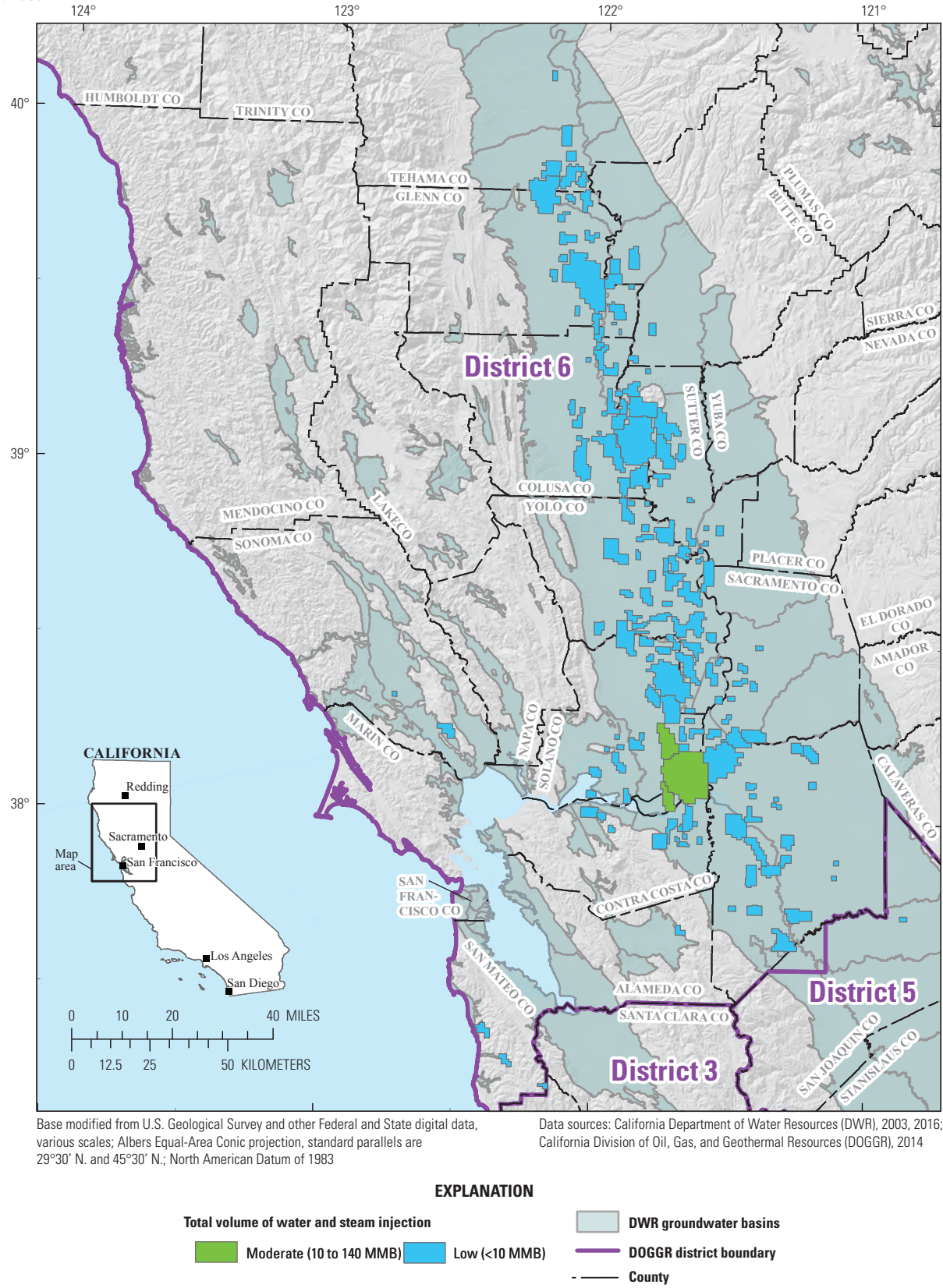


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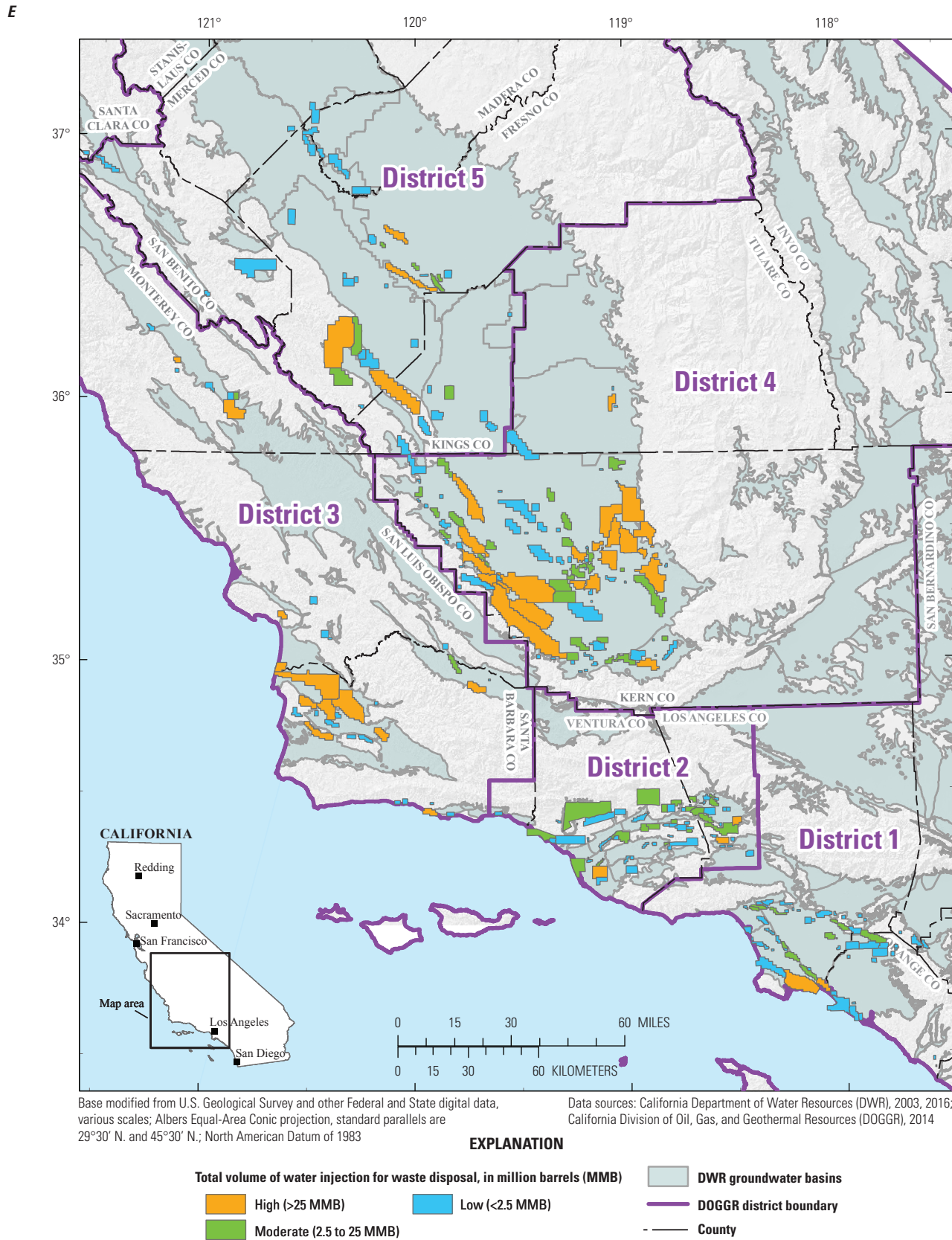


Figure 9. —Continued

E—Continued

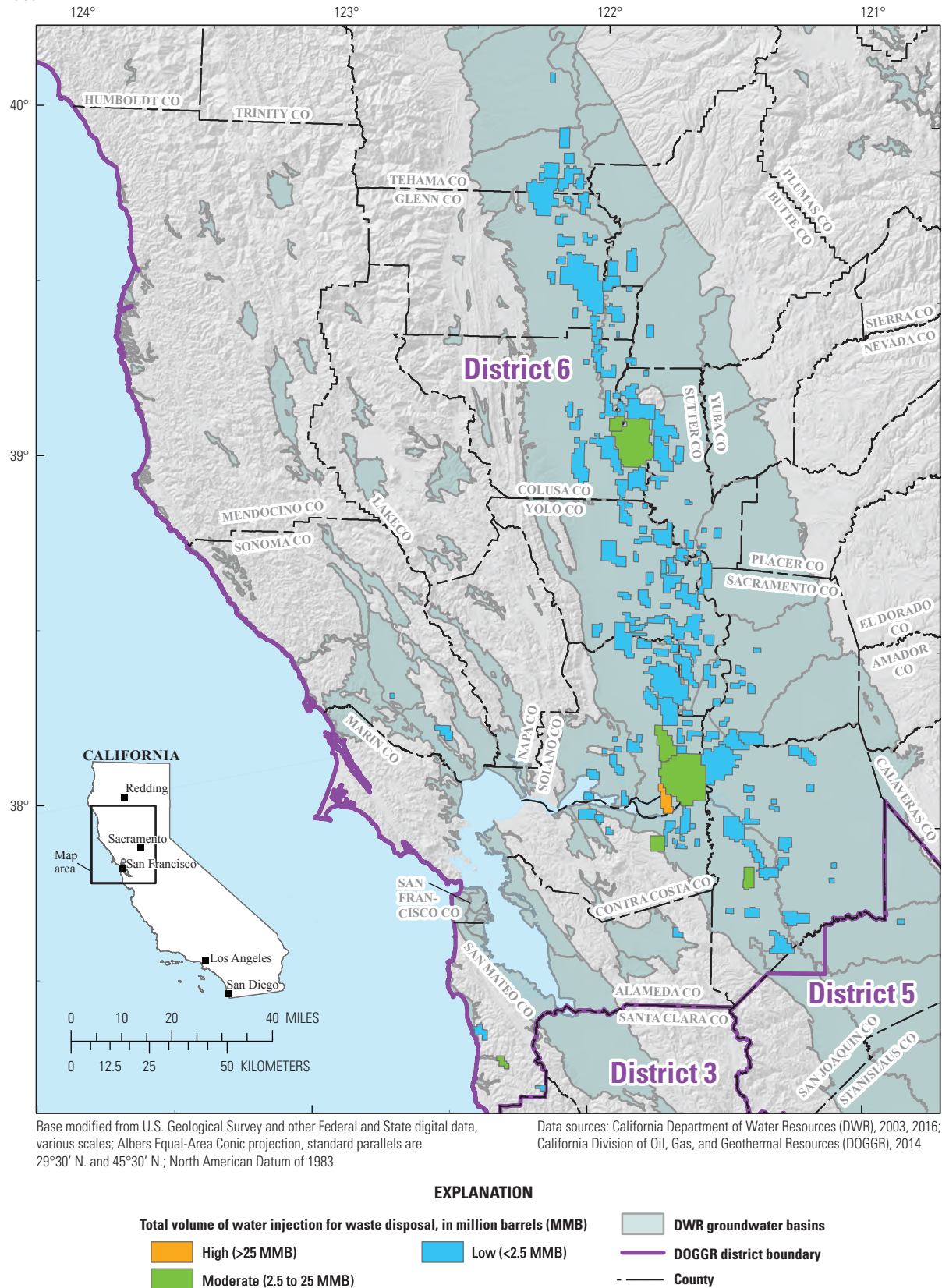


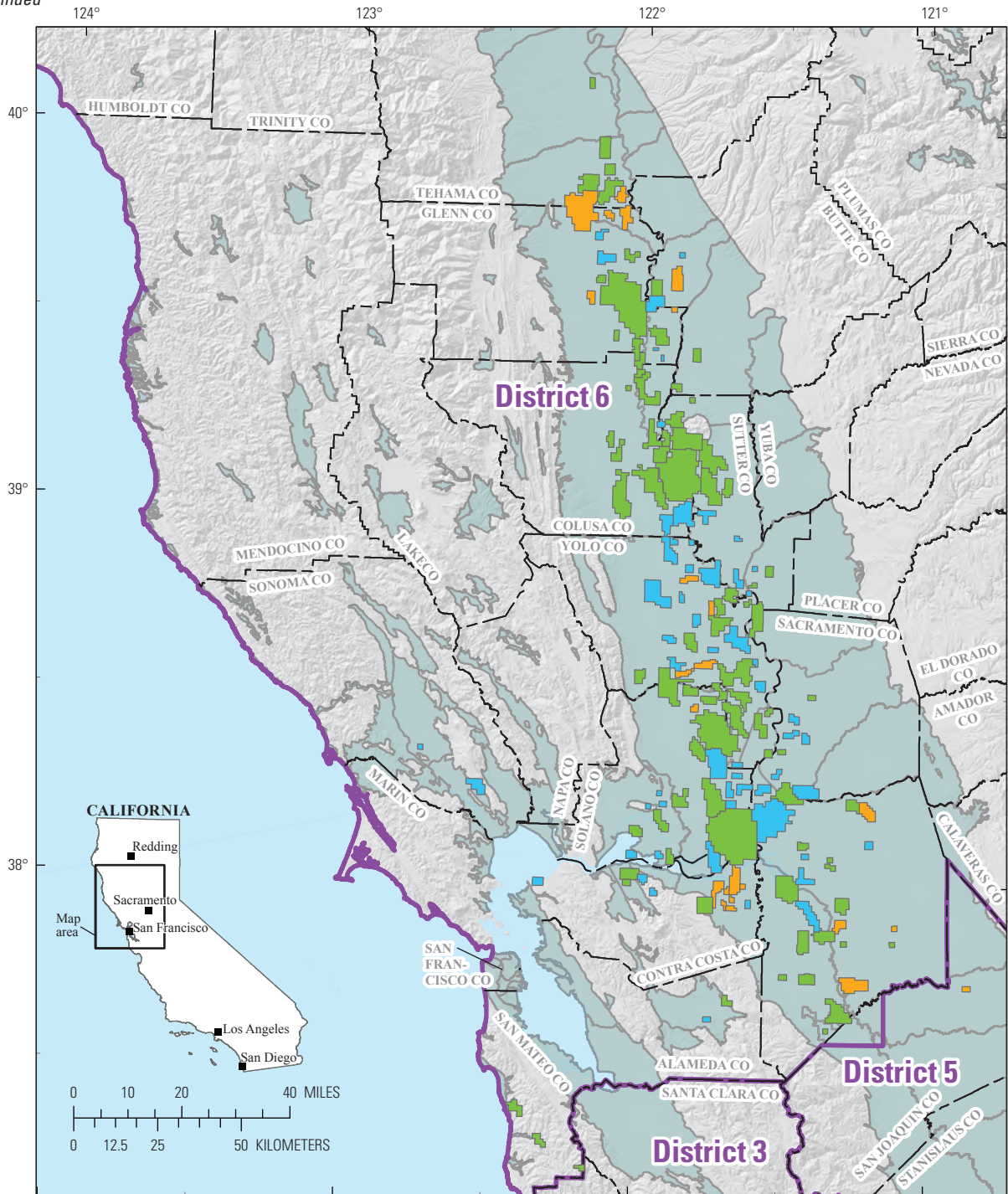
Figure 9. —Continued

F



Figure 9. —Continued

F—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 overlying the field, in wells per square mile (mi ²)	DWR groundwater basins
Orange: High (>8 wells/mi ²)	Blue: Low (<1 well/mi ²)
Green: Moderate (1 to 8 wells/mi ²)	Purple line: DOGGR district boundary
	Black line: County

Figure 9. —Continued

G

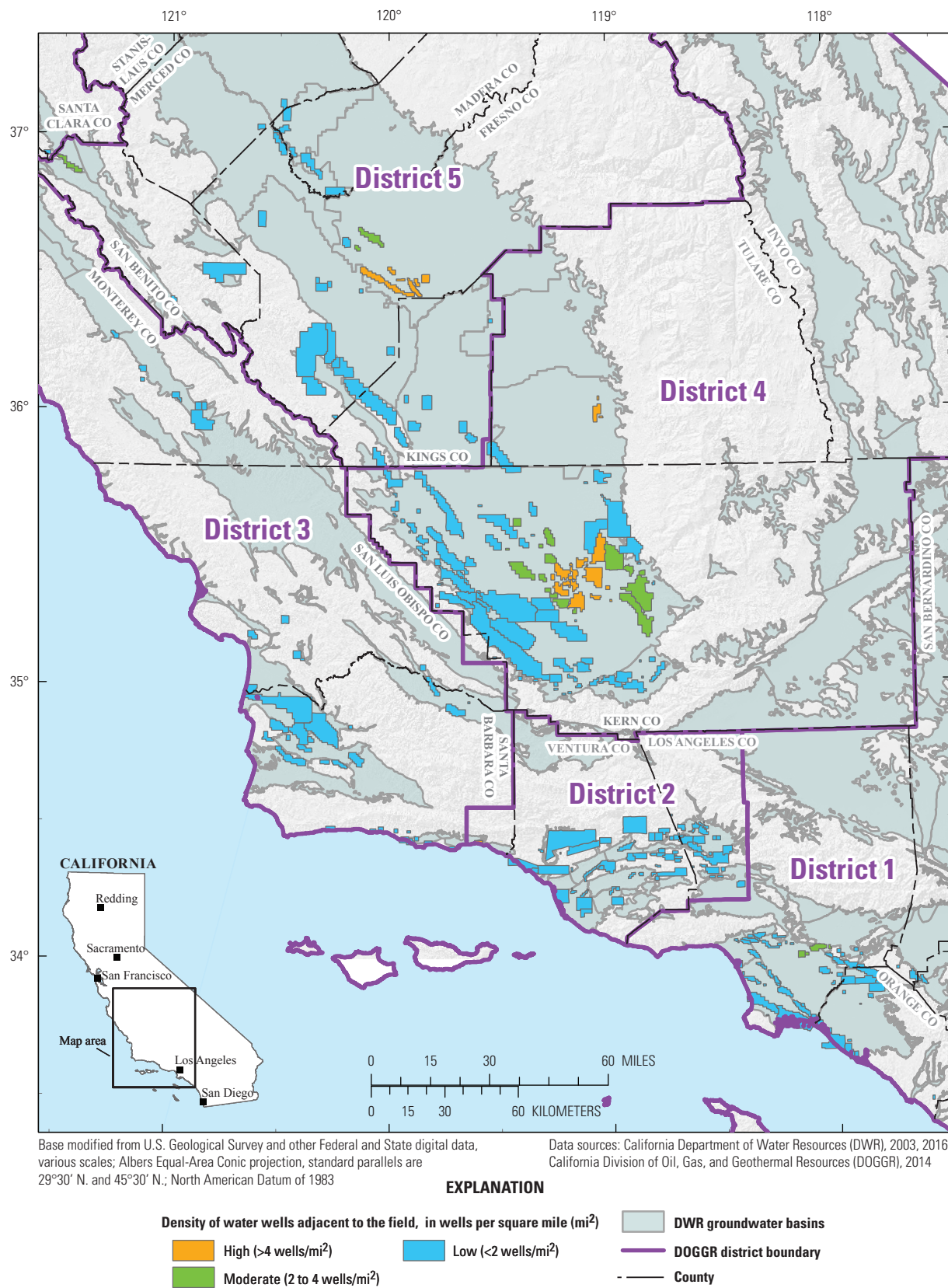
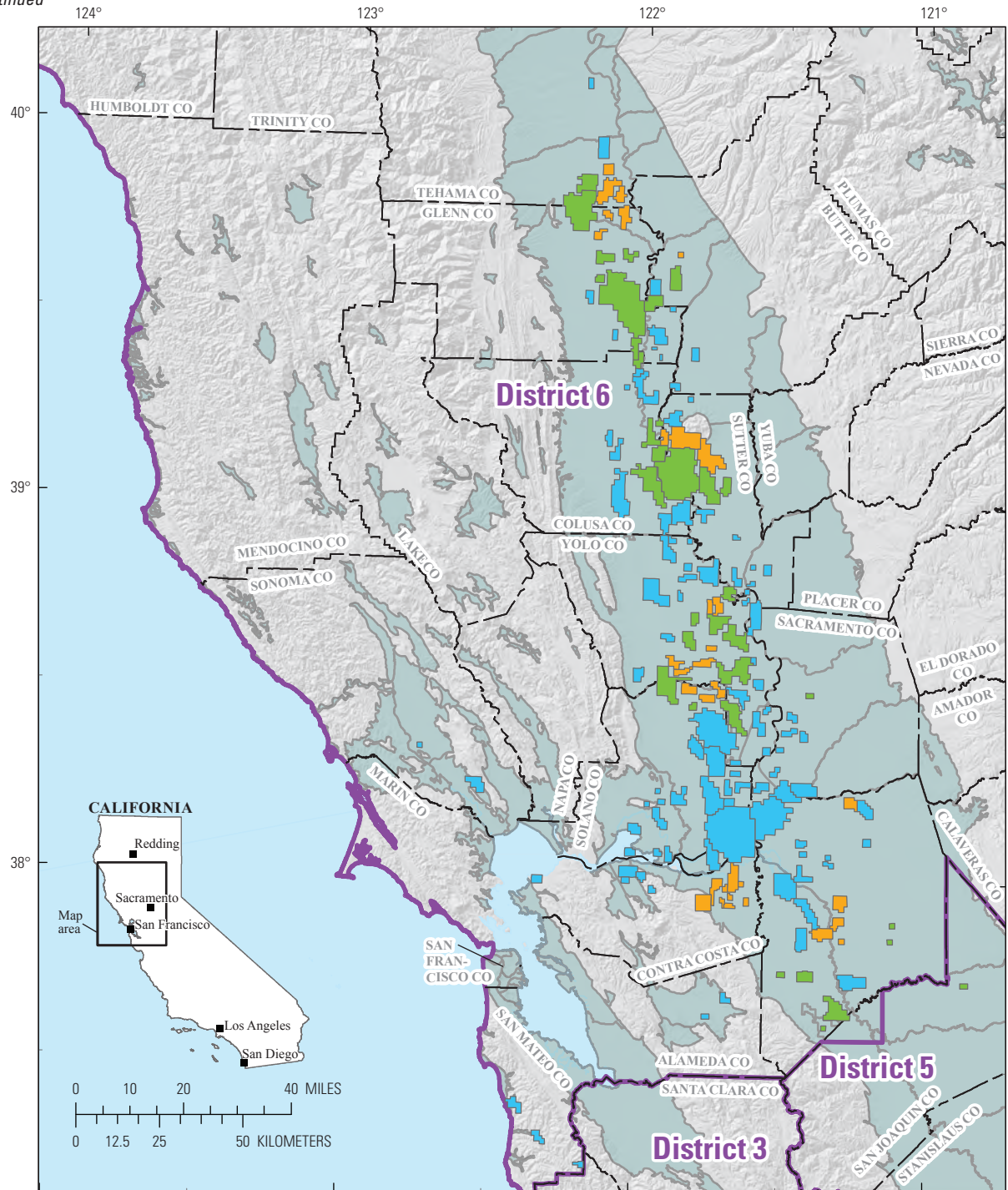


Figure 9. —Continued

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/mi ²)	Low (<2 wells/mi ²)
Moderate (2 to 4 wells/mi ²)	

DWR groundwater basins
DOGGR district boundary
County

Figure 9. —Continued

A

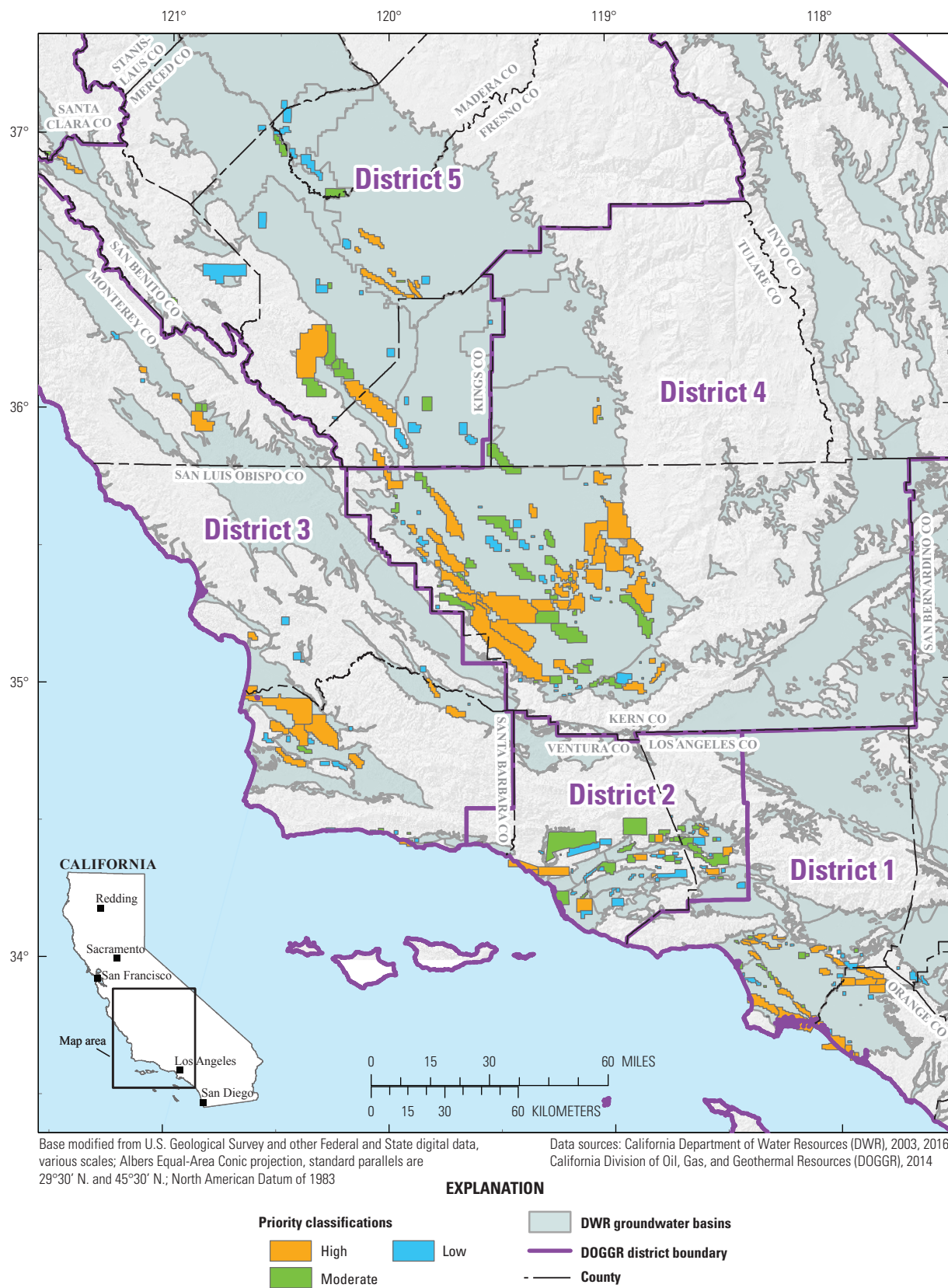


Figure 10. Overall priority classification for oil and gas fields in A, California Division of Oil, Gas, and Geothermal Resources (DOGGR) districts 1–5 and B, DOGGR district 6.

B

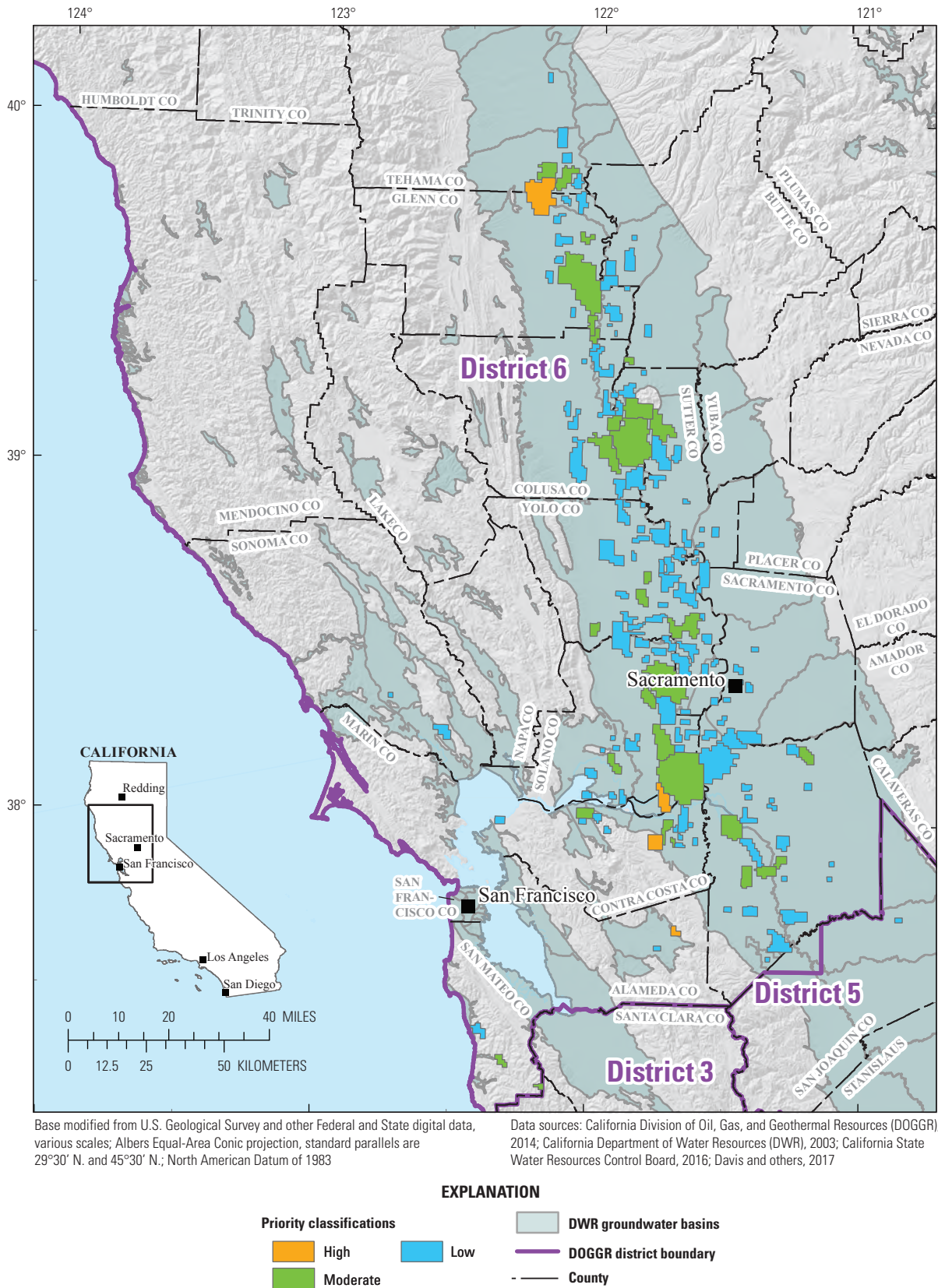


Figure 10. —Continued

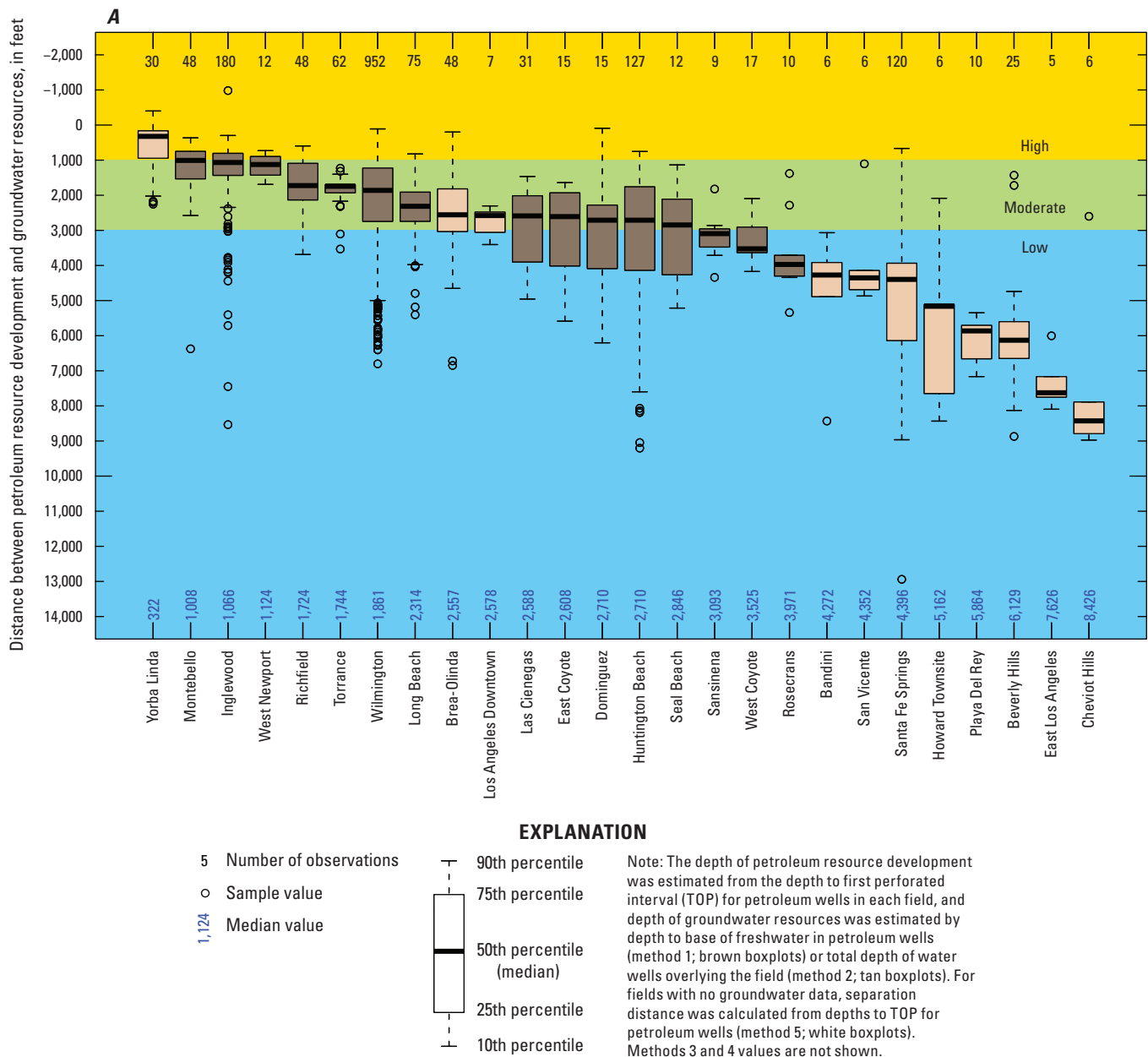


Figure 11. Vertical separation distance values calculated using a combination of methods for each oil and gas field with sufficient data by California Division of Oil, Gas, and Geothermal Resources (DOGGR) district: *A*, district 1; *B*, district 2; *C*, district 3; *D*, district 4; *E*, district 5;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

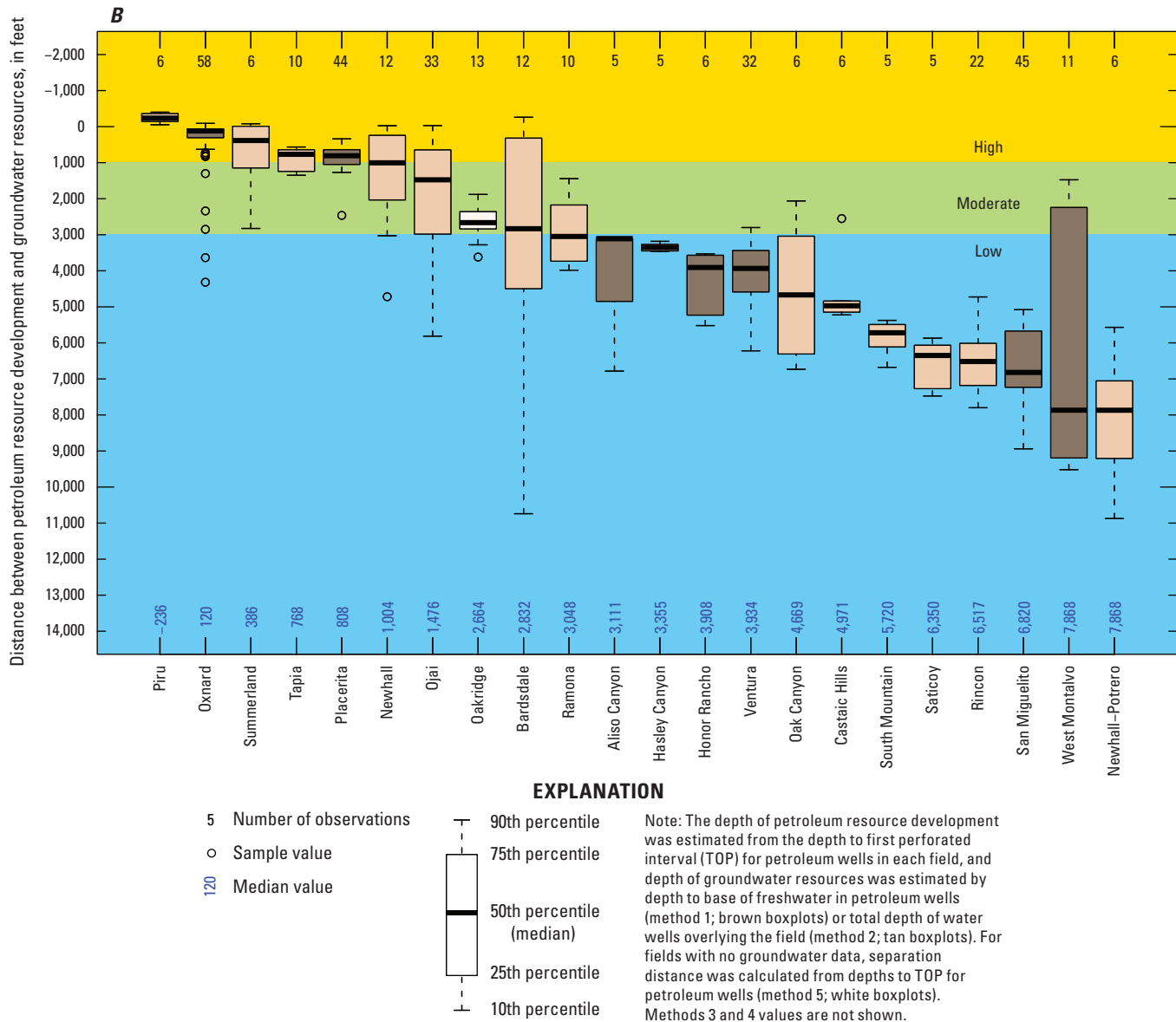


Figure 11. —Continued

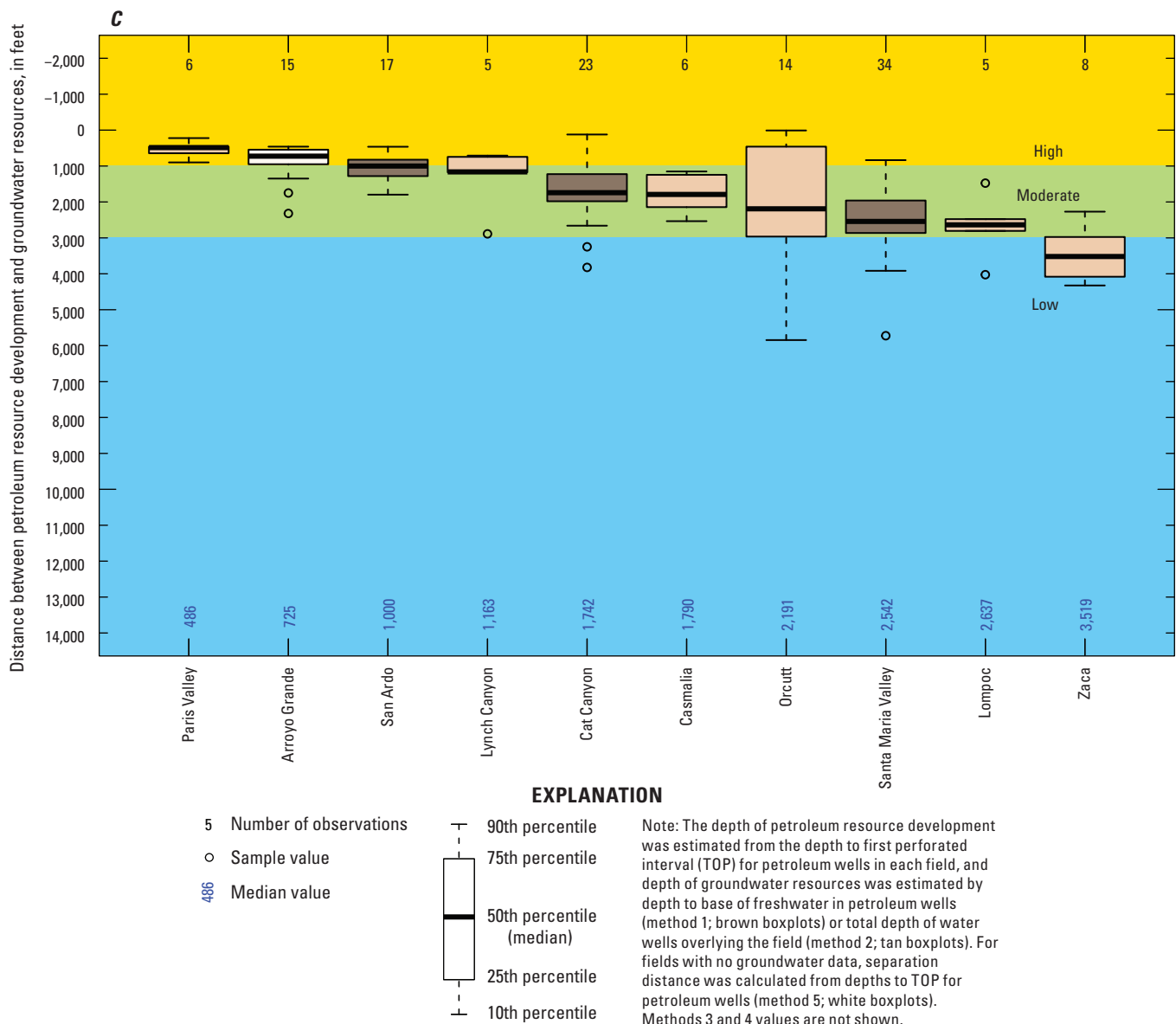


Figure 11. —Continued

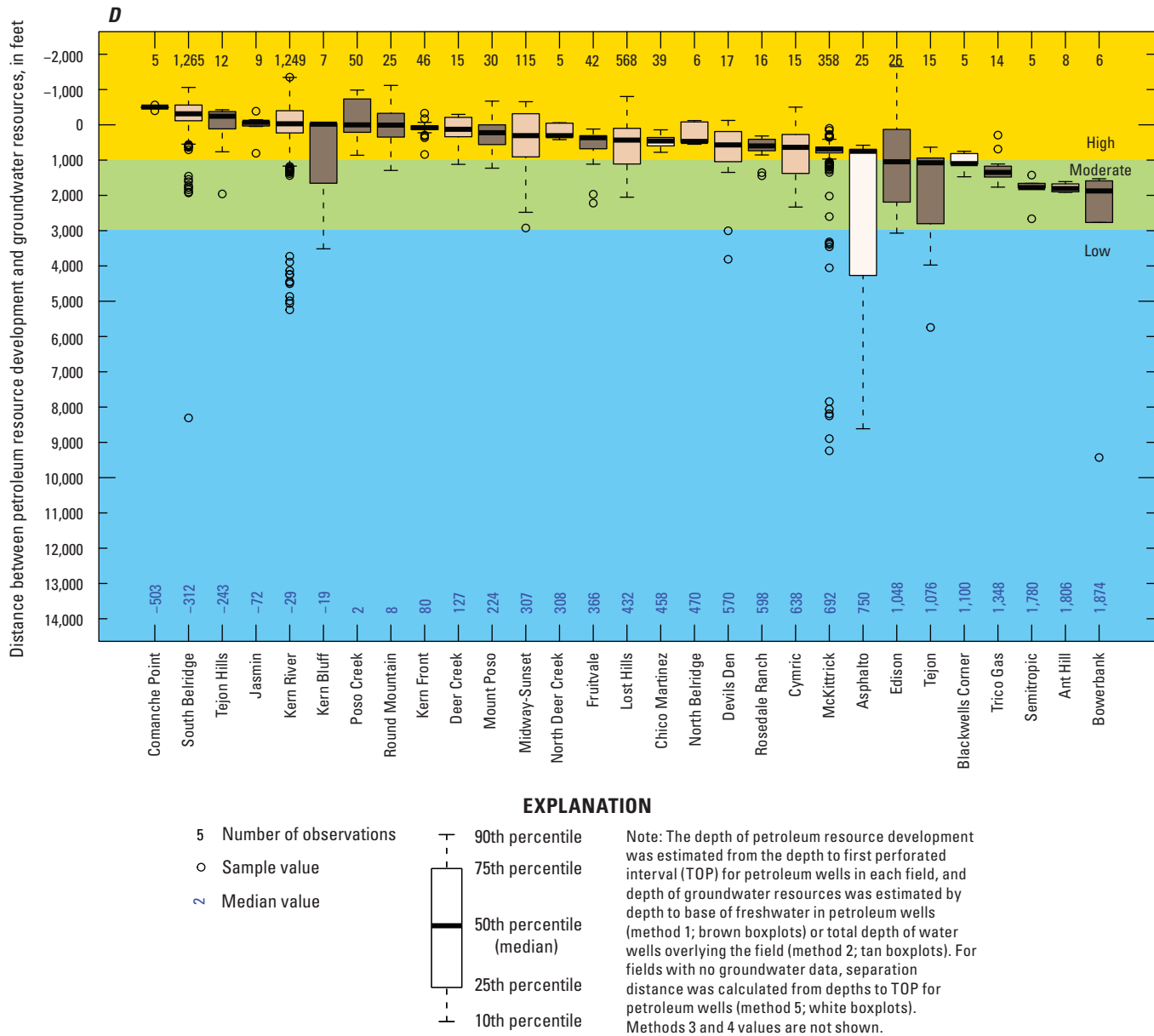


Figure 11. —Continued

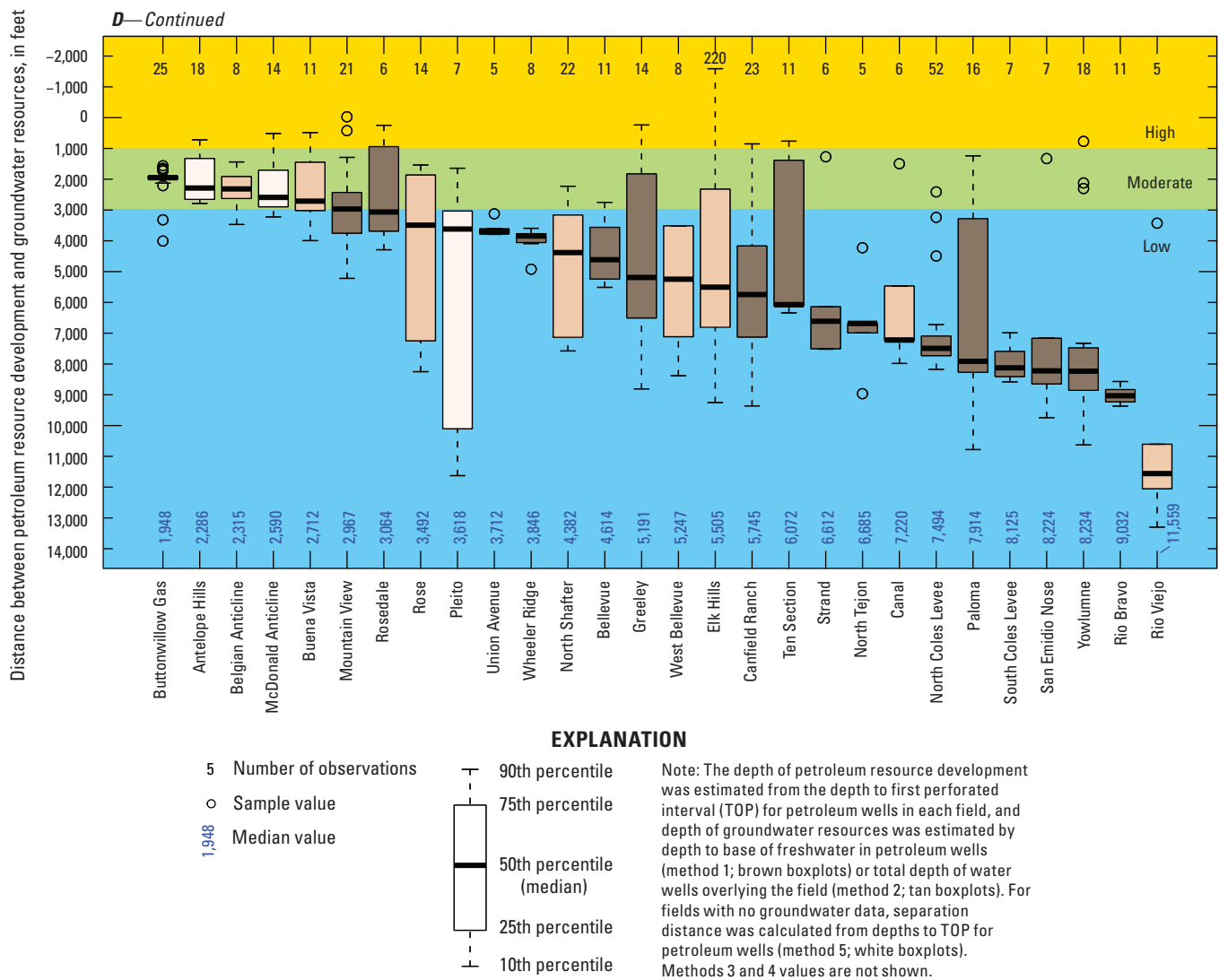


Figure 11. —Continued

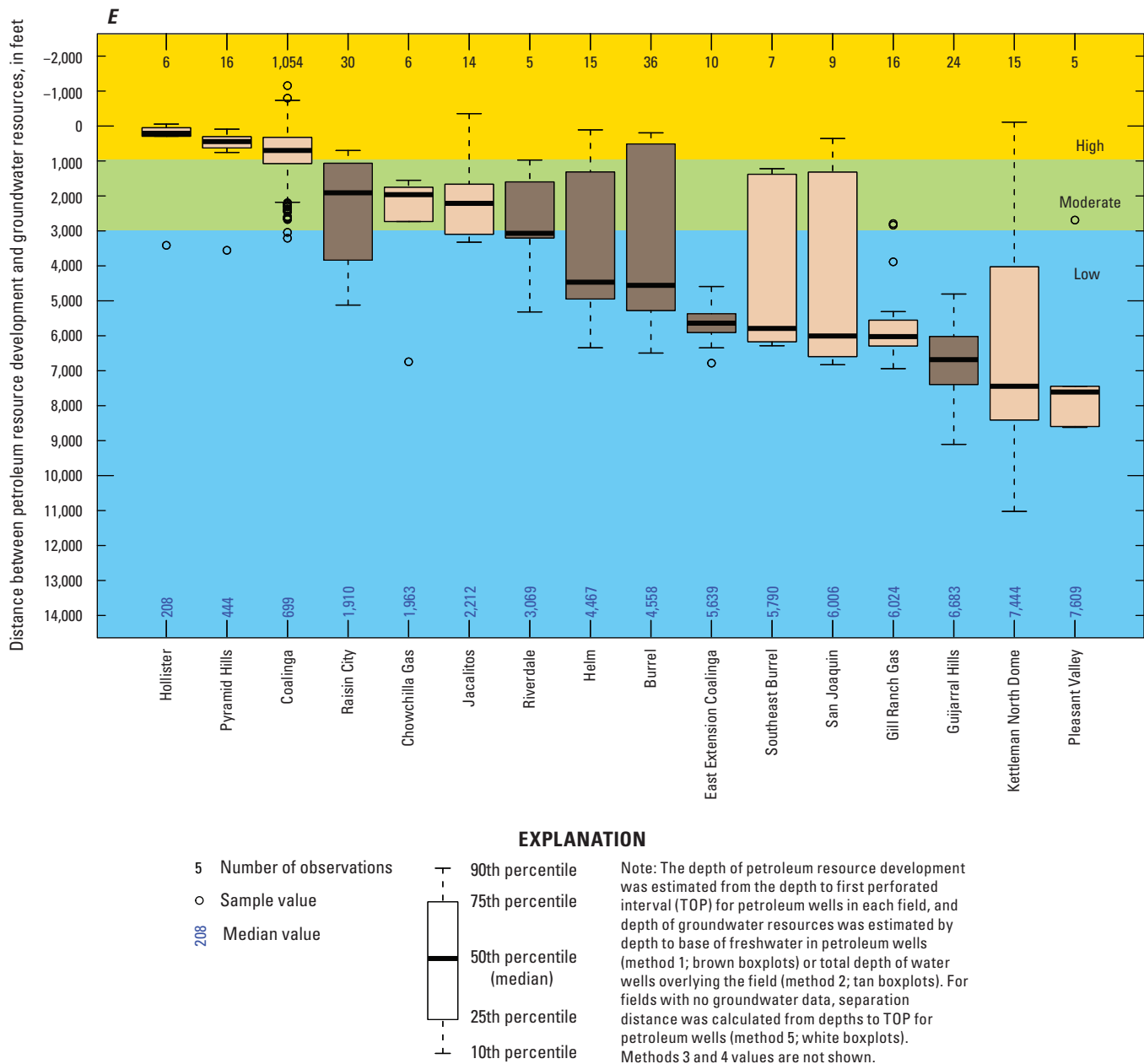


Figure 11. —Continued

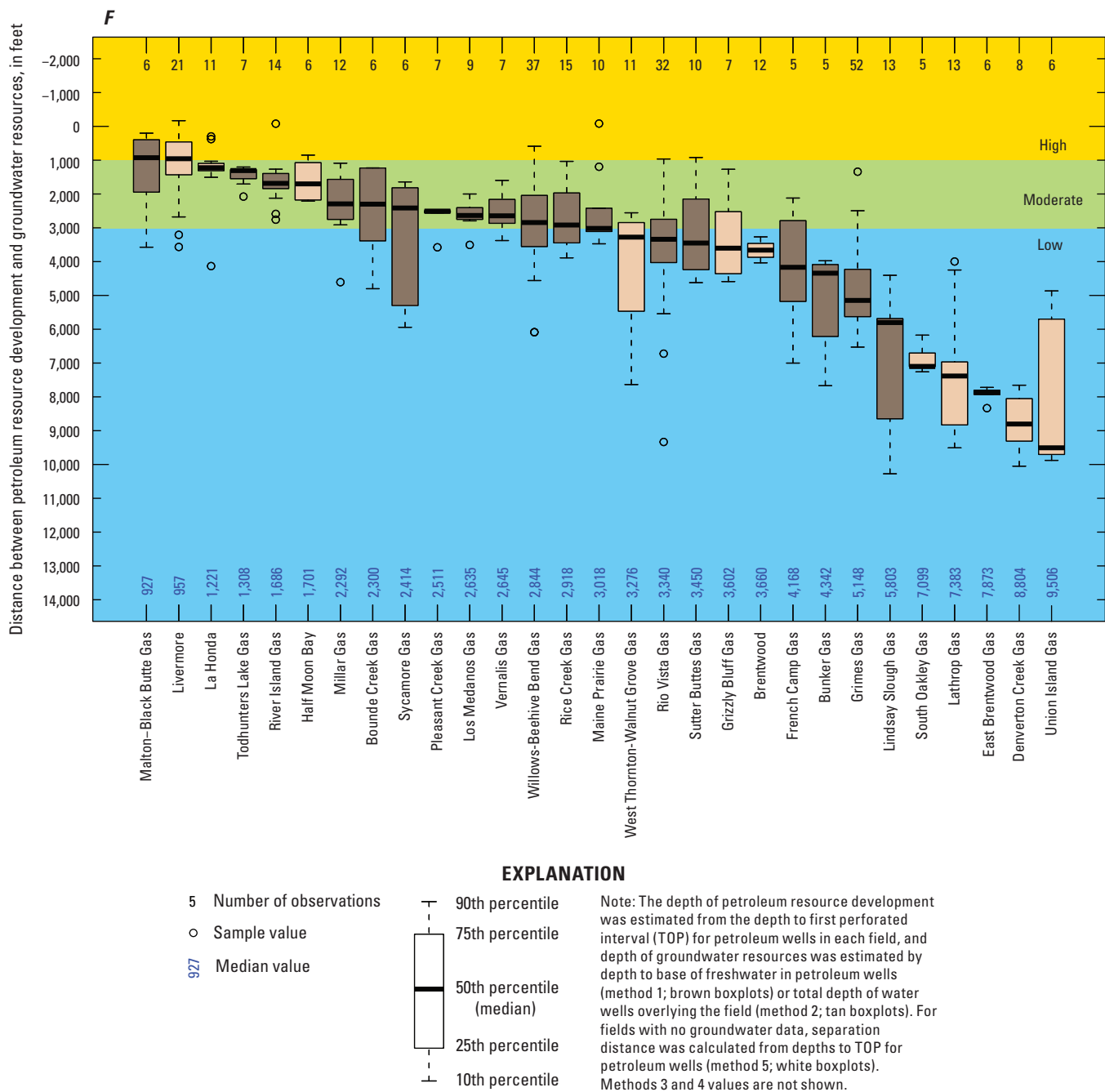


Figure 11. —Continued

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/mi² (San Miguelito field) and 11 wells/mi² (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)

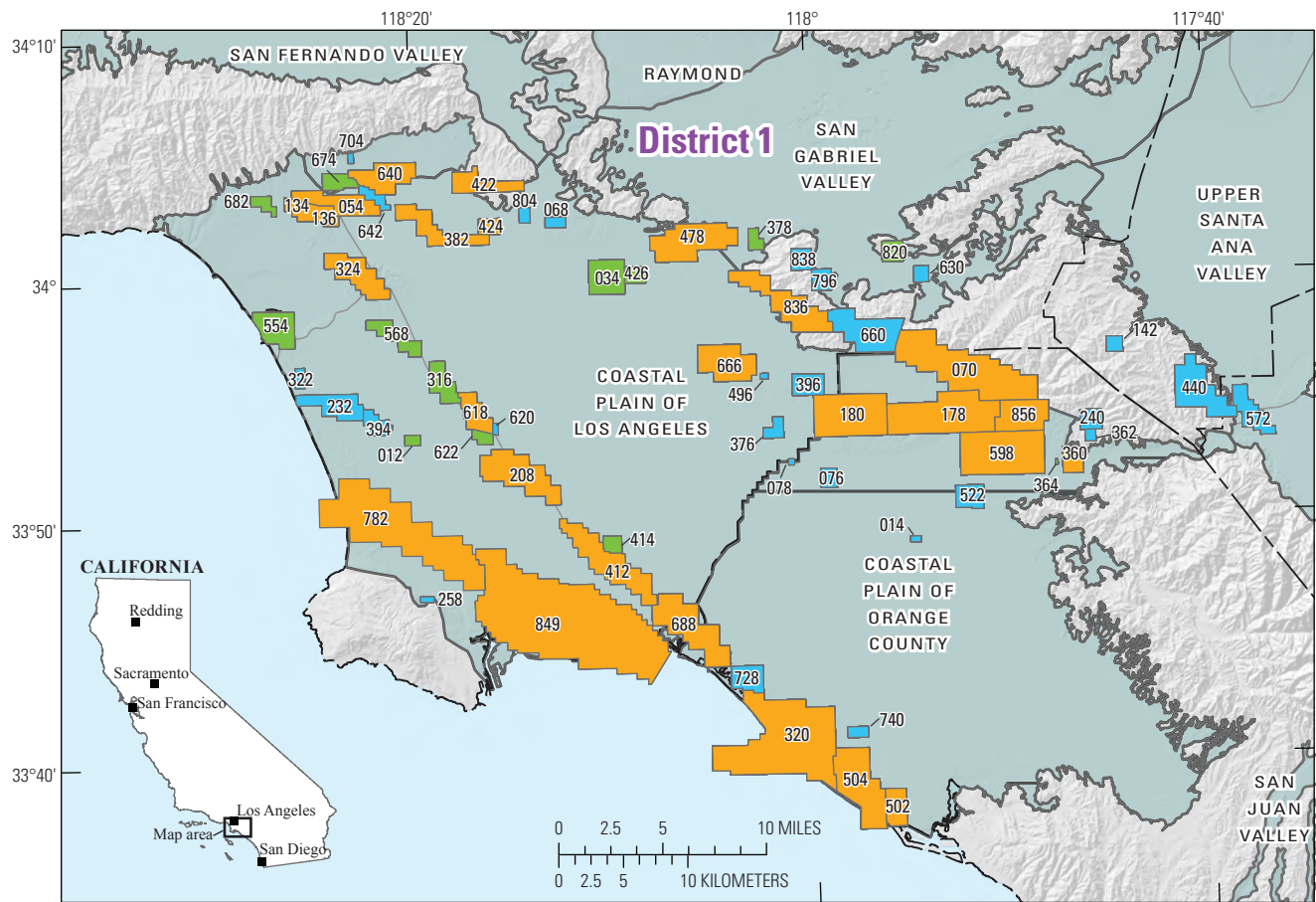
District 3 includes counties along the central coast of California from Santa Barbara to Santa Clara County (fig. 10A). The 39 fields in the district have an aggregated field area of 264 mi² (table 5). There were about 12,600 DOGGR oil and gas wells in the district, including 11,000 production wells 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 mi²) that is greater than the 67 fields in district 1 (214 mi²). 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 mi²) 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 mi²) 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

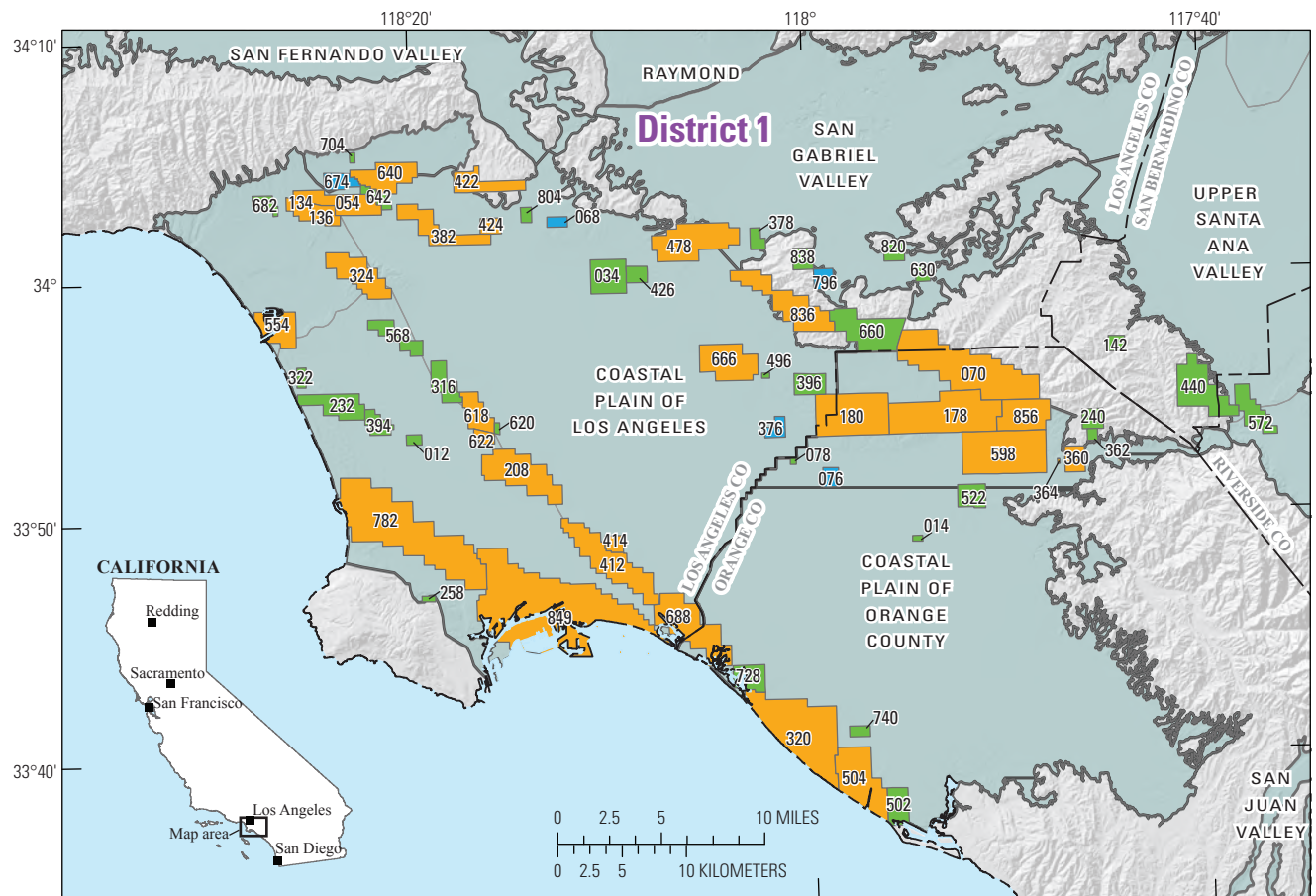
Numbers in priority classifications indicate the field codes

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



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

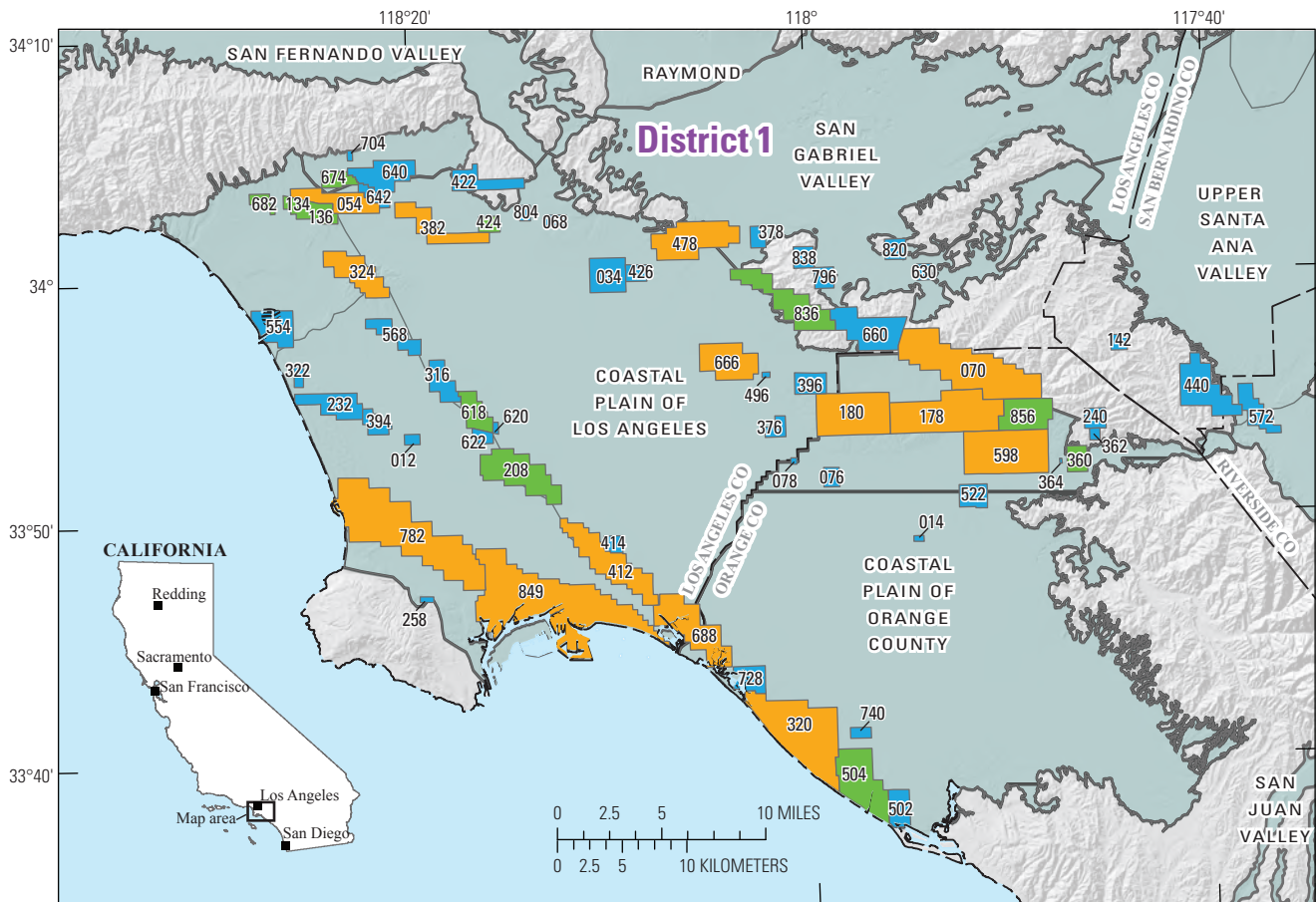
DWR groundwater subbasins

County

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				 DWR groundwater basins			
 High  Moderate  Low				 DWR groundwater subbasins			
Numbers in volume of injection classifications indicate the field codes				 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

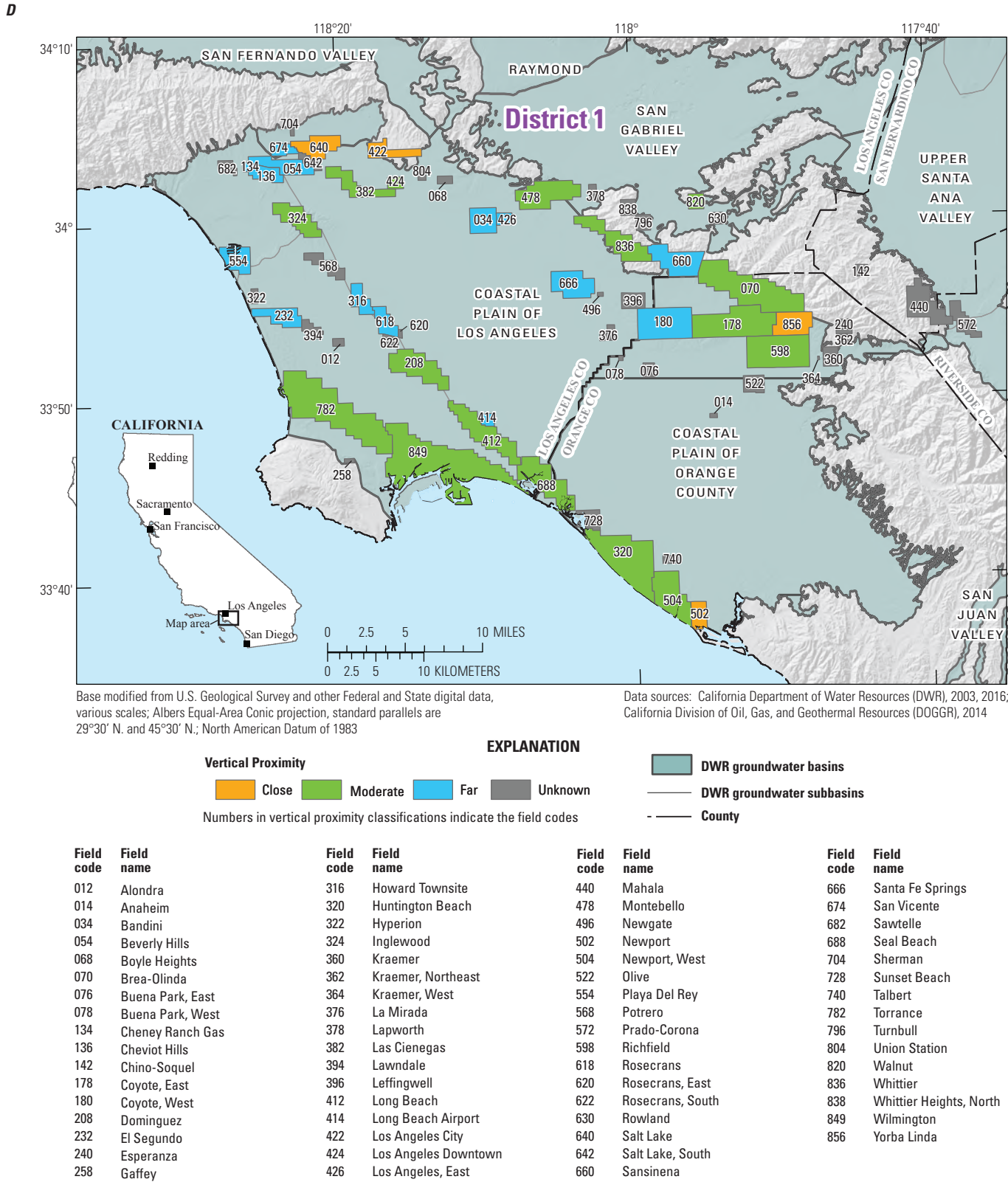
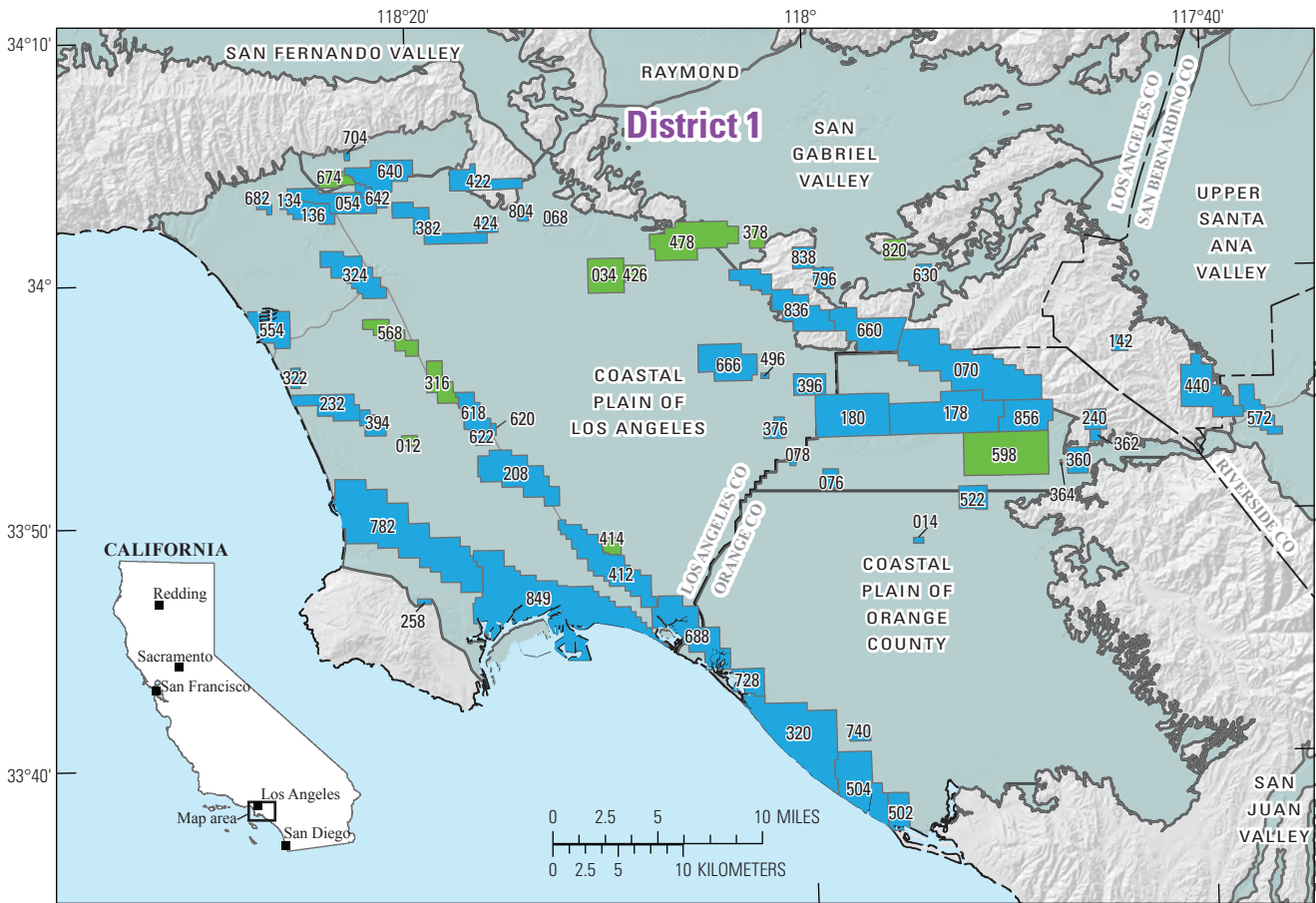


Figure 12. —Continued

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







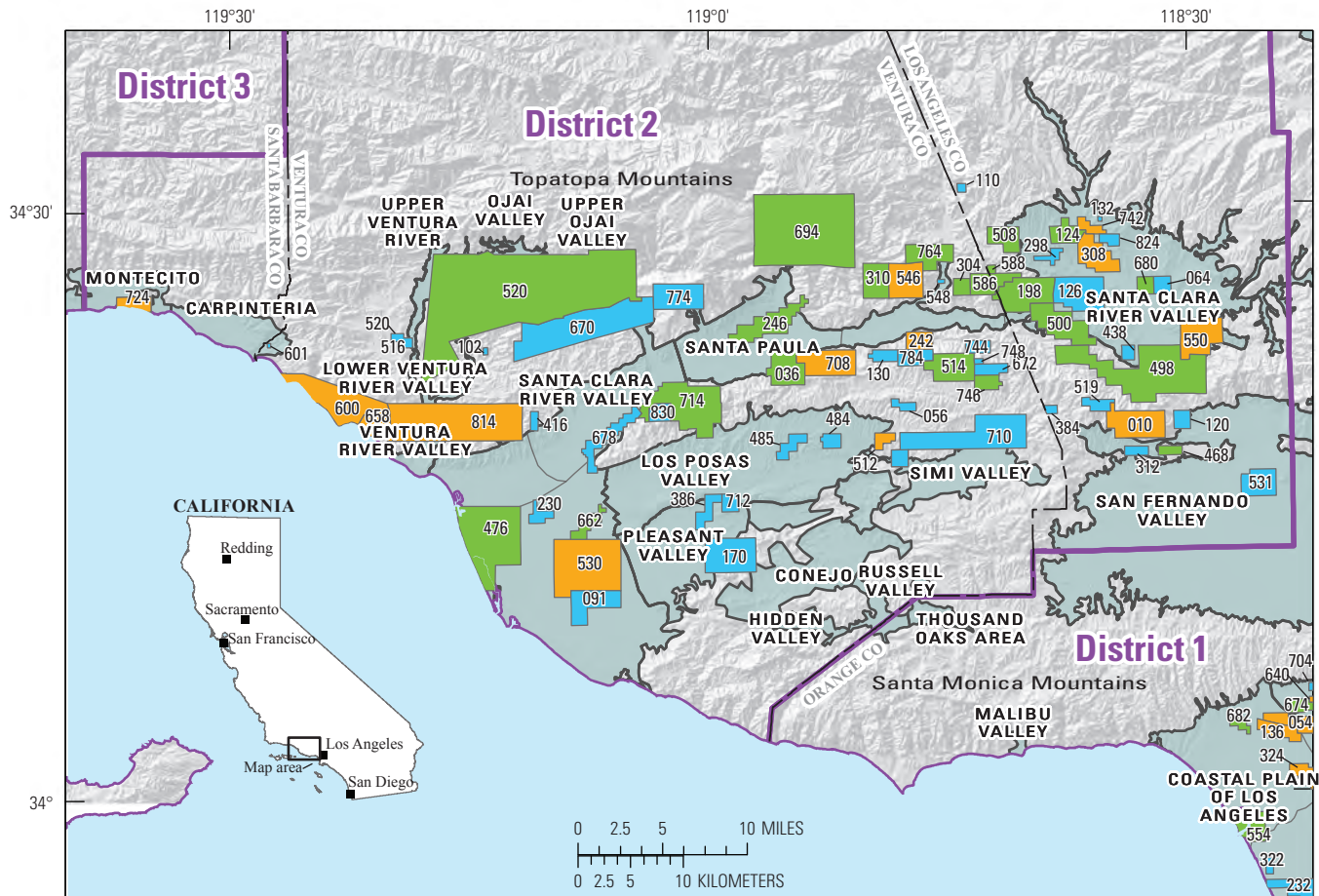
EXPLANATION							
Water-well density				 DWR groundwater basins			
 High  Moderate  Low				 DWR groundwater subbasins			
Numbers in water-well density classifications indicate the field codes				-  County			
Field code	Field name	Field code	Field name	Field code	Field name	Field code	Field name
012	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



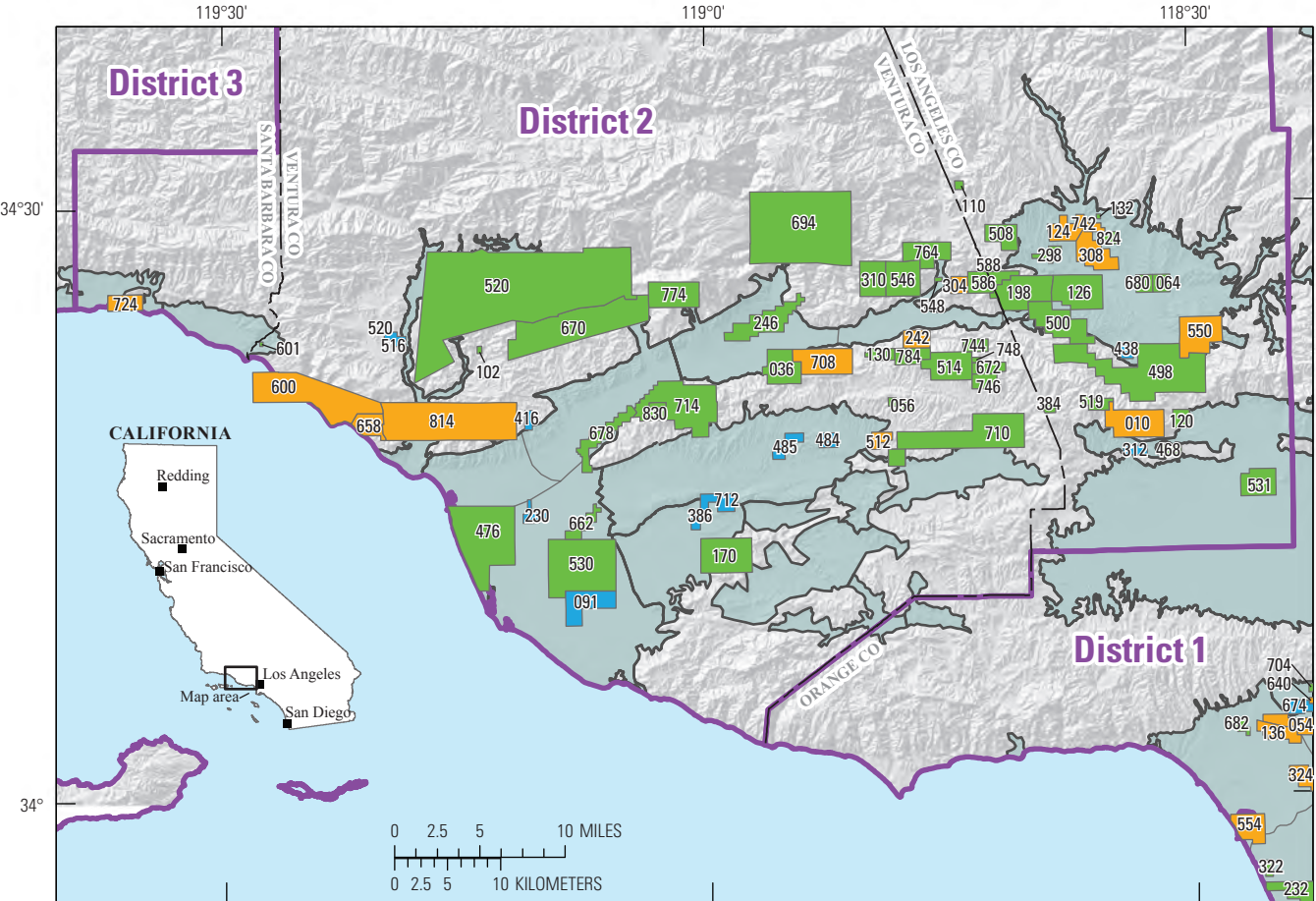
Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

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

Priority classifications				EXPLANATION			
<div><div></div> High</div> <div><div></div> Moderate</div> <div><div></div> Low</div>				<div></div> DWR groundwater basins	- County		
Numbers in priority classifications indicate the field codes				<div></div> DWR groundwater subbasins	<div></div> 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 Lajas	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.

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' 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

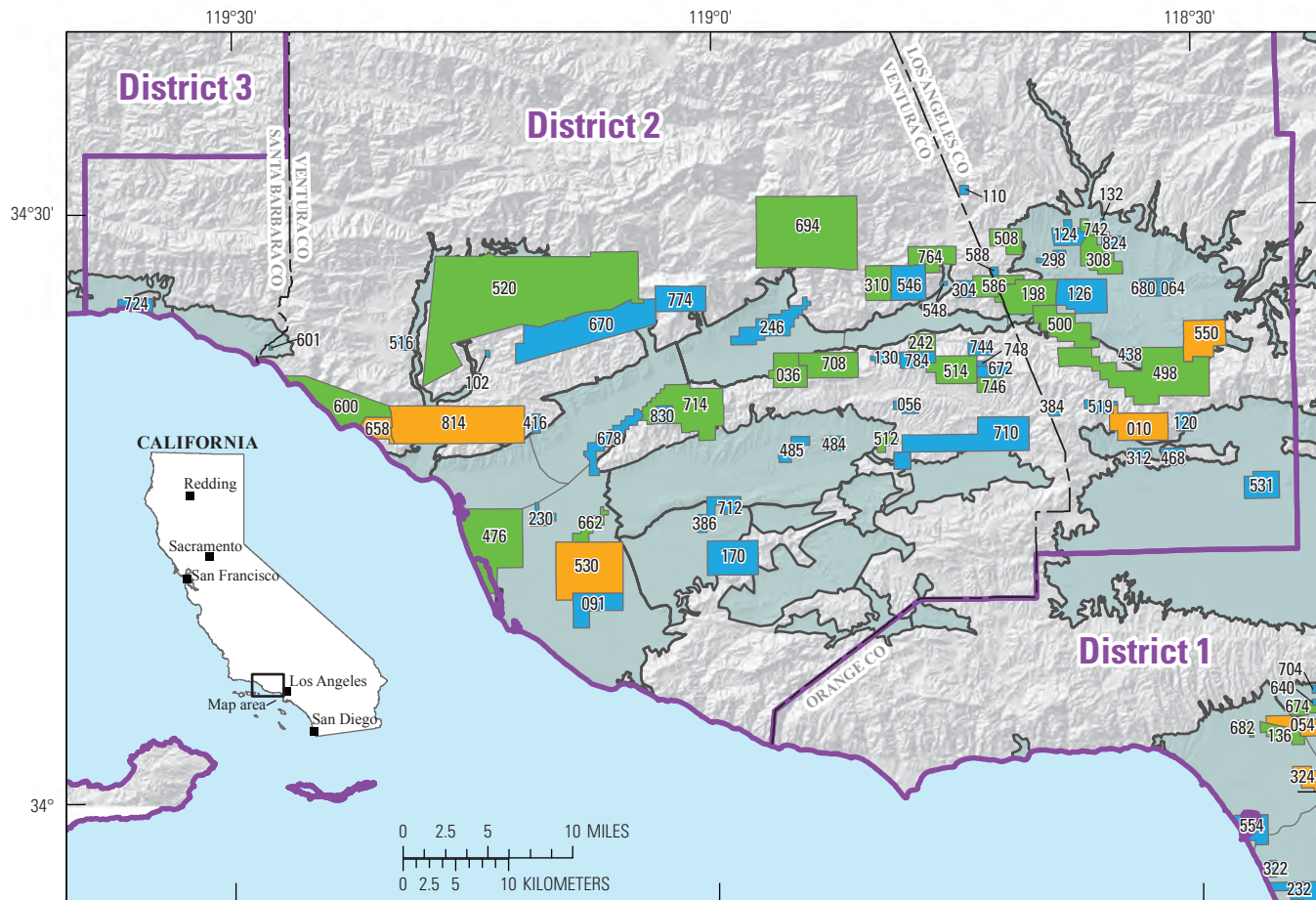
EXPLANATION

- Petroleum-well density**
- High (orange)
 - Moderate (green)
 - Low (blue)
- Numbers in petroleum-well density classifications indicate the field codes
- DWR groundwater basins** (light blue)
- DWR groundwater subbasins** (light green)
- County** (dashed line)
- DOGGR district boundary** (thick purple line)

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 Lajas	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

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

Field codes

010

036

054

056

064

091

102

110

120

124

126

130

132

136

170

198

230

232

242

246

Field names

Aliso Canyon

Bardsdale

Beverly Hills

Big Mountain

Bouquet Canyon

Cabrillo

Canada Larga

Canton Creek

Cascade

Castaic Hills

Castaic Junction

Chaffee Canyon

Charlie Canyon

Cheviot Hills

Conejo

Del Valle

El Rio

El Segundo

Eureka Canyon

Fillmore

Field codes

298

304

308

310

312

322

324

384

386

416

438

468

476

484

485

498

500

508

512

514

Field names

Hasley Canyon

Holser

Honor Rancho

Hopper Canyon

Horse Meadows

Hyperion

Inglewood

Las Lajas

Las Posas

Long Canyon

Lyon Canyon

Mission

Montalvo, West

Moorpark

Moorpark West

Newhall

Newhall-Potrero

Oak Canyon

Oak Park

Oakridge

Field codes

516

519

520

530

531

546

548

550

554

586

588

600

601

640

658

662

670

672

674

678

Field names

Oakview

Oat Mountain

Ojai

Oxnard

Pacoima

Piru

Piru Creek

Placerita

Playa Del Rey

Ramona

Ramona, North

Rincon

Rincon Creek

Salt Lake

San Miguelito

Santa Clara Avenue

Santa Paula

Santa Susana

San Vicente

Saticoy

Field codes

680

682

694

704

708

710

712

714

724

742

744

746

748

764

774

784

814

824

830

Field names

Saugus

Sawtelle

Sespe

Sherman

Shiells Canyon

Simi

Somis

South Mountain

Summerland

Tapia

Tapo, North

Tapo Canyon, South

Tapo Ridge

Temescal

Timber Canyon

Torrey Canyon

Ventura

Wayside Canyon

West Mountain

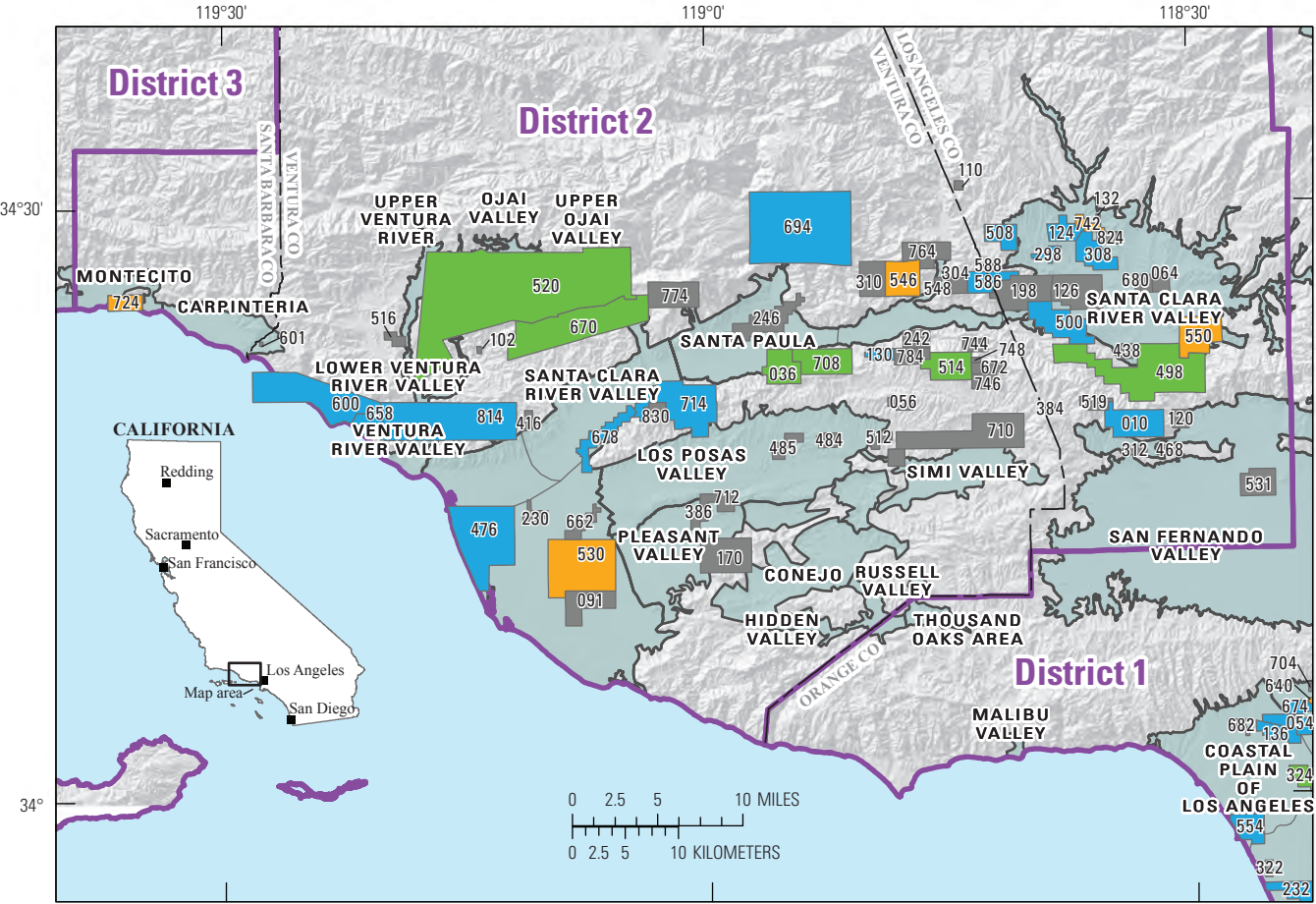
Numbers in injection classifications indicate the field codes

Legend:

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

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 Lajas	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

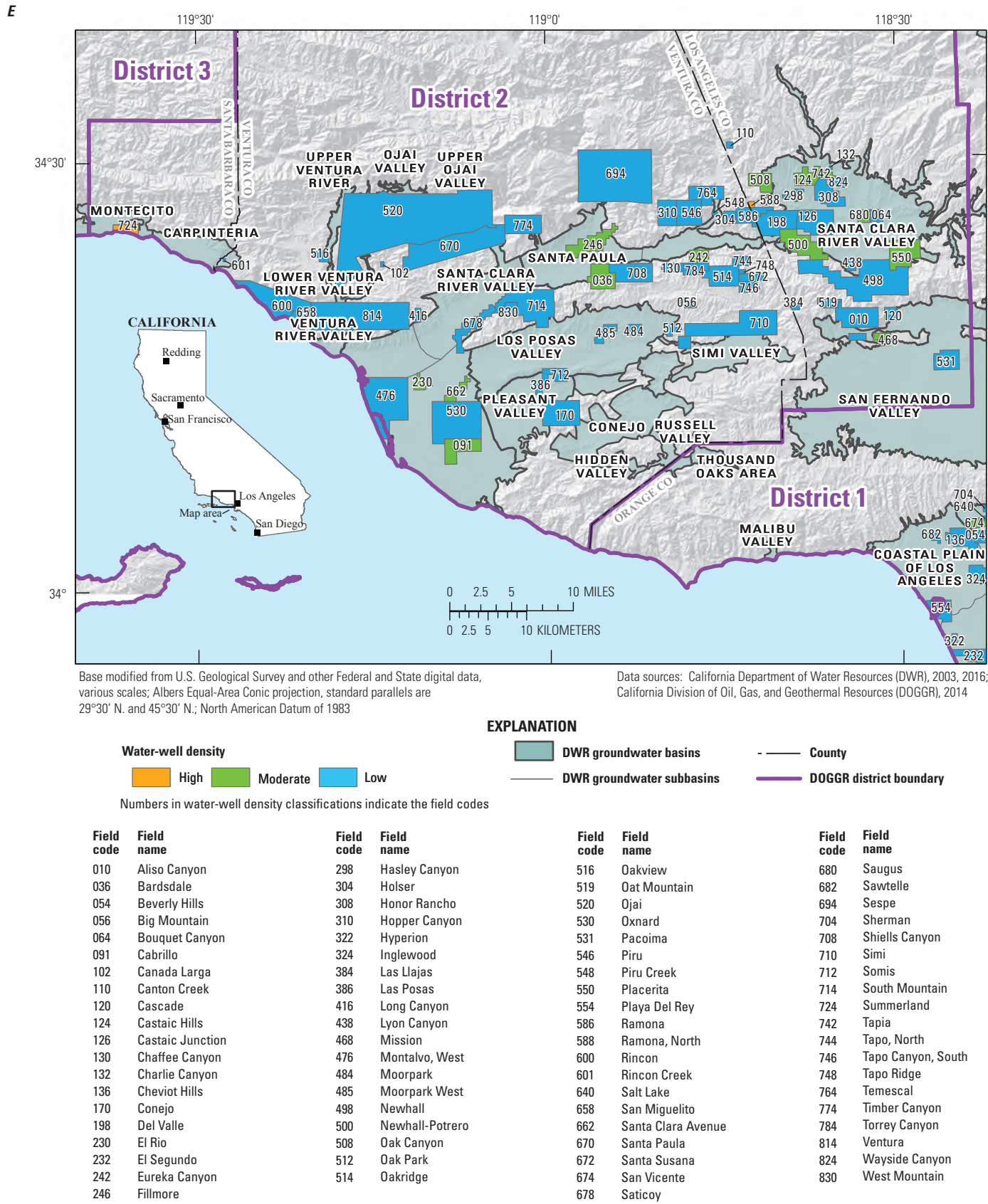
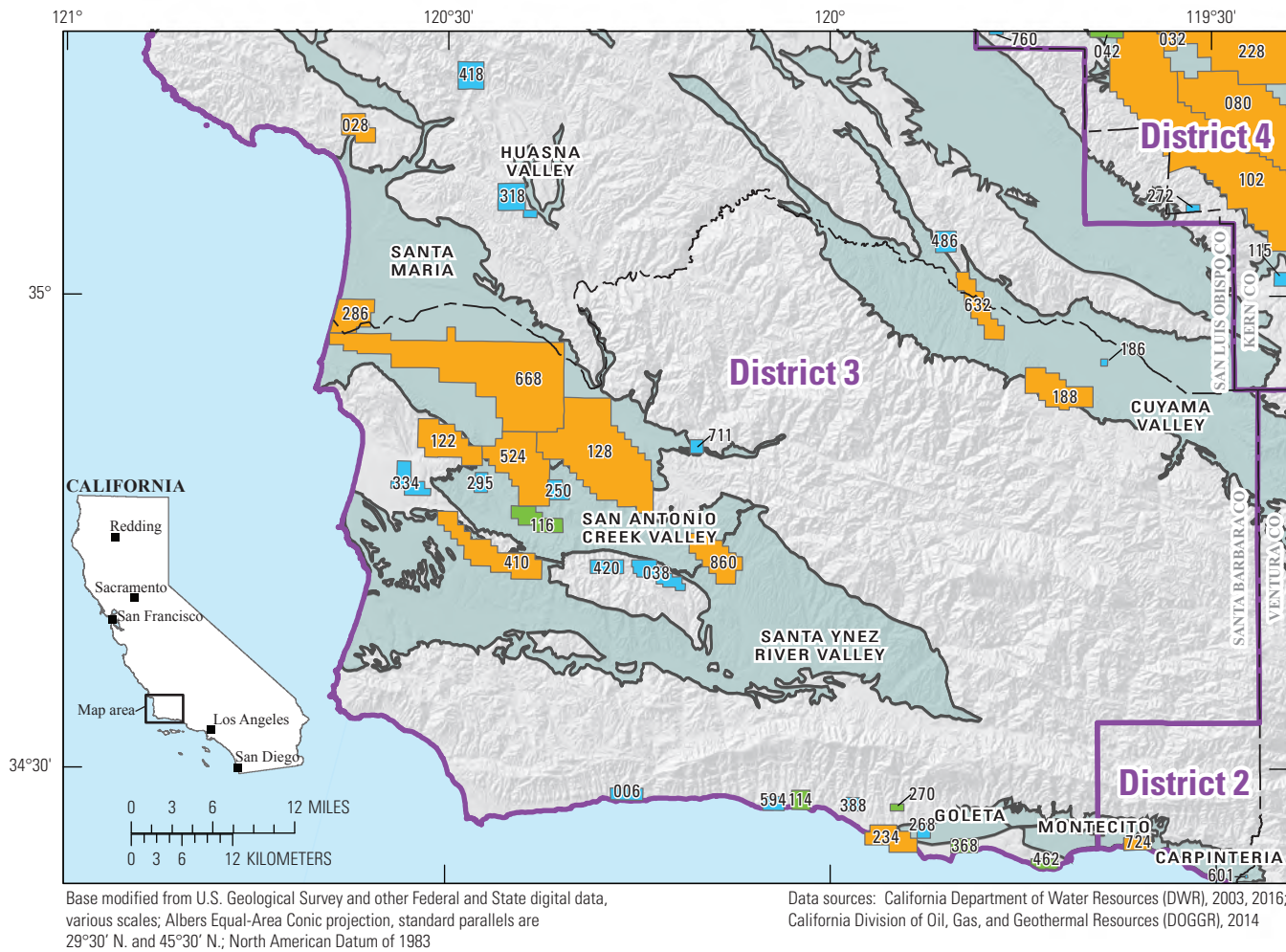


Figure 13. —Continued

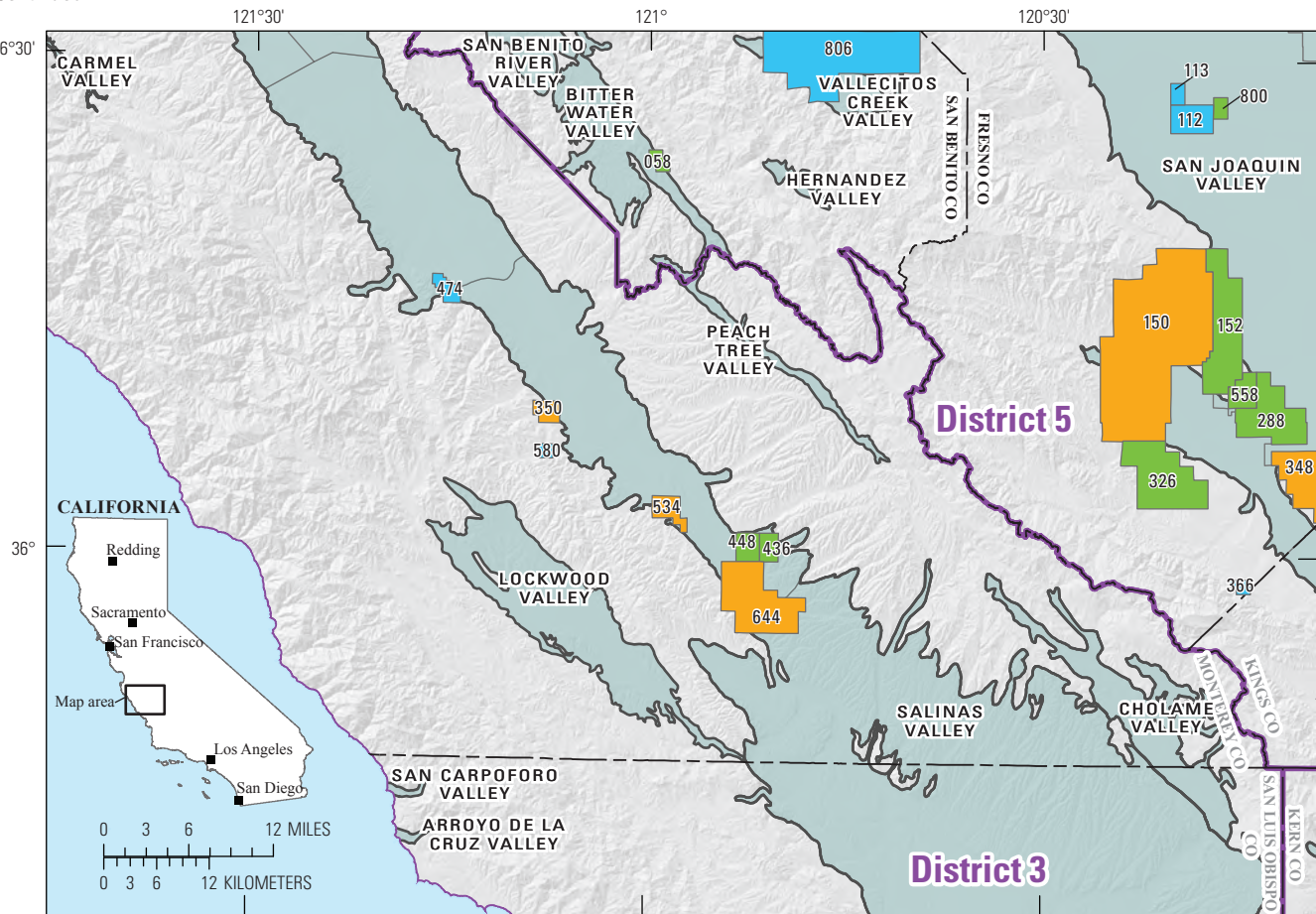
A



Priority classifications				EXPLANATION			
High		Moderate	Low	DWR groundwater basins	County		
Numbers in priority classifications indicate the field codes				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			
<div>High</div> <div>Moderate</div> <div>Low</div>			
Numbers in priority classifications indicate the field codes			
<div>DWR groundwater basins</div>	<div>County</div>	<div>DWR groundwater subbasins</div>	<div>DOGGR district boundary</div>
Field code	Field name	Field code	Field name
058	Bitterwater	288	Guijarral Hills
112	Cantua Creek	326	Jacalitos
113	Cantua Nueva	348	Kettleman North Dome
150	Coalinga	350	King City
152	Coalinga, East Extension	366	Kreyenhagen
		436	Lynch Canyon
		448	Merritt Gas
		474	Monroe Swell
		534	Paris Valley
		558	Pleasant Valley
		580	Quinada Canyon
		644	San Ardo
		800	Turk Anticline
		806	Vallecitos

Figure 14. —Continued

B

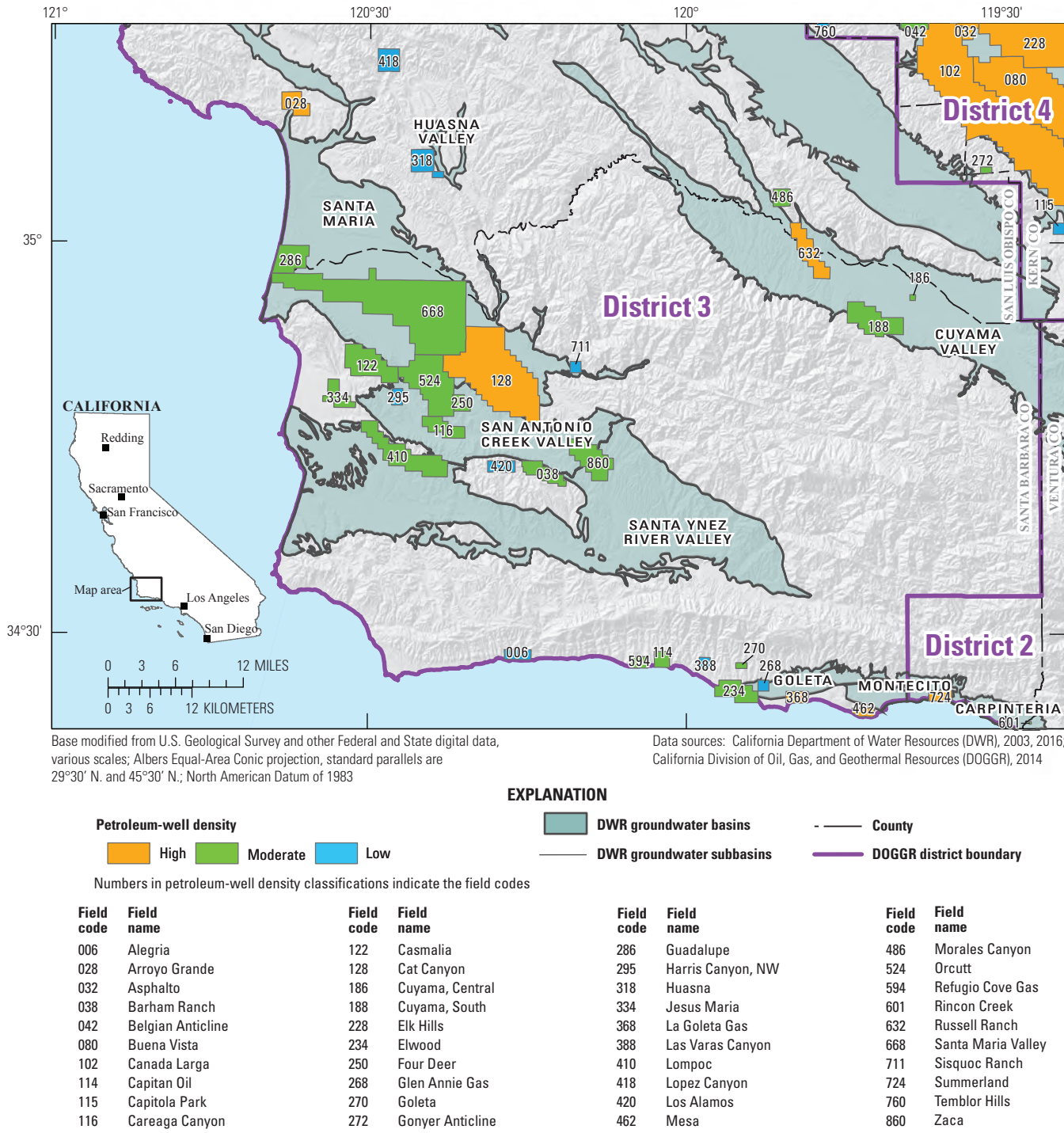
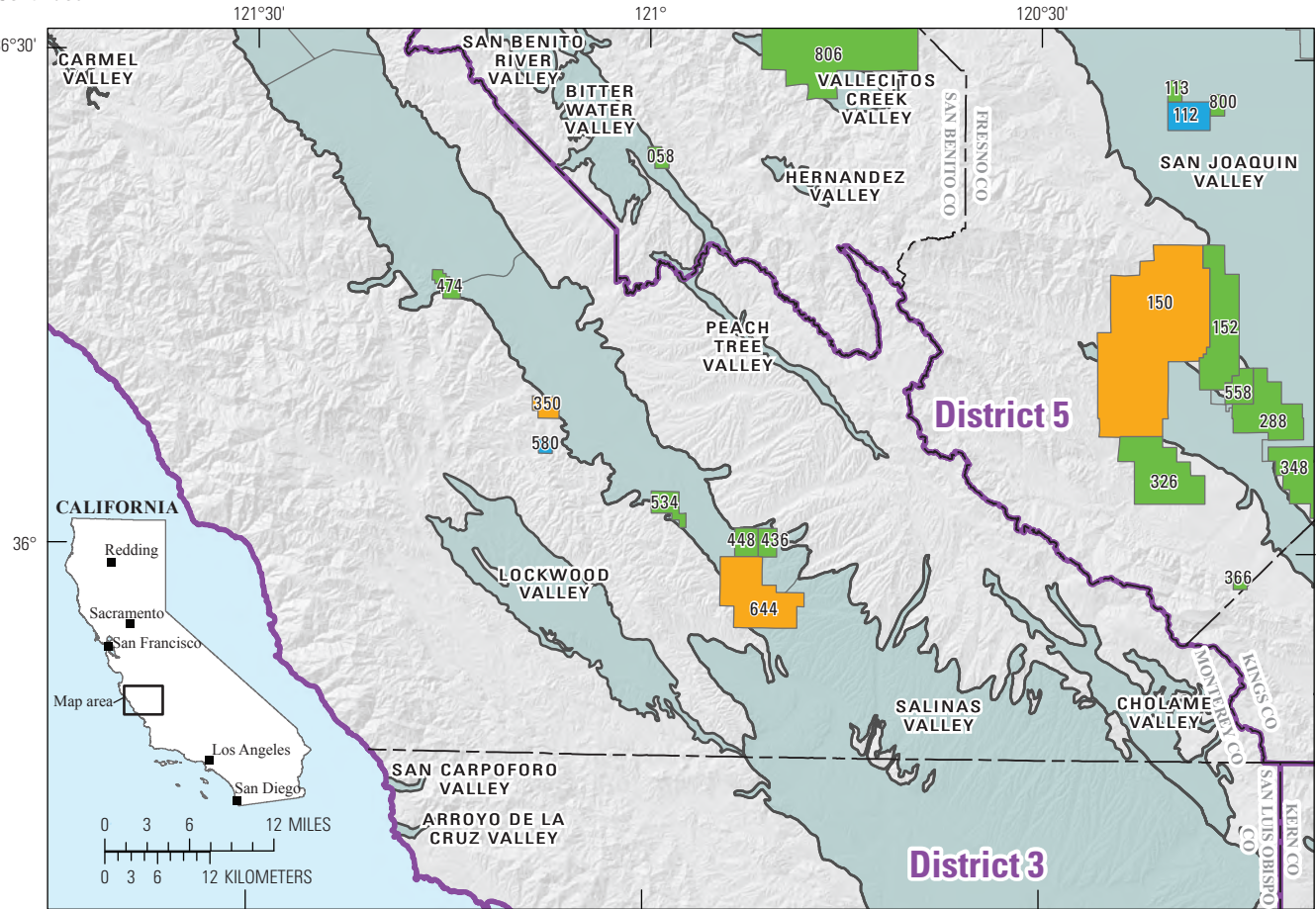


Figure 14. —Continued

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			
Numbers in petroleum-well density classifications indicate the field codes			
Field code	Field name	Field code	Field name
058	Bitterwater	288	Guajarral Hills
112	Cantua Creek	326	Jacalitos
113	Cantua Nueva	348	Kettleman North Dome
150	Coalinga	350	King City
152	Coalinga, East Extension	366	Kreyenhagen
Field code	Field name	Field code	Field name
436	Lynch Canyon	580	Quinada Canyon
448	McCool Ranch	644	San Ardo
474	Monroe Swell	800	Turk Anticline
534	Paris Valley	806	Vallecitos
558	Pleasant Valley		

Figure 14. —Continued

C

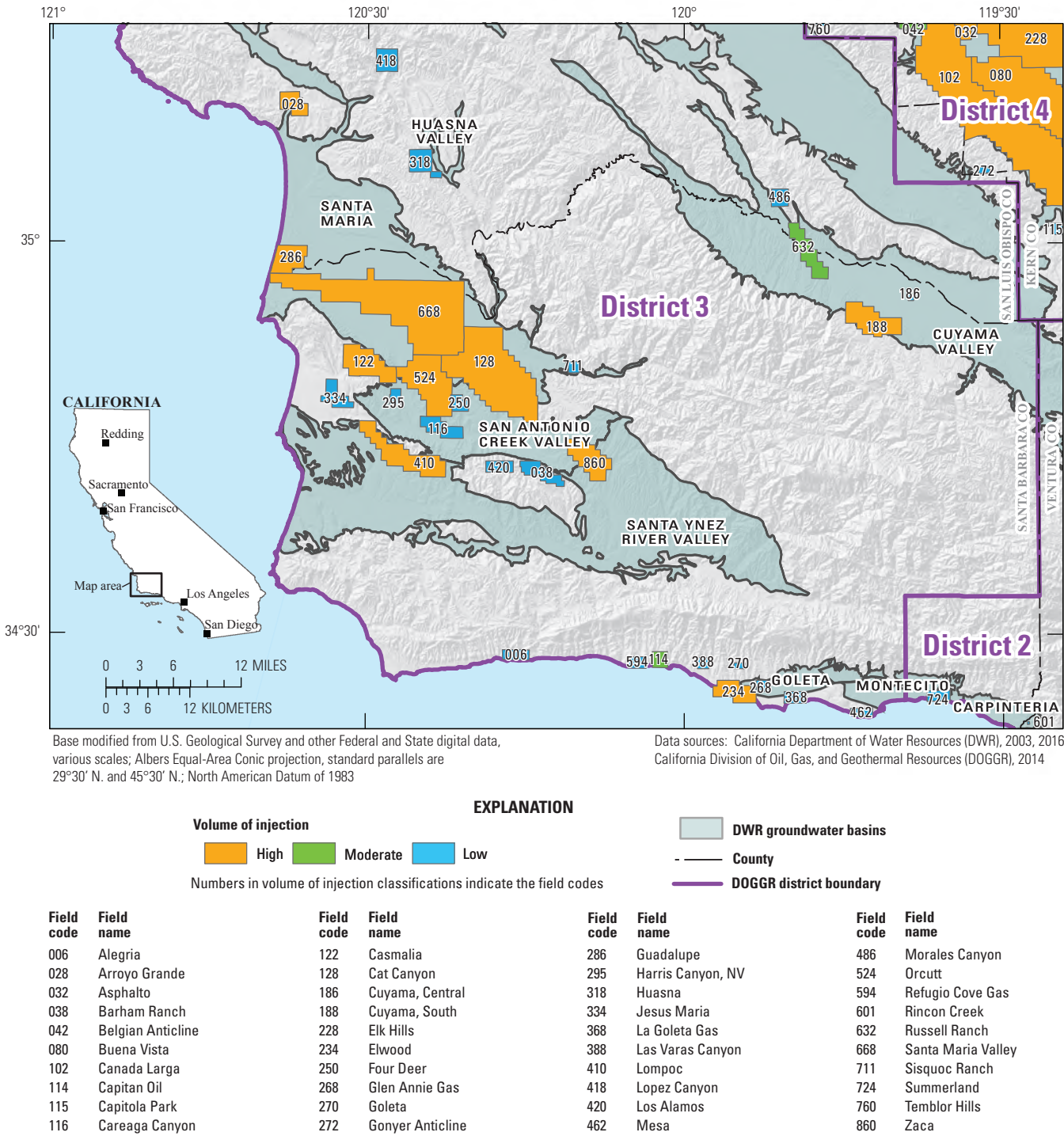


Figure 14. —Continued

C—Continued

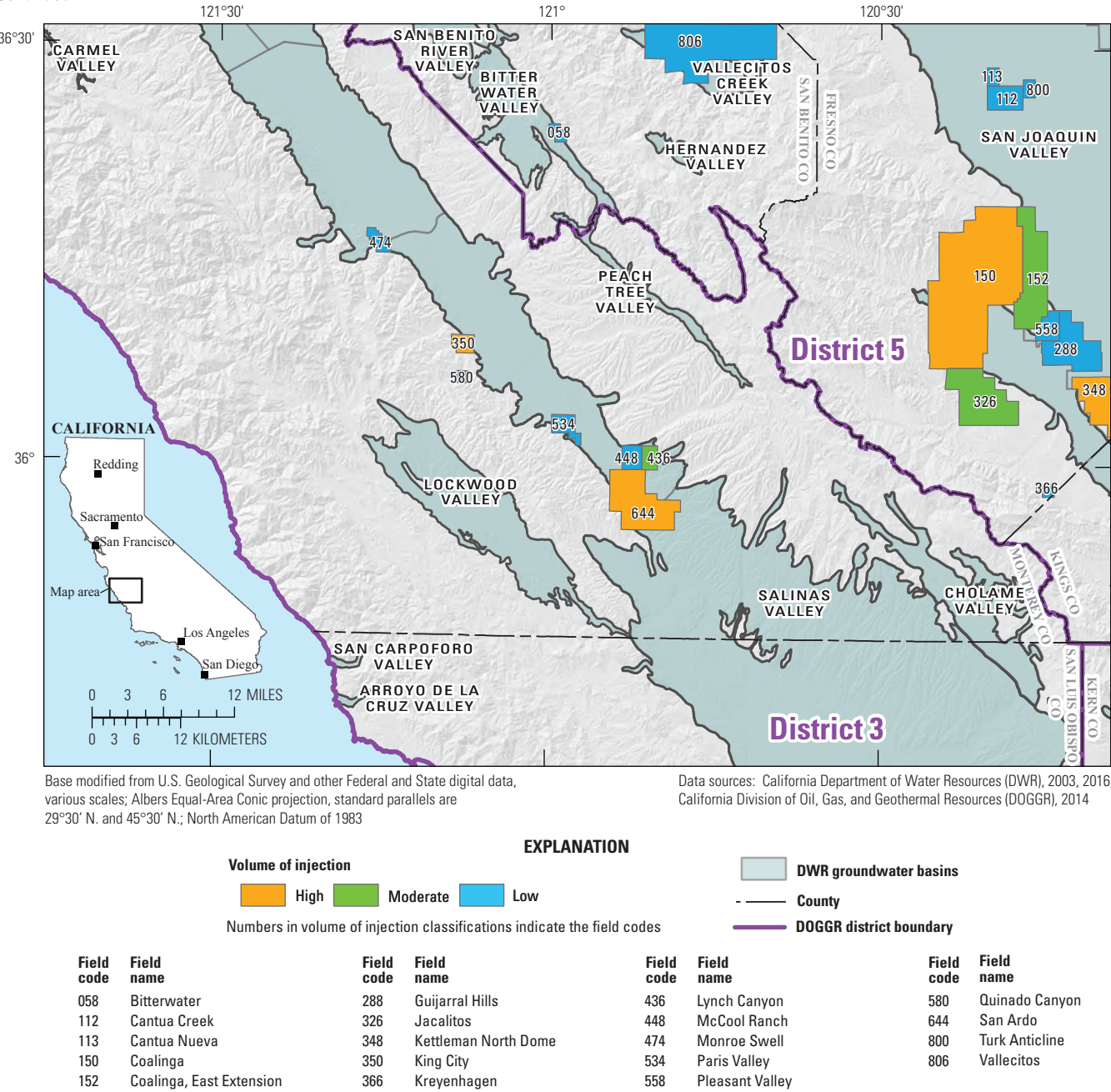
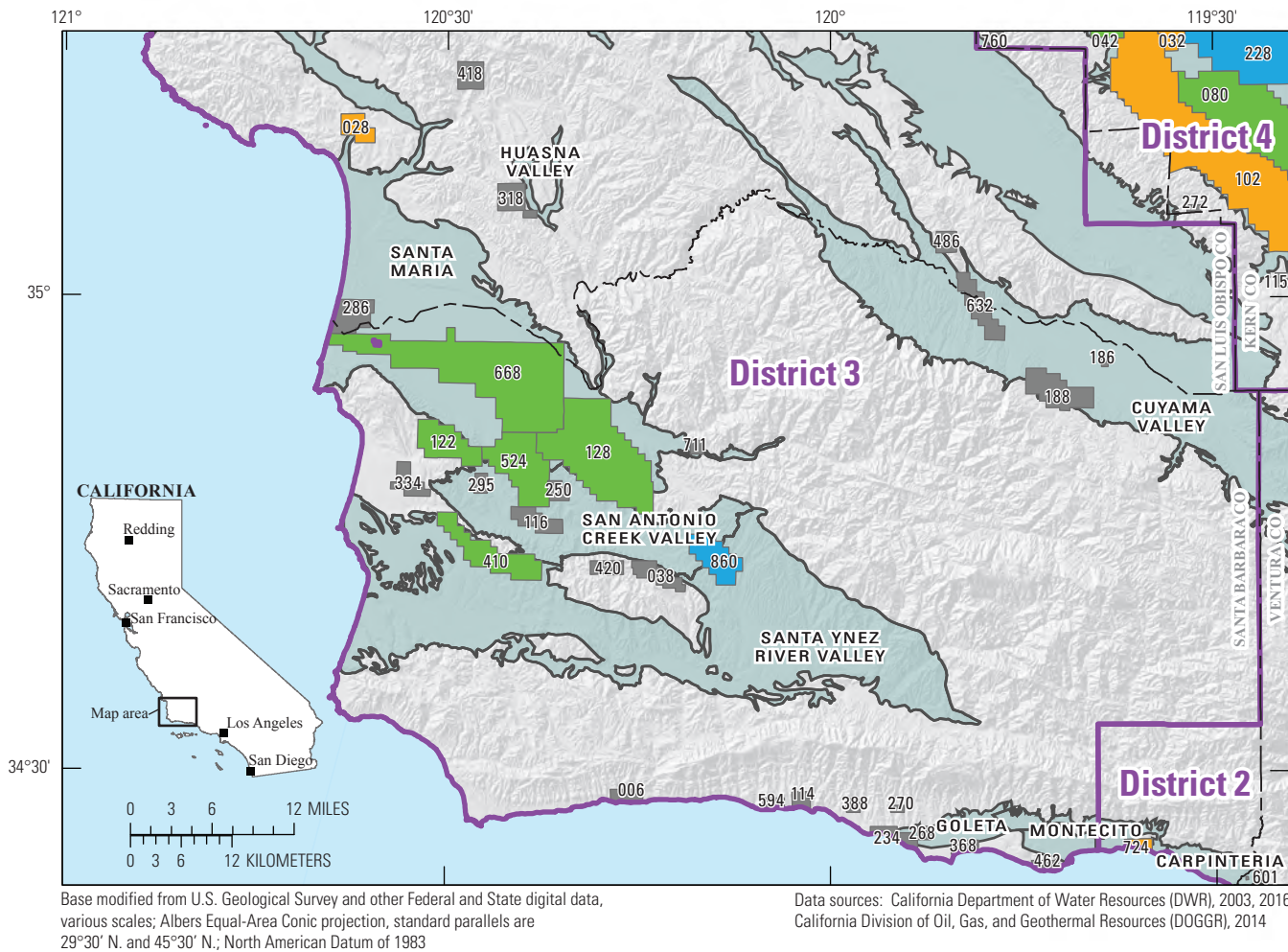


Figure 14. —Continued

D











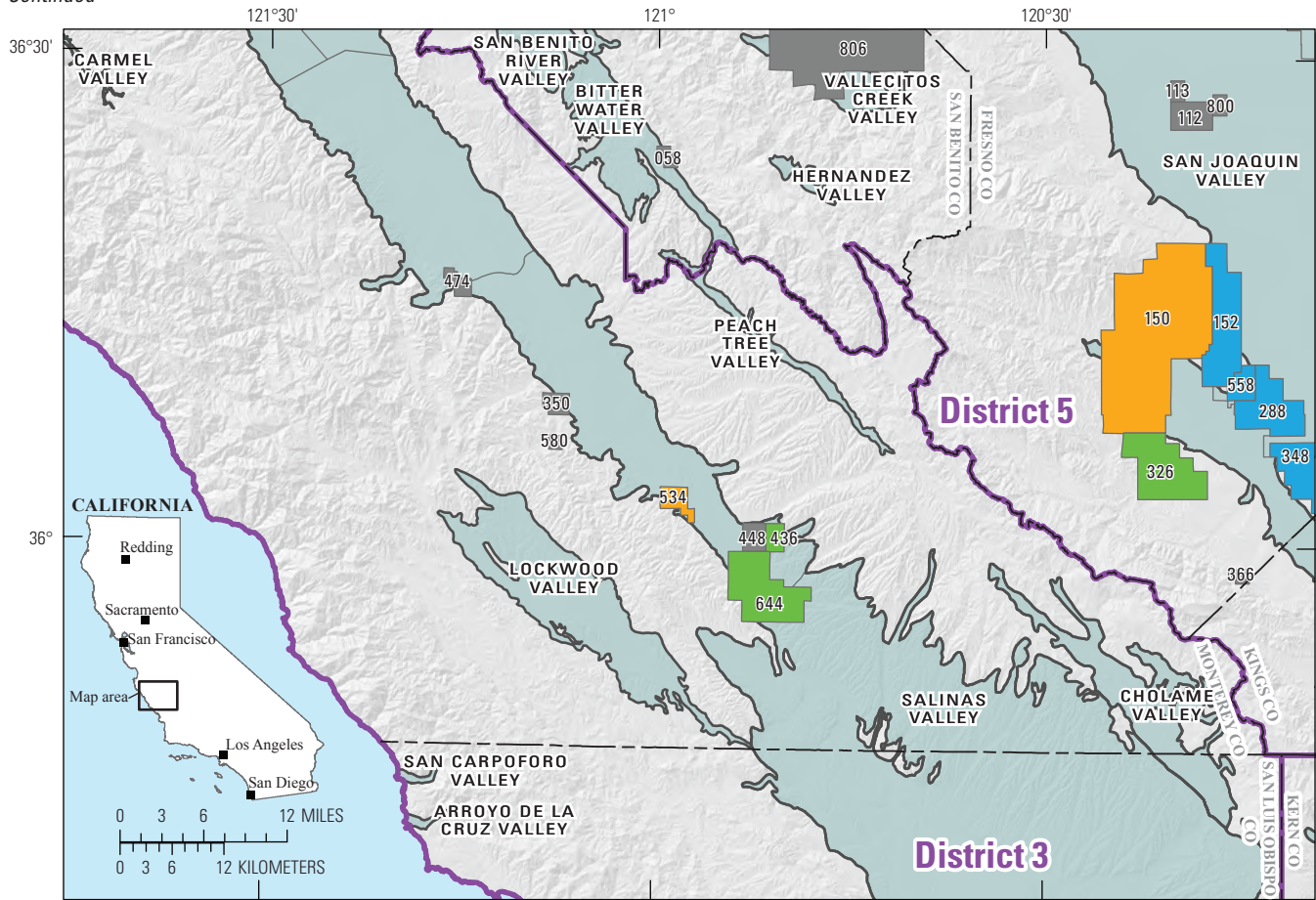
EXPLANATION							
Vertical proximity				 DWR groundwater basins	-  County		
 Close	 Moderate	 Far	 Unknown	 DWR groundwater subbasins	 DOGGR district boundary		
Numbers in vertical proximity classifications indicate the field codes							
Field code	Field name	Field code	Field name	Field code	Field 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	Guajarral 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

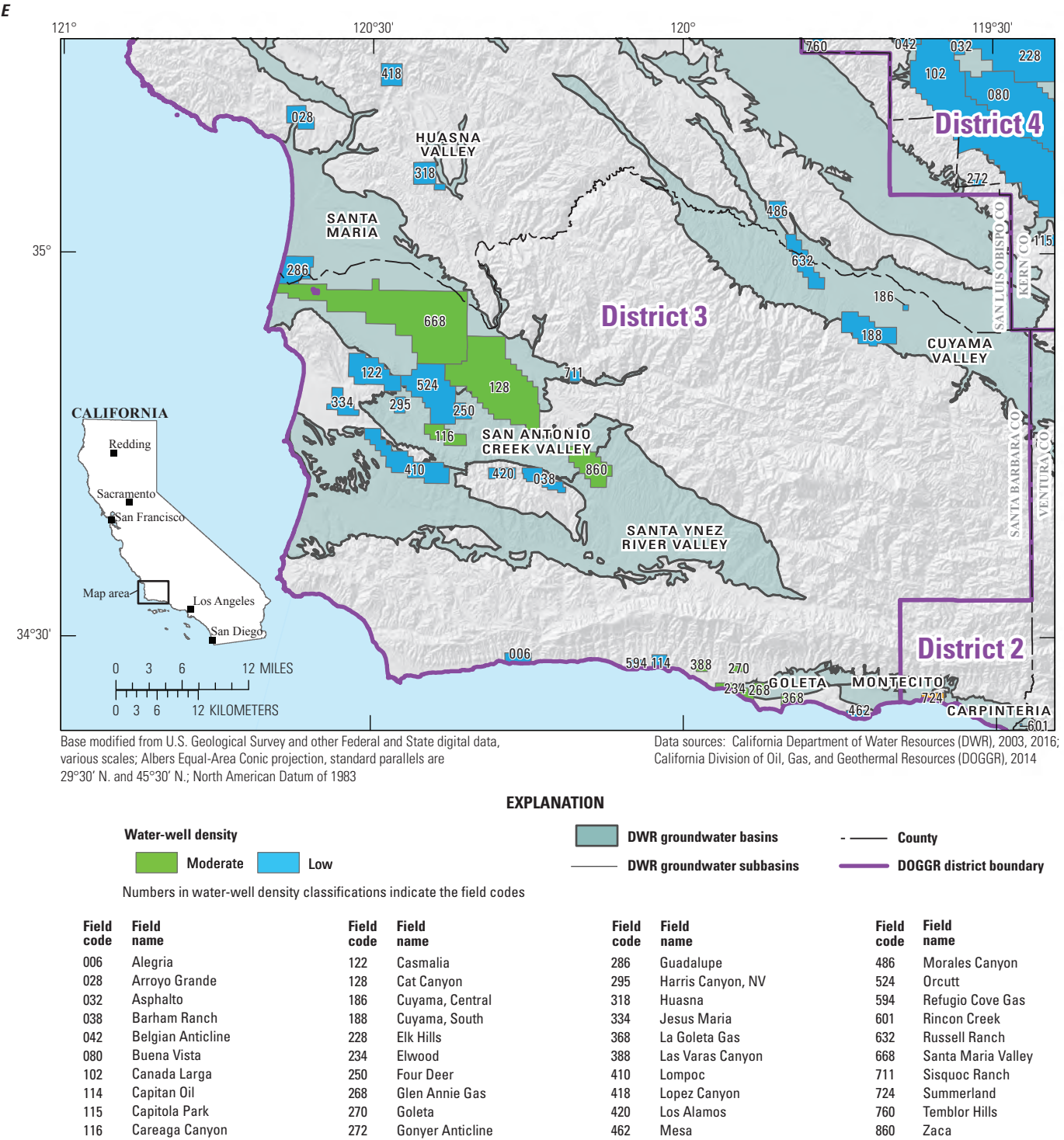


Figure 14. —Continued

E—Continued

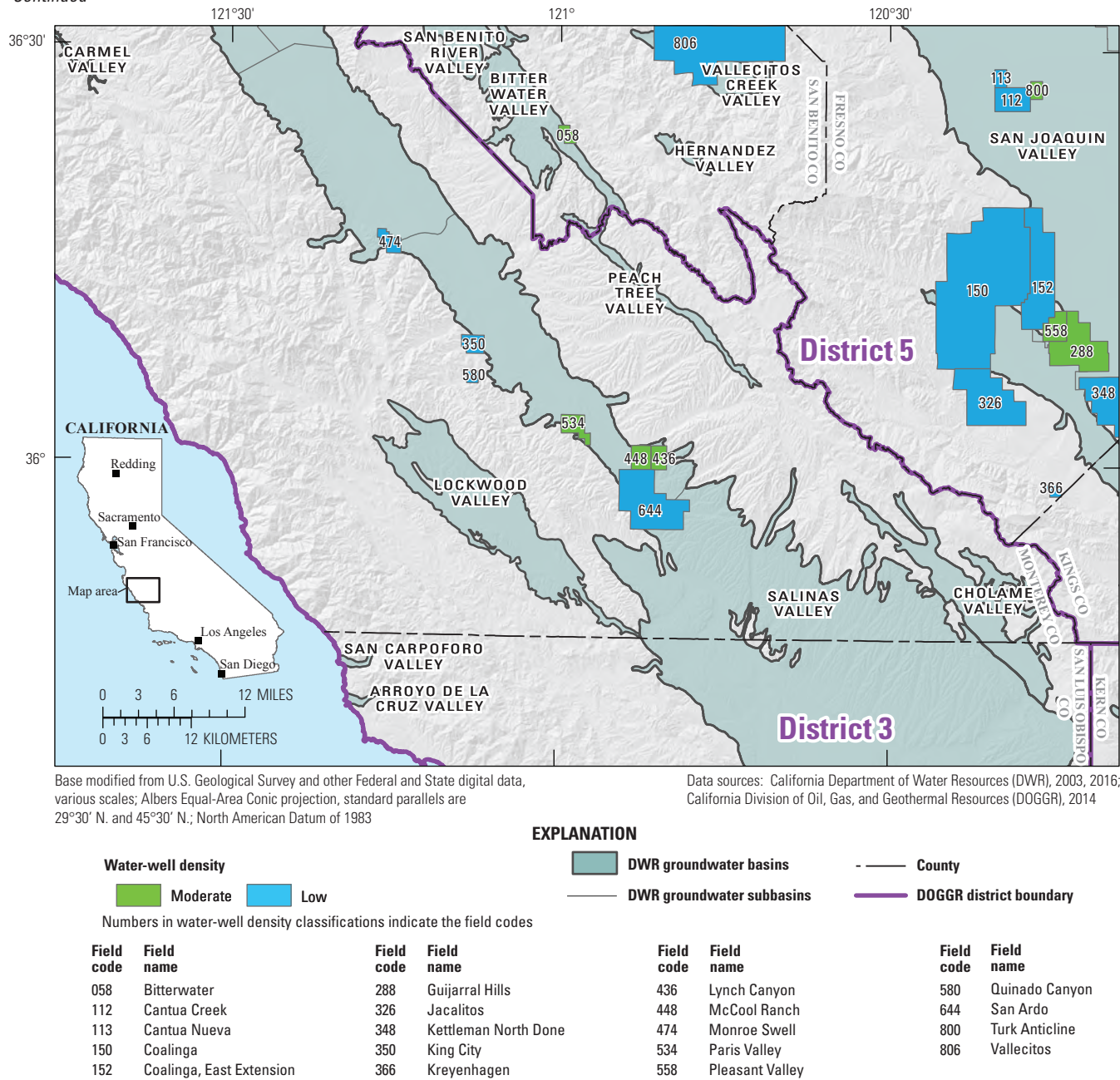


Figure 14. —Continued

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. 16A](#)). 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 6A–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. 16B, 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 6C](#)).

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. 16D](#)). 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 6A](#)). 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 mi²). 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. 17A](#); 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. 17A](#)). 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. 17B](#)), virtually no injection for enhanced oil recovery, and comparatively low injection volume for waste-water disposal ([fig. 17C](#)). 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 6A](#)). 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).

A

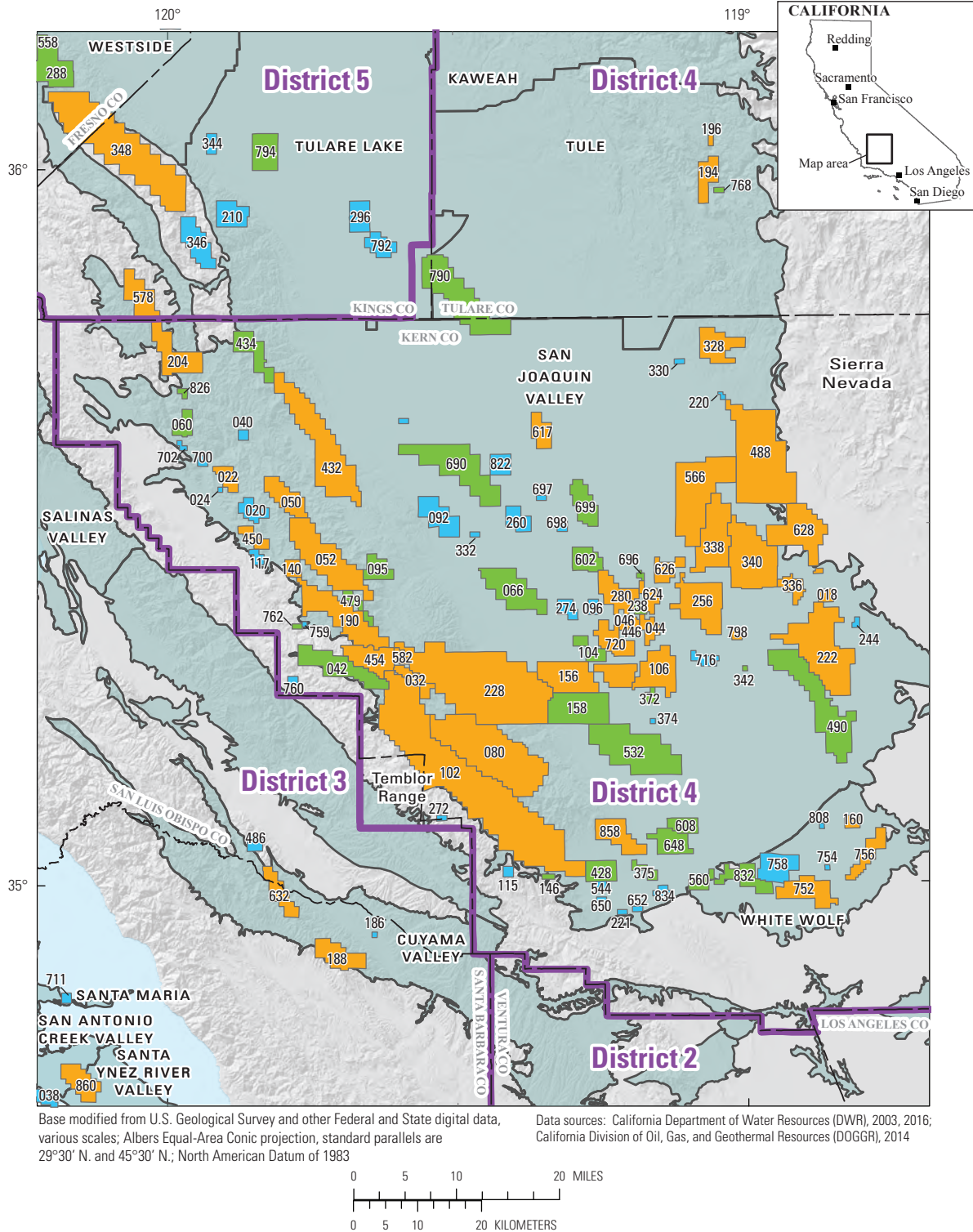


Figure 15. Oil and gas fields in district 4, San Joaquin Basin—South, showing classifications for *A*, priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

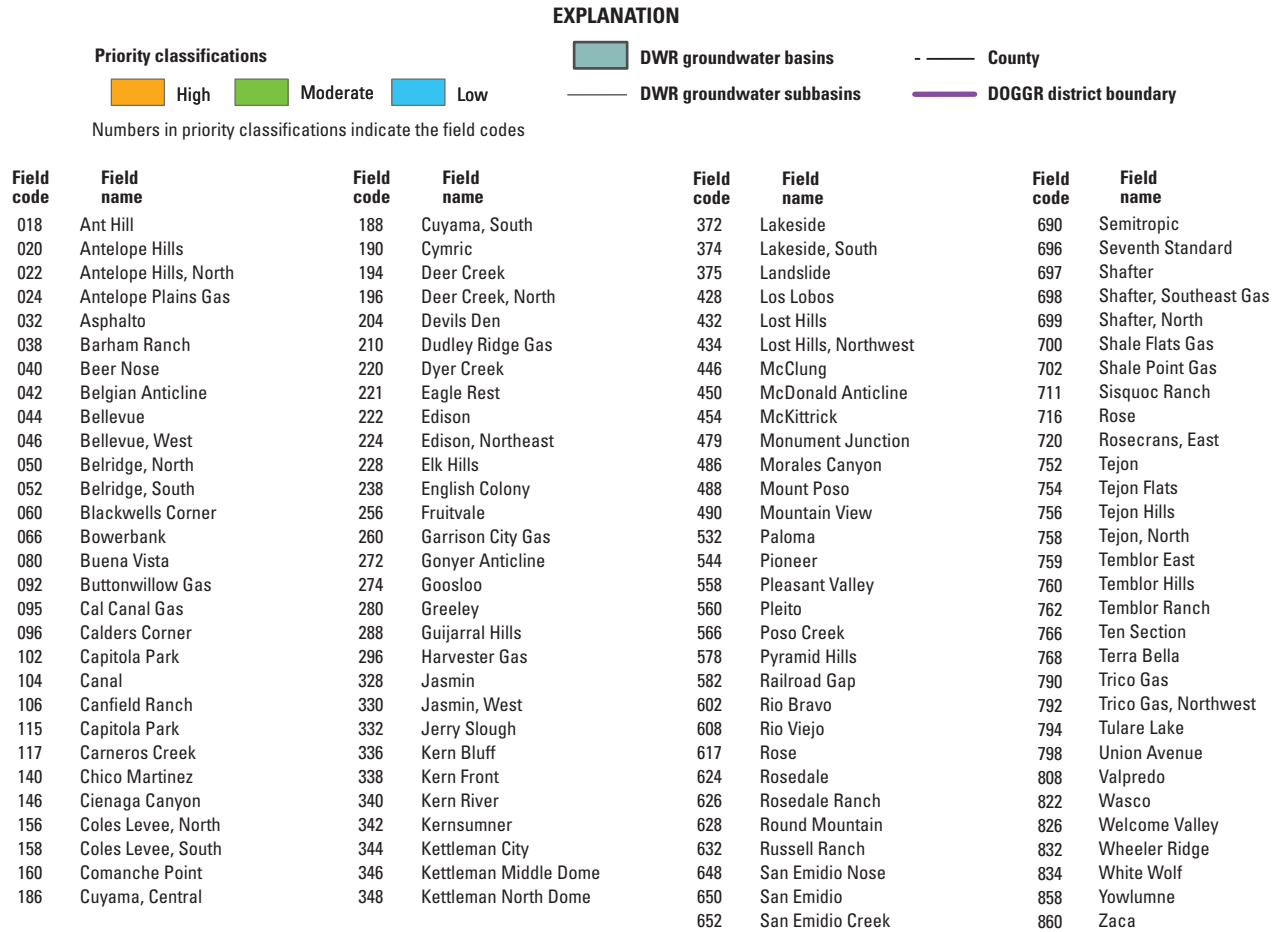


Figure 15. —Continued

B

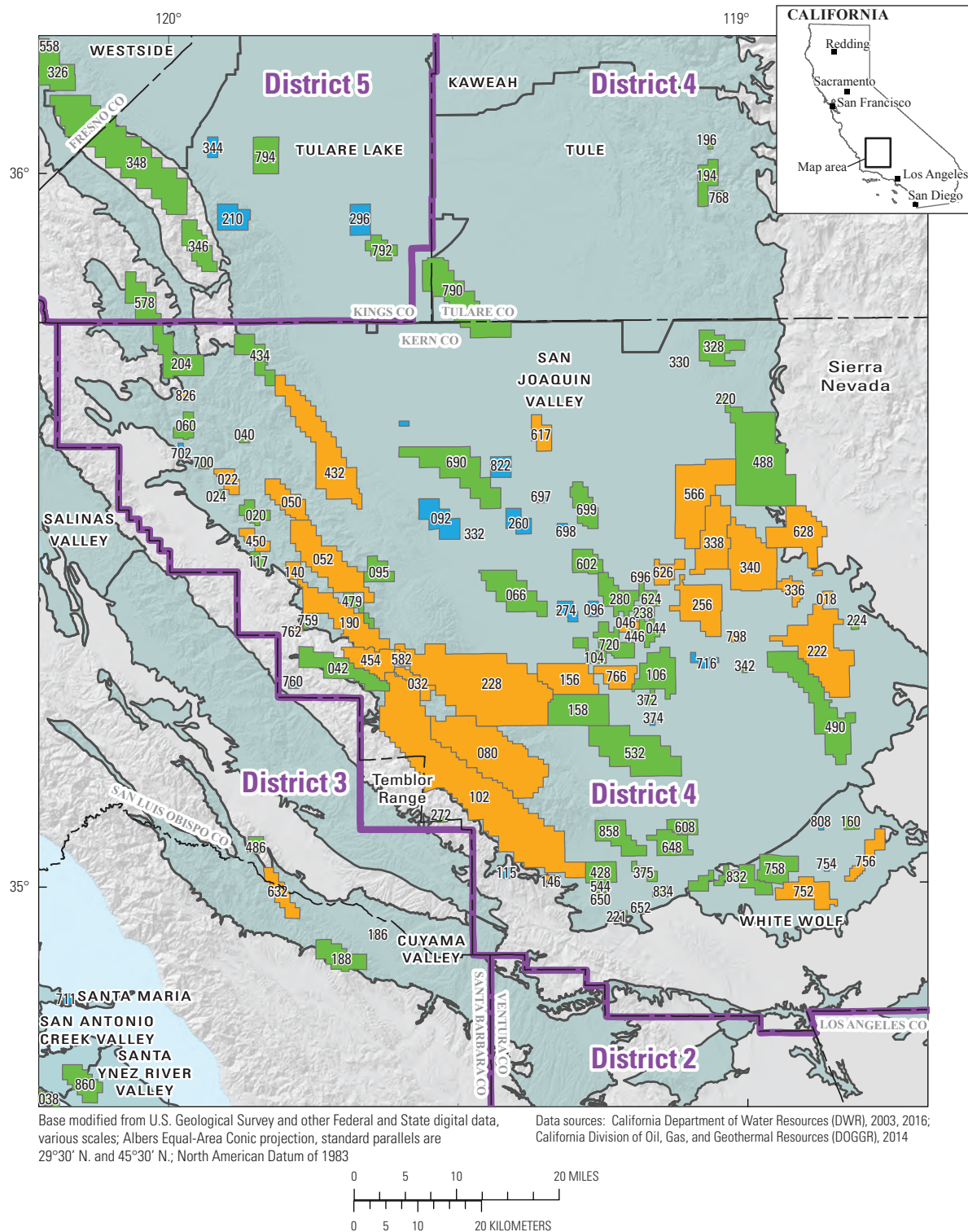


Figure 15. —Continued

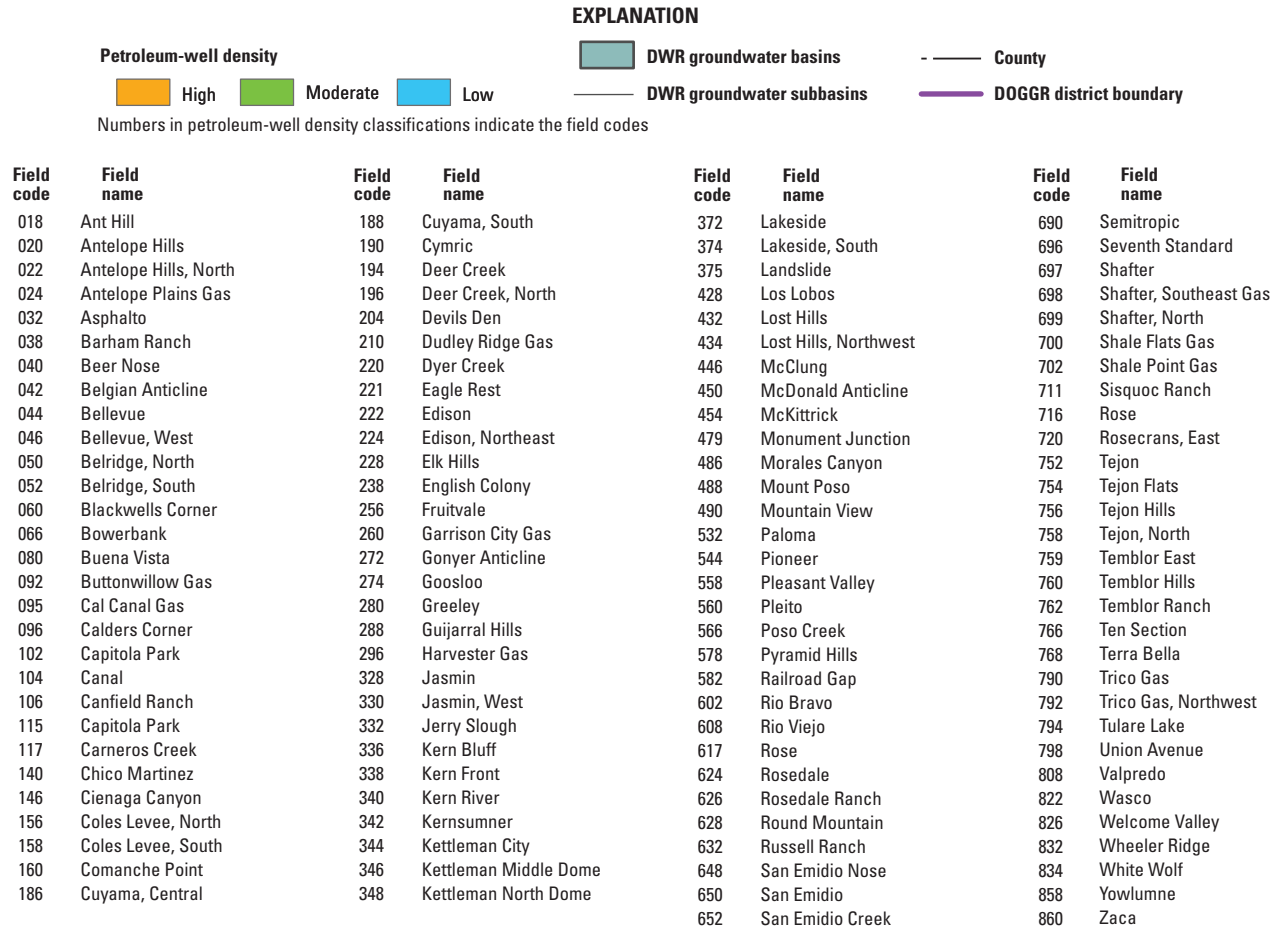


Figure 15. —Continued

C

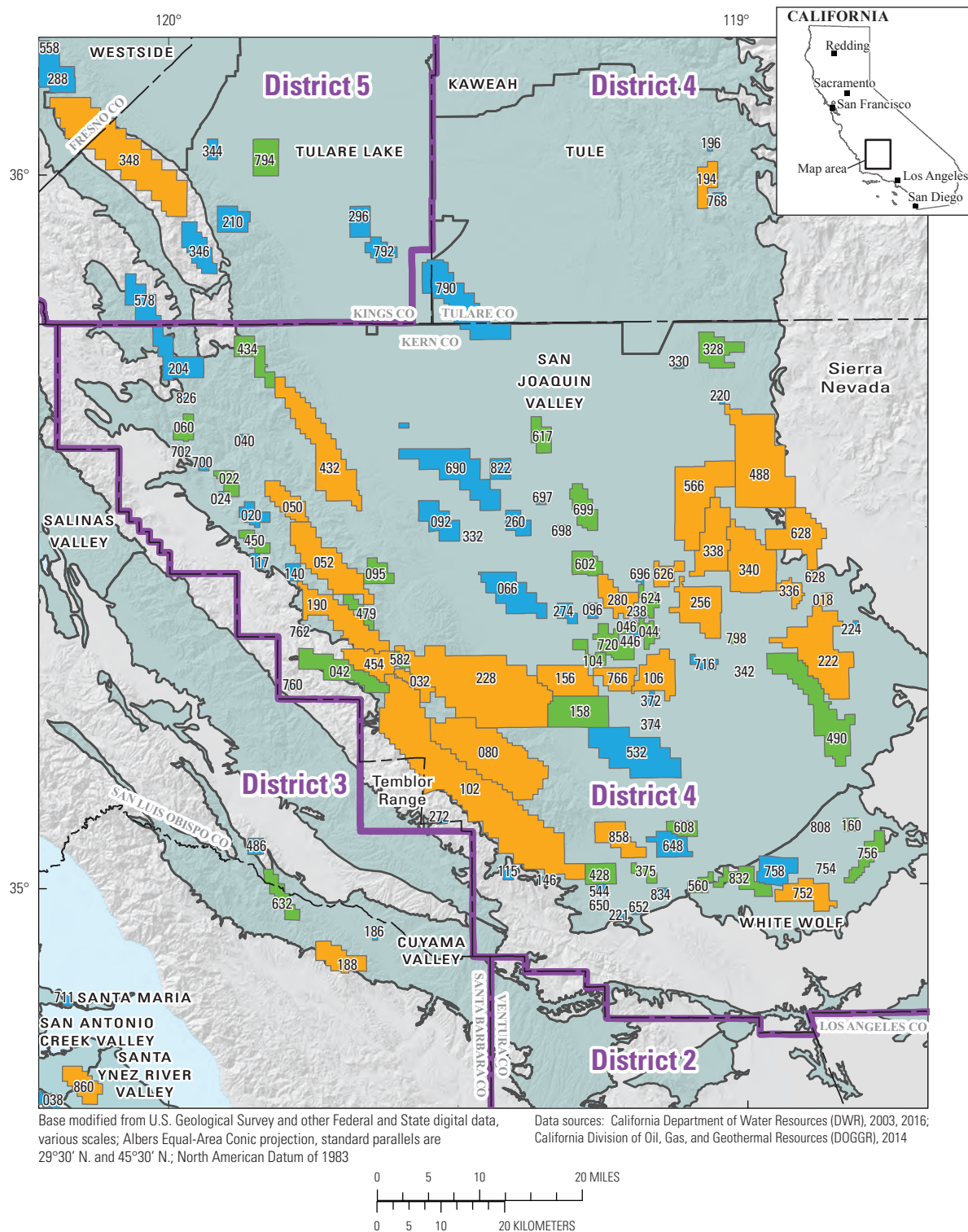


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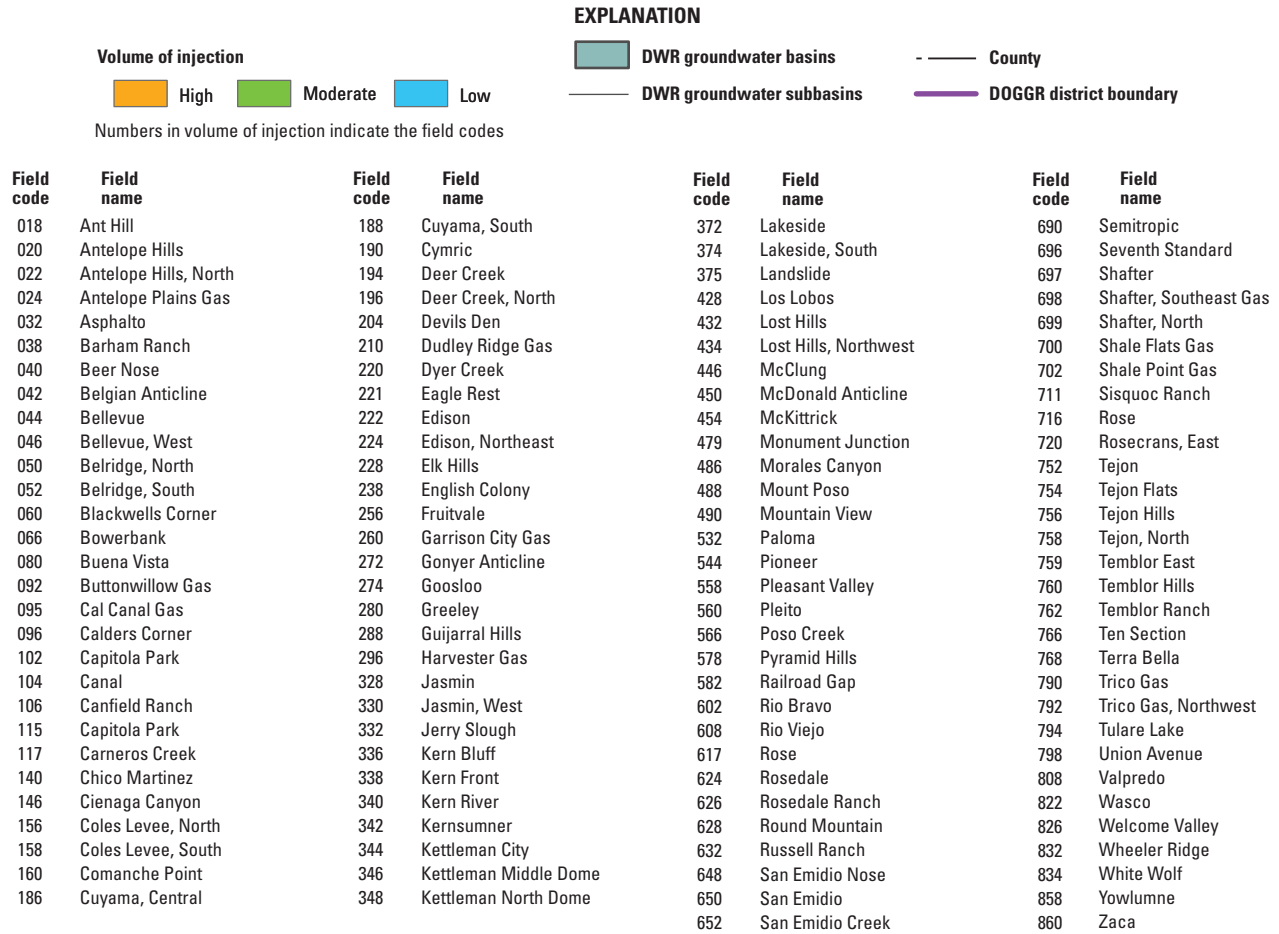


Figure 15. —Continued

D

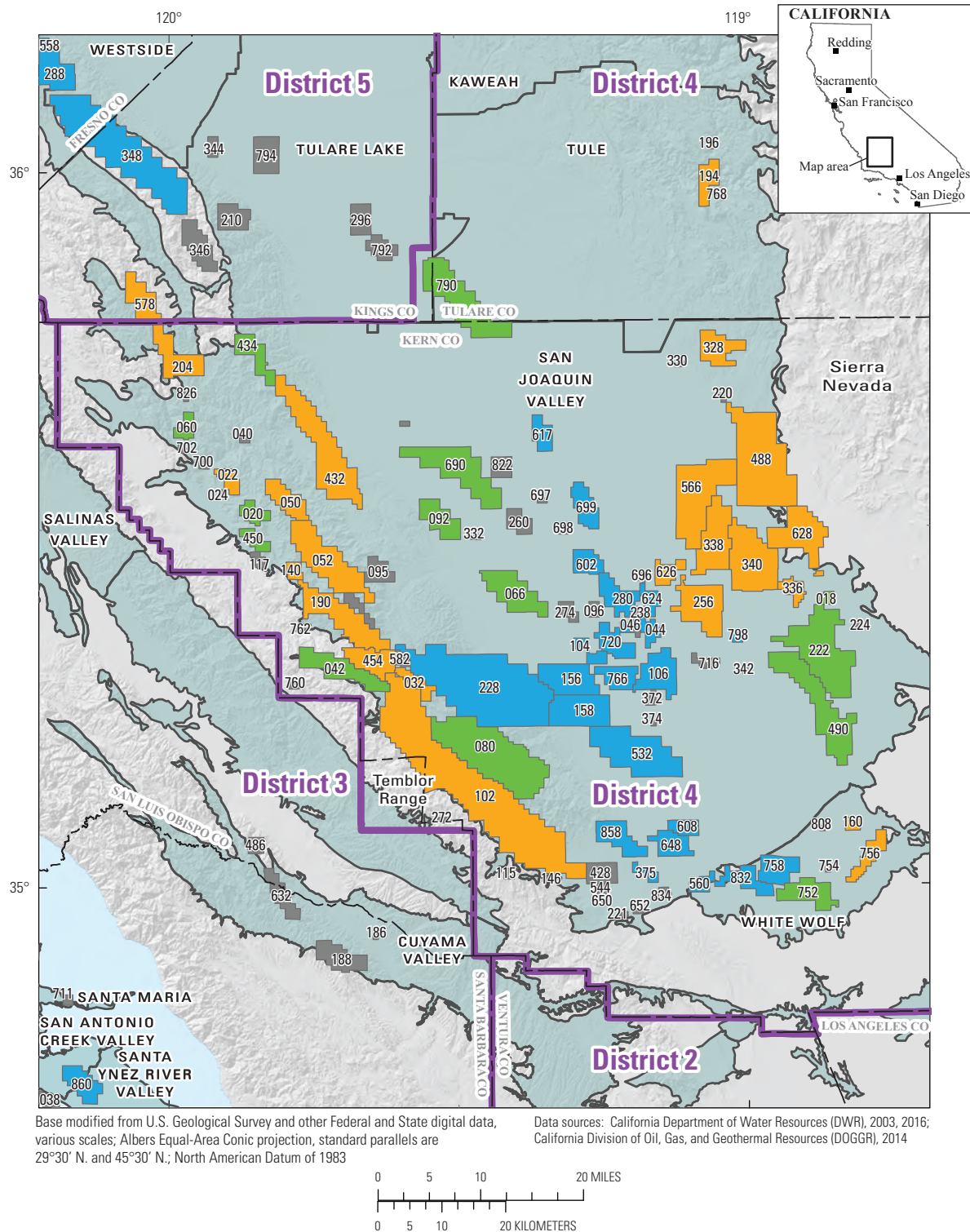


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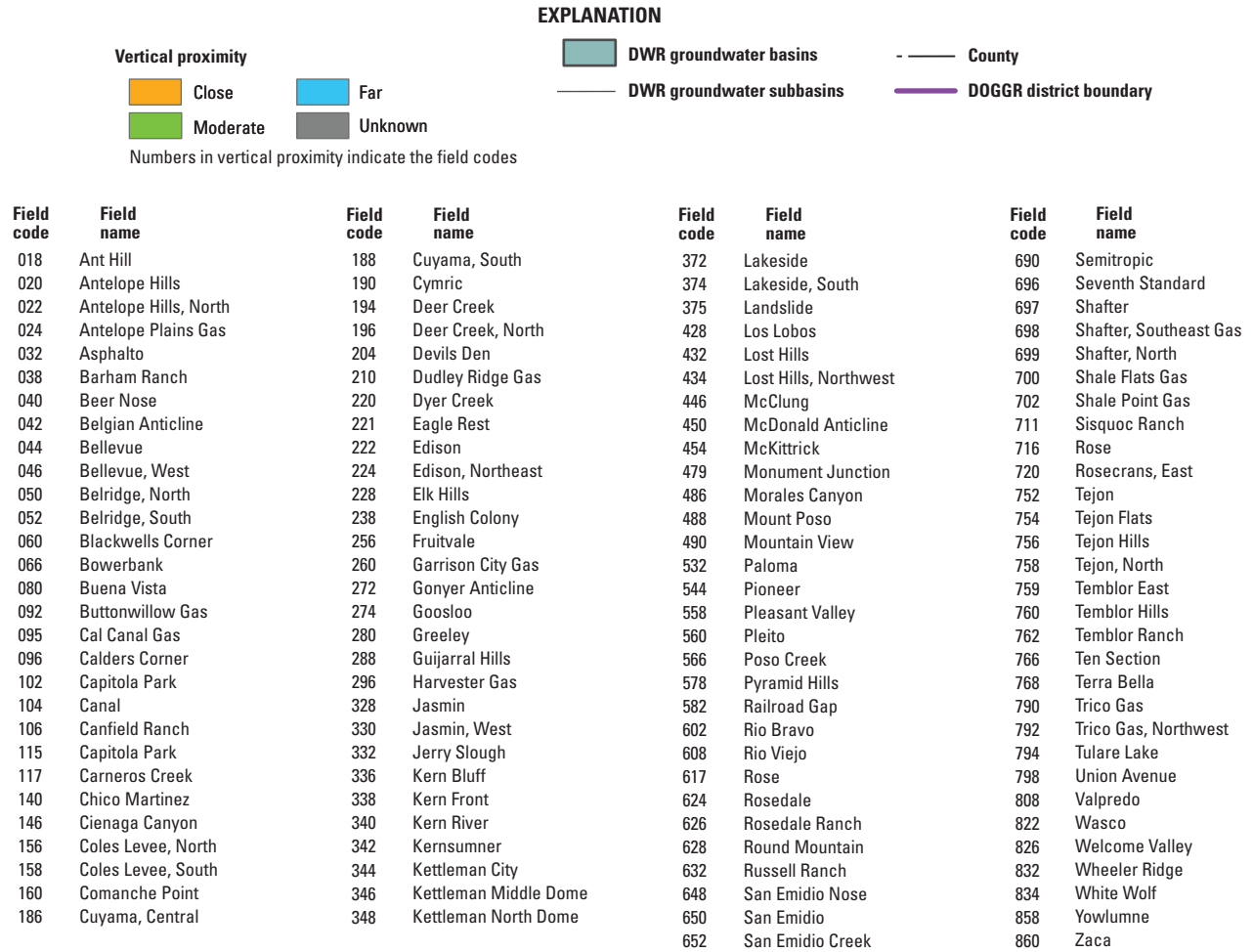


Figure 15. —Continued

E

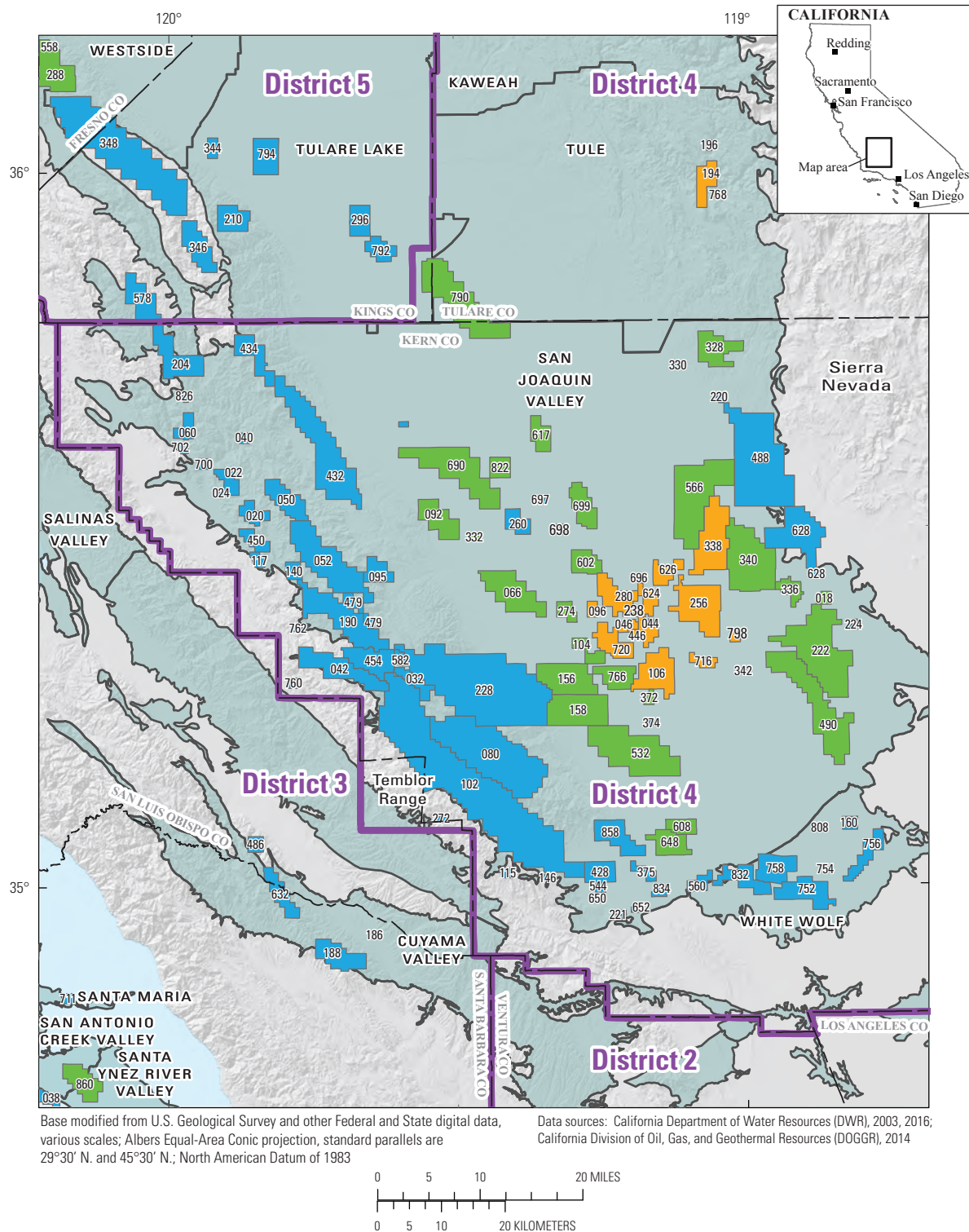


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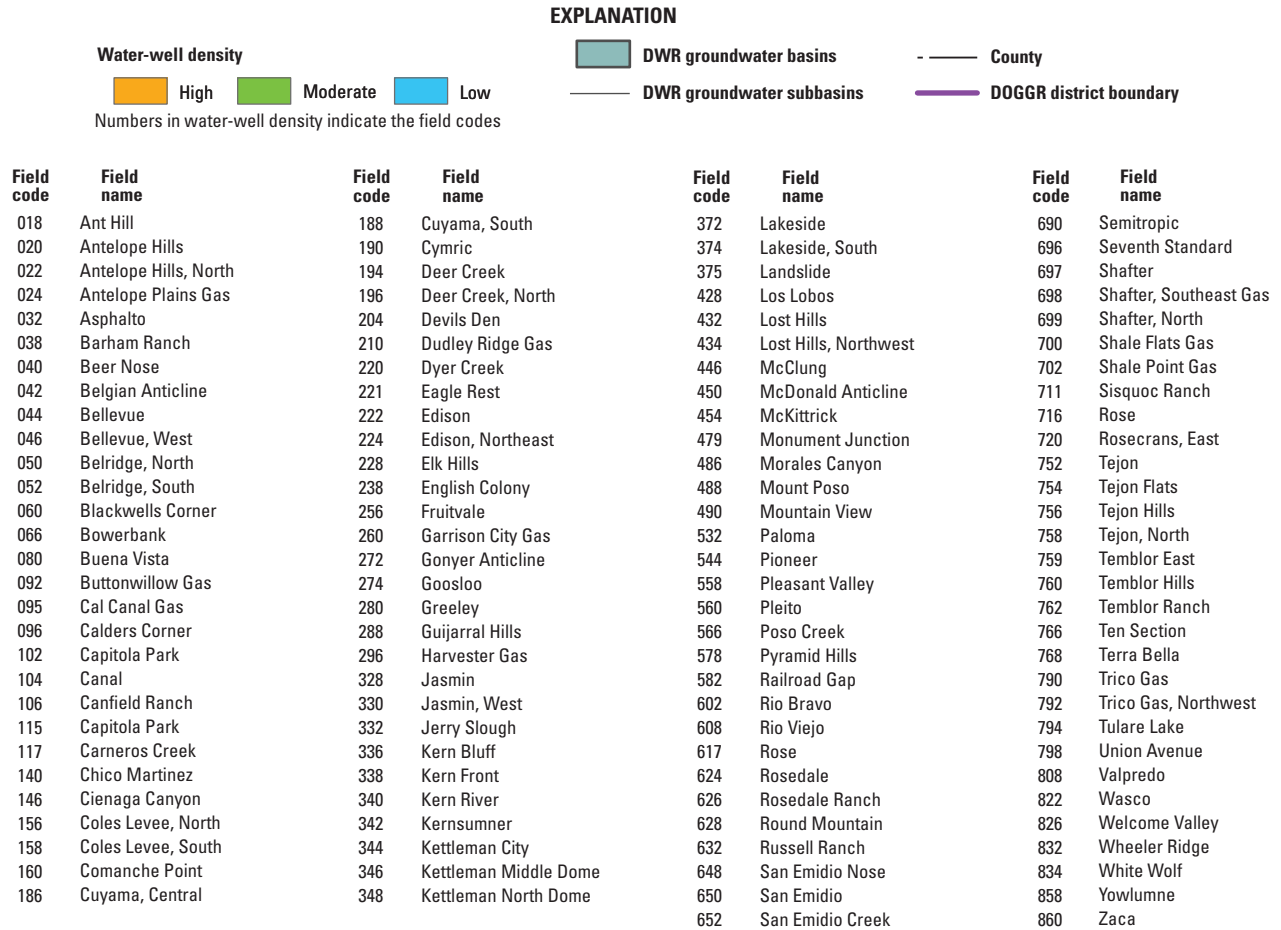


Figure 15. —Continued

A

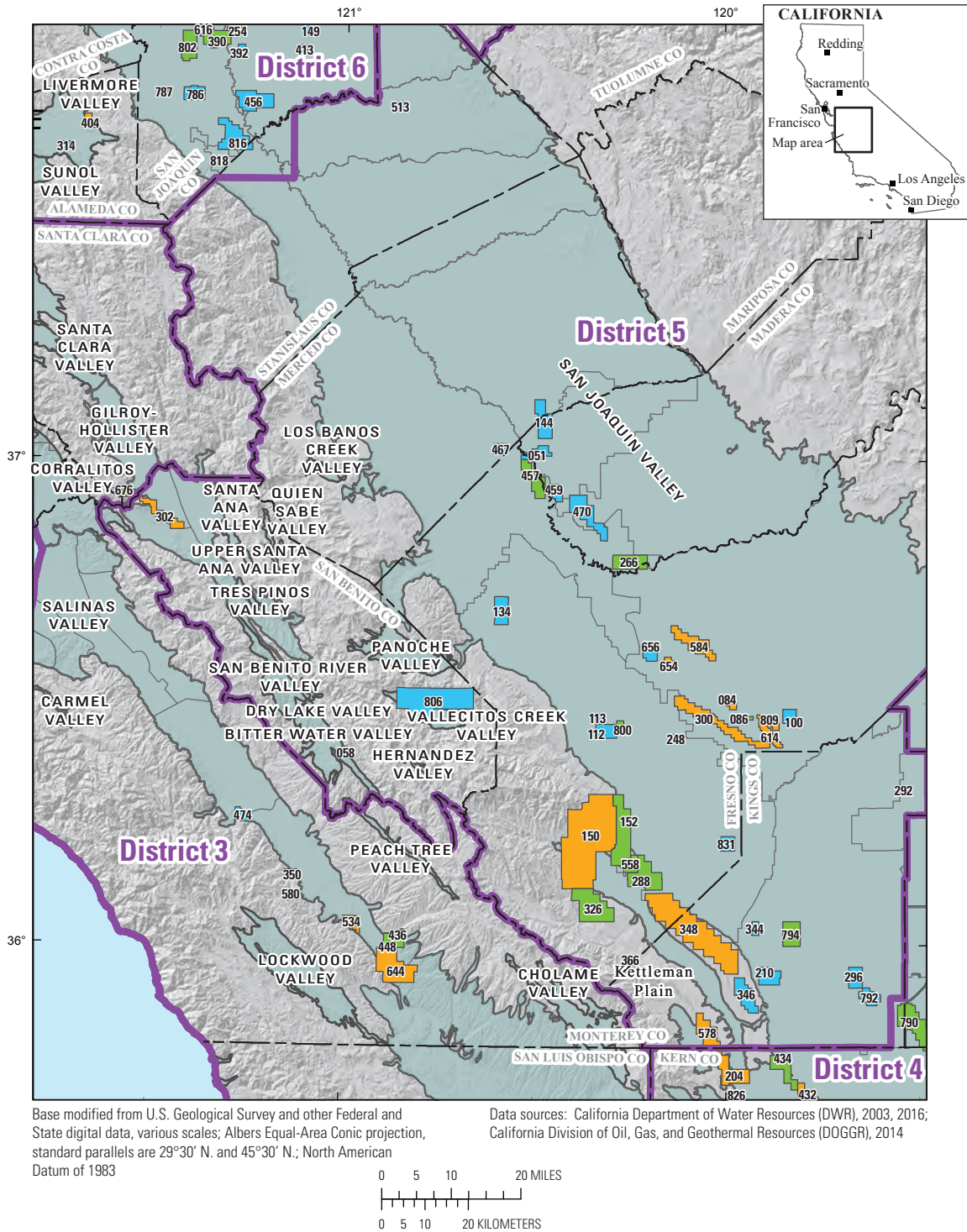


Figure 16. Oil and gas fields in district 5, San Joaquin Basin—North/Central, showing classifications for *A*, priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

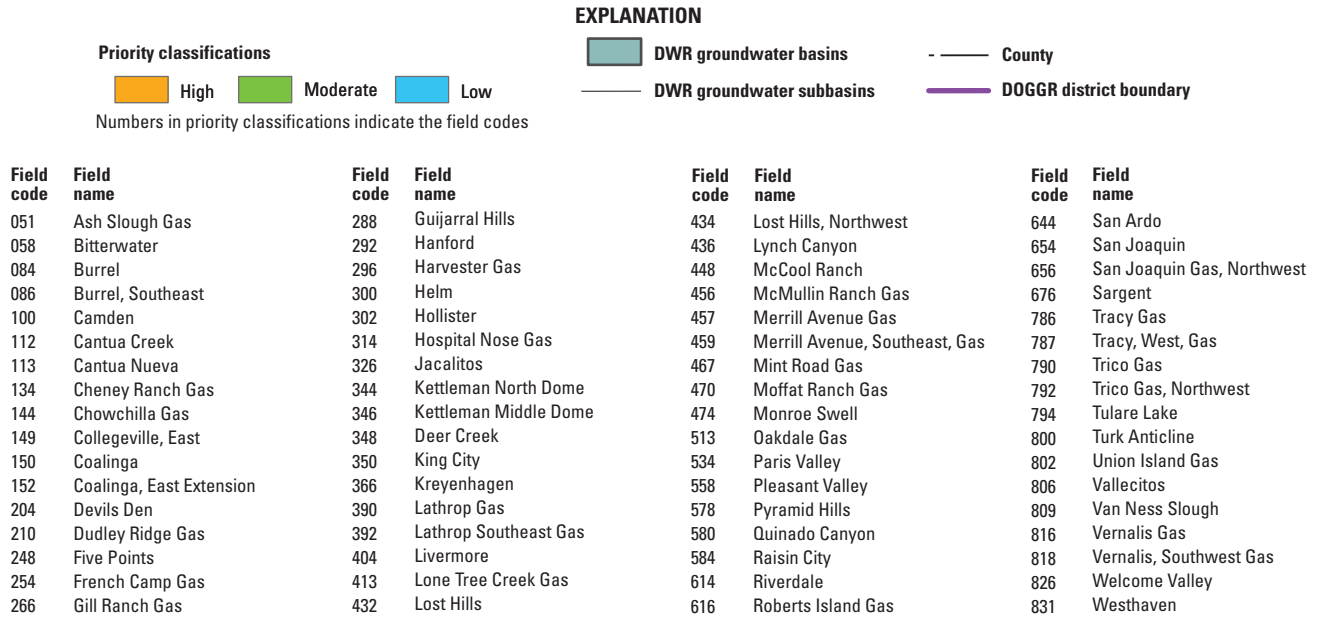


Figure 16. —Continued

B

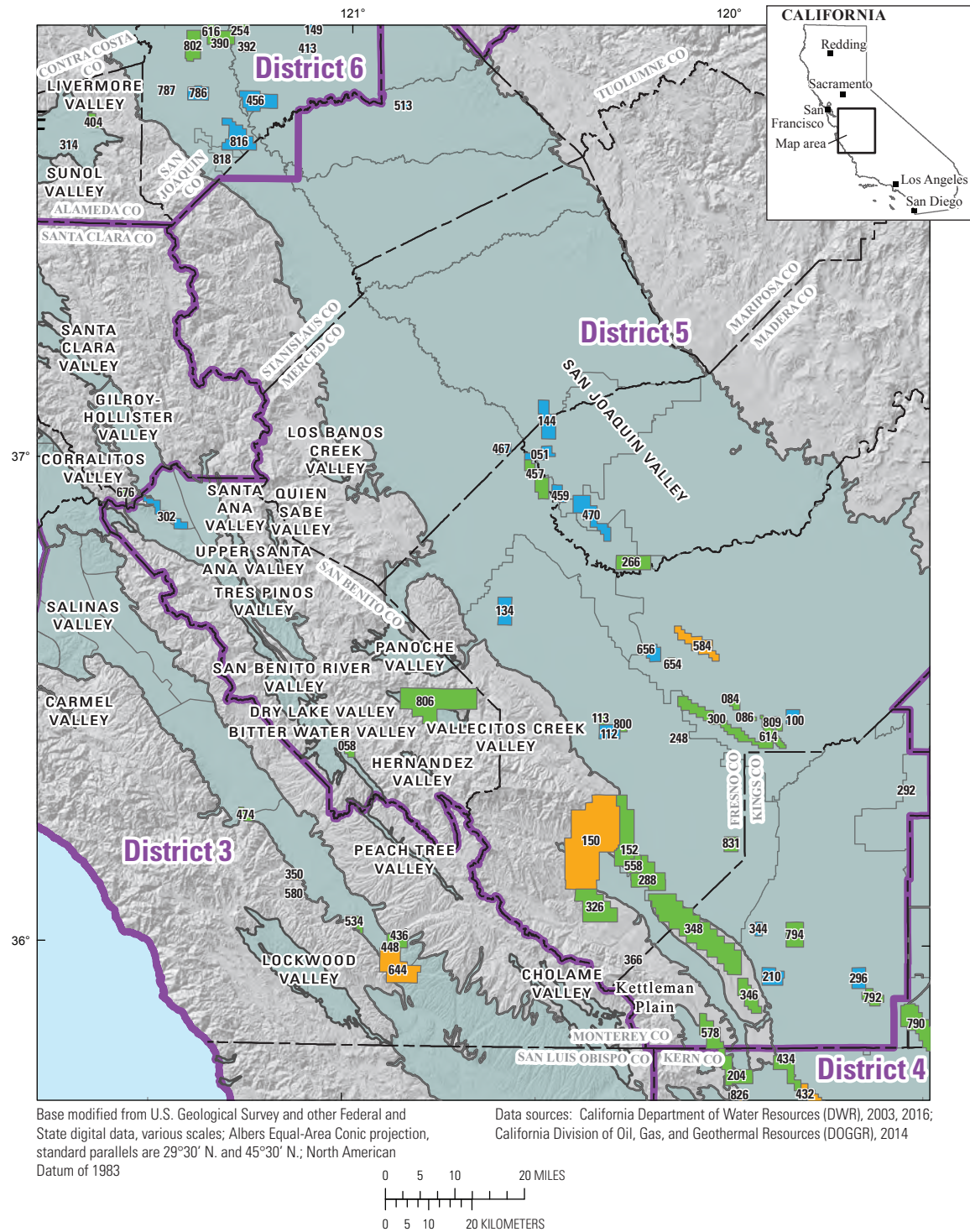


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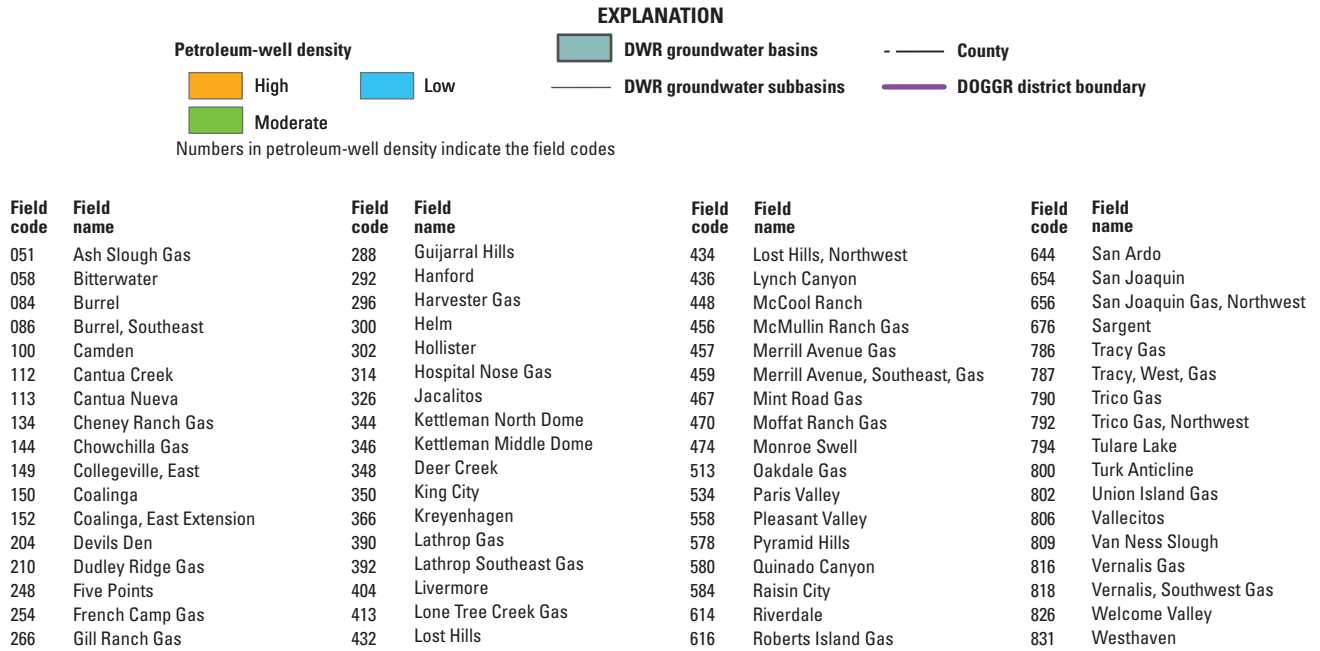


Figure 16. —Continued

C

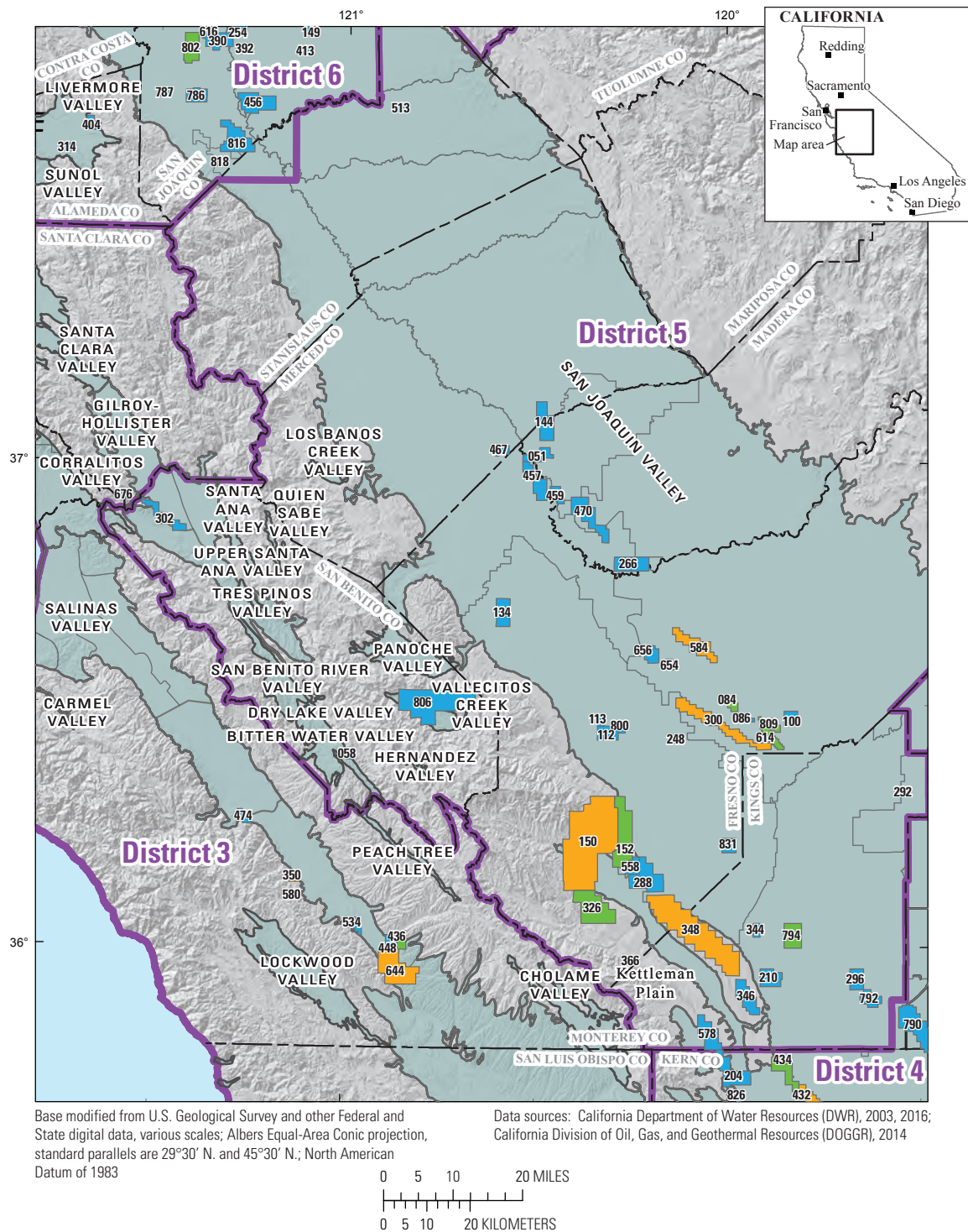


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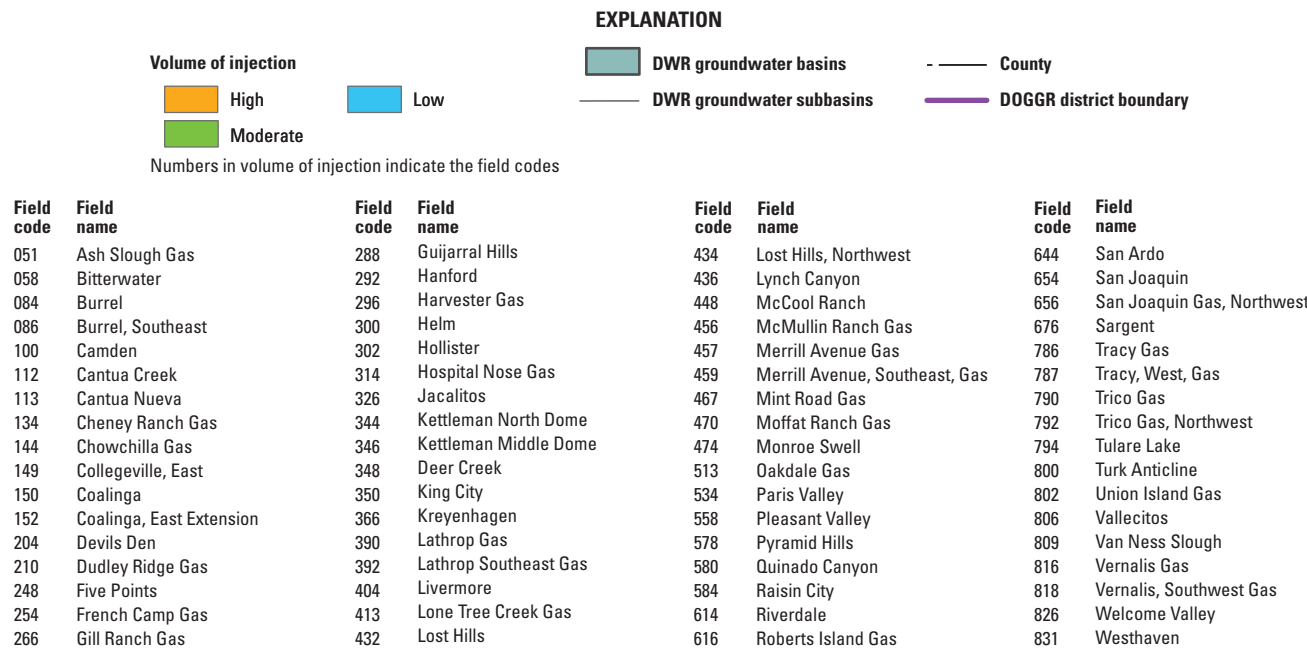


Figure 16. —Continued

D

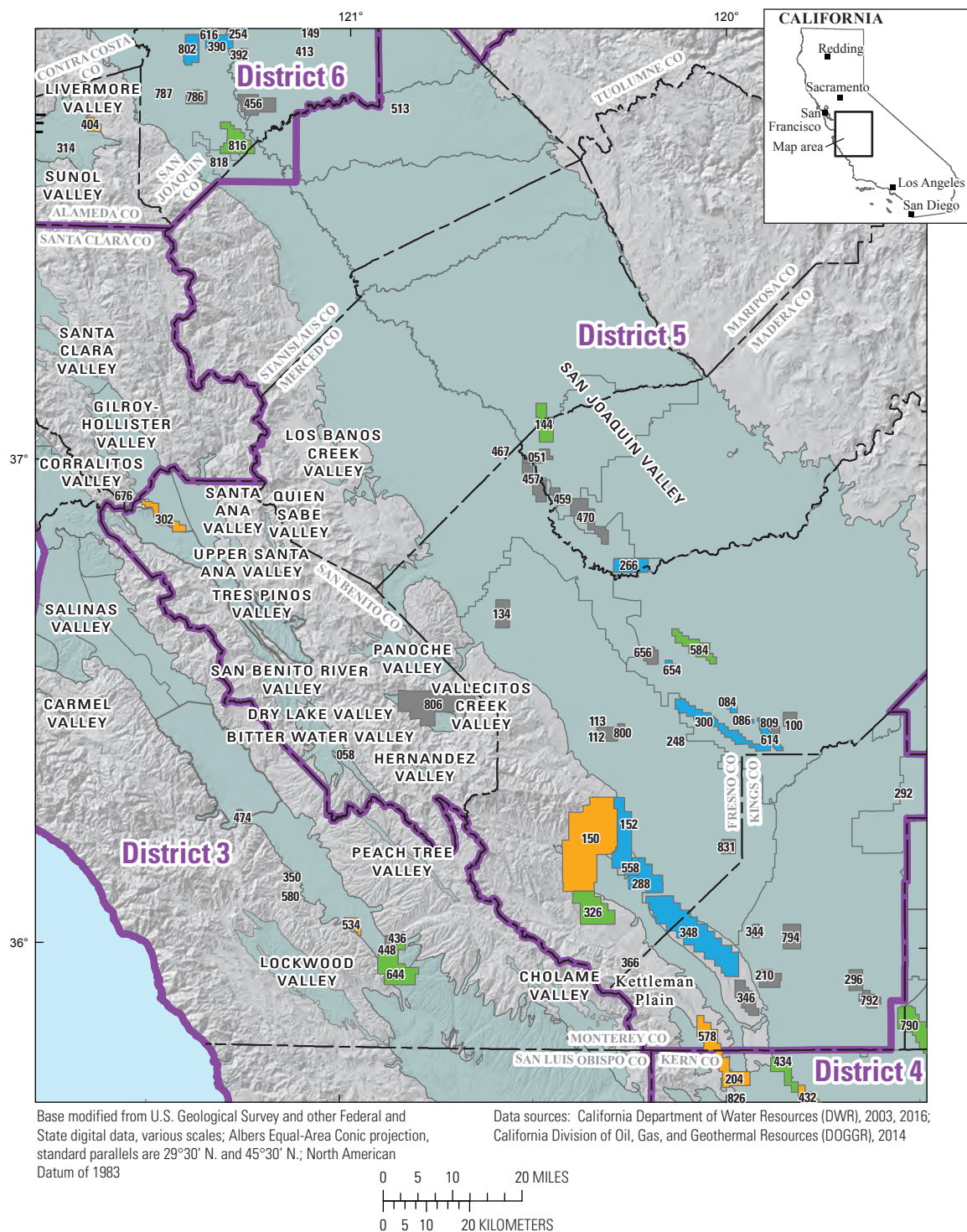


Figure 16. —Continued

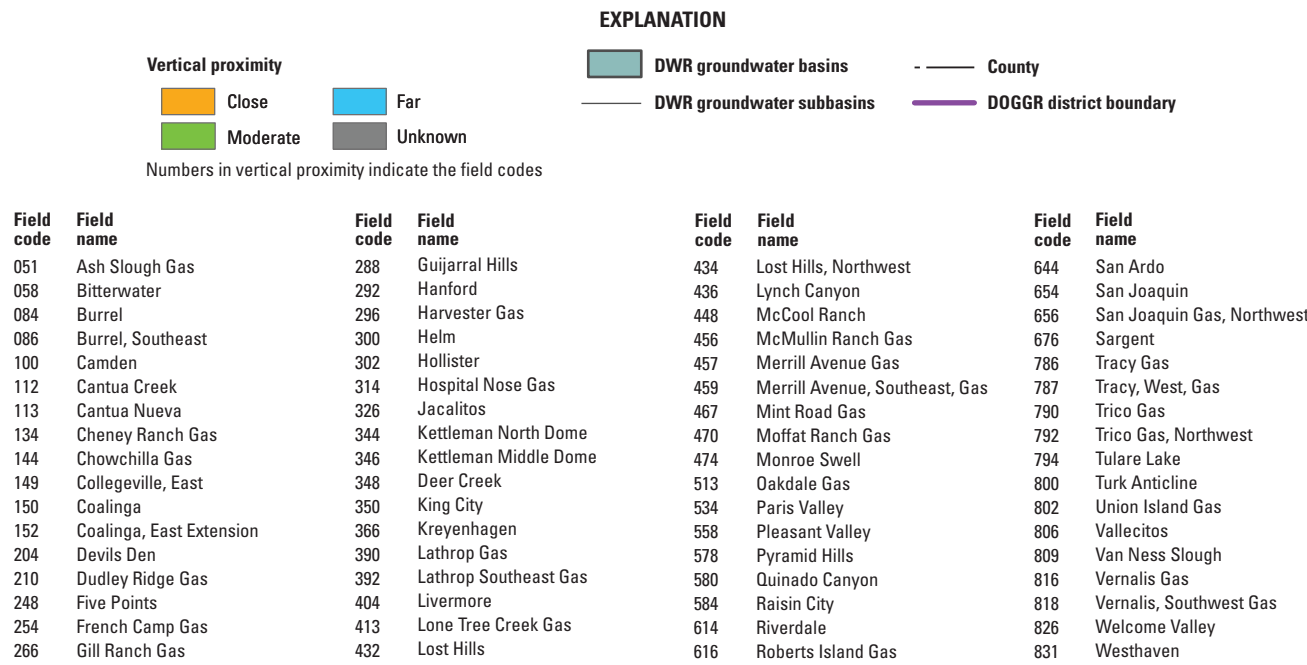


Figure 16. —Continued

E

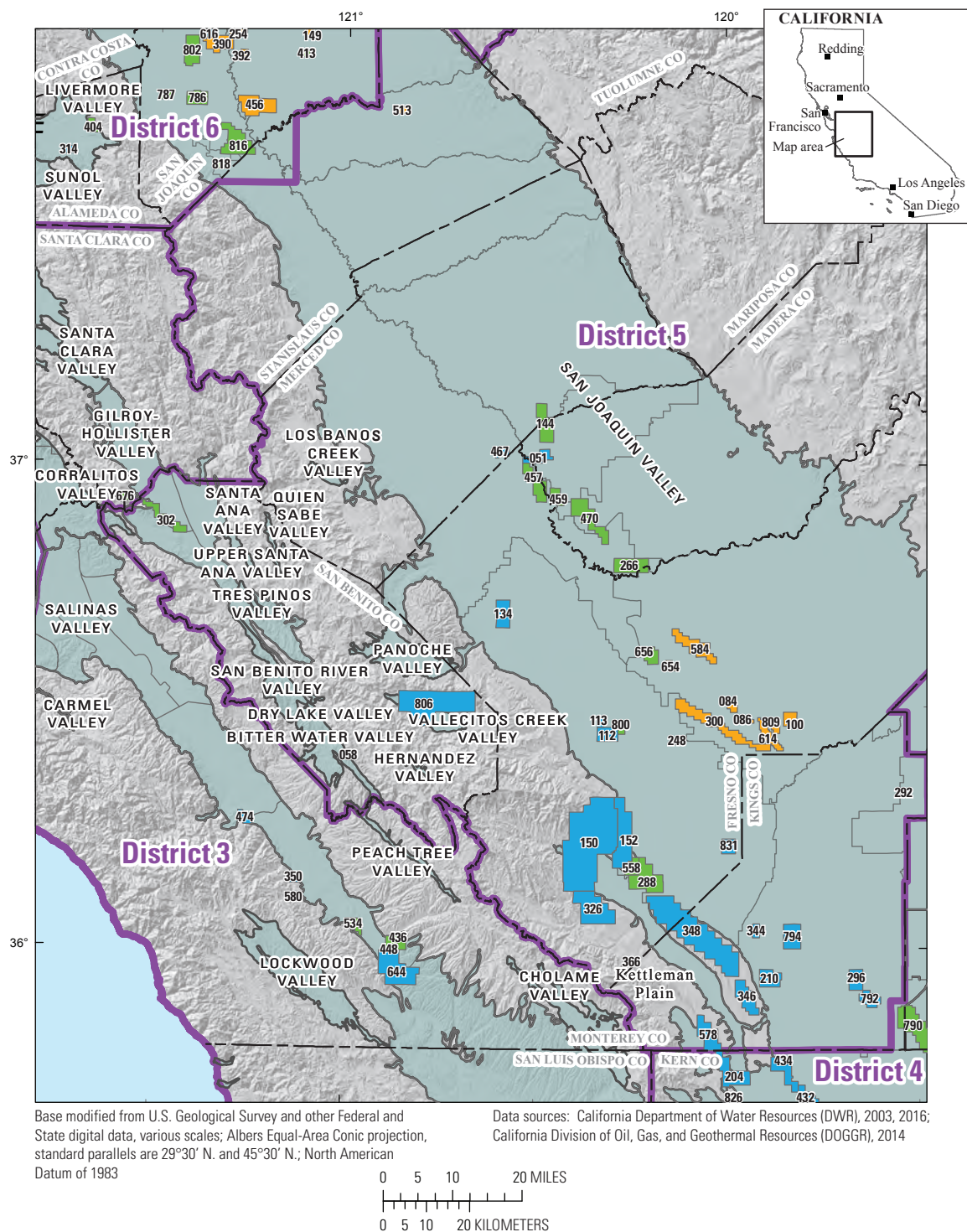


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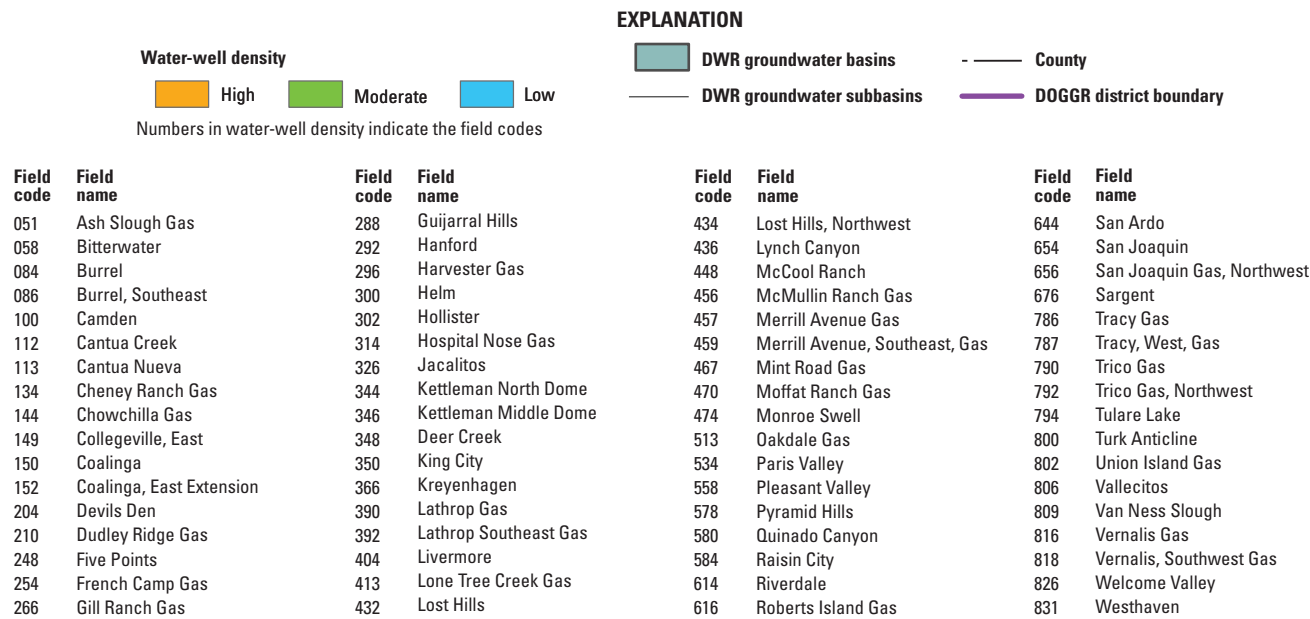


Figure 16. —Continued

A

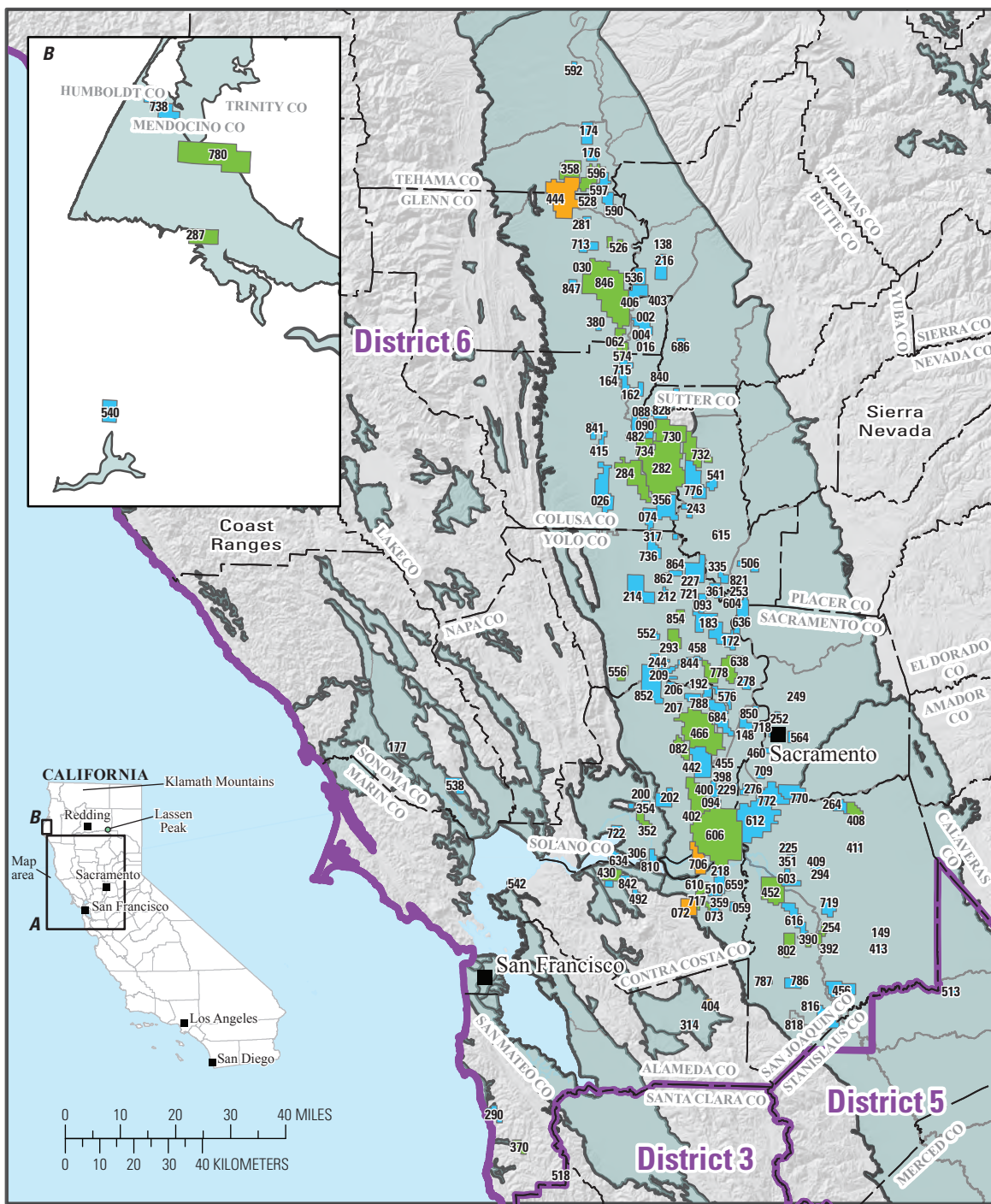


Figure 17. Oil and gas fields in district 6, Sacramento Valley, showing classifications for *A*, priority; *B*, petroleum-well density; *C*, volume of injection; *D*, vertical proximity; and *E*, water-well density.

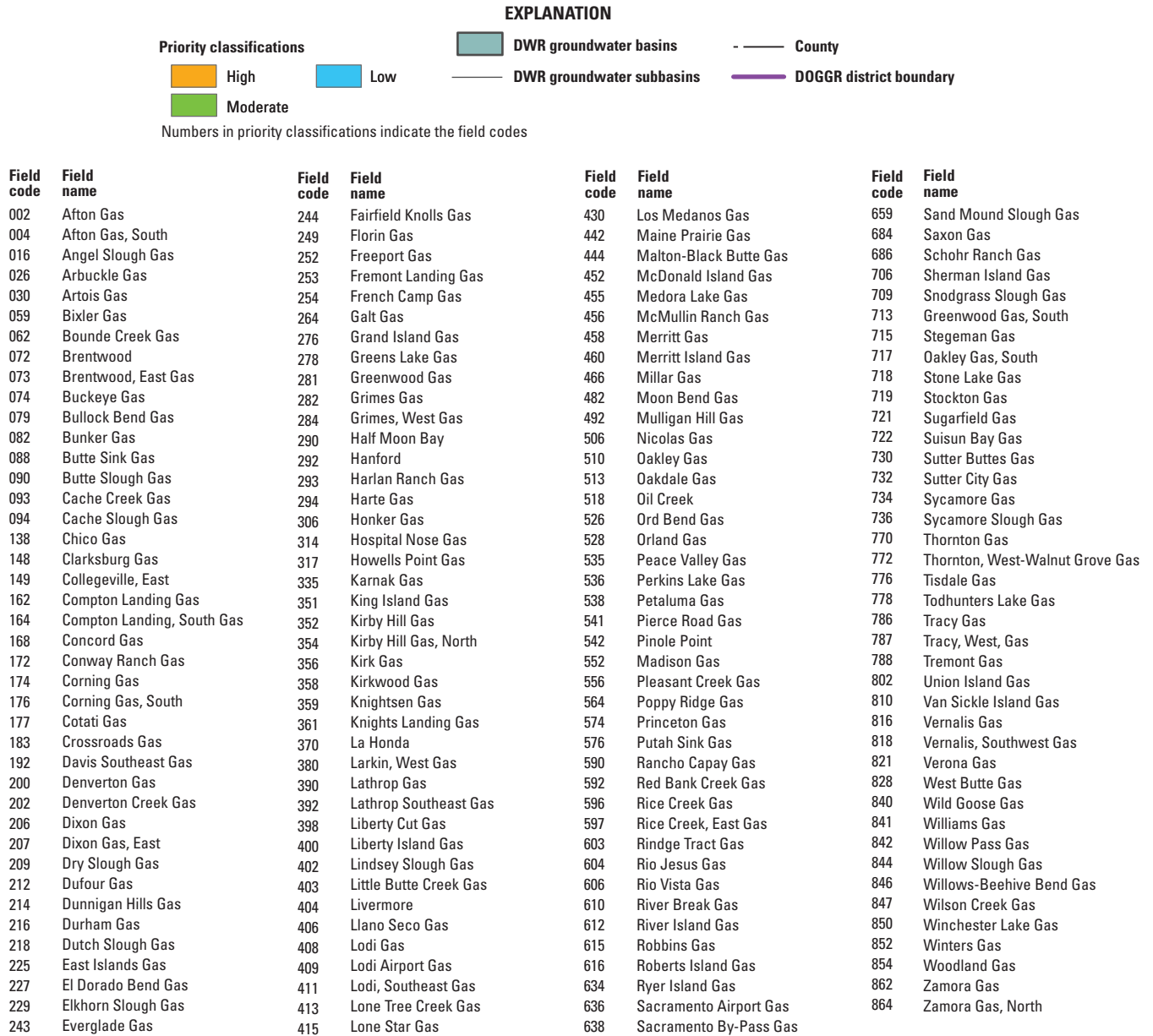
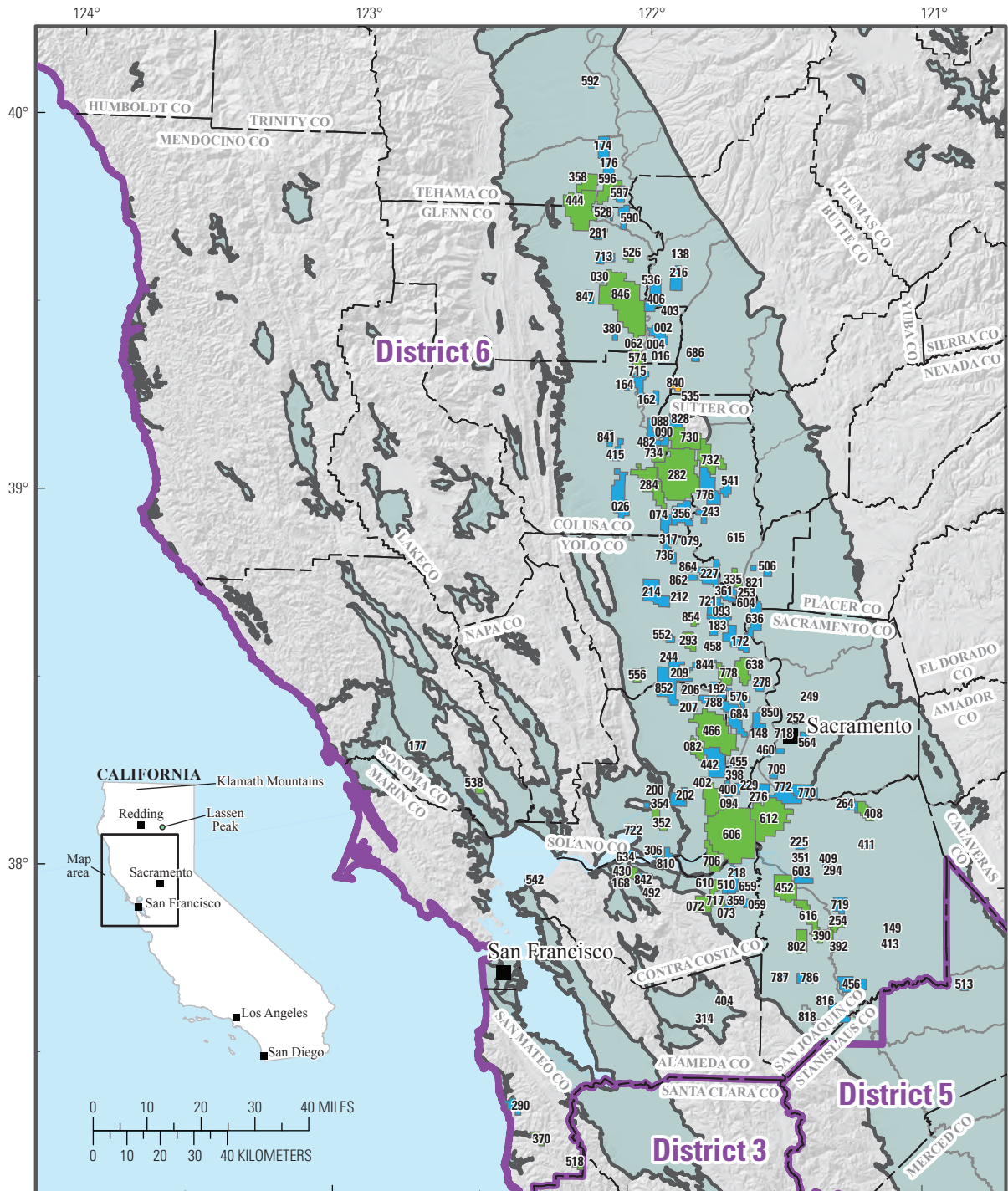


Figure 17. —Continued

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 17. —Continued

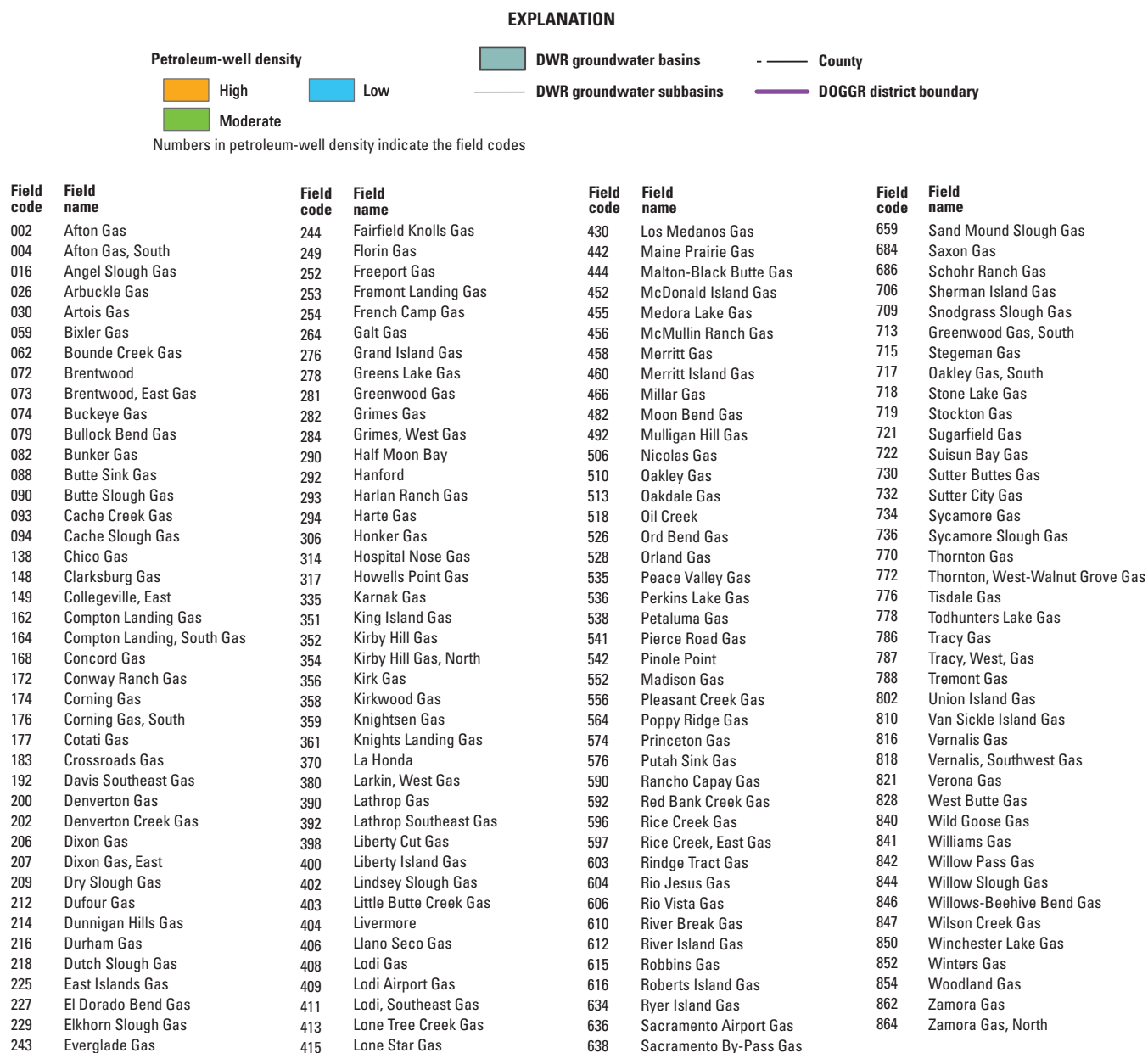
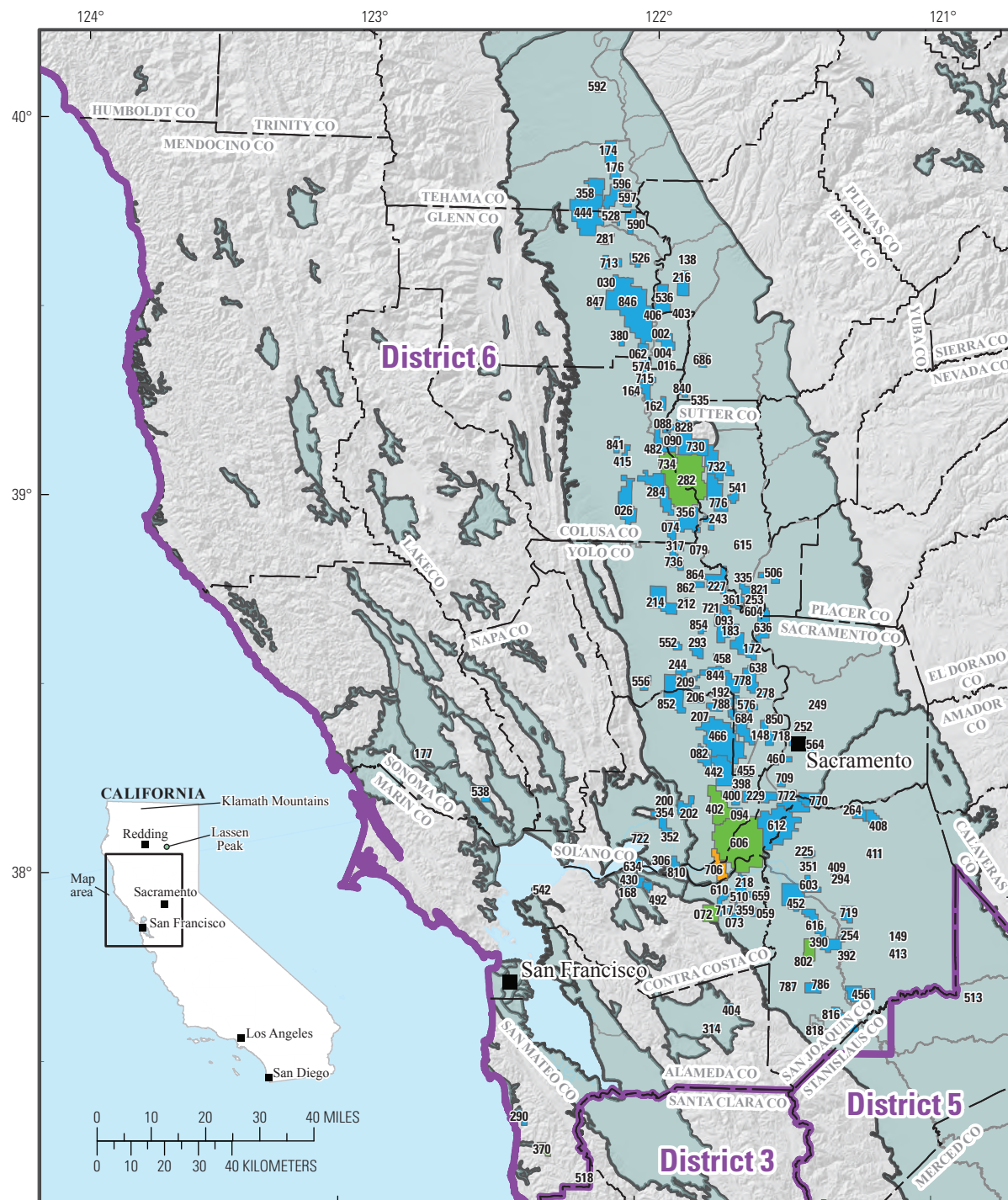


Figure 17. —Continued

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

Figure 17. —Continued

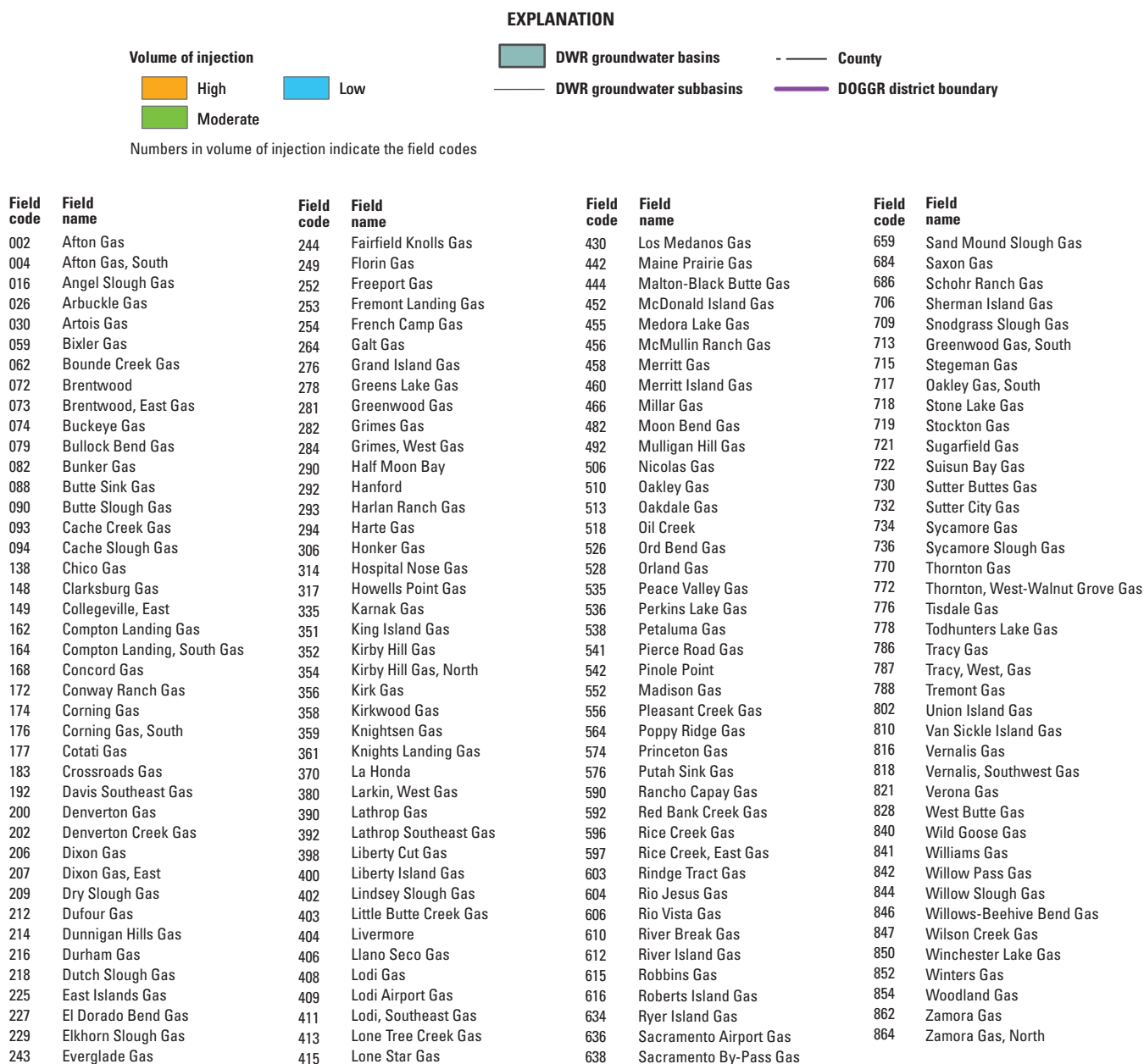
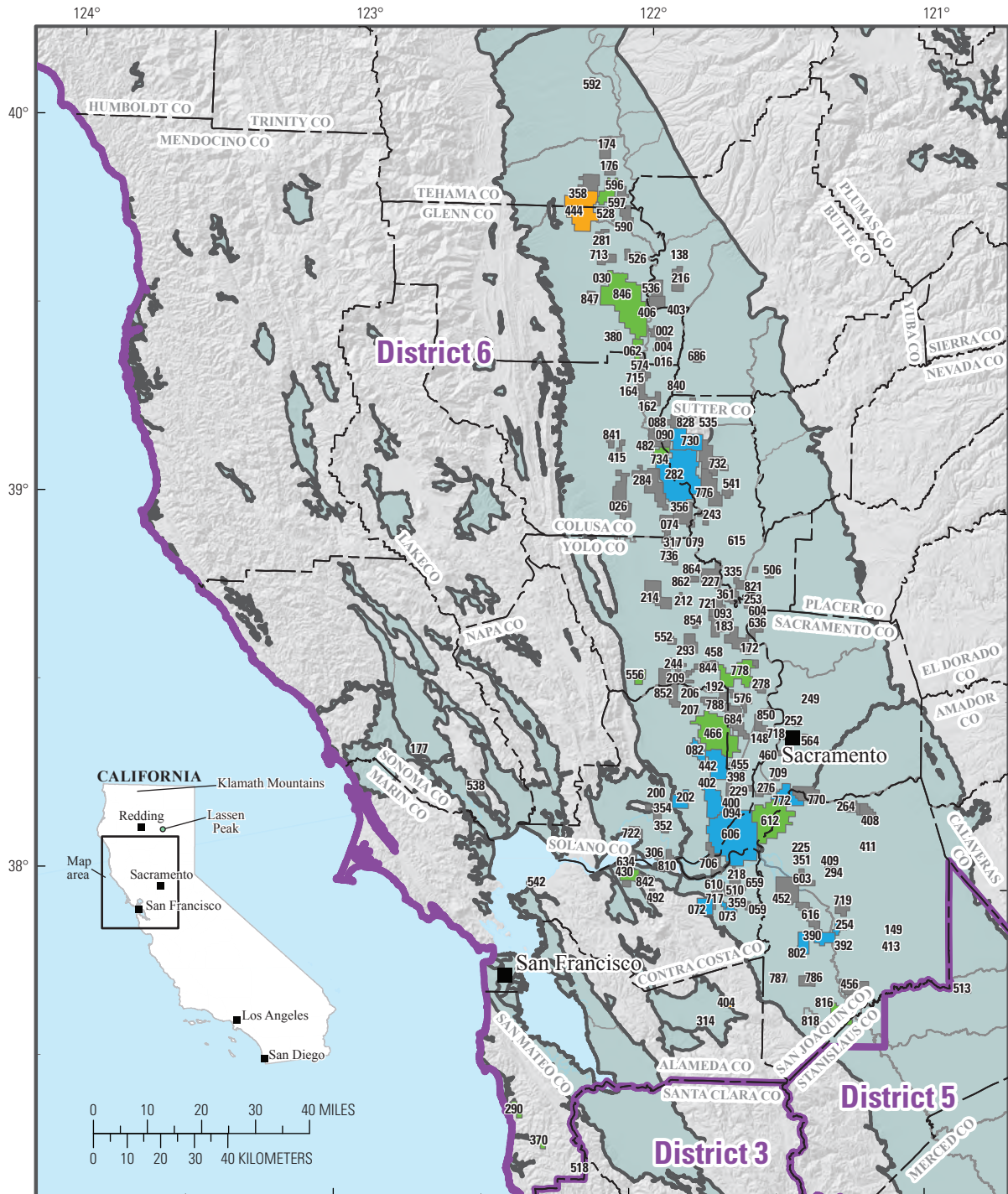


Figure 17. —Continued

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

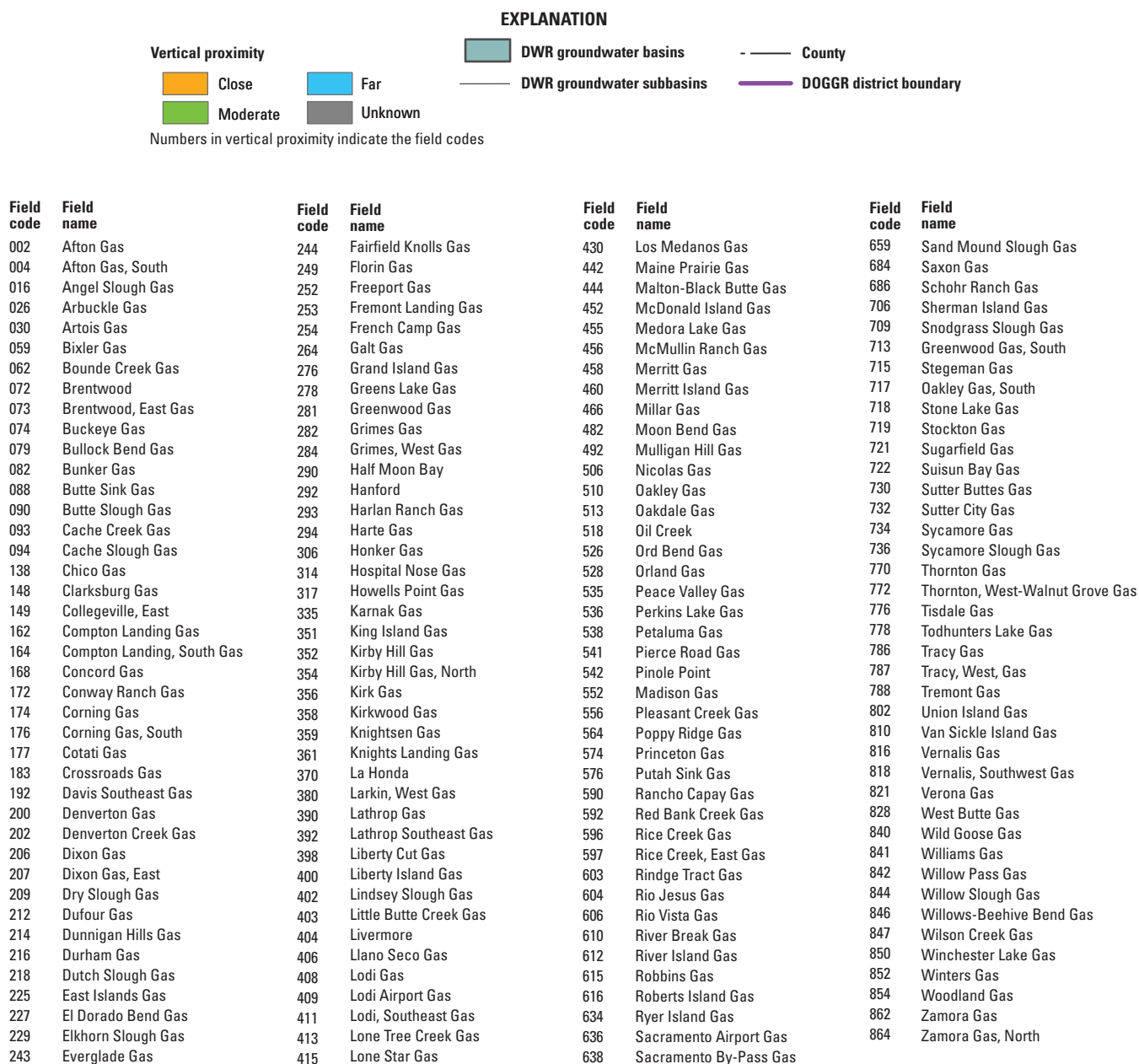


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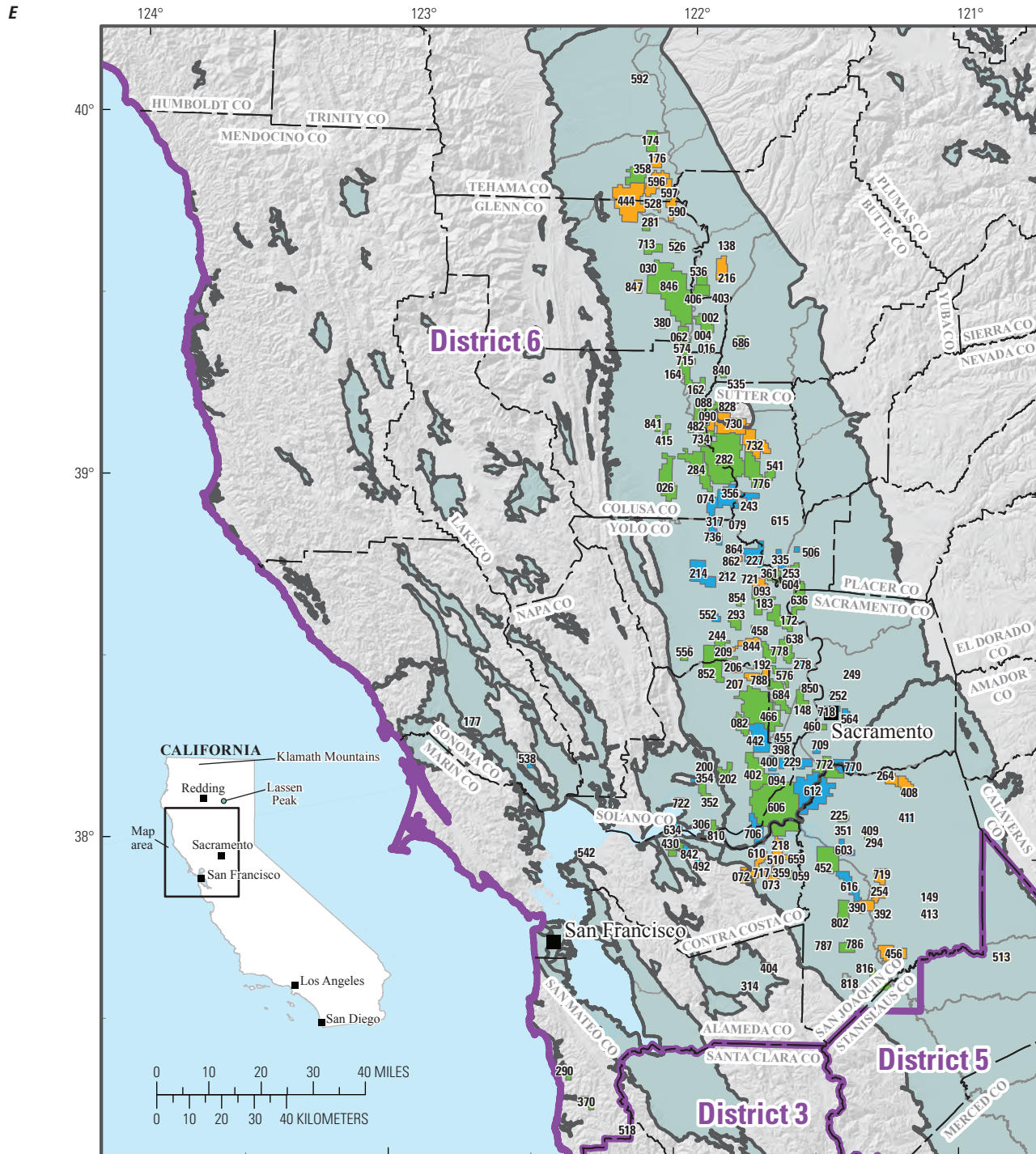


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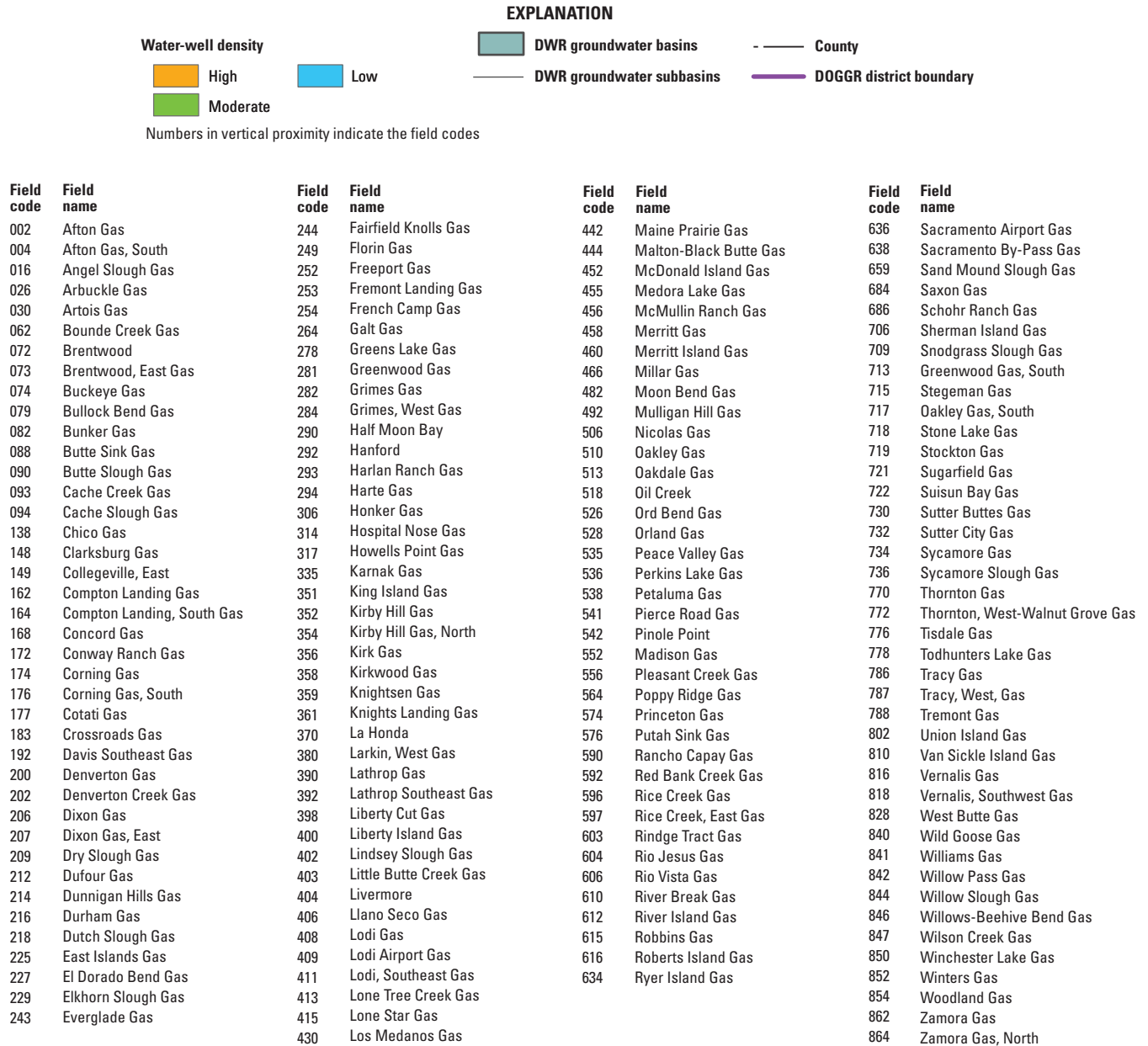


Figure 17. —Continued

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.

References Cited

- Beyer, L.A., 1995, Los Angeles Basin Province (014), in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS-30, Release 2, one CD-ROM, <http://certmapper.cr.usgs.gov/data/noga95/prov14/text/prov14.pdf>.
- Brandt, J., Sneed, M., Rogers, L.L., Metzger, L.F., Rewis, D., and House, S., 2014, California water use: U.S. Geological Survey data website, doi:10.5066/F7KD1VSV, https://ca.water.usgs.gov/water_use/.
- Bureau of Land Management, 2001, California idle well policy: Sacramento, BLM Instruction Memorandum No. CA-2002-011, 7 p., 3 attachments, accessed April 15, 2015, at <https://www.blm.gov/ca/dir/pdfs/2002/im/CAIM2002-011.pdf>.
- California Council on Science and Technology, 2014, revised 2016, Advanced well stimulation technologies in California—An independent review of scientific and technical information: California Council on Science and Technology web page, accessed June 12, 2017, at http://ccst.us/projects/hydraulic_fracturing_public/BLM.php.
- California Council on Science and Technology, 2015, An independent scientific assessment of well stimulation in California: California Council on Science and Technology web page, accessed June 12, 2017, at https://ccst.us/projects/hydraulic_fracturing_public/SB4.php.

- California Department of Water Resources, 2003, California's groundwater: California Department of Water Resources Bulletin 118, 246 p., accessed December 15, 2014, at http://www.water.ca.gov/pubs/groundwater/bulletin_118/california's_groundwater_bulletin_118_-_update_2003_/bulletin118_entire.pdf, available at <https://www.water.ca.gov/Programs/Groundwater-Management/Bulletin-118>.
- California Department of Water Resources, 2015, California's groundwater update 2013: California Department of Water Resources web page, accessed January 11, 2017 at <http://www.water.ca.gov/waterplan/topics/groundwater/index.cfm>, available at https://www.water.ca.gov/LegacyFiles/waterplan/docs/groundwater/update2013/other/webex_presentations/july_27_2015/2-3_California_Groundwater_Update_2013_SR_SC_SFB_HRs_Final.pdf.
- California Department of Water Resources, 2016, B118 interim update 2016 data: California Department of Water Resources, California's Groundwater, Bulletin 118, accessed January 11, 2017, at http://www.water.ca.gov/groundwater/bulletin118/b118_2016_data.cfm, available at http://wdl.water.ca.gov/groundwater/bulletin118/b118_2016_data.cfm.
- California Division of Oil, Gas, and Geothermal Resources, 1982, California oil and gas fields; Volume III—northern California: California Department of Conservation Division of Oil, Gas, and Geothermal Resources, 330 p., accessed June 14, 2017, at ftp://ftp.consrv.ca.gov/pub/oil/publications/Datasheets/Dtasheet_vol_3.pdf.
- California Division of Oil, Gas, and Geothermal Resources, 1992, California oil and gas fields; Volume II—southern, central coastal, and offshore California: California Department of Conservation Division of Oil, Gas, and Geothermal Resources, 645 p., accessed June 14, 2017, at ftp://ftp.consrv.ca.gov/pub/oil/publications/Datasheets/Dtasheet_vol_2.pdf.
- California Division of Oil, Gas, and Geothermal Resources, 1998, California oil and gas fields; Volume I—central California: California Department of Conservation Division of Oil, Gas, and Geothermal Resources, 499 p., accessed June 14, 2017, at ftp://ftp.consrv.ca.gov/pub/oil/publications/Datasheets/Dtasheet_vol_1.pdf.
- California Division of Oil, Gas, and Geothermal Resources, 2014, DOGGR GIS mapping: California Department of Conservation Division of Oil, Gas, and Geothermal Resources web page, accessed December 29, 2014, at <http://www.conservation.ca.gov/dog/maps/Pages/GISMapping2.aspx>.
- California Division of Oil, Gas, and Geothermal Resources, 2015, Production access databases 1977–2015: California Department of Conservation Division of Oil, Gas, and Geothermal Resources web page, accessed November 30, 2015, at ftp://ftp.consrv.ca.gov/pub/oil/new_database_format/.
- California State Water Resources Control Board, 2014, State and Regional Water Boards geospatial data: California State Water Resources Control Board web page, accessed December 15, 2014, at http://www.waterboards.ca.gov/waterboards_map.shtml.
- California State Water Resources Control Board, 2015, Model criteria for groundwater monitoring in areas of oil and gas well stimulation: California State Water Resources Control Board, 39 p., http://www.waterboards.ca.gov/water_issues/programs/groundwater/sb4/additional_resources/index.shtml.
- California State Water Resources Control Board, 2016, Geotracker GAMA data download: California State Water Resources Control Board web page, accessed January 12, 2017, at <https://geotracker.waterboards.ca.gov/gama/datadownload>.
- California State Water Resources Control Board, 2017a, Geotracker: California State Water Resources Control Board web page, accessed January 12, 2017, at <http://geotracker.waterboards.ca.gov/>.
- California State Water Resources Control Board, 2017b, Water quality in areas of oil and gas production: California State Water Resources Control Board web page, accessed January 12, 2017, at http://www.waterboards.ca.gov/water_issues/programs/groundwater/sb4/index.shtml.
- Central Valley Regional Water Quality Control Board, 2017, Oil field issues: Central Valley Regional Water Quality Control Board web page, accessed January 12, 2017, at http://www.swrcb.ca.gov/centralvalley/water_issues/oil_fields/index.shtml.
- Davies, R.J., Amond, S., Ward, R.S., Jackson, R.B., Adams, C., Worrall, F., Herringshaw, L.G., Gluyas, J.G., and Whitehead, M.A., 2014, Oil and gas wells and their integrity—Implications for shale and unconventional resource exploitation: *Marine and Petroleum Geology*, v. 56, p. 239–254, <https://doi.org/10.1016/j.marpetgeo.2014.03.001>.
- Davis, T.A., Bennett, G.L., Metzger, L., Kjos, A., Peterson, M., Johnson, J., Johnson, T., Brilmyer, C., and Dillon, D.B., 2018, Data analyzed for the preliminary prioritization of California oil and gas fields for regional groundwater monitoring: U.S. Geological Survey data release, <https://doi.org/10.5066/F7FJ2DV3>.
- Dusseault, M.B., Jackson, R.E., and MacDonald, D., 2014, Towards a road map for mitigating the rates and occurrences of long-term wellbore leakage: University of Waterloo and Geofirma Engineering Ltd., 69 p., http://geofirma.com/wp-content/uploads/2015/05/lwp-final-report_compressed.pdf.

- Faunt, C.C., ed., 2009, Groundwater availability of the Central Valley aquifer, California: U.S. Geological Survey Professional Paper 1766, 227 p., <https://pubs.er.usgs.gov/publication/pp1766>.
- Gautier, D.L., Hosford Scheirer, A., Tennyson, M.E., Peters, K.E., Magoon, L.B., Lillis, P.G., Charpentier, R.R., Cook, T.A., French, C.D., Klett, T.R., Pollastro, R.M., and Schenk, C.J., 2004, Assessment of undiscovered oil and gas resources of the San Joaquin Basin Province of California, 2003: U.S. Geological Survey Fact Sheet 2004–0343, 2 p., <https://pubs.usgs.gov/fs/2004/3043/fs-2004-3043.html>.
- Gautier, D.L., Tennyson, M.E., Cook, T.A., Chapentier, R.R., and Klett, T.R., 2012, revised 2013, Remaining recoverable petroleum in ten giant oil fields of the Los Angeles Basin, southern California: U.S. Geological Survey Fact Sheet 2012–3120, 2 p., <https://pubs.usgs.gov/fs/2012/3120/>.
- Hosford Scheirer, A., ed., 2007, Petroleum systems and geologic assessment of oil and gas in the San Joaquin Basin Province, California: U.S. Geological Survey Professional Paper 1713, <https://pubs.usgs.gov/pp/pp1713/>.
- Hosford Scheirer, A., Tennyson, M.E., Magoon, L.B., Charpentier, R.R., Cook, T.A., Klett, T.R., Pollastro, R.M., and Schenk, C.J., 2007, Assessment of undiscovered natural gas resources of the Sacramento Basin Province of California, 2006: U.S. Geological Survey Fact Sheet 2007–3014, 2 p., <http://pubs.usgs.gov/fs/2007/3014/>.
- Jackson, R.B., Lowry, E.R., Pickle, A., Kang, M., DiGiulo, D., and Zhao, K., 2015, The depths of hydraulic fracturing and accompanying water use across the United States: *Environmental Science and Technology*, v. 49, no. 15, p. 8969–8976, <https://doi.org/10.1021/acs.est.5b01228>.
- Johnson, T.D., and Belitz, K., 2015, Identifying the location and population served by domestic wells in California: *Journal of Hydrology, Regional Studies*, v. 3, p. 31–86, <https://doi.org/10.1016/j.ejrh.2014.09.002>.
- Keller, M.A., 1995, Ventura Basin Province (013), in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, Release 2, one CD-ROM, 19 p. plus supporting maps, figures, and tables, <http://certmapper.cr.usgs.gov/data/noga95/prov13/text/prov13.pdf>.
- Los Angeles Regional Water Quality Control Board, 2017, Oil and gas operation—Water quality: Los Angeles Regional Water Quality Control Board web page, accessed January 12, 2017, at http://www.waterboards.ca.gov/losangeles/water_issues/programs/Oil_and_Gas/index.shtml.
- Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., <https://doi.org/10.3133/cir1405>.
- Planert, M., and Williams, J.S., 1995, Ground water atlas of the United States, chap. B, California, Nevada: U.S. Geological Survey Hydrologic Atlas (HA) 730–B, accessed at http://pubs.usgs.gov/ha/ha730/ch_b/index.html.
- Stanley, R.G., 1995, Central Coastal Province (011), with a section on Cuyama Basin, by M.E. Tennyson, in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, Release 2, one CD-ROM, <http://certmapper.cr.usgs.gov/data/noga95/prov11/text/prov11.pdf>.
- State of California, 2013, Senate Bill No. 4, Chapter 313: California Legislative Information, accessed January 5, 2017, at https://leginfo.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB4.
- Tennyson, M.E., 1995, Cuyama Basin Province (011), in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, Release 2, one CD-ROM, <http://certmapper.cr.usgs.gov/data/noga95/prov11/text/prov11.pdf>.
- Tennyson, M.E., 1996, Santa Maria Basin Province (012), in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, Release 2, 144 p., one CD-ROM, <http://certmapper.cr.usgs.gov/data/noga95/prov12/text/prov12.pdf>.
- Tennyson, M.E., Cook, T.A., Charpentier, R.R., Gautier, D.L., Klett, T.R., Verma, M.K., Ryder, R.T., Attanasi, E.D., Freeman, P.A., and Le, P.A., 2012, Assessment of remaining recoverable oil in selected major oil fields of the San Joaquin Basin, California: U.S. Geological Survey Fact Sheet 2012–3050, 2 p., <http://pubs.usgs.gov/fs/2012/3050/>.
- U.S. Energy Information Administration, 2016, California state profile and energy estimates: U.S. Energy Information Administration web page, accessed January 11, 2017, at <https://www.eia.gov/state/?sid=CA>.
- U.S. Environmental Protection Agency, 2016, Underground injection control: U.S. Environmental Protection Agency web page, accessed January 11, 2017, at <https://www.epa.gov/uic/underground-injection-control-regulations-and-safe-drinking-water-act-provisions>.

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 $p \leq 0.05$, 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 Asphaltto ($RPD = 164$ 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 Asphaltto 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.

References Cited

- California Division of Oil, Gas, and Geothermal Resources, 2014, DOGGR GIS mapping: California Department of Conservation Division of Oil, Gas, and Geothermal Resources web page, accessed December 29, 2014, at <http://www.conservation.ca.gov/dog/maps/Pages/GISMapping2.aspx>.
- California Division of Oil, Gas, and Geothermal Resources, 2015, Production access databases 1977–2015: California Department of Conservation Division of Oil, Gas, and Geothermal Resources web page, accessed November 30, 2015, at ftp://ftp.consrv.ca.gov/pub/oil/new_database_format/.
- Davis, T.A., Bennett, G.L., Metzger, L., Kjos, A., Peterson, M., Johnson, J., Johnson, T., Brilmyer, C., and Dillon, D.B., 2018, Data analyzed for the preliminary prioritization of California oil and gas fields for regional groundwater monitoring: U.S. Geological Survey data release, <https://doi.org/10.5066/F7FJ2DV3>.
- Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water Resources Investigations, book 4, chap. A3, 522 p., <https://pubs.usgs.gov/twri/twri4a3/>.

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