Prepared in cooperation with the California State Water Resources Control Board and the Bureau of Land Management

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

Preliminary Groundwater Salinity Mapping Near Selected Oil Fields Using Historical Water-Sample Data, Central and Southern California

Scientific Investigations Report 2018–5082

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

Cover graphic. Oil fields included in this study area and colorized land areas underlying study subregions in central and southern California.

Preliminary Groundwater Salinity Mapping Near Selected Oil Fields Using Historical Water-Sample Data, Central and Southern California

By Loren F. Metzger and Matthew K. Landon

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

Prepared in cooperation with the California State Water Resources Control Board and the Bureau of Land Management

Scientific Investigations Report 2018–5082

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

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

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

U.S. Geological Survey, Reston, Virginia: 2018

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
Metzger, L.F., and Landon, M.K., 2018, Preliminary Groundwater Salinity Mapping Near Selected Oil Fields Using Historical Water-Sample Data, Central and Southern California: U.S. Geological Survey Scientific Investigations Report 2018–5082, 54 p., https://doi.org/10.3133/sir20185082.

ISSN 2328-0328 (online)

Acknowledgments

The authors thank the California State Water Resources Control Board and Bureau of Land Management for data and funding for salinity mapping near selected oil fields. We also thank the California Division of Oil, Gas, and Geothermal Resources and California Depart-ment of Water Resources for providing data and insight. Funding for this work was authorized by California Senate Bill 4.

Contents

Figures

Figures—Continued

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
	Mass	
milligram (g)	0.00003527	ounce, avoirdupois (oz)

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

$$°F = (1.8 \times °C) + 32.$$

Datum

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

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

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

Supplemental Information

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L). One milligram per liter is equivalent to 1 part per million (ppm).

Abbreviations

bls	below land surface
CB	central block
CDWR	California Department of Water Resources
COGG	California Oil, Gas, and Groundwater Project
DEM	digital elevation model
DOGGR	Division of Oil, Gas, and Geothermal Resources (California)
EC	electrical conductivity
ESI	electronic submission of information
GIS	geographic information system
GMP	groundwater management plan
MTS	Maricopa-Tejon subbasin
NEB	northeastern block
NWIS	National Water Information System
RMP	regional monitoring program
RWQCB	Regional Water Quality Control Board
SC	specific conductance
SSB	southern Sierran block
SWB	southwestern block
SWRCB	State Water Resources Control Board (California)
SWRCB-DDW	State Water Resources Control Board Division of Drinking Water (California)
TDS	total dissolved solids
UIC	Underground Injection Control
USDW	underground source of drinking water
USGS	U.S. Geological Survey
USGS-PWDB	U.S. Geological Survey Produced Waters Database
WDL	Water Data Library
WFB	west-side fold belt
WRD	Water Replenishment District of Southern California

Preliminary Groundwater Salinity Mapping Near Selected Oil Fields Using Historical Water-Sample Data, Central and Southern California

By Loren F. Metzger and Matthew K. Landon

Abstract

The distribution of groundwater salinity was mapped for 31 oil fields and adjacent aquifers and summarized by 8 subregions across major oil-producing areas of central and southern California. The objectives of this study were to describe the distribution of groundwater near oil fields having total dissolved solids less than 10,000 milligrams per liter (mg/L) based on available data and to document where data gaps exist. Salinity was represented by the measured or calculated concentration of total dissolved solids (TDS) in samples of produced water obtained from petroleum wells and groundwater obtained from water wells. The water chemistry data were used to estimate the minimum depths of TDS greater than 3,000 mg/L and greater than 10,000 mg/L in areas near selected oil fields using historical water-chemistry data coupled with available well-location and construction information.

The 10,000 mg/L threshold, representing the highest level of TDS concentration of water that could be considered as a potential source of drinking water, was present in all but 4 (Jasmin, Kern Bluff, Kern Front, and Mount Poso) of the 31 individual oil fields. Among petroleum wells, the median TDS concentration of produced water ranged from 500 mg/L for the Jasmin field to 32,636 mg/L for the Elk Hills field. Among water wells, median TDS concentrations, either reported or calculated from specific conductance, ranged from 151 mg/L for wells within 2 miles of the Ten Section field to 9,750 mg/L for wells within 2 miles of the combined North and South Belridge fields.

In general, TDS across the eight geographic subregions increased with depth, but the relation of TDS with depth varied regionally. The most pronounced increases in TDS with depth were across the West Kern Valley Floor and West Kern Valley Margin subregions on the west side of the San Joaquin Valley, and in the vicinity of the Wilmington field in the Los Angeles Basin subregion; in these areas, relatively high TDS concentrations greater than 10,000 mg/L were present within the upper few hundred to several thousand feet of land surface. Total dissolved solids concentrations increased more gradually with depth in the Middle Kern Valley Floor subregion, in the South Kern Valley Margin subregion, in the vicinity of the Montebello and Santa Fe Springs fields in the Los Angeles Basin subregion, and in the Central Coast Basin subregion. The Kern Sierran Foothills and East Kern Valley Floor subregions, on the east side of the San Joaquin Valley, had the most gradual increases in TDS with depth. Fields in the East Kern Valley Floor subregion generally had groundwater and produced water with TDS less than 10,000 mg/L that extended to a large depth compared to most other subregions.

Overall, the west side of the San Joaquin Valley in Kern County and the Wilmington field in Los Angeles County generally have the highest TDS values and the shallowest depths to high TDS. High TDS at relatively shallow depths on the west side of the San Joaquin Valley may be because of a combination of natural conditions and anthropogenic factors. In the vicinity of the Wilmington field in the Los Angeles Basin subregion, high TDS at relatively shallow depths is attributable at least in part to seawater intrusion. Fields on the east side of the San Joaquin Valley in Kern County have the lowest TDS and greatest depths to TDS greater than 10,000 mg/L because of their geologic setting adjacent to Sierra Nevada recharge areas.

Reconnaissance salinity mapping was limited by several factors. The primary limitation was the lack of well-construction data for a significant number of water wells. Bottom perforation, well depth, or hole depth were not available for 35 percent of wells used for salinity mapping. A second limitation was variability in data quality.

Total dissolved solids and specific conductance data were compiled from different data sources with varying degrees of documentation that ranged from comprehensive to very little or none. As a result, it was not always possible to assess the quality of the provided data with respect to either conditions at each well during sampling or the methodology used for sample collection and analysis. A third limitation was the lack of wells, either petroleum or water, and associated TDS data over large vertical intervals for some fields. As a result, the distribution of salinity and the depths at which TDS concentration exceeds the 3,000 and 10,000 mg/L thresholds could not always be precisely determined. This analysis highlights key gaps that need to be filled with additional analysis of other sources of information, such as borehole geophysical logs and new water sample or geophysical data collection.

Introduction

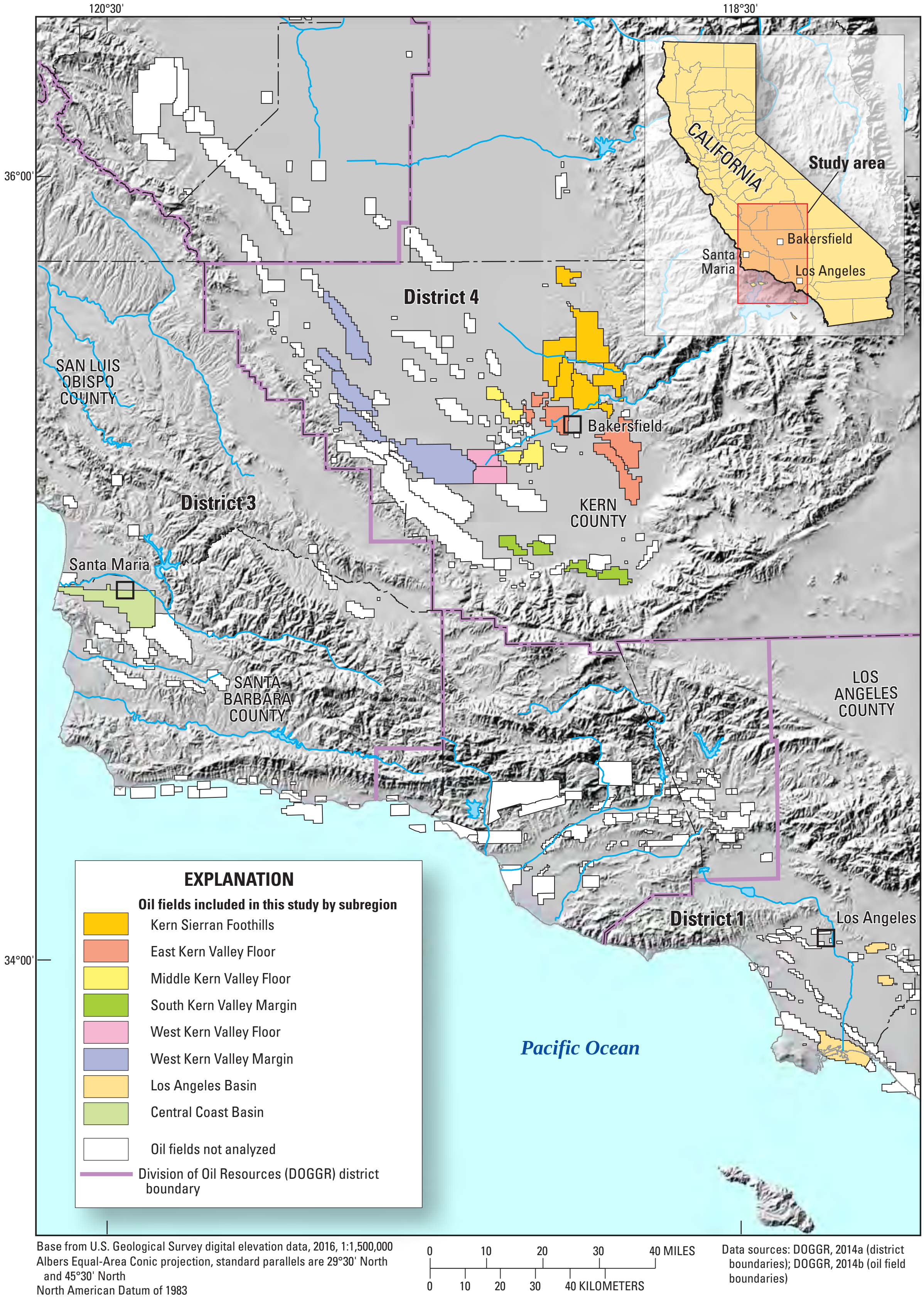
The California State Water Resources Control Board (SWRCB) initiated a regional monitoring program (RMP) in July 2015, intended to determine where and to what degree groundwater quality may be at potential risk from oil and gas well stimulation and associated production activities, including disposal of produced waters by means of surface-water ponds and underground injection. Other events or activities that have the potential to impact groundwater include the breaching of oil and gas well casings. The SWRCB also directed the RMP to establish baseline water-quality information for all fields and prioritize sampling in areas where groundwater is or may be an underground source of drinking water (USDW) as defined by the 10,000 milligrams per liter (mg/L) total dissolved solids (TDS) concentration threshold established by the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 2017).

The U.S. Geological Survey (USGS) is collaborating with the SWRCB to implement the RMP through the California Oil, Gas, and Groundwater (COGG) cooperative project and coordinating with other agencies involved in managing groundwater and oil/gas resources, including the Bureau of Land Management, the Regional Water Quality Control Boards (RWQCBs), the California Department of Conservation's Division of Oil, Gas, and Geothermal Resources (DOGGR), and local water agencies.

Groundwater resources in California that are relatively close to the land surface (less than 1,000 feet [ft]) and of the highest quality, usually containing TDS less than 1,000 mg/L, have been tapped for drinking water, irrigation, and other beneficial uses. The location, extent, and quality of those resources are relatively well understood. The use of groundwater resources in deeper zones (greater than 1,000 ft) and areas containing poorer quality water has been expanding, particularly during recent droughts (California Department of Water Resources, 2015a). The oil and gas industry has historically been responsible for protecting groundwater in California containing less than 3,000 mg/L TDS through proper well-construction techniques and avoiding waste injection into these zones (Bishop, 2014). As a result, there is information in oil and gas well records about the location of the "base of fresh water," or estimates of the depth at which 3,000 mg/L TDS is reached (Horsely Witten Group, 2011). However, there is relatively little information about the distribution of groundwater resources containing between 3,000 and 10,000 mg/L TDS in areas near oil fields.

Purpose and Scope

The objectives of this study were to describe the distribution of groundwater near oil fields having TDS less than 10,000 mg/L based on available water-sample data and to document where data gaps exist. This report presents a compilation of water-quality data collected in and around 31 oil fields in southern and central California (fig. 1); no new samples were collected as part of this study. These fields were selected for reconnaissance regional salinity mapping because water-sample data were available in proximity to these fields, and these fields represent a range of geographic and hydrogeologic settings across major oil-producing areas of central and southern California.



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

Data sources: DOGGR, 2014a (district boundaries); DOGGR, 2014b (oil field boundaries)

Figure 1. Locations of oil fields included in this report grouped by assigned subregion, locations of unanalyzed oil fields, and the Division of Oil, Gas, and Geothermal Resources (DOGGR) district boundaries.

Methods

The spatial (areal and vertical) distribution of groundwater salinity was analyzed and mapped using available data for petroleum and water wells. For this initial salinity mapping effort, 31 oil fields were selected, and data from a variety of sources were compiled, processed, and attributed.

Field Selection Process

Oil fields included in this reconnaissance salinity mapping effort were selected as a subset of fields categorized as high and moderate priority fields by Davis and others (2018) based on (1) vertical proximity of useable groundwater to oil/gas resources, (2) the density of all petroleum wells and those used for injection and waste disposal, and (3) the volume of produced water re-injected into oil-bearing formations via injection and waste-disposal wells. The objective of the study by Davis and others (2018) was to support planning of regional groundwater monitoring tasks, including prioritizing which of the 487 onshore oil and gas fields in California should be addressed by this reconnaissance salinity mapping study. Davis and others (2018) identified 112 fields as having a high priority and 111 fields as having a moderate priority for regional monitoring of nearby groundwater. Of these, a subset of 31 (26 high, 5 moderate) fields were selected for this reconnaissance salinity mapping study: 27 fields in DOGGR District 4 (Kern County), 3 fields in DOGGR District 1 (Los Angeles), and 1 field in DOGGR District 3 (Central Coast; table 1). These fields were chosen because water-sample data were available in proximity to these fields and because the fields represent a range of geographic and hydrogeologic settings across major oil-producing areas of central and southern California. For the purposes of salinity mapping, individual fields were grouped based on geographic area but analyzed at both field and subregional scales. The designated subregional groupings and number of individual fields assigned to each, denoted in parentheses, include Kern Sierran Foothills (seven), East Kern Valley Floor (five), Middle Kern Valley Floor (four), South Kern Valley Margin (four), West Kern Valley Floor (two), West Kern Valley Margin (five), Los Angeles Basin (three), and Central Coast Basin (one; fig. 1). Within these subregional groupings, some fields (North and South Belridge, North and South Coles Levee) were combined because of their proximity and (or) limited data. The combination of North Belridge with South Belridge and North Coles Levee with South Coles Levee resulted in 31 individual fields being treated as 29 aggregated fields for the purposes of this report.

Table 1. Oil fields listed by Division of Oil, Gas, and Geothermal Resources (DOGGR) district and geographic region included in reconnaissance salinity mapping, central and southern California.

[See figure 1 for locations of DOGGR districts, geographic subregions, and oil fields. Subregions are listed in the order presented in the report]

Subregion	Field
DOGGR District 4	
Kern Sierran Foothills	Jasmin
Kern Sierran Foothills	Kern Bluff
Kern Sierran Foothills	Kern Front
Kern Sierran Foothills	Kern River
Kern Sierran Foothills	Mount Poso
Kern Sierran Foothills	Poso Creek
Kern Sierran Foothills	Round Mountain
East Kern Valley Floor	Edison
East Kern Valley Floor	Fruitvale
East Kern Valley Floor	Mountain View
East Kern Valley Floor	Rosedale
East Kern Valley Floor	Rosedale Ranch
Middle Kern Valley Floor	Canfield Ranch
Middle Kern Valley Floor	Greeley
Middle Kern Valley Floor	Rio Bravo
Middle Kern Valley Floor	Ten Section
South Kern Valley Margin	San Emidio Nose
South Kern Valley Margin	Tejon
South Kern Valley Margin	Wheeler Ridge
South Kern Valley Margin	Yowlumne
West Kern Valley Floor	Coles Levee, North and South
West Kern Valley Margin	Belridge, North and South
West Kern Valley Margin	Cymric
West Kern Valley Margin	Elk Hills
West Kern Valley Margin	Lost Hills
DOGGR District 1	
Los Angeles Basin	Montebello
Los Angeles Basin	Santa Fe Springs
Los Angeles Basin	Wilmington
DOGGR District 3	
Central Coast Basin	Santa Maria Valley

Data Sources

Sources of water-quality data included DOGGR, the California Department of Water Resources (CDWR), the SWRCB, the USGS, and the Water Replenishment District of Southern California (WRD). The number of wells from each of these data sources and period of record is summarized in table 2. These data sources included widely varying degrees of documentation, ranging from detailed information about sample type and methodology to little or no supporting information. Given the uncertainty of data quality, it was not possible to screen out all unrepresentative samples. For the purposes of this report, petroleum wells are defined as including all wells installed in support of developing oil and gas resources, including oil and gas recovery, injection, and water source wells. Petroleum well samples were screened to omit samples representing injectate, tank, or composite samples where the sample was not collected from a specific well. Although samples derived from drill stem tests (DSTs) or Johnson formation testers (JFTs) are not considered to be as representative of formation water as produced-water samples, owing to possible mixing with fluids used for well construction, these samples were retained for the sake of consistency with similar efforts at characterizing salinity across oil fields (Gillespie and others, 2017). For water-well samples, care was taken to omit samples not representing groundwater, such as pore-water samples obtained from the unsaturated zone above the water table. Other samples, particularly from relatively shallow water wells (bottom perforation, completion depth, or hole depth less than 200 ft), appear to represent sources such as perched groundwater or infiltration from surface impoundments, which may not be representative of regional groundwater conditions. However, given the uncertainty in being able to distinguish regional from local effects of salinity at the scales used for this report, samples from shallow water wells were retained as part of the salinity mapping effort.

The Division of Oil, Gas, and Geothermal Resources was the primary source of TDS data for petroleum wells and consisted of two separate databases. The first was the Underground Injection Control (UIC) database, from DOGGR's California Well Information Management System (CalWIMS). The database includes information on each well, including location, type, status, construction, geologic formation, and water analyses. Data were provided by DOGGR in the form of a Microsoft Access file on February 28, 2015, containing information on more than 13,000 wells in the study area used primarily for injection (water flood, steam flood, or cyclic steam) in support of petroleum production activities. Water-sample data in the UIC database is limited to TDS and boron for both produced and injectate waters. Injectate analyses were not used for salinity mapping because that water can be a mixture of produced waters, wastewater, or water mixed with chemicals that is unrepresentative of the formation into which it is injected. Although documentation of the reported TDS values was not available, the values are referred to as "zone water" in the dataset and are understood to represent water sampled in the injection zone prior to injection (Curtis Welty, DOGGR, written commun., June 22, 2015). Many of the sample data values appear to be non-unique, with just 289 values representing TDS for all 13,219 study-area wells in the UIC database. For 9 of the 31 oil fields analyzed for this report, more than 50 percent of the UIC wells in each field were represented by a single TDS value. The highest percentages of wells represented by a single TDS value were associated with Kern River field (1,719 of 1,868 wells), Rio Bravo field (11 of 12 wells), and Yowlumne field (38 of 42 wells) at 92 percent, 92 percent, and 90 percent, respectively. The reporting of a limited number of identical values for numerous wells indicates that most of the TDS data do not represent unique analytical results. The TDS values may have been assigned to UIC wells based on location or other factors such as the geologic formation corresponding to the depth of injection. A detailed assessment to determine possible commonalities of wells with identical TDS values was beyond the scope to this study. In cases where it was not possible to distinguish actual versus assigned TDS values, only wells having a unique TDS value not associated with any other well within the same field were retained for salinity mapping. As a result of this approach, the report used a total of 114 UIC wells (table 2).

The second DOGGR database that was used for this report is the Oil and Gas Online Data website (http://www.conservation.ca.gov/dog), which includes separate archives of water analyses and well completion reports for petroleum wells. The archive of water analyses includes scanned copies of analyses for oil-field waters, but the archive is limited to District 4 (ftp://ftp.consrv.ca.gov/pub/oil/chemical_analysis). In addition to TDS data, many of these analyses include results for inorganic constituents, trace elements, and nutrients. The DOGGR Well Finder, an online archive of well completion reports, includes information on location, geology, well construction, and documentation of well modifications throughout each well's history (http://www.conservation.ca.gov/dog/Pages/Wellfinder.aspx). The DOGGR Well Finder was also used for wells in the UIC database that were lacking data for depth to top of perforated interval. Gillespie and others (2017) used the DOGGR archives to compile water sample and related data for about 580 wells as part of a previous study to evaluate groundwater salinity in the southern San Joaquin Valley. Many of the 580 wells in the report by Gillespie and others (2017), plus additional wells compiled as part of the COGG project, were used for the salinity mapping presented in this report, for a total of 764 wells from the DOGGR-online data sources (table 2). Records obtained from the DOGGR archives generally included sample date, depth of the tested interval, and source of the water (Gillespie and others, 2017). Where available, sample source is indicated in the USGS data release accompanying this report (Metzger and others, 2018).

Table 2. Summary by data source of petroleum and water wells compiled for salinity mapping, central and southern California.

[Numbers in parenthesis represent the value shown as a percentage of the corresponding total number of wells. **Abbreviations**: CDWR-WDL, California Department of Water Resources, Water Data Library; DOGGR, California Division of Oil, Gas, and Geothermal Resources; DOGGR-UIC, California Division of Oil, Gas, and Geothermal Resources, Underground Injection Control; SWRCB, California State Water Resources Control Board; SWRCB-DDW, California State Water Resources Control Board, Division of Drinking Water; TDS, total dissolved solids; USGS-NWIS, U.S. Geological Survey, National Water Information System; USGS-PWDB, U.S. Geological Survey, Produced Waters Database; WRD, Water Replenishment District of Southern California; %, percent]

Primary database[1]	Well type	Number of wells	Number of wells with construction data[2]	Number and percentage of wells with multiple TDS[3] entries	Number and percentage of wells wholly or partially represented by TDS calculated from specific conductance	Period of record for wells used in salinity mapping
DOGGR-UIC	Petroleum	114	111	None	None	1952–2013
DOGGR-online data	Petroleum	764	763	100 (13%)	None	1930–2014
SWRCB-GeoTracker	Petroleum	11	11	2 (18%)	None	2015
USGS-PWDB	Petroleum	[4]272	241	63 (23%)	None	[5]1937–80
CDWR-WDL	Water	[6]2,182	1,202	966 (44%)	797 (36%)	1930–2014
SWRCB-DDW	Water	[7]430	302	387 (90%)	27 (6%)	1978–2014
SWRCB-GeoTracker	Water	8	8	8 (100%)	None	2014–16
SWRCB-miscellaneous	Water	98	68	None[8]	None	1994–2015
USGS-NWIS	Water	[9]698	612	225 (32%)	325 (46%)	1927–2014
WRD	Water	[10]130	130	122 (94%)	3 (2%)	1998–2013
TOTALS		[11]4,677	[12]3,418	[13]1,867 (40%)	1,152 (25%)	—

[1]Some wells have records in multiple databases.

[2]Top perforation for petroleum wells, and bottom perforation, well depth, or hole depth for water wells.

[3]Reported TDS or calculated TDS from specific conductance; wells with multiple values represented by the median.

[4]Includes an undetermined number of wells that are also in the DOGGR archives.

[5]Information on sample dates incomplete, so period of record may be longer.

[6]Includes 74 wells that are also in other listed data sources.

[7]Includes 100 wells that are also in other listed data sources.

[8]Multiple records available for an undetermined number of wells. Only most recent analysis used for salinity mapping.

[9]Includes six wells that are also in other listed data sources.

[10]Includes 81 wells that are also in other listed data sources.

[11]Number of unique wells, not counting those present in multiple data sources: 1,131 petroleum and 3,546 water wells.

[12]Number of unique wells, not counting those present in multiple data sources: 1,096 petroleum and 2,322 water wells.

[13]Number of unique wells, not counting those present in multiple data sources: 159 petroleum and 1,708 water wells.

A third source of data for petroleum wells was the SWRCB's GeoTracker database. This is a website data portal that contains information on facilities having the potential to affect groundwater quality (http://geotracker.waterboards.ca.gov/search.asp). GeoTracker includes water analyses from petroleum wells specifically compiled as part of monitoring impacts from oil and gas production activities. Total dissolved solids data were retrieved from GeoTracker for 11 wells in the study area (table 2).

The fourth and final data source for petroleum wells was the USGS National Produced Waters Geochemical Database (USGS-PWDB), administered by the USGS Energy Resources Program. This database is a nationwide compilation of various individual databases and reports (Blondes and others, 2014). It contains geochemical data for produced-water samples plus ancillary well information. The USGS-PWDB contains data for inorganic (including TDS), trace element, and physical parameters for petroleum wells in California from 1937 to 1980. This database contains information on 272 wells in the oil fields mapped for this report, including an undetermined number of wells that are also in the DOGGR archives (table 2). For the version (v2.1) of the USGS-PWDB available at the time salinity maps were originally created, approximately 40 percent of the petroleum well entries for California were lacking data for top perforation, 15 percent had no sample date, and about 10 percent were duplicates. The information is neither independently verified nor systematically checked for inconsistencies, but errors are corrected when noted by database users (Blondes and others, 2014). The latest version of this database (v2.3) includes data for top perforation for several wells for which this information was previously unavailable (Blondes and others, 2017). These additional data were included in this report and salinity maps modified as necessary. The DOGGR archives were also queried for wells missing data for top perforation, which resulted in locating data for top perforation for all but 31 of the 272 USGS-PWDB wells used for salinity mapping.

The first source for water-well data was a CDWR database referred to as the Water Data Library (WDL). This source contains inorganic chemistry data for groundwater and surface-water samples dating back to 1930. The WDL is a publicly accessible online database that can be searched by map-based interface, by county, or by site (station name or number; California Department of Water Resources, 2015b). Data in the WDL for TDS and specific conductance (primarily laboratory measurements) for 2,182 wells were used for salinity mapping, including 74 wells that are also in the other water-well databases (table 2). Well-construction information is not available in this database; however, bottom perforation, well depth, and (or) hole depth data for 1,202 of the CDWR-sampled wells were found in well drillers' logs compiled by CDWR and in USGS National Water Information System (NWIS) and SWRCB databases.

The SWRCB was the second major source of water-well data, comprised of several individual sources including the SWRCB Division of Drinking Water (SWRCB-DDW), GeoTracker, and miscellaneous sources. The SWRCB-DDW database contains water analyses for public-supply wells located throughout the State (California State Water Resources Control Board, 2015). Total dissolved solids and specific conductance data for 430 public-supply wells available in the SWRCB-DDW database were used for salinity mapping (table 2). Although well-construction data is not available in the SWRCB-DDW geochemical database, a separate database referred to as the California Drinking Water Source Assessment and Protection Program (CADWSAP), obtained from the SWRCB in 2015, contains limited well-construction data (top perforation and screen length) for 191 of the SWRCB-DDW wells used for salinity mapping. Depth to bottom perforation for these particular wells was estimated as the sum of depth to top perforation and screen length based on the assumption that the screened interval was continuous. Well-construction information for an additional 111 wells was located in other data sources used for this report. The SWRCB GeoTracker database contains water analyses for samples from monitoring wells in areas requiring cleanup as a result of activities that have affected or may affect groundwater quality (California State Water Resources Control Board, 2016). This database includes TDS and specific conductance data for eight wells used for salinity mapping (table 2). Miscellaneous SWRCB data sources accounted for TDS and specific conductance data from 98 wells used for monitoring or water supply in support of oil and gas production. These miscellaneous data sources included electronic submission of information (ESI) reports, groundwater management plans (GMP), and historical data sets submitted to the SWRCB by oil and gas producers. The ESI and GMP documents included well-construction information for most of the wells used for salinity mapping.

The third source of data for water wells used for salinity mapping was the USGS NWIS, a repository for the storage of all data collected by the USGS to document, describe, and measure water-resource conditions (U.S. Geological Survey, 2015). Total dissolved solids and specific conductance data are available for 698 wells used for salinity mapping, of which 612 wells had pertinent construction information, either bottom perforation depth, completed well depth, or hole depth (table 2). The NWIS also contains well-construction information for 700 WDL wells having TDS and specific conductance data used for salinity mapping.

The WRD database was the fourth and final source of data from water wells used for salinity mapping. Data were provided by WRD in the form of a Microsoft Access file on August 7, 2013. This dataset represents a compilation of location, well type, construction, geologic formation, and inorganic chemical analyses from various sources, including USGS, CDWR, WRD, and local water agencies for about 2,500 wells located in the Los Angeles Basin. For the purposes of this report, TDS and specific conductance data from 130 wells located in and around the Montebello, Santa Fe Springs, and Wilmington fields, including 81 wells also available in the previously described data sources, were used for salinity mapping (table 2).

The resulting data compiled for this study, including metadata, are available as a USGS data release (Metzger and others, 2018).

Data Processing

Salinity datasets were assembled for all wells having TDS or specific conductance data and organized by well type: (1) production and injection petroleum wells and (2) water wells (supply and monitoring). In addition to TDS and specific conductance, pertinent information extracted and compiled for both well types included data source, well identifier, relevant oil field, well location, well-construction information (particularly perforation depths), and land-surface altitude. Land-surface altitudes were estimated using a USGS 30-meter digital elevation model (DEM) in ArcGIS based on well location. For petroleum wells, depth to the top perforation was the primary well-construction attribute of interest because it potentially represents the closest depth of oil/gas production activities to overlying aquifers. For water wells, depth to the bottom perforation was the primary well-construction attribute of interest because it potentially represents the maximum depth at which water may be currently extracted for beneficial use. Although sample data from water and petroleum wells may represent mixtures of water from large vertical perforated intervals, the bottom perforations of water wells and top perforations of petroleum wells are the bounding values for the depths those samples represent.

Salinity Data

Total dissolved solids and specific conductance data compiled for the salinity datasets represent all values that were available at the time reconnaissance salinity mapping was undertaken for this report. For the purposes of data processing and mapping, data for petroleum and water wells were handled separately, but within each dataset, wells were grouped regardless of well subtype or data source. For example, all petroleum wells, whether identified as being used for injection and obtained from the UIC database or identified as being used for production and obtained from the USGS-PWDB or DOGGR-Well Finder, were combined into a single dataset. Among the data available were multiple TDS and (or) specific conductance analyses from different sampling dates. For petroleum wells, approximately 14 percent of wells included TDS and (or) specific conductance for more than one date. For water wells, approximately 48 percent of wells included data for multiple dates, with about 9 percent of such wells (314) having TDS and (or) specific conductance spanning at least 25 years (Metzger and others, 2018). For those particular wells, mapped TDS values represent the median for the entire record, irrespective of the beginning and ending date or overall length of record. These median values are included in the USGS data release for this study (Metzger and others, 2018). For the SWRCB-miscellaneous data, time-series data exist but were not readily available for salinity mapping; the data used represented the most recently measured TDS or specific conductance data reported (table 2). For all other data sources, mapped TDS values represent a single discrete sample for a particular date (some dates in the USGS-PWDB are not specified).

As noted previously, TDS data were not available for all wells. Although TDS data were available for all petroleum wells used for salinity mapping, approximately 25 percent of water wells were lacking TDS data for all or at least some sample dates. Specific conductance, a measure of water's ability to conduct an electrical current, is a good approximation of the salinity of natural waters (Drever, 1982). For water wells wholly (no samples with TDS analyses) or partially (selected dates within period of record without TDS analyses) lacking reported TDS, specific conductance was used to calculate TDS. A simple linear regression model (ordinary least squares; Helsel and Hirsch, 2002) was developed for each of four combinations of hydrogeologic province (Belitz and others, 2003) and DOGGR district where the two coincided: (area 1) the Transverse and Selected Peninsular Ranges hydrogeologic province and DOGGR District 1, (area 2) the San Joaquin Valley part of the Central Valley hydrogeologic province and DOGGR District 4, (area 3) the Sierra Nevada hydrogeologic province and DOGGR District 4, and (area 4) the Southern Coast Ranges hydrogeologic province and DOGGR District 3 (fig. 2). The simple linear regression models for areas 1, 2, 3, and 4 used approximately 38,110, 8,010, 165, and 8,674 pairs of data from all data sources for 7,001, 3,526, 137, and 3,048 wells, respectively, located throughout the four areas irrespective of oil field. Data pairs used to derive this relation were included in the regression model only if (1) TDS was less than 50,000 mg/L, (2) computed values for TDS were within 25 percent of measured values for TDS, and (3) TDS ranged between 0.55 and 0.81 percent of the value of specific conductance. The third criteria used to qualify the data used in this report represents the expected range of the ratio of TDS to specific conductance for most natural waters and is a recommended quality-assurance check for computed TDS (Friedman and Erdmann, 1982). Slightly different ranges for this ratio have been cited for use as a general quality-assurance check (0.55–0.75; Hem, 1985) and for measured TDS determined by residue on evaporation at 180 °C (0.55–0.86; Friedman and Erdmann, 1982). The resulting regression equations for the four areas (area 1, equation 1; area 2, equation 2; area 3, equation 3; area 4, equation 4), with the intercept set to zero and R-squared values between 0.98 and 1, were used to calculate TDS for analyses in the water-well salinity dataset based on reported specific conductance:

$$TDS = 0.6888SC \qquad (1)$$

$$TDS = 0.718SC \qquad (2)$$

$$TDS = 0.6527SC \qquad (3)$$

$$TDS = 0.6825SC \qquad (4)$$

where

SC is the reported specific conductance in microsiemens per centimeter (µS/cm) at 25 °C, and

TDS is the calculated TDS in mg/L.

Subsets of wells and their associated data for the 31 oil fields and surrounding buffer areas within 2 miles of administrative field boundaries included 1,131 petroleum wells and 3,546 water wells (table 3). A small number of wells (26) were represented by multiple (2–3) discrete samples collected at unique depths within the same well. The petroleum wells selected for the mapped fields were located within the administrative boundaries of each field. These boundaries mark the areal extent, both on and offshore, of an oil or gas field within which all producing wells are located. Petroleum wells in the Wilmington field (Los Angeles Basin subregion) identified as being located offshore were omitted from salinity mapping. The water wells selected for the mapped fields were located both within and outside the administrative field boundaries (version dated November 19,

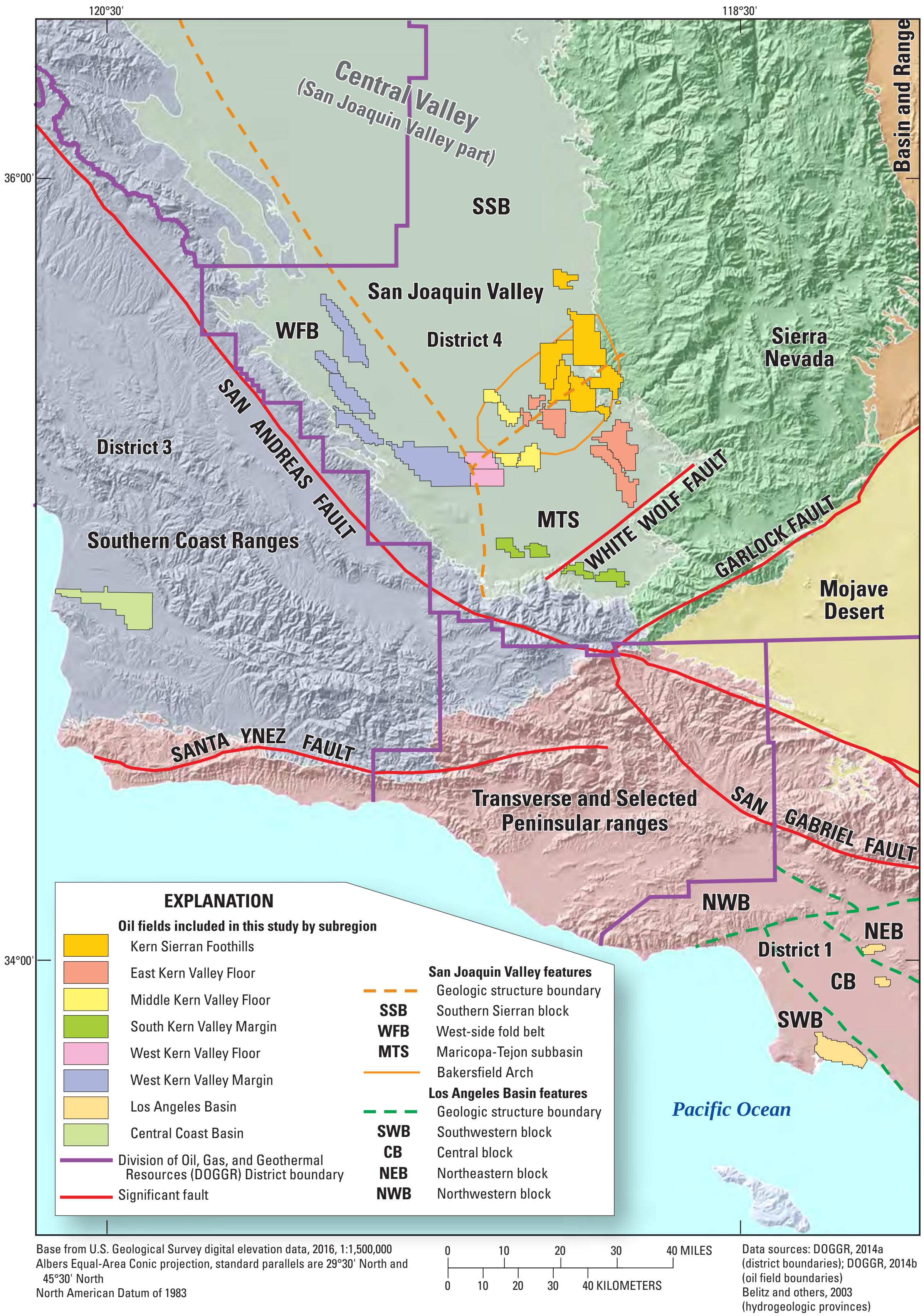


Figure 2. Major geographic and geological features and Division of Oil, Gas, and Geothermal Resources (DOGGR) district boundaries, central and southern California. Broader colorized land areas underlying study subregions represent hydrogeologic provinces.

2014, and downloaded December 1, 2014, from http://www.conservation.ca.gov/dog/maps/Pages/GISMapping2.aspx) to a distance of up to 2 miles. The exception was the Wilmington field, where well selection was limited to a 1-mile buffer area to avoid including what would have constituted a majority of water wells within the administrative field boundaries of several adjacent unmapped fields with a 2-mile buffer. The designation of a buffer area around each mapped field was done with the idea that the effects of oil and gas activities could laterally extend some distance outward beyond administrative field boundaries. Where mapped fields were adjacent or in proximity with each other, overlapping buffer areas resulted in some water wells being used for salinity mapping for more than one field. A geographic information system (GIS) and its associated ArcGIS tools was used to delineate the areal extent of the buffers and identify which wells were located within administrative field boundaries and the surrounding buffer area for each mapped field. The resulting data compiled for this study, including metadata, are available as a USGS data release (Metzger and others, 2018).

Well-Construction Data

Wells that were compiled as part of the data processing step, but that were missing pertinent information needed for salinity mapping, were referred to as unattributed. For petroleum wells, the top perforation was not available for a relatively small number of wells, ranging from about 1 percent (Edison and Fruitvale fields) up to 40 percent (Santa Fe Springs field) for 12 of the 29 aggregated fields (table 3). For the remaining 17 aggregated fields, top perforation was known for all petroleum wells. For the purposes of this report, petroleum wells missing top perforation (unattributed) information were assigned a value representing the median top perforation for all attributed wells located within the same field as the unattributed wells.

Unattributed water wells were dealt with somewhat differently than petroleum wells. Bottom perforation was the preferred attribute for water wells, but it was available for only 36 percent (1,268) of the 3,546 compiled water wells. An additional 197 wells (including 191 with SWRCB-DDW as the primary TDS data source and 2 wells with CDWR-WDL as the primary TDS data source, but also available in SWRCB-DDW) had top perforation and reported screen length data from which an approximate bottom perforation could be estimated. Wells lacking any perforation information but having completed well depth and (or) hole depth numbered 857. Given that for most water wells the completed well depth and hole depth are typically not much deeper than the bottom perforation, these were considered acceptable substitutions. Even allowing for estimated bottom perforation and completed well or hole depth substitutions, 1,224 (35 percent) of all water wells compiled had insufficient construction information. Instead of perforation data, or acceptable alternatives, values representing the median bottom perforation for attributed wells were assigned to all of the 1,224 unattributed wells on a field-by-field basis (table 3). A number of the salinity mapped fields, particularly in Kern County, share the same water wells within overlapping buffer areas. For the purposes of this report, each field and its associated well data were treated independently. As a result, the median value assigned to unattributed water wells was as much as several hundred feet different in adjacent fields despite having overlapping buffer areas. However, in comparison with depths of petroleum wells, these uncertainties in estimated water-well depths had relatively little effect on aggregate salinity profiles for oil field areas.

Salinity Mapping and Depth-to-TDS Profile Plots

The results of this reconnaissance salinity mapping study are displayed through a series of maps and profile plots. ArcGIS was used to determine which wells to include for mapping salinity for each priority oil/gas field based on geographic location as described earlier. Once wells were assigned to the relevant field, or fields in the case of water wells located within overlapping buffer areas, they were categorized based on depth (perforation depth, or well or hole depth instead of bottom perforation for water wells) and TDS concentration. Depth classifications portrayed as top perforation (petroleum wells) or bottom perforation, well depth, or hole depth (water wells) relative to land surface include less than 1,000 ft, 1,000–2,000 ft, 2,001–5,000 ft, and greater than 5,000 ft. On the salinity maps, these depths are represented by a triangle, circle, square, and inverted triangle, respectively. Total dissolved solids classifications and their corresponding descriptions (shown in parentheses) include less than 1,000 mg/L (fresh), 1,000–3,000 mg/L (mildly saline), 3,001–10,000 mg/L (moderately saline), and greater than 10,000 mg/L (very saline, if less than 35,000 mg/L, to brine, if greater than 35,000 mg/L; Stanton and others, 2017). These categories are represented on the salinity maps by the depth symbols colored blue, green, orange, and red, respectively. Salinity maps for all subregions show petroleum and water wells on separate figures to help distinguish well type, depth, and TDS classifications where well density is high.

Table 3. Summary for each oil field of the number of wells, median perforation depth and altitude, range and median total dissolved solids (TDS) value, and minimum depths to TDS greater than 3,000 and 10,000 mg/L for petroleum and water wells, central and southern California`

[Values for water wells in some adjacent fields may be identical owing to mapping wells shared by overlapping buffer areas. Depths are below land surface. Altitudes are referenced to the North American Vertical Datum of 1988 (NAVD 88). Total dissolved solids minimum, maximum, and median values highlighted in orange and red represent values greater than 3,000 and 10,000 mg/L, respectively. **Abbreviations**: bls, below land surface; DOGGR, California Division of Oil, Gas, and Geothermal Resources; ft, feet; mg/L, milligram per liter; na, not applicable; >, greater than; —, no data]

Subregion	Field[1]	Well type	Number of wells	Wells with construction data	Percentage of wells with construction data	Median perforation depth (ft)[2]	Median perforation altitude (ft)[3]	Petroleum well highest top perforation altitude (ft)	Water well lowest bottom perforation altitude (ft)[4]	TDS minimum (mg/L)	TDS maximum (mg/L)	TDS median (mg/L)	Approximate depth to TDS >3,000 mg/L (ft bls)[5]	Approximate depth to TDS >10,000 mg/L (ft bls)[5]
DOGGR District 4														
Kern Sierran Foothills	Jasmin	Water	42	23	55	[6]1,602	–1,066	—	–2,993	212	1,010	341	**2,800**	**na[7]**
Kern Sierran Foothills	Jasmin	Petroleum	3	3	100	2,784	–2,062	–1,896	—	482	6,090	500		
Kern Sierran Foothills	Kern Bluff	Water	33	17	52	461	116	—	–1,336	146	2,384	459	**na[7]**	**na[7]**
Kern Sierran Foothills	Kern Bluff	Petroleum	7	7	100	1,070	–339	–44	—	572	1,300	644		
Kern Sierran Foothills	Kern Front	Water	159	92	58	[6]686	–180	—	–1,142	139	2,077	445	**na[7]**	**na[7]**
Kern Sierran Foothills	Kern Front	Petroleum	31	31	100	2,321	–1,665	–853	—	386	2,318	1,049		
Kern Sierran Foothills	Kern River	Water	123	80	65	670	–161	—	–1,336	111	2,384	295	**600**	**1,700**
Kern Sierran Foothills	Kern River	Petroleum	82	82	100	941	–322	501	—	240	25,500	745		
Kern Sierran Foothills	Mount Poso	Water	13	7	54	[6]600	493	—	–244	115	2,480	372	**1,100**	**na[7]**
Kern Sierran Foothills	Mount Poso	Petroleum	42	41	98	1,660	–468	619	—	206	4,566	1,391		
Kern Sierran Foothills	Poso Creek	Water	121	76	63	920	–385	—	–1,371	130	3,712	297	**1,200**	**2,800**
Kern Sierran Foothills	Poso Creek	Petroleum	57	57	100	2,558	–1,857	–377	—	570	13,100	1,341		
Kern Sierran Foothills	Round Mountain	Water	14	6	43	[6]308	255	—	116	160	2,480	750	**1,200**	**2,000**
Kern Sierran Foothills	Round Mountain	Petroleum	17	17	100	1,675	–622	–82	—	854	16,300	2,150		

Table 3. Summary for each oil field of the number of wells, median perforation depth and altitude, range and median total dissolved solids (TDS) value, and minimum depths to TDS greater than 3,000 and 10,000 mg/L for petroleum and water wells, central and southern California`—Continued

[Values for water wells in some adjacent fields may be identical owing to mapping wells shared by overlapping buffer areas. Depths are below land surface. Altitudes are referenced to the North American Vertical Datum of 1988 (NAVD 88). Total dissolved solids minimum, maximum, and median values highlighted in orange and red represent values greater than 3,000 and 10,000 mg/L, respectively. **Abbreviations**: bls, below land surface; DOGGR, California Division of Oil, Gas, and Geothermal Resources; ft, feet; mg/L, milligram per liter; na, not applicable; >, greater than; —, no data]

Subregion	Field[1]	Well type	Number of wells	Wells with construction data	Percentage of wells with construction data	Median perforation depth (ft)[2]	Median perforation altitude (ft)[3]	Petroleum well highest top perforation altitude (ft)	Water well lowest bottom perforation altitude (ft)[4]	TDS minimum (mg/L)	TDS maximum (mg/L)	TDS median (mg/L)	Approximate depth to TDS >3,000 mg/L (ft bls)[5]	Approximate depth to TDS >10,000 mg/L (ft bls)[5]
						DOGGR District 4—Continiued								
East Kern Valley Floor	Edison	Water	507	280	55	600	–74	—	–1,730	125	3,060	550	600	3,000
East Kern Valley Floor	Edison	Petroleum	67	66	99	3,415	–2,841	291	—	444	20,775	1,664		
East Kern Valley Floor	Fruitvale	Water	456	321	70	583	–182	—	–752	97	2,377	242	2,900	3,700
East Kern Valley Floor	Fruitvale	Petroleum	98	97	99	3,624	–3,220	–2,404	—	632	24,930	3,699		
East Kern Valley Floor	Mountain View	Water	570	285	50	600	–129	—	–1,537	92	3,060	459	5,300	5,600
East Kern Valley Floor	Mountain View	Petroleum	40	40	100	6,099	–5,646	–2,459	—	900	39,900	4,880		
East Kern Valley Floor	Rosedale	Water	146	91	62	[6]526	–181	—	–722	110	2,377	332	900	1,900
East Kern Valley Floor	Rosedale	Petroleum	4	4	100	4,836	–4,481	–3,095	—	28,000	38,515	31,882		
East Kern Valley Floor	Rosedale Ranch	Water	150	95	63	[6]610	–231	—	–1,142	118	3,712	524	1,000	3,500
East Kern Valley Floor	Rosedale Ranch	Petroleum	43	42	98	4,161	–3,789	–2,878	—	5,550	33,106	24,867		

Table 3. Summary for each oil field of the number of wells, median perforation depth and altitude, range and median total dissolved solids (TDS) value, and minimum depths to TDS greater than 3,000 and 10,000 mg/L for petroleum and water wells, central and southern California`—Continued

[Values for water wells in some adjacent fields may be identical owing to mapping wells shared by overlapping buffer areas. Depths are below land surface. Altitudes are referenced to the North American Vertical Datum of 1988 (NAVD 88). Total dissolved solids minimum, maximum, and median values highlighted in orange and red represent values greater than 3,000 and 10,000 mg/L, respectively. **Abbreviations**: bls, below land surface; DOGGR, California Division of Oil, Gas, and Geothermal Resources; ft, feet; mg/L, milligram per liter; na, not applicable; >, greater than; —, no data]

Subregion	Field[1]	Well type	Number of wells	Wells with construction data	Percentage of wells with construction data	Median perforation depth (ft)[2]	Median perforation altitude (ft)[3]	Petroleum well highest top perforation altitude (ft)	Water well lowest bottom perforation altitude (ft)[4]	TDS minimum (mg/L)	TDS maximum (mg/L)	TDS median (mg/L)	Approximate depth to TDS >3,000 mg/L (ft bls)[5]	Approximate depth to TDS >10,000 mg/L (ft bls)[5]
DOGGR District 4—Continiued														
Middle Kern Valley Floor	Canfield Ranch	Water	120	96	80	[6]606	–266	—	–452	92	826	187	1,300	3,000
Middle Kern Valley Floor	Canfield Ranch	Petroleum	20	20	100	7,914	–7,567	–2,815	—	2,902	38,141	28,403		
Middle Kern Valley Floor	Greeley	Water	135	77	57	[6]510	–167	—	–466	96	2,690	317	1,600	2,800
Middle Kern Valley Floor	Greeley	Petroleum	23	22	96	11,390	–11,054	–2,865	—	10,825	39,029	19,815		
Middle Kern Valley Floor	Rio Bravo	Water	81	43	53	[6]422	–90	—	–461	104	2,690	271	1,400	4,100
Middle Kern Valley Floor	Rio Bravo	Petroleum	24	17	71	6,417	–6,089	–3,791	—	13,968	41,693	25,035		
Middle Kern Valley Floor	Ten Section	Water	45	38	84	688	–342	—	–493	91	826	151	1,000	2,300
Middle Kern Valley Floor	Ten Section	Petroleum	4	4	100	2,986	–2,661	–1,979	—	12,077	30,600	21,324		
South Kern Valley Margin	San Emidio Nose	Water	110	40	36	[6]1,200	–673	—	–2,058	424	3,042	1,094	2,000	5,000
South Kern Valley Margin	San Emidio Nose	Petroleum	5	4	80	8,376	–7,823	–4,454	—	13,709	21,974	19,333		

Table 3. Summary for each oil field of the number of wells, median perforation depth and altitude, range and median total dissolved solids (TDS) value, and minimum depths to TDS greater than 3,000 and 10,000 mg/L for petroleum and water wells, central and southern California`—Continued

[Values for water wells in some adjacent fields may be identical owing to mapping wells shared by overlapping buffer areas. Depths are below land surface. Altitudes are referenced to the North American Vertical Datum of 1988 (NAVD 88). Total dissolved solids minimum, maximum, and median values highlighted in orange and red represent values greater than 3,000 and 10,000 mg/L, respectively. **Abbreviations**: bls, below land surface; DOGGR, California Division of Oil, Gas, and Geothermal Resources; ft, feet; mg/L, milligram per liter; na, not applicable; >, greater than; —, no data]

Subregion	Field[1]	Well type	Number of wells	Wells with construction data	Percentage of wells with construction data	Median perforation depth (ft)[2]	Median perforation altitude (ft)[3]	Petroleum well highest top perforation altitude (ft)	Water well lowest bottom perforation altitude (ft)[4]	TDS minimum (mg/L)	TDS maximum (mg/L)	TDS median (mg/L)	Approximate depth to TDS >3,000 mg/L (ft bls)[5]	Approximate depth to TDS >10,000 mg/L (ft bls)[5]
DOGGR District 4—Continiued														
South Kern Valley Margin	Tejon	Water	68	40	59	1,070	–238	—	–1,065	271	2,090	425	1,800	3,100
South Kern Valley Margin	Tejon	Petroleum	15	15	100	5,370	–4,213	–994	—	1,084	21,700	7,000		
South Kern Valley Margin	Wheeler Ridge	Water	50	22	44	[6]1,109	–370	—	–1,065	258	2,685	825	1,200	1,200
South Kern Valley Margin	Wheeler Ridge	Petroleum	47	41	87	3,889	–2,383	519	—	3,749	46,139	21,944		
South Kern Valley Margin	Yowlumne	Water	81	36	44	[6]1,099	–514	—	–2,058	350	3,800	1,192	1,200	4,100
South Kern Valley Margin	Yowlumne	Petroleum	1	1	100	4,202	–3,650	–3,650	—	17,000	17,000	17,000		
West Kern Valley Floor	Coles Levee, North and South	Water	111	92	83	422	–128	—	–841	105	[9]231,000	380	0	1,500
West Kern Valley Floor	Coles Levee, North and South	Petroleum	18	18	100	8,815	–8,419	–1,249	—	4,508	36,985	24,549		
West Kern Valley Margin	Belridge, North and South	Water	82	51	62	238	253	—	–226	2,300	48,000	9,750	100	100
West Kern Valley Margin	Belridge, North and South	Petroleum	131	128	98	965	–384	552	—	560	48,262	19,506		

Table 3. Summary for each oil field of the number of wells, median perforation depth and altitude, range and median total dissolved solids (TDS) value, and minimum depths to TDS greater than 3,000 and 10,000 mg/L for petroleum and water wells, central and southern California`—Continued

[Values for water wells in some adjacent fields may be identical owing to mapping wells shared by overlapping buffer areas. Depths are below land surface. Altitudes are referenced to the North American Vertical Datum of 1988 (NAVD 88). Total dissolved solids minimum, maximum, and median values highlighted in orange and red represent values greater than 3,000 and 10,000 mg/L, respectively. **Abbreviations**: bls, below land surface; DOGGR, California Division of Oil, Gas, and Geothermal Resources; ft, feet; mg/L, milligram per liter; na, not applicable; >, greater than; —, no data]

Subregion	Field[1]	Well type	Number of wells	Wells with construction data	Percentage of wells with construction data	Median perforation depth (ft)[2]	Median perforation altitude (ft)[3]	Petroleum well highest top perforation altitude (ft)	Water well lowest bottom perforation altitude (ft)[4]	TDS minimum (mg/L)	TDS maximum (mg/L)	TDS median (mg/L)	Approximate depth to TDS >3,000 mg/L (ft bls)[5]	Approximate depth to TDS >10,000 mg/L (ft bls)[5]
DOGGR District 4—Continued														
West Kern Valley Margin	Cymric	Water	4	1	25	[8]542	–73	—	–73	901	11,900	2,359	500	700
West Kern Valley Margin	Cymric	Petroleum	33	32	97	1,895	–999	225	—	1,607	29,000	16,767		
West Kern Valley Margin	Elk Hills	Water	84	70	83	[6]332	9	—	–516	110	[9]231,000	1,438	300	1,800
West Kern Valley Margin	Elk Hills	Petroleum	151	148	98	3,287	–2,603	–266	—	4,638	50,005	32,636		
West Kern Valley Margin	Lost Hills	Water	59	49	73	304	2	—	–719	165	23,000	4,100	100	100
West Kern Valley Margin	Lost Hills	Petroleum	66	66	100	1,720	–1,332	325	—	5,657	85,000	31,336		
DOGGR District 1														
Los Angeles Basin	Montebello	Water	261	180	69	336	–118	—	–1,267	176	2,514	512	1,500	2,500
Los Angeles Basin	Montebello	Petroleum	3	3	100	5,500	–5,130	–2,123	—	25,677	27,583	25,690		
Los Angeles Basin	Santa Fe Springs	Water	202	145	72	450	–319	—	–1,363	200	2,490	580	1,100	4,400
Los Angeles Basin	Santa Fe Springs	Petroleum	5	3	60	5,991	–5,837	–4,197	—	13,059	33,000	18,114		

Table 3. Summary for each oil field of the number of wells, median perforation depth and altitude, range and median total dissolved solids (TDS) value, and minimum depths to TDS greater than 3,000 and 10,000 mg/L for petroleum and water wells, central and southern California`—Continued

[Values for water wells in some adjacent fields may be identical owing to mapping wells shared by overlapping buffer areas. Depths are below land surface. Altitudes are referenced to the North American Vertical Datum of 1988 (NAVD 88). Total dissolved solids minimum, maximum, and median values highlighted in orange and red represent values greater than 3,000 and 10,000 mg/L, respectively. **Abbreviations**: bls, below land surface; DOGGR, California Division of Oil, Gas, and Geothermal Resources; ft, feet; mg/L, milligram per liter; na, not applicable; >, greater than; —, no data]

Subregion	Field[1]	Well type	Number of wells	Wells with construction data	Percentage of wells with construction data	Median perforation depth (ft)[2]	Median perforation altitude (ft)[3]	Petroleum well highest top perforation altitude (ft)	Water well lowest bottom perforation altitude (ft)[4]	TDS minimum (mg/L)	TDS maximum (mg/L)	TDS median (mg/L)	Approximate depth to TDS >3,000 mg/L (ft bls)[5]	Approximate depth to TDS >10,000 mg/L (ft bls)[5]
						DOGGR District 1—Continued								
Los Angeles Basin	Wilmington	Water	330	244	74	282	–265	—	–1,869	204	48,250	1,070	0	0
Los Angeles Basin	Wilmington	Petroleum	118	111	94	3,124	–3,109	–2,318	—	10,258	38,886	30,957		
						DOGGR District 3								
Central Coast Basin	Santa Maria Valley	Water	471	373	79	[6]238	–52	—	–1,199	127	6,840	901	200	4,100
Central Coast Basin	Santa Maria Valley	Petroleum	6	6	100	4,798	–4,702	–1,683	—	8,000	84,891	24,742		
—	TOTALS	Water	[10]3,546	[10]2,322	65	—	—	—	—	—	—	—	—	—
—	TOTALS	Petroleum	[11]1,161	1,126	97	—	—	—	—	—	—	—	—	—

[1]Includes 2-mile buffer area around administrative boundaries of field with the exception of Wilmington where a 1-mile buffer was applied.

[2]Median of top perforation for petroleum wells and bottom perforation for water wells. Well or hole depth used in lieu of bottom perforation for individual water wells.

[3]Median of top perforation altitude for petroleum wells and bottom perforation altitude for water wells. Based on wells having reported top perforation for petroleum wells and bottom perforation, well depth, or hole depth for water wells.

[4]Includes well depth or hole depth in lieu of bottom perforation. For several fields (Tejon and Wheeler Ridge), same well applies.

[5]Value collectively represents both water and petroleum wells within each field and is the minimum depth from average land-surface altitude at the wells, rounded to the nearest 100 ft.

[6]Represents well or hole depth in lieu of sufficient perforation data.

[7]Not applicable. Threshold not encountered.

[8]Represents a single value.

[9]Represents same well located within South Coles Levee field and adjacent to, but within buffer area, of Elk Hills field.

[10]Total number of unique wells and not the sum of each field because some water wells were mapped more than once where buffer areas overlap adjacent mapped fields.

[11]Includes 25 wells with a total of 52 unique sample depths.

In addition to regional-scale maps, profile plots of TDS concentration versus perforation depth, represented as altitude above the North American Vertical Datum of 1988 (NAVD 88), were created for each field and grouped by subregion. Depths corresponding to the TDS concentrations were depicted as altitudes rather than depth below land surface (bls) to account for variations in both land-surface elevation and geological structural changes within fields and to be able to more directly compare differences in vertical distribution of TDS concentrations between nearby fields. Petroleum wells were generally represented by black symbols, with the exception of wells having uncertain locations and plotted based on township, range, and section to the corresponding centroid. A total of 27 wells having approximate locations were distinguished using a gray symbol. Water wells located within versus outside the administrative field boundaries were distinguished by using different symbol colors, red and green, respectively. Finally, the profile plots show the approximate altitude at which TDS concentration exceeds the 3,000 and 10,000 mg/L thresholds. These are primarily based on the shallowest depth at which TDS equal to or greater than those concentrations is encountered. For some fields, denoted by an asterisk (*) on figures 6, 8, 10, 14, and 16, the altitudes of these thresholds were determined using regression analysis of TDS concentration versus perforation altitude. These were used for fields where the R-square value was 0.6 or greater and where these altitudes corresponded reasonably well with visually determined altitudes.

Results of Salinity Mapping by Geographic Subregion

Results of the salinity mapping in each of the studied fields are summarized in table 3, which shows (1) the number of wells with TDS data by type (petroleum and water) mapped for each field; (2) the number and percentage of wells with known top (petroleum wells) or bottom (water wells) perforation, well depth, or hole depth; (3) the median perforation depth in feet below land surface; (4) the mean perforation altitude relative to NAVD 88; (5) the minimum, maximum, and median TDS value for each field by well type; and (6) the approximate depth to TDS threshold values of 3,000 and 10,000 mg/L.

Among the 31 individual fields or 29 aggregated fields studied (including combined entries for the North and South Coles Levee fields and the North and South Belridge fields), the median TDS concentration of produced water from petroleum wells ranged from 500 mg/L (for the Jasmin field in the Kern Sierran Foothills subregion) to 32,636 mg/L (for the Elk Hills field in West Kern Valley Margin subregion; table 3). Median TDS concentrations in produced water from petroleum wells were less than 10,000 mg/L in 11 of 29 aggregated fields, including 8 fields with median TDS concentrations less than 3,000 mg/L; these fields were located in the eastern part of the San Joaquin Valley in Kern County, specifically the Kern Sierran Foothills and East Kern Valley Floor subregions. Among fields having median TDS concentrations less than both threshold values, Kern Bluff and Kern Front in the Kern Sierran Foothills were the only fields where the maximum TDS concentration in produced water was less than 3,000 mg/L, at 1,300 mg/L (7 wells) and 2,318 mg/L (31 wells), respectively.

Among water wells, median TDS concentrations, either reported as TDS or calculated from specific conductance using equations 1–4, were less than 10,000 mg/L for all fields, ranging from 151 mg/L (for wells within 2 miles of the Ten Section field in Middle Kern Valley Floor subregion) to 9,750 mg/L (for wells within 2 miles of the combined North and South Belridge fields in the West Kern Valley Margin subregion; table 3). The combined North and South Belridge fields and Lost Hills field were the only fields for which the median TDS concentration in water from wells was greater than 3,000 mg/L. However, the maximum TDS concentration in water wells was greater than 3,000 in 13 fields and greater than 10,000 mg/L in 6 fields. The three highest TDS concentrations among all wells used for reconnaissance salinity mapping were 87,500 mg/L (from water wells in the vicinity of the Elk Hills field in the West Kern Valley Margin subregion) and 161,730 and 231,000 mg/L (from overlapping buffer areas of the Elk Hills and the South Coles Levee fields in the West Kern Valley Margin and West Kern Valley Floor subregions, respectively; Metzger and others, 2018). These exceptionally high TDS values in groundwater in the southwestern San Joaquin Valley may be associated with infiltration from produced water disposal ponds (Bean and Logan, 1983). Alternatively or in addition, high TDS values may be the result of perched water subject to evaporative pumping or agricultural drainage ponds (Swain and Duell, 1993).

Results of reconnaissance salinity mapping for each of the eight geographic subregions (Kern Sierran Foothills, East Kern Valley Floor, Middle Kern Valley Floor, South Kern Valley Margin, West Kern Valley Floor, West Kern Valley Margin, Los Angeles Basin, and Central Coast Basin) are described in more detail below through a series of maps and field-specific depth-to-TDS profile plots grouped by subregion.

Kern Sierran Foothills

Located to the north of Bakersfield, California, on the eastern side of the southern San Joaquin Valley (fig. 1), the Kern Sierran Foothills subregion includes the following seven oil fields: Jasmin, Kern Bluff, Kern Front, Kern River, Mount Poso, Poso Creek, and Round Mountain. These 7 fields included a widely varying number of petroleum and water wells with TDS data for each field; petroleum wells numbered between 3 (Jasmin) and 82 (Kern River), and within-field or assigned water wells located within 2 miles of administrative boundaries numbered between 6 (Round Mountain) and 92 (Kern Front; table 3). The number of wells having perforation and (or) depth information (attributed) by type ranged from 98 percent (Mount Poso) to 100 percent (all other fields) of petroleum wells and 43 percent (Round Mountain) to 65 percent (Kern River) of water wells.

Geologically, the Kern Sierran Foothills subregion coincides with the eastern part of a feature referred to as the Bakersfield Arch, a ridge of southwest-plunging basement rock (Sierran metamorphic and plutonic rocks) that separates two structural regions of the San Joaquin Valley, the southern Sierran block (SSB) and the Maricopa-Tejon subbasin (MTS; Bartow, 1991; Hosford Scheirer, 2007, chap. 5; fig. 2). The sedimentary rock that overlies this geologic feature consists primarily of sandstone and siltstone of Tertiary age and younger (Bartow and Pittman, 1983). The thickness of these deposits increases from about 1,000 feet (ft) at the eastern edge of the Mount Poso field to close to 8,000 ft at the western edge of the Poso Creek field (Hosford Scheirer, 2007, chap. 7). The primary stratigraphic units associated with these deposits, in ascending order and from older to younger, include the Walker Formation, Famoso sand of Edwards (1943), Vedder Sand, Freeman Silt–Jewett Sand, Round Mountain Silt (a member of the Monterey Formation), Santa Margarita Sandstone, the Chanac Formation, and the Kern River Formation. On the western side of this subregion, beginning in the vicinity of the Kern River field and increasing in thickness towards the west, is an additional formation of marine origin referred to as the Etchegoin, situated between the Chanac Formation (below) and the Kern River Formation (above). In the eastern part of the Kern Sierran Foothills subregion, roughly coinciding with the Round Mountain field and eastern part of the Mount Poso field, the Round Mountain Silt, Santa Margarita Sandstone, and the Chanac Formation pinch out and are replaced with the Olcese Sand, a formation that is commonly more saline than both the overlying and underlying units (Hosford Scheirer, 2007, chap. 13; Gillespie and others, 2017). The Kern River Formation is nonmarine in origin and contains the most productive hydrocarbon-bearing intervals in the subregion (Hosford Scheirer, 2007, chap. 13). It has a maximum thickness of about 2,500 ft at its western edge (Bartow, 1983). Most water wells used for salinity mapping were completed at depths of less than 2,000 ft bls, with the deepest well perforated at just over 2,300 ft bls; therefore, most if not all are located within the Kern River Formation. In comparison, the deepest petroleum wells in the Kern Sierran Foothills subregion used for salinity mapping extend into the Famoso and Vedder sands beneath the Kern River field.

Groundwater in the Kern Sierran Foothills subregion can be characterized as having relatively low TDS concentrations (less than 3,000 mg/L), particularly in and around the Kern River and Kern Front fields, where many of the wells were shallow (less than 1,000 ft bls; figs. 3*A*–*B*). Total dissolved solids concentrations were generally higher in water from wells in the Round Mountain, Poso Creek, and Mount Poso fields, with a number of wells having concentrations between 1,000 and 10,000 mg/L. Jasmin field, the most northerly field of the Kern Sierran Foothills subregion, included the deepest petroleum and water wells based on median perforation depth but the lowest overall TDS concentrations. Median TDS concentrations in produced water ranged from 500 mg/L (Jasmin field) to 2,150 mg/L (Round Mountain field). For water wells, median TDS concentrations in groundwater ranged from 295 mg/L (Kern River field) to 750 mg/L (Round Mountain field).

Profile plots of the vertical distribution of TDS show that produced-water samples generally have higher TDS than water-well samples, but there is considerable overlap in TDS concentrations between the two well types (fig. 4). The lower end of the range of TDS values in samples from petroleum wells overlaps the upper end of the range of TDS values in samples from water wells for all fields. The profile plots also show little to no separation (close vertical proximity) between the altitudes of perforations for petroleum and water wells for most of the fields. This is particularly true in the Kern River field and its adjacent buffer area, where the median altitude of the top perforation for mapped petroleum wells is –322 ft compared to a median altitude of the bottom perforation for mapped water wells of –161ft. For six of the seven fields and adjacent buffer areas, the shallowest top perforations of petroleum wells and deepest bottom perforations of water wells overlap (table 3). This means that a number petroleum wells are perforated closer to land surface than some water wells, although the majority of the water wells in question are located within the buffer area and outside of the administrative field boundaries. This vertical proximity may be the result of perforation placement with respect to where recoverable oil is located. In some fields, petroleum well perforations do not necessarily coincide with where oil is structurally or stratigraphically trapped, but rather where oil may be present as a result of upward migration. If a pathway is available for upward migration, oil has a tendency to ride on top of the water table as it fluctuates, thereby allowing it to reach altitudes corresponding with the perforation depths of water wells (Jan Gillespie, written commun., 2016). The largest vertical contrast is in the Kern Front and Poso Creek fields where the separation between the median perforation altitudes of petroleum and water wells is about 1,500 ft.

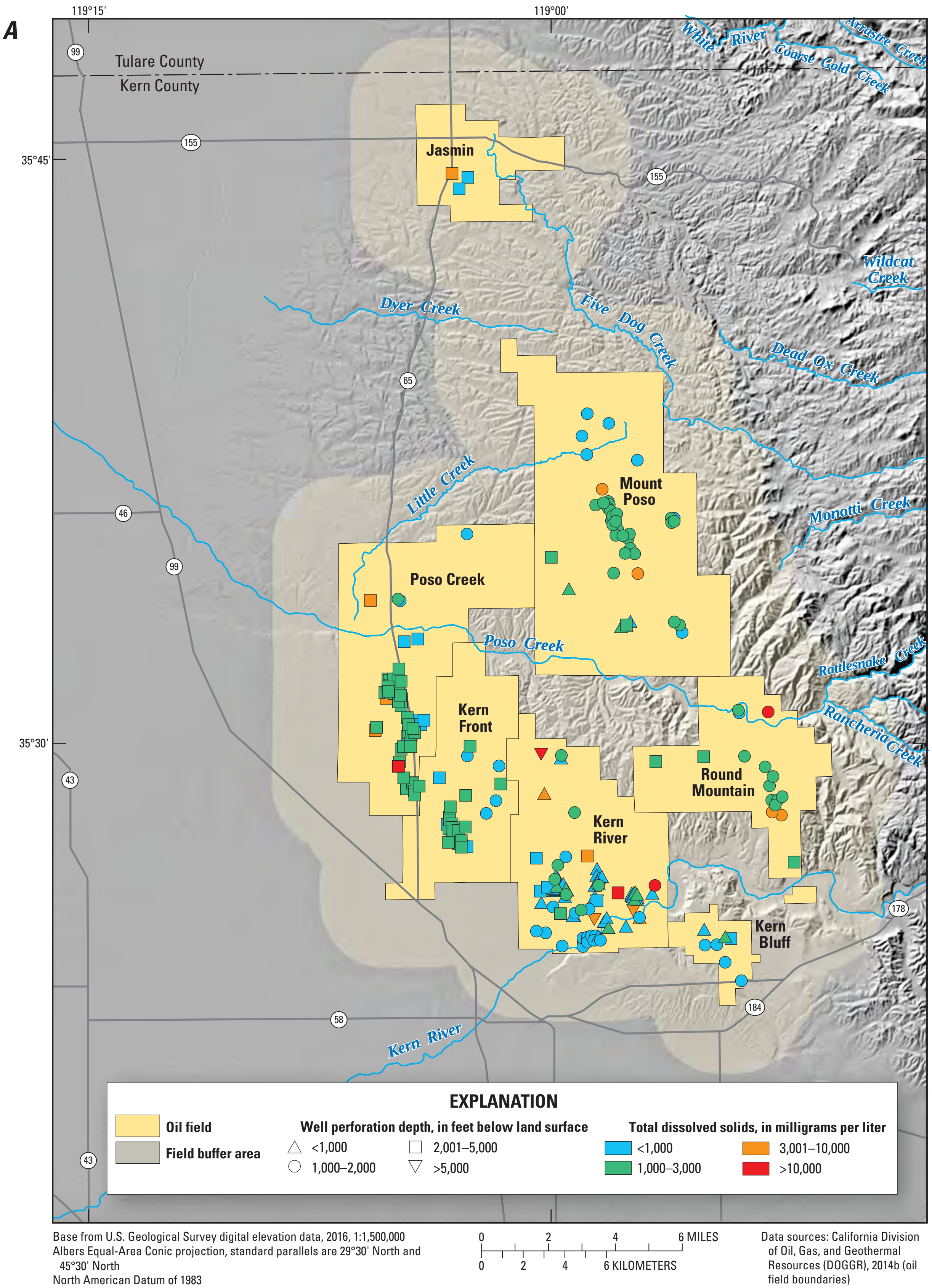
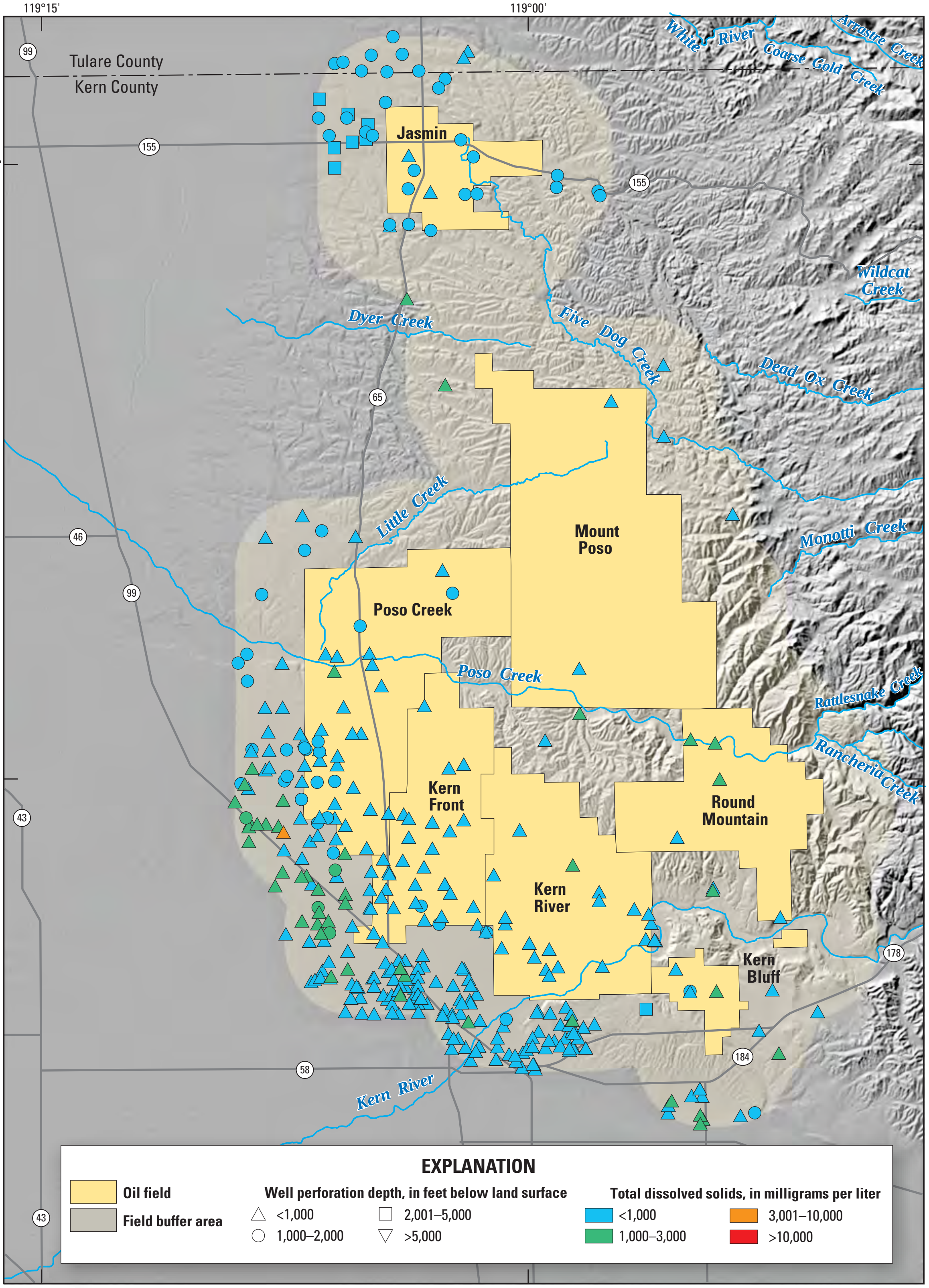


Figure 3. Distribution of total dissolved solids in *A*, produced water from petroleum wells, and *B*, water from water wells, for selected oil fields in the Kern Sierran Foothills subregion, central California.

B



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

0 2 4 6 MILES
0 2 4 6 KILOMETERS

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014b (oil field boundaries)

Figure 3. —Continued

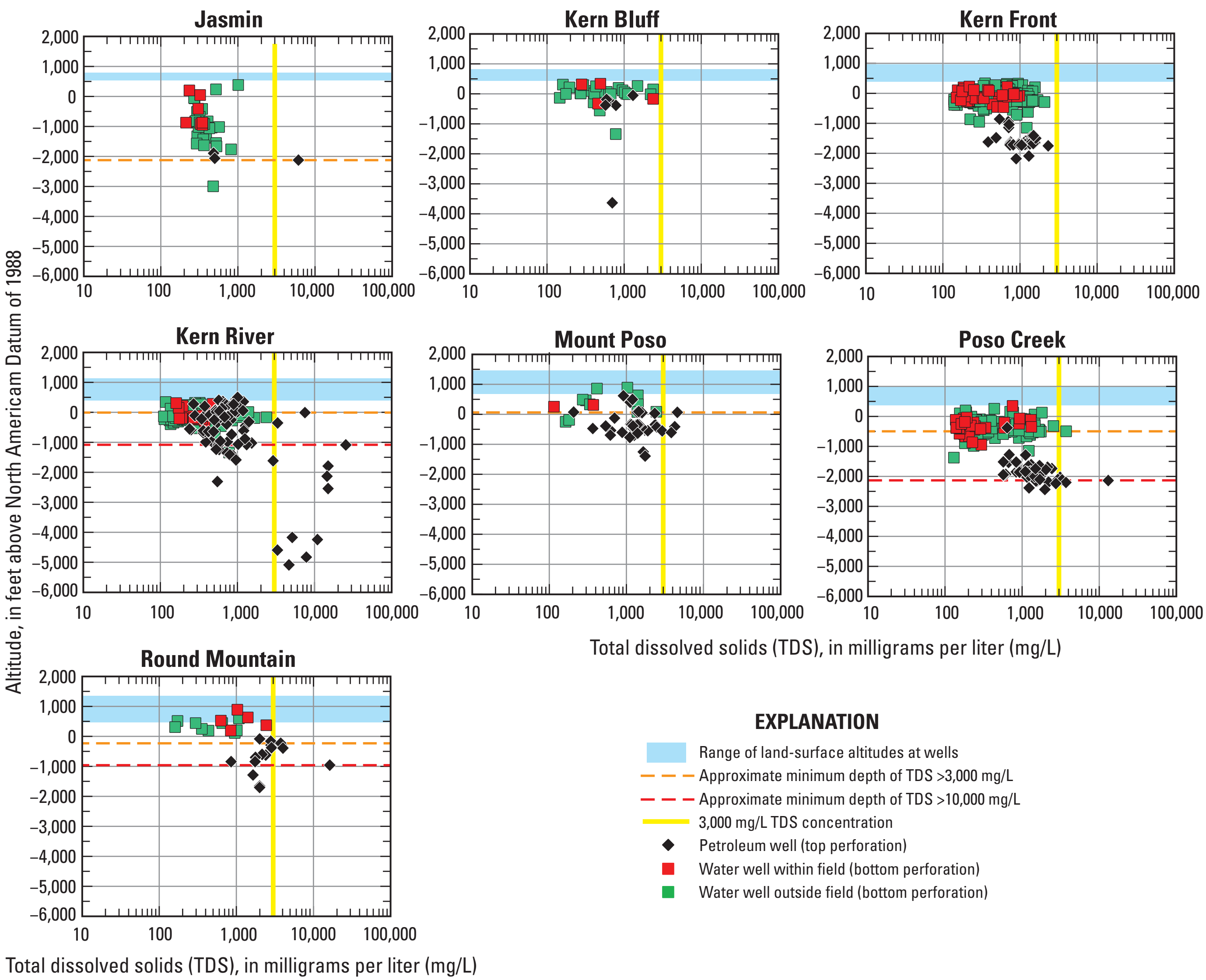


Figure 4. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the Kern Sierran Foothills subregon, central California.

Median TDS concentrations for both petroleum and water wells in all seven fields were less than 3,000 mg/L, indicating that the water was fresh to mildly saline. In addition, TDS concentrations for all mapped wells in the Kern Bluff and Kern Front fields were less than 3,000 mg/L. Total dissolved solids concentrations were between 3,000 and 10,000 mg/L in 7 percent of all petroleum wells (16 of 239) in the subregion used for mapping. These were distributed among five fields: Kern River (six), Round Mountain (three), Mount Poso (three), Poso Creek (three), and Jasmin (one; fig. 3*A*). Except for one water well located in the Poso Creek field buffer area, samples from water wells had TDS concentrations less than 3,000 mg/L, with the majority (87 percent) of those less than 1,000 mg/L (fig. 3*B*). Total dissolved solids concentrations greater than 10,000 mg/L were present in produced water from three petroleum wells in the Kern River field (including one well having samples from three distinct depths) and one petroleum well each in the Poso Creek and Round Mountain fields (Metzger and others, 2018). The top perforations or sample depths corresponding with these high TDS values ranged in altitude from about –1,000 to –5,000 ft. Based on this limited set of data points and using the shallowest depth of TDS greater than 10,000 mg/L as the criteria for designating where this threshold is met, an altitude of –1,000 ft is the approximate minimum depth of this threshold in the Kern River and Round Mountain fields, and –2,000 ft is the approximate minimum depth of this threshold in the Poso Creek field (fig. 4). These depths are 700 (Kern River field) to 1,200 ft (Round Mountain field) below the deepest overlying (within-field) water wells but may not represent the deepest or typical depth of USDW in this subregion. According to Gillespie and others (2017), USDW extends to depths as great as 6,000 ft. This is supported by the profile plot for the Kern River field (fig. 4), which shows samples from four petroleum wells with TDS concentrations between 3,000 and 10,000 mg/L. The top perforation of these particular wells ranged from –4,200 to –5,100 ft, placing them within the Vedder Sand unit, which in the Kern River, Kern Front, and Mount Poso fields is characterized by waters having relatively low salinity (Fisher and Boles, 1990).

East Kern Valley Floor

Encompassing the area around the city of Bakersfield, Calif., on the eastern side of the southern San Joaquin Valley (fig. 1), the East Kern Valley Floor subregion includes the following five oil fields: Edison, Fruitvale, Mountain View, Rosedale, and Rosedale Ranch. Wells used for mapping salinity across these 5 fields numbered between 4 (Rosedale) and 98 (Fruitvale) petroleum wells and between 146 (Rosedale) and 570 (Mountain View) water wells within or assigned to each field (table 3). The number of wells attributed with construction information by type ranged from 98 percent (Rosedale Ranch) to 100 percent (Mountain View and Rosedale) of petroleum wells and 50 percent (Mountain View) to 70 percent (Fruitvale) of water wells.

Geologically, the East Kern Valley Floor subregion is located along and to the south of the Bakersfield Arch (fig. 2). The Rosedale, Rosedale Ranch, and Fruitvale fields straddle the crest of the Bakersfield Arch. The Edison and the Mountain View fields are located to the southeast of the Bakersfield Arch, and entirely within the Maricopa-Tejon subbasin (MTS). Depth to basement rock in the vicinity of the Rosedale, Rosedale Ranch, and Fruitvale fields ranges from about 8,000 to 12,000 ft bls (Hosford Scheirer, 2007, chap. 7). The overlying strata are similar to but deeper than fields to the northeast, owing to the greater depth to basement rock. In contrast to the Kern Sierran Foothills subregion, the Etchegoin and Kern River Formations are generally thicker in the East Kern Valley Floor subregion. This subregion also has an additional unit not present in the Kern Sierran Foothills subregion, referred to as the Fruitvale shale of Miller and Bloom (1939; a member of the Monterey Formation), situated between the Round Mountain Silt (below) and the Santa Margarita Sandstone (above; Hosford Scheirer, 2007, chap. 7). The nonmarine Chanac Formation is the principal hydrocarbon reservoir for the Rosedale Ranch and Fruitvale fields (Hosford Scheirer, 2007, chap. 13). The Fruitvale shale of Miller and Bloom (1939) is the principal reservoir in the Rosedale field (Division of Oil, Gas, and Geothermal Resources, 1998). In the vicinity of the Edison and Mountain View fields, depth to basement ranges between about 4,000 to 10,000 ft bls (Hosford Scheirer, 2007, chap. 7). The Walker, Vedder, Freeman-Jewett, Olcese, Round Mountain, Fruitvale, Santa Margarita, Chanac, and Kern River stratigraphic units are present to various extents and tapped as hydrocarbon reservoirs in the Edison and Mountain View fields (Department of Oil, Gas, and Geothermal Resources, 1998). Additionally, fractured schist, which forms part of the basement surface, also serves as a hydrocarbon reservoir under parts of both of these fields (Division of Oil, Gas, and Geothermal Resources, 1998; Hosford Sheirer, 2007, chap. 5).

Groundwater in the East Kern Valley Floor subregion can be characterized as spanning a greater range of TDS concentrations than the adjacent Kern Sierran Foothills subregion. Total dissolved solids concentrations in samples from most wells (70 percent) were less than 10,000 mg/L (figs. 5*A*–*B*). Total dissolved solids greater than 10,000 mg/L were only in samples from petroleum wells having relatively deep top perforations or sample depths greater than 2,000 ft bls. Many of these wells are located in the Rosedale Ranch, Rosedale, and Mountain View fields. Median TDS concentrations in produced water from petroleum wells ranged from 1,664 mg/L (Edison) to 31,882 mg/L (Rosedale). For samples from water wells, median TDS concentrations ranged from 242 mg/L (Fruitvale) to 550 mg/L (Edison; table 3).

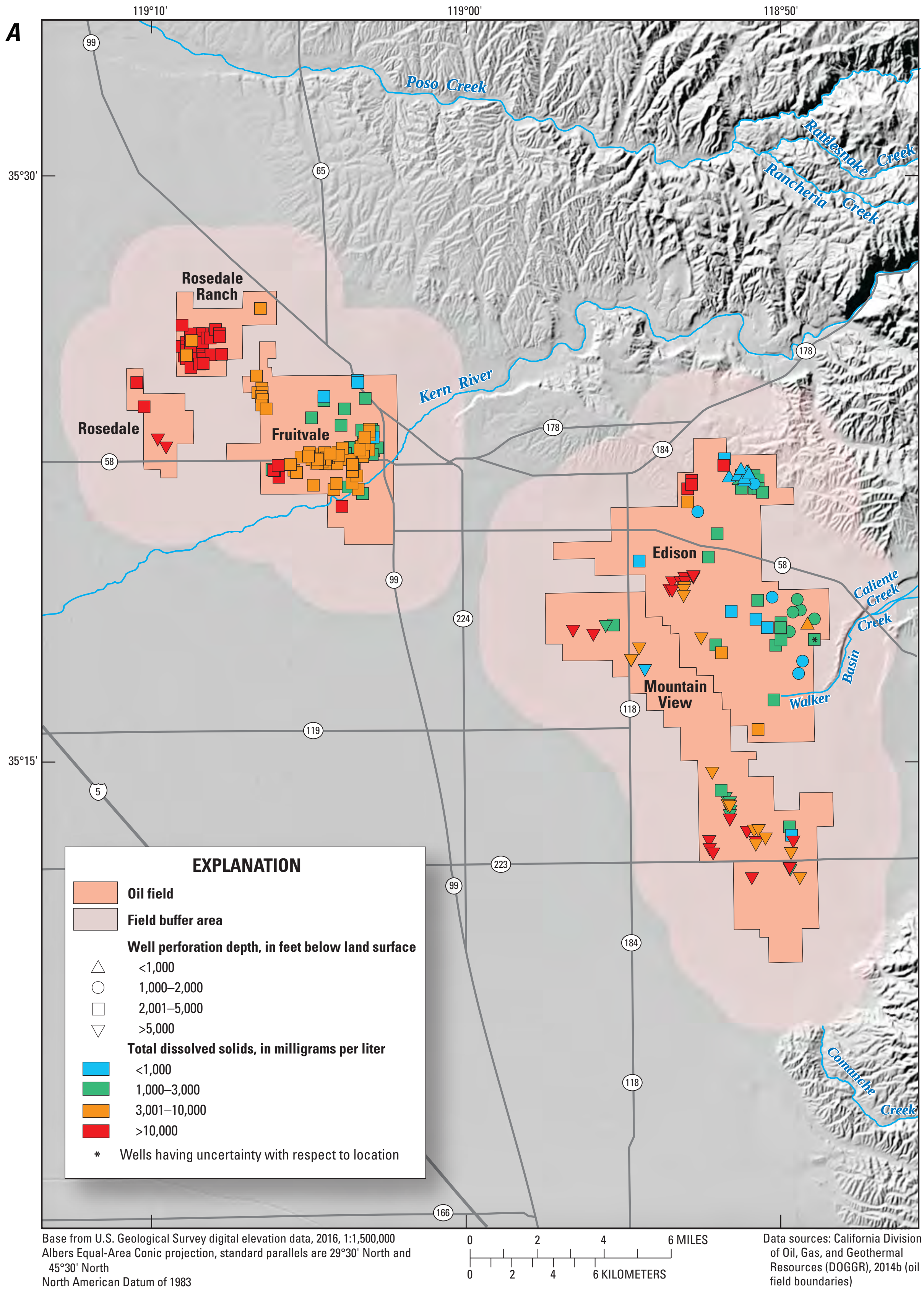
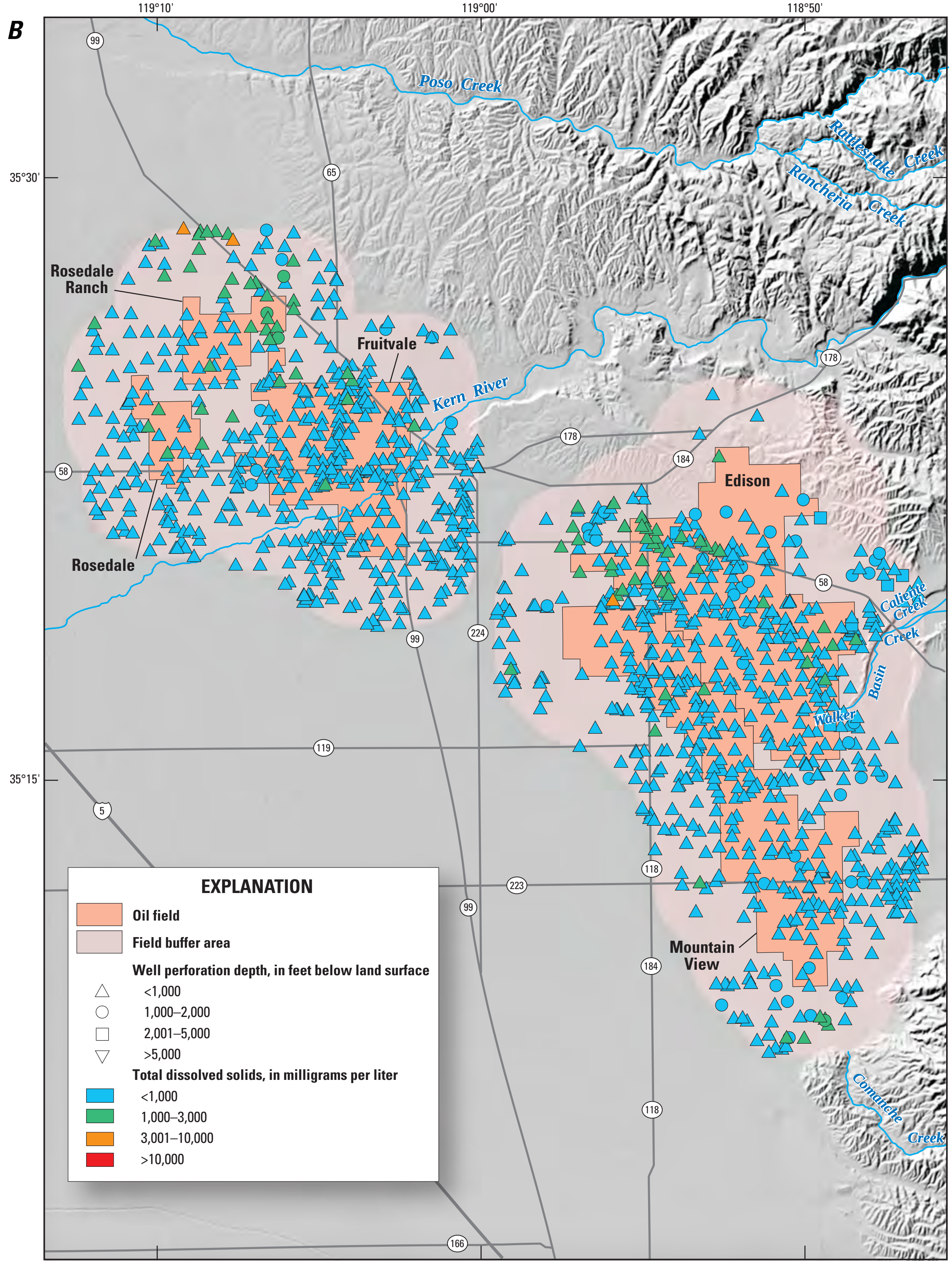


Figure 5. Distribution of total dissolved solids in *A*, produced water from petroleum wells, and *B*, water from water wells, for selected oil fields in the East Kern Valley Floor subregion, central California.



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014b (oil field boundaries)

Figure 5. —Continued

Profile plots of the vertical distribution of TDS show that produced-water samples generally had much higher TDS concentrations than water-well samples, as evidenced by relatively little overlap between the two well types (fig. 6). The exception is the Edison field, where approximately 40 percent of TDS concentrations in produced-water samples were similar (less than 3,000 mg/L) to all samples from within-field water wells, possibly owing to the relatively shallow perforation depths (less than 2,000 ft bls) of those particular petroleum wells. The Edison field had the smallest vertical separation (about 2,800 ft) between mapped petroleum and water wells based on median altitudes of well perforation and (or) completed well depth (water wells; table 3). For several dozen petroleum wells in the Edison field, the top perforation was higher than the bottom perforation of numerous water wells, including some located within the administrative field boundaries (figs. 5, 6). Profile plots for the other four fields show larger vertical separation between the median perforation altitudes of petroleum and water wells. The largest vertical contrast is in the Mountain View field, where the separation between the median perforation altitudes of petroleum and water wells was about 5,500 ft (table 3).

Median TDS concentrations for both petroleum and water wells were less than 3,000 mg/L for only one of five fields (Edison). For all other fields, only water wells had median TDS concentrations less than 3,000 mg/L (table 3). Total dissolved solids concentrations were between 3,000 and 10,000 mg/L in 32 percent of petroleum wells (81 of 252) in the East Kern Valley Floor subregion used for mapping. These petroleum wells were distributed among 4 fields: Fruitvale (57), Mountain View (13), Edison (8), and Rosedale Ranch (3; fig. 5*A*). Except for three water wells, two in the buffer area of Rosedale Ranch and one within the overlapping buffer areas of the Edison and Mountain View fields, samples from water wells had TDS concentrations less than 3,000 mg/L, with the majority (92 percent) of those less than 1,000 mg/L (fig. 5*B*). Total dissolved solids concentrations were greater than 10,000 mg/L in produced water from all petroleum wells in Rosedale, all but three petroleum wells in Rosedale Ranch, and approximately one-quarter of all petroleum wells in Mountain View. Smaller proportions of petroleum wells in both the Edison and Fruitvale fields, about 20 and 5 percent, respectively, had TDS concentrations greater than 10,000 mg/L. The top perforations or sample depths corresponding with these high TDS values ranged in altitude from about –2,500 to –10,000 ft. In comparison, water wells were generally perforated at altitudes above –1,000 ft with the exception of the Edison field where the deepest bottom perforation was at about –1,700 ft (fig. 6). Using either the shallowest depth of TDS greater than 10,000 mg/L based on the actual perforation depth, or predicted depth based on regression analysis (Rosedale and Rosedale Ranch), the

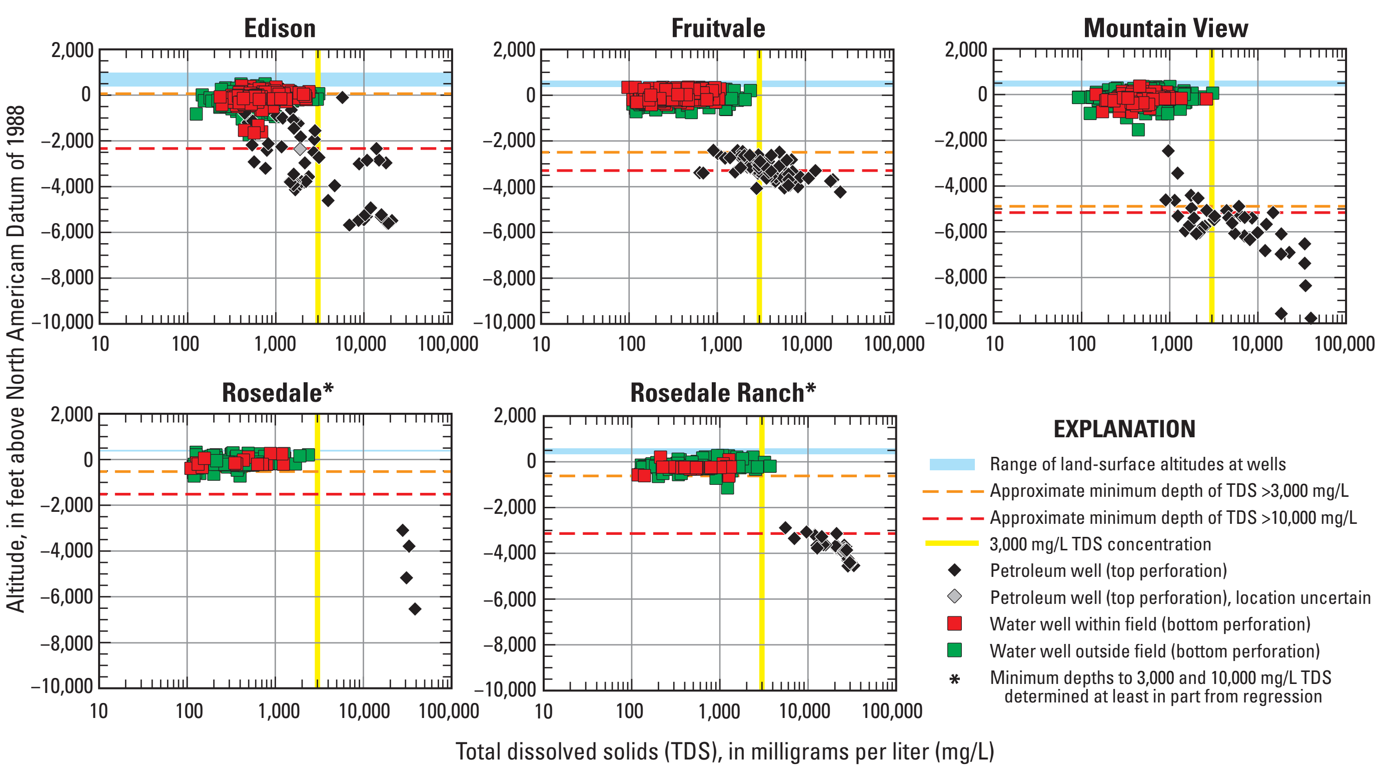


Figure 6. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the East Kern Valley Floor subregion, central California.

approximate minimum depth of TDS greater than 10,000 mg/L ranges from an altitude of about –1,300 ft (1,900 ft bls) in Rosedale to about –5,200 ft (5,600 ft bls) in Mountain View. All samples from water wells had TDS concentrations below the 10,000 mg/L threshold. Only a few water wells had TDS concentrations greater than 3,000 mg/L, with the highest concentration of about 3,800 mg/L in a sample from a well located almost 2 miles north of the Rosedale Ranch field (fig. 5*B*).

Middle Kern Valley Floor

The Middle Kern Valley Floor subregion is in the center of the southern San Joaquin Valley to the west of Bakersfield, Calif. (fig. 1), and includes the following four oil fields: Canfield Ranch, Greeley, Rio Bravo, and Ten Section. These four fields included a relatively small number of petroleum wells (4–24) within each field in comparison to the number of water wells located within or assigned to each field (45–135; table 3). The number of wells attributed by type ranged from 71 percent (Rio Bravo) to 100 percent (Canfield Ranch and Ten Section) of petroleum wells and 53 percent (Rio Bravo) to 84 percent (Ten Section) of water wells (table 3).

Geologically, the Middle Kern Valley Floor subregion overlies (Greeley) or is on the periphery of (Rio Bravo, Ten Section, and Canfield Ranch) the southwestern extent of the Bakersfield Arch (fig. 2). Depth to basement rock increases north to south from about 13,000 to 17,000 ft bls (Hosford Scheirer, 2007, chap. 7). The overlying strata from oldest to youngest are the Kreyenhagen Formation, Vedder Sand, Freeman Silt–Jewett Sand, member units of the Monterey Formation (Round Mountain Silt, Fruitvale shale of Miller and Bloom [1939], Stevens sand of Eckis [1940], and Reef Ridge Shale), the Chanac Formation (confined to eastern part of the subregion), the Etchegoin Formation, and the San Joaquin Formation (Gillespie and others, 2017; Hosford Scheirer, 2007, chap. 13). The Monterey Formation is the primary hydrocarbon reservoir in the Middle Kern Valley Floor subregion, specifically the Fruitvale shale of Miller and Bloom (1939) in the Canfield Ranch, Greeley, and Ten Section fields, and Round Mountain Silt in the Rio Bravo field (Division of Oil, Gas, and Geothermal Resources, 1998). Additional hydrocarbon reservoirs include the Vedder and Jewett Sands in the Greeley and Rio Bravo fields, and the Etchegoin Formation in the Rio Bravo field (Division of Oil, Gas, and Geothermal Resources, 1998).

Groundwater in the Middle Kern Valley Floor subregion can be characterized as having a large contrast in TDS concentrations across all fields, owing to significant differences in depths between petroleum and water wells. All except two wells perforated at depths greater than 2,000 ft bls yielded samples with TDS concentrations greater than 10,000 mg/L (figs. 7*A*–*B*). In contrast, all wells perforated at depths less than 1,000 ft bls yielded samples with TDS concentrations less than 3,000 mg/L, with the vast majority of those less than 1,000 mg/L. Median TDS concentrations in produced water were greater than 10,000 mg/L in all four fields, ranging from 19,815 mg/L (Greeley) to 28,403 mg/L (Canfield Ranch). For water wells, median TDS concentrations in groundwater were fresh in all four fields, ranging from 151 mg/L (Ten Section) to 317 mg/L (Greeley; table 3).

Profile plots of the vertical distribution of TDS show that produced-water samples in the four mapped Middle Kern Valley Floor subregion fields all had much higher TDS concentrations than water-well samples, as evidenced by the complete lack of overlap between where samples plot for the two well types (fig. 8). In addition, the profile plots show a large vertical separation based on the median altitude of top perforation of petroleum wells versus median bottom perforation, completed well depth, or hole depth for water wells, ranging from about 2,300 ft for Ten Section to about 10,900 ft for Greeley (fig. 8; table 3).

Total dissolved solids concentrations less than 10,000 mg/L were present in all samples from water wells but in only 3 percent (2 of 71) of produced-water samples from petroleum wells. Overall, TDS concentrations in produced water ranged from 2,902 mg/L from a well in Canfield Ranch to 41,693 mg/L from a well in Rio Bravo (table 3). The top perforation of these wells ranged from altitudes of –2,000 to about –11,500 ft. In comparison, all water-well samples had TDS concentrations less than 3,000 mg/L and were from wells perforated at altitudes between 500 and –500 ft (fig. 8). Based on a combination of linear regression analysis (R-squared values between 0.57 and 0.84) and visual assessment, the approximate minimum depth marking the 10,000 mg/L threshold ranges from an altitude of about –2,000 ft (2,300 bls) in Ten Section to about –3,800 ft (4,100 bls) in Rio Bravo (table 3). Similarly, the approximate minimum depth of the 3,000 mg/L threshold ranges from an altitude of about –700 ft (1,000 ft bls) in Ten Section to about –1,300 ft (1,600 ft bls) in Greeley. These altitudes for the 3,000 mg/L threshold in the four fields are deeper than the bottom perforation, completed well depth, or hole depth of all water wells used for salinity mapping in the Middle Kern Valley Floor subregion.

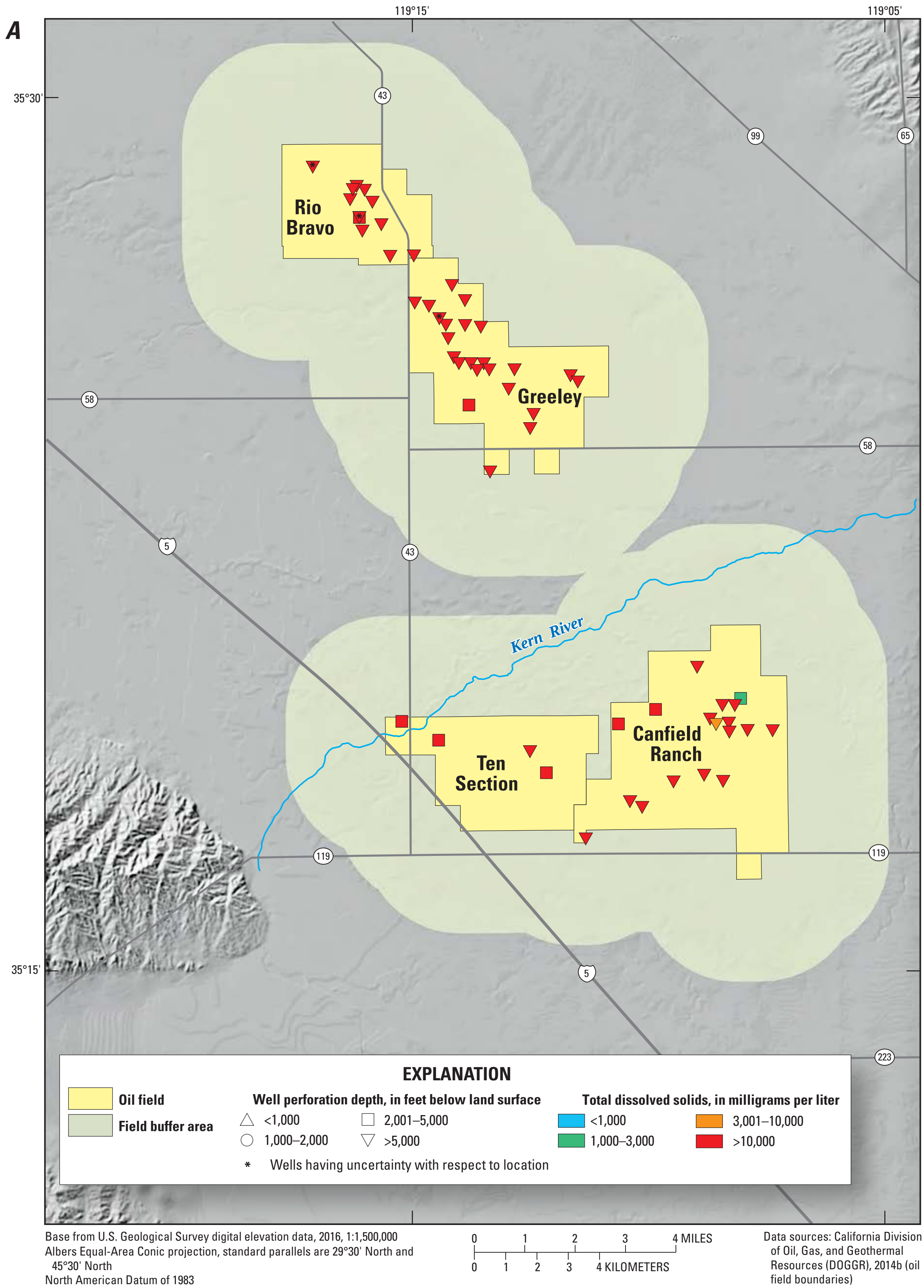
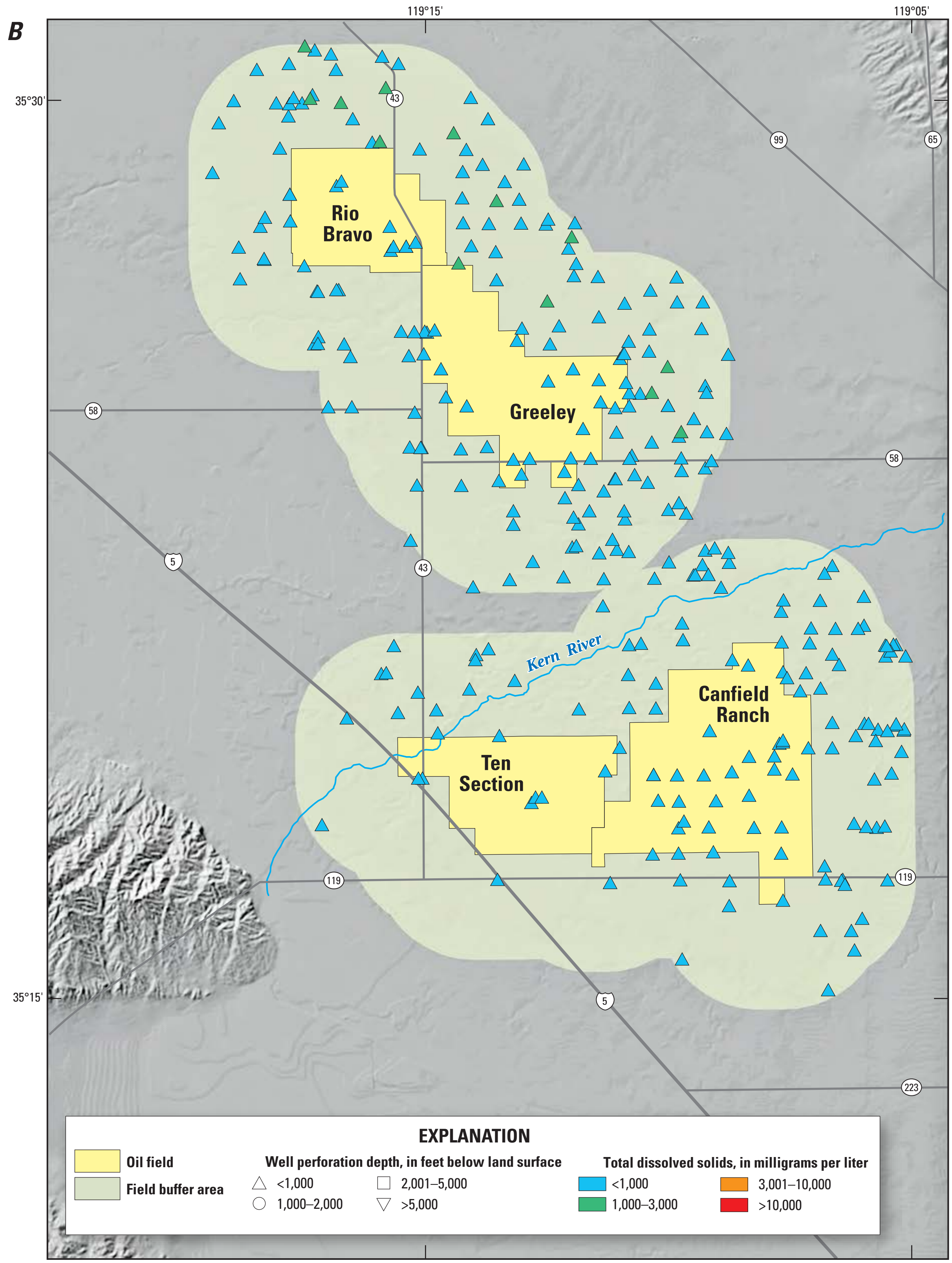


Figure 7. Distribution of total dissolved solids in *A,* produced water from petroleum wells, and *B,* water from water wells, for selected oil fields in the Middle Kern Valley Floor subregion, central California.



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014b (oil field boundaries)

Figure 7. —Continued

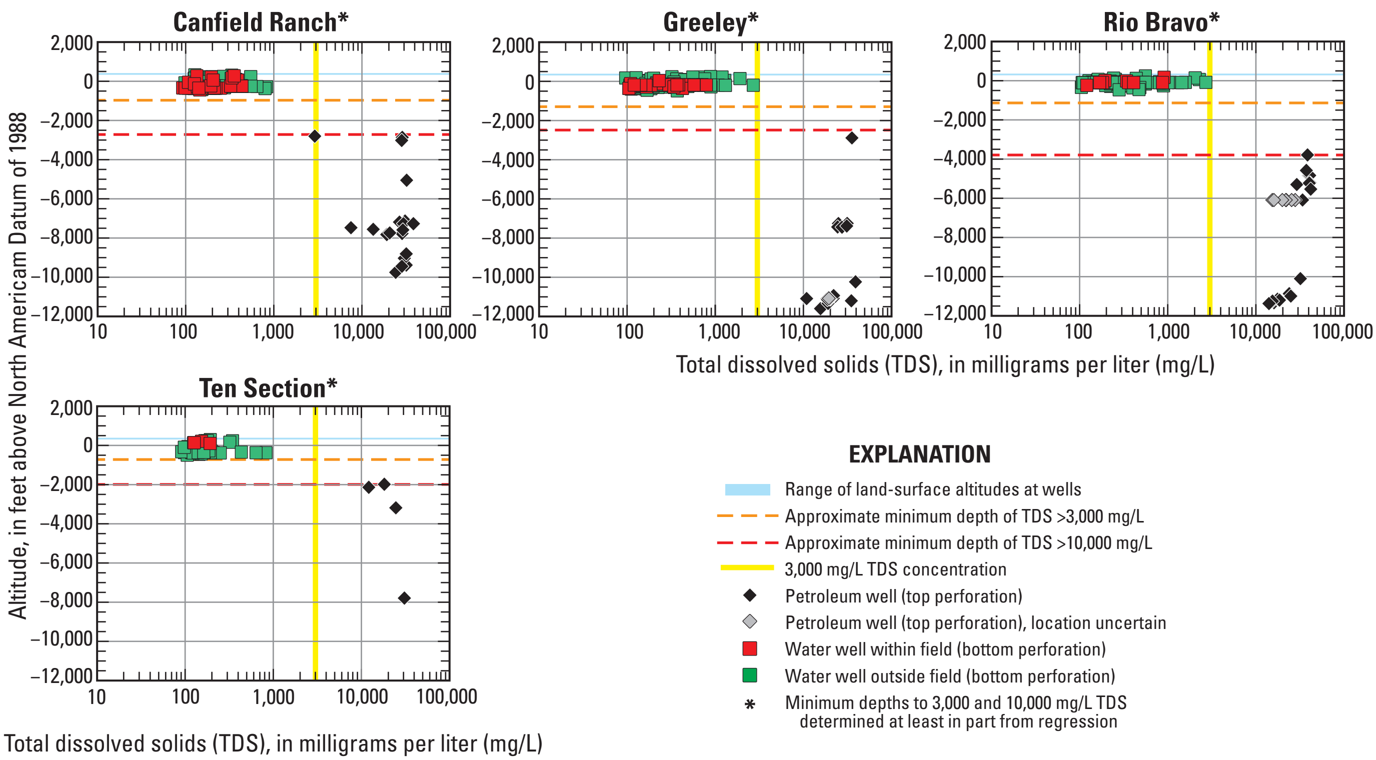


Figure 8. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the Middle Kern Valley Floor subregion, central California.

South Kern Valley Margin

Situated across the southern end of the San Joaquin Valley and bordering the junction of three geologic provinces (the Sierra Nevada, Transverse and Selected Peninsular Ranges, and Southern Coast Ranges; fig. 1), the South Kern Valley Margin subregion includes the following four oil fields: San Emidio Nose, Tejon, Wheeler Ridge, and Yowlumne. Wells used for mapping salinity across these 4 fields numbered between 1 (Yowlumne) and 47 (Wheeler Ridge) petroleum wells and between 50 (Wheeler Ridge) and 110 (San Emidio Nose) water wells within or assigned to each field (table 3). The number of wells attributed with depth data ranged from 80 percent (San Emidio Nose) to 100 percent (Tejon and Yolumne) of petroleum wells and 36 percent (San Emidio Nose) to 59 percent (Tejon) of water wells (table 3).

Geologically, the South Kern Valley Margin subregion resides within the MTS (fig. 2), an area characterized by Cenozoic deposits that increase in thickness from the southeast towards the northwest (Hosford Scheirer, 2007, chap. 7). The thickness of these deposits, and thus depth to underlying basement rock, ranges from about 12,000 ft near the eastern end of the Tejon field to about 22,000 ft in the vicinity of the Yowlumne field (Hosford Scheirer, 2007, chap. 13). The White Wolf Fault separates the Tejon and Wheeler Ridge fields to the southeast from the San Emidio and Yowlumne fields to the northwest (fig. 2). The most productive hydrocarbon-bearing zones common to both the Tejon and Wheeler Ridge fields from oldest to youngest include the Freeman Silt–Jewett Sand, Olcese Sand, Round Mountain Silt, Fruitvale shale of Miller and Bloom (1939), and Santa Margarita Sandstone (Division of Oil, Gas, and Geothermal Resources, 1998). The most productive hydrocarbon-bearing zone common to both the San Emidio and Yowlumne fields is the Monterey Formation, particularly the Reef Ridge Shale (Division of Oil, Gas, and Geothermal Resources, 1998).

Groundwater in the South Kern Valley Margin subregion has a wide range of TDS concentrations. Total dissolved solids concentrations in samples from most wells (87 percent) were less than 10,000 mg/L (figs. 9*A*–*B*). This included about 29 percent (20 of 68) of petroleum wells and all (309) water wells. Total dissolved solids concentrations were generally highest across the Yowlumne, Wheeler Ridge, and San Emidio Nose fields, owing to the majority of petroleum wells in those fields yielding produced-water samples with concentrations more than 10,000 mg/L. Comparatively low TDS concentrations (less than 1,000 mg/L) were prevalent in samples from water wells within northern parts of the buffer areas for the Tejon and Wheeler Ridge fields (fig. 9*B*). In addition, about 30 percent of water wells with bottom perforation, completed well depth, or hole depth between 1,000 and 2,000 ft bls near the San Emidio Nose field yielded samples with TDS concentrations less than 1,000 mg/L. Median TDS concentrations in produced water ranged from 7,000 mg/L (Tejon) to 21,944 mg/L (Wheeler Ridge). For water wells, median TDS concentrations in groundwater ranged from 425 mg/L (Tejon) to 1,192 mg/L (Yowlumne; table 3).

Profile plots of the vertical distribution of TDS show that concentrations in produced-water samples were almost all higher than water-well samples. Some produced-water samples from the Tejon field had TDS overlapping with values in water-well samples. In the two fields with a relatively high number of produced-water samples, Tejon and Wheeler Ridge, produced-water samples showed increasing TDS concentration with depth. In the Wheeler Ridge field, several petroleum wells were perforated at a higher altitude than associated water wells; this is because land-surface elevations differ by up to 1,500 ft between the hills in the western part of the field, where many of the petroleum wells are located, and the more gently sloping and lower elevations several miles to the north, outside of the administrative field boundaries, where many of the water wells are located (fig. 10). For the remaining three fields, the vertical separation based on the individual (Yowlumne, with only one well) or median altitude of top perforation of petroleum wells versus median bottom perforation, completed well depth, or hole depth for water wells ranged from about 3,100 ft for Yowlumne to about 7,100 ft for San Emidio Nose (fig. 10; table 3).

Total dissolved solids concentrations exceeded 10,000 mg/L in produced-water samples from all petroleum wells in the San Emidio Nose and Yowlumne fields, in produced-water samples from about three-quarters of the petroleum wells in the Wheeler Ridge field, and in produced-water samples from one-third of the petroleum wells in the Tejon field. Petroleum wells having TDS greater than 10,000 mg/L were perforated at altitudes of 500 to –11,000 ft. Using either the shallowest depth of TDS greater than 10,000 mg/L based on the actual perforation depth, or predicted depth based on regression analysis (San Emidio Nose), the approximate minimum depth of TDS greater than 10,000 mg/L ranges from an altitude of about 500 ft (1,200 ft bls) in Wheeler Ridge to about –4,500 ft (5,000 ft bls) in San Emidio Nose. Groundwater samples from water wells had TDS concentrations generally less than 3,000 mg/L, with the exception of maximum concentrations of 3,800 mg/L and 3,042 mg/L in samples from water wells located in the buffer areas of the Yowlumne and San Emidio Nose fields, respectively (figs. 9*B*, 10). Based on these concentrations, the shallowest depth of TDS greater than 3,000 mg/L ranges from an altitude of about 500 ft (1,200 ft bls) in Wheeler Ridge to about –1,500 ft (2,000 ft bls) in San Emidio Nose (fig. 10; table 3). The reported 3,000 and 10,000 mg/L thresholds in Wheeler Ridge are at the same depth, owing to the lack of samples with TDS concentrations between 3,000 and 10,000 mg/L from wells perforated shallower than the shallowest well having a TDS concentration greater than 10,000 mg/L (fig. 10).

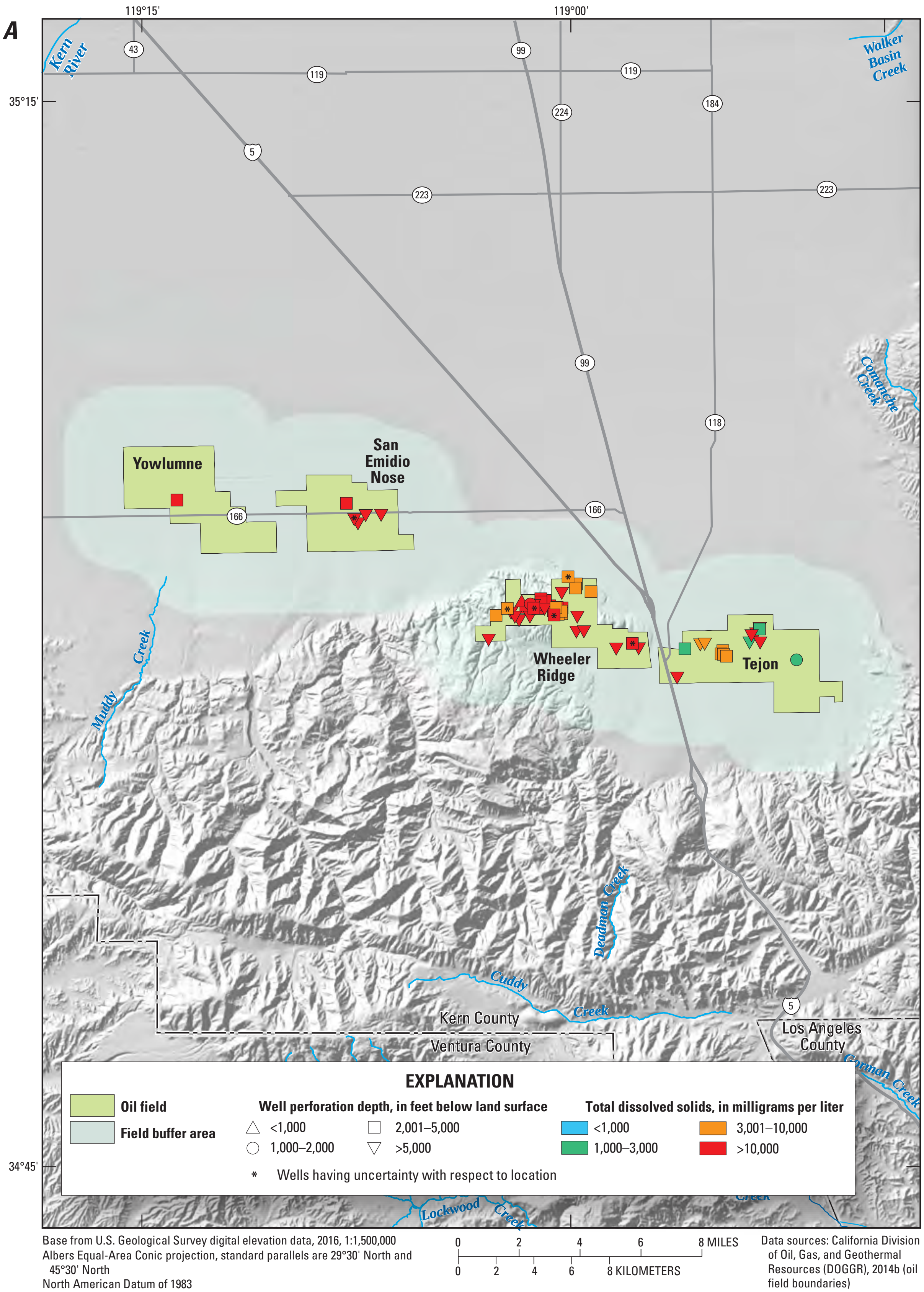


Figure 9. Distribution of total dissolved solids in *A*, produced water from petroleum wells, and *B*, water from water wells, for selected oil fields in the South Kern Valley Margin subregion, central California.

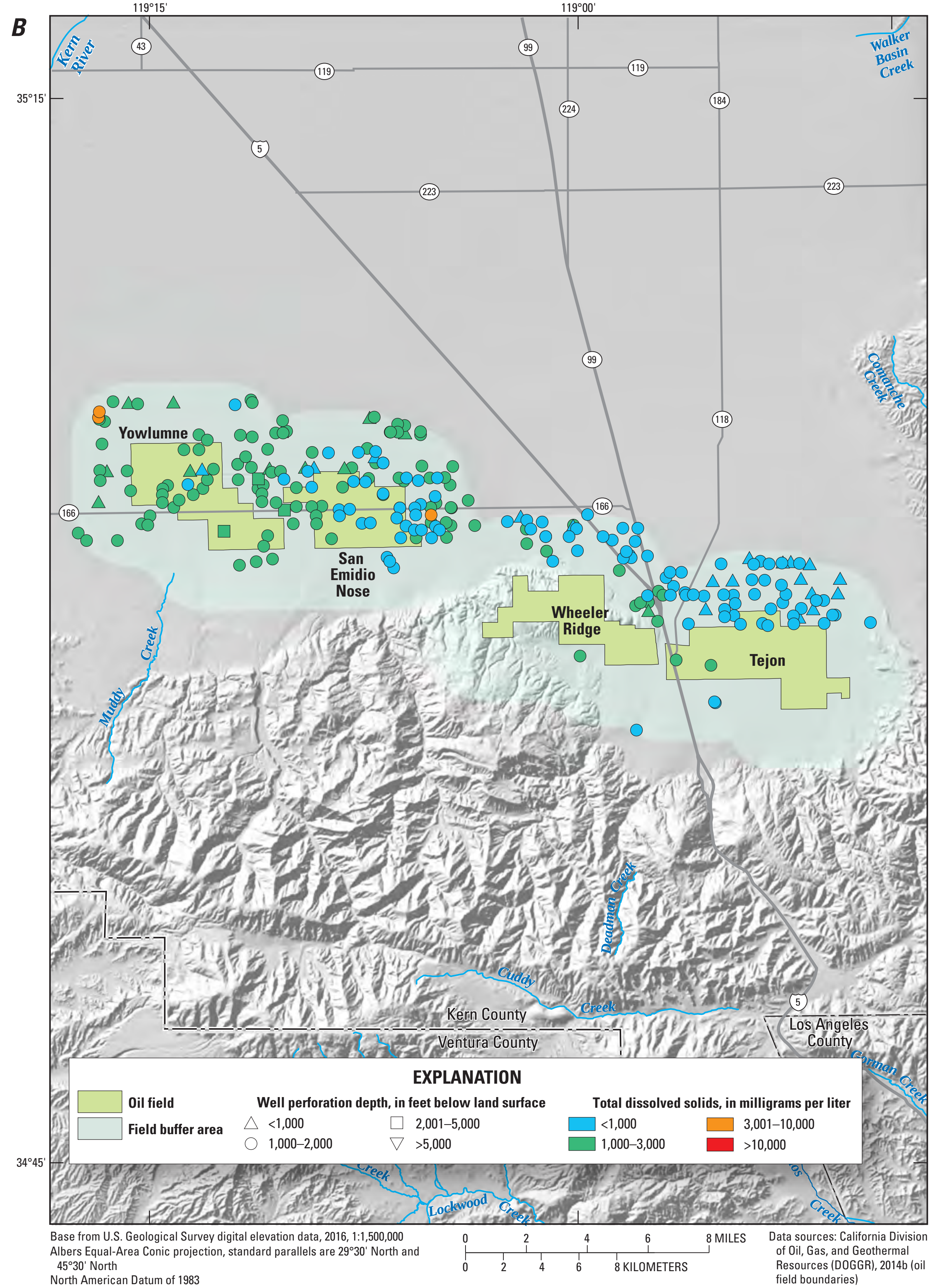


Figure 9. —Continued

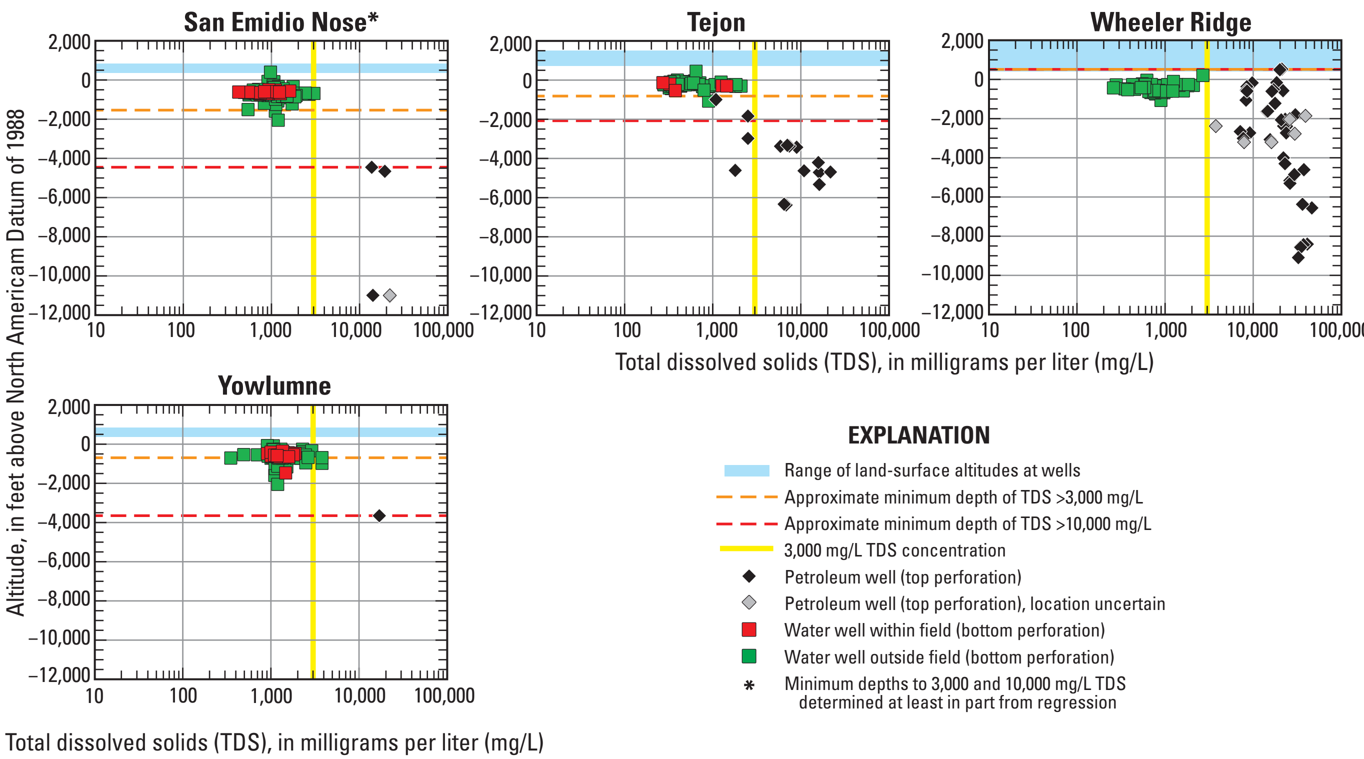


Figure 10. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the South Kern Valley Margin subregion, central California.

West Kern Valley Floor

The West Kern Valley Floor subregion is located slightly west of the center of the southern San Joaquin Valley floor (fig. 1) and includes the North and South Coles Levee fields. These two oil fields were combined for the purposes of salinity mapping because of their proximity as adjoining fields. The North and South Coles Levee fields directly abut the Elk Hills field in the adjacent West Kern Valley Margin subregion to the west; thus for the purposes of salinity mapping, these fields share many of the same within- and outside-field water wells (45) as a result of overlapping 2-mile buffer areas. Total dissolved solids and (or) specific conductance analyses were available for 18 petroleum wells and 111 water wells (table 3). All petroleum wells and 83 percent of water wells were attributed with perforation or well depth information (table 3).

Geologically, the West Kern Valley Floor subregion resides at the junction of three structural regions of the southern San Joaquin Valley, the SSB, MTS, and west-side fold belt (WFB; Bartow, 1991). This junction also coincides with the west end of the Bakersfield Arch (Bartow, 1991). The thickness of Cenozoic strata in this subregion ranges between 16,000 and 20,000 ft and generally increases from north to south (Hosford Scheirer, 2007, chap. 7). The most productive hydrocarbon-bearing zones include the Kreyenhagen, Monterey, and Etchegoin Formations in North Coles Levee and the Etchegoin and San Joaquin Formations in South Coles Levee (Division of Oil, Gas, and Geothermal Resources, 1998). Among these formations, the Monterey is the only reservoir for petroleum; the others are reservoirs for natural gas (Division of Oil, Gas, and Geothermal Resources, 1998).

Groundwater in the West Kern Valley Floor subregion can be characterized as having a large contrast in TDS concentrations particularly among samples from water wells (figs. 11*A*–*B*). Median TDS concentrations were 380 mg/L for samples from water wells to 24,549 mg/L in produced-water samples from petroleum wells (table 3). The majority of petroleum wells (16 of 18) had TDS concentrations greater than 10,000 mg/L (fig. 11*A*). Total dissolved solids concentrations in samples from most water wells (102 of 111) were less than 10,000 mg/L. Total dissolved solids concentrations from the remaining nine water wells (not all visible on fig. 11*B* because five wells plot in the same locations as other wells), were as high as 231,000 mg/L (table 3). All of these nine wells were outside of and to the southwest of the administrative field boundaries (fig. 11*B*). The source of high TDS concentrations in samples from these water wells is unknown but could potentially be associated with infiltration of evaporatively concentrated produced water from formerly used, unlined disposal ponds, as has been discussed in previous studies in the region (Bean and Logan, 1983). Degradation of water quality may also be associated with agricultural practices including the application of imported water for irrigation, resulting in downward leaching of salts from the root zone to the water table and infiltration of evaporatively concentrated irrigation water from agricultural sumps (Swain and Duell, 1993). Regardless of the source, data in this area indicate that depth to groundwater is shallow, and salinity, as represented by electrical conductivity (EC), is elevated. Contour maps from 2013 (the latest year available) and earlier indicated that depth to water in much of the West Kern Valley Floor subregion was 10–15 ft bls, and even shallower at 5–10 ft bls to the southwest, coinciding with the highest TDS samples from water wells (California Department of Water Resources, 2017). Electrical conductivity of shallow groundwater in this subregion was as high as 20,000 microsiemens per centimeter (µS/cm; California Department of Water Resources, 2017).

A profile plot of the vertical distribution of TDS shows overlap between TDS values of produced water and water-well samples, owing to the very large range of TDS values for groundwater from water wells, particularly those outside of the North and South Coles Levee fields, coupled with a relatively narrow range of TDS values for produced waters (fig. 12). The shallowest depth for petroleum wells with TDS greater than 10,000 mg/L was at an altitude of –1,200 ft. This altitude corresponds to a depth of about 1,500 ft bls and translates into vertical separation of about 700 ft between the shallowest top perforation for a mapped petroleum well and the deepest bottom perforation or completed well depth for a mapped within-field water well. Total dissolved solids concentrations of groundwater from water wells within these fields were less than 3,000 mg/L, with the exception of samples from three water wells with concentrations up to almost 5,300 mg/L. These wells were relatively shallow with completed depths between 52 and 682 ft (Metzger and others, 2018). Based on TDS concentrations of samples from petroleum and water wells located within the administrative boundaries of the North and South Coles Levee fields, thresholds for 3,000 and 10,000 mg/L are at about 300 ft (near land surface) and –1,200 ft (1,500 ft bls), respectively (fig. 12).

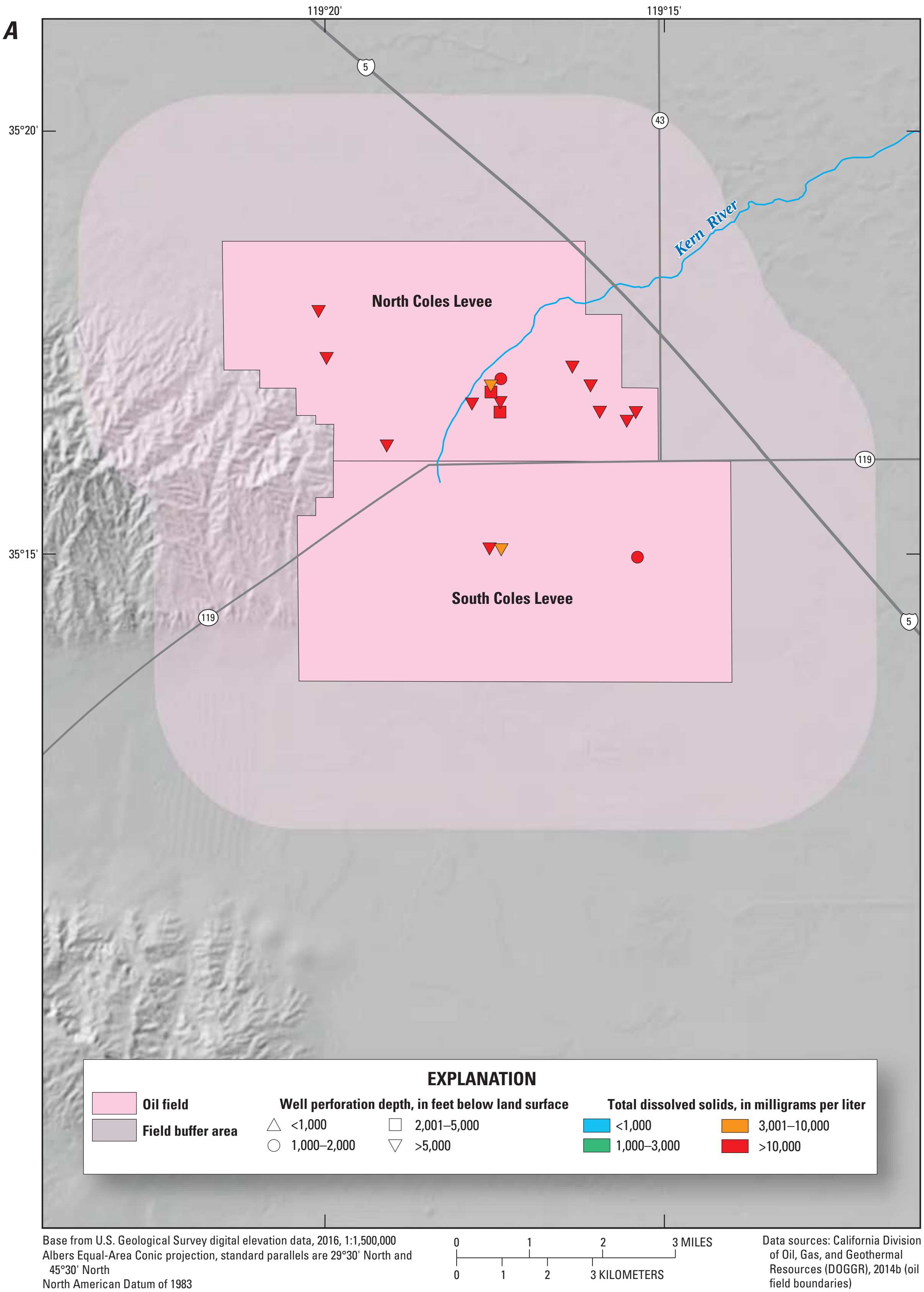


Figure 11. Distribution of total dissolved solids in *A*, produced water from petroleum wells, and *B*, water from water wells (not all wells visible because five wells plot in the same locations as other wells), for selected oil fields in the West Kern Valley Floor subregion, central California.

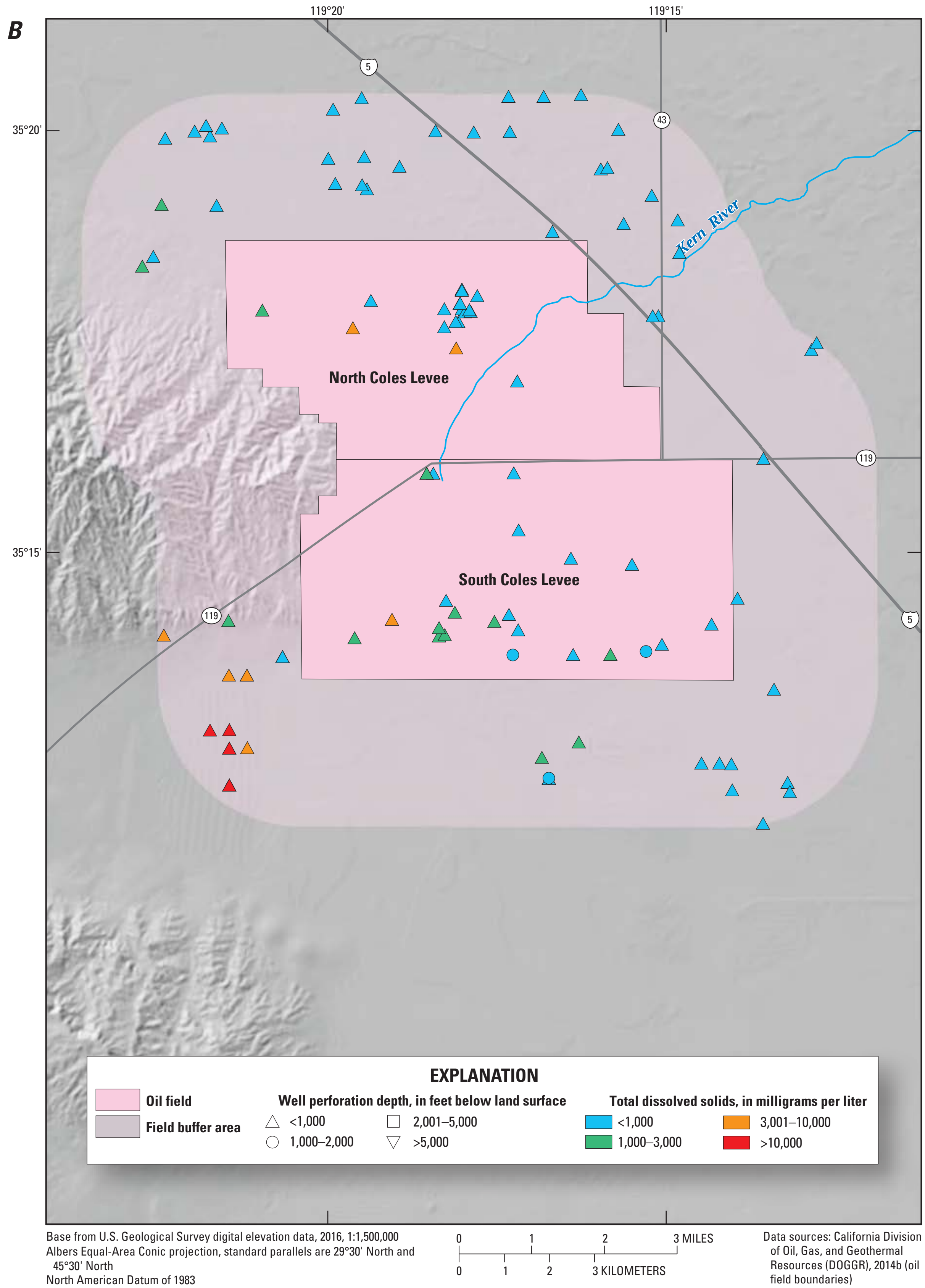


Figure 11. —Continued

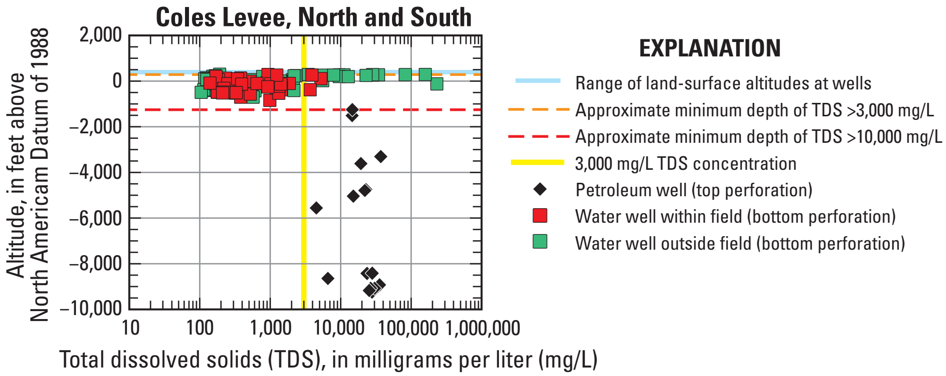


Figure 12. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the West Kern Valley Floor subregion, central California.

West Kern Valley Margin

The West Kern Valley Margin subregion represents the western side of the southern San Joaquin Valley (fig. 1) and includes the following five oil fields: North Belridge, South Belridge, Cymric, Elk Hills, and Lost Hills. North and South Belridge were combined for the purposes of salinity mapping because of the proximity of these fields and limited availability of TDS data from water wells. Wells used for mapping salinity across these 5 fields numbered between 33 (Cymric) and 151 (Elk Hills) petroleum wells and between 4 (Cymric) and 84 (Elk Hills) water wells within or assigned to each individual or aggregated field (table 3). The number of wells attributed by type ranged from 97 percent (Cymric) to 100 percent (Lost Hills) of petroleum wells and 25 percent (Cymric) to 83 percent (Elk Hills) percent of water wells (table 3). For water wells used to map salinity in the Cymric field, construction information was unavailable for three out of four wells, including two wells located in a part of the Cymric field's 2-mile buffer area where it overlaps the South Belridge field. In the absence of construction information, and for the purposes of salinity profile plots, the three unattributed Cymric water wells were assigned alternative values for bottom perforation. Unattributed water wells included in the profile plot for Cymric were assigned the bottom perforation value (542 ft bls) representing the single water well within 2 miles of the Cymric field having known construction information. Similarly unattributed water wells included in the profile plot for the combined North and South Belridge fields were assigned the median bottom perforation value (238 ft bls) representing all water wells in the North and South Belridge fields (table 3). As with other fields having a high proportion of unattributed wells used for the reconnaissance salinity mapping, the assignment of alternative values to represent depths results in some uncertainty as to the vertical distribution of TDS in the Cymric and combined North and South Belridge fields.

Geologically, the West Kern Valley Margin occupies the southern part of the WFB (fig. 2). This structural block is bounded on the west and south sides by the Southern Coast Ranges geographic province and the San Andreas fault zone. The WFB is characterized by extensive folding and faulting and variable stratigraphy (Bartow, 1991). Depth to basement and thickness of overlying Mesozoic and Cenozoic deposits increases substantially from southeast to northwest, ranging from about 20,000 ft at the eastern end of the Elk Hills field to about 40,000 ft near the northern end of the North Belridge field (Hosford Scheirer, 2007, chap. 7). The most productive hydrocarbon reservoirs in the subregion are associated with Cenozoic deposits and include, from oldest to youngest, the Tumey, Temblor, Monterey, Etchegoin, and Tulare Formations (Division of Oil, Gas, and Geothermal Resources, 1998).

Groundwater in the West Kern Valley Margin subregion has relatively high TDS concentrations, often greater than 10,000 mg/L, compared to other subregions. Total dissolved solids concentrations in samples were less than 10,000 mg/L in 14 percent (54 of 381) of petroleum wells and about 74 percent (164 of 222) of water wells (figs. 13*A*–*B*). Large contrasts in TDS concentrations were present in samples from petroleum wells, particularly in the Cymric field and combined North and South Belridge fields, where minimum TDS concentrations were 1,607 and 560 mg/L, respectively, and maximum concentrations were 29,000 and 48,262 mg/L, respectively (table 3). Median TDS concentrations in produced water ranged from 16,767 mg/L (Cymric) to 32,636 mg/L (Elk Hills). Large contrasts in TDS also were present for water wells; median concentrations for the West Kern Valley Margin subregion were higher than for any other subregion, ranging from 1,438 mg/L (Elk Hills) to 9,750 mg/L (combined North and South Belridge fields). Total dissolved solids concentrations greater than 3,000 mg/L in samples from water wells were prevalent within and outside the administrative field boundaries for Lost Hills and the combined North and South Belridge fields (fig. 13*B*). Significant contrasts in the areal distribution of TDS were evident for Elk Hills;

concentrations generally were greater than 3,000 mg/L in samples from water wells located on the south side of Elk Hills, in comparison to less than 3,000 mg/L in samples from water wells on the north side of Elk Hills.

Similar to the West Kern Valley Floor subregion, the source of moderately saline to very saline TDS in the West Kern Valley Margin subregion could also be the result of agricultural practices or oil production activities (Bean and Logan, 1983; Swain and Duell, 1993). Because many of the affected water wells are relatively shallow (less than 200 ft bls), areas of TDS greater than 3,000 mg/L may be indicative of localized perched aquifers. Contour maps available from CDWR for 2013 and earlier years indicated shallow groundwater and elevated EC in the 2-mile buffer area southeast of Elk Hills (including the overlapping 2-mile buffer area shared with the West Kern Valley Floor subregion) and within the 2-mile buffer area east of Lost Hills (California Department of Water Resources, 2017). Depth to water was generally 5–20 ft bls southeast of Elk Hills and east of Lost Hills. Electrical conductivity of shallow groundwater to the southeast of Elk Hills was generally 4,000–10,000 µS/cm (California Department of Water Resources, 2017). Electrical conductivity of shallow groundwater to the east of the Lost Hills field and south of Highway 46 was generally less than 2,000 to 10,000 µS/cm, but east of the Lost Hills field and north of Highway 46, EC was 10,000 to greater than 20,000 µS/cm (California Department of Water Resources, 2017).

Profile plots of the vertical distribution of TDS show considerable overlap in concentrations from petroleum and water wells. In fields having petroleum and within-field water wells (all except Cymric), vertical separation between petroleum and within-field water wells is minimal to nonexistent because a number of petroleum wells were perforated at similar and even shallower depths than water wells. As discussed earlier, the juxtaposition of petroleum- and water-well vertical proximity may not necessarily coincide with where oil is structurally or stratigraphically trapped, but rather where oil may be present as a result of upward migration. The Tulare Formation is the shallowest hydrocarbon reservoir, present within 1,000 ft of land surface with a thickness of several hundred feet. As such, at least some within-field water wells, the majority of which are designated as monitoring wells, may be perforated or completed at altitudes corresponding with perforation depths of petroleum wells. Total dissolved solids concentrations in water-well samples largely coincided with the low end of TDS concentrations in produced water in the North and South Belridge, Cymric, and Lost Hills fields (fig. 14). Elk Hills field is a notable exception because the range of TDS concentrations in samples from water wells greatly exceeded the overall range of produced water concentrations. Total dissolved solids concentrations ranged from 110 to 231,000 mg/L (table 3), including samples from five water wells, all located outside of the field and within the 2-mile buffer area, with concentrations greater than 50,000 mg/L (fig. 13*B*). Three of these five wells are also located in the overlapping 2-mile buffer area of the West Kern Valley Floor subregion. Although somewhat less than concentrations in water-well samples from Elk Hills, high TDS greater than 10,000 mg/L in samples from water wells were also prevalent both within and outside of the combined North and South Belridge fields and the Lost Hills field. For the combined North and South Belridge fields, approximately 49 percent of water wells had TDS greater than 10,000 mg/L. For the Lost Hills field, approximately 15 percent of water wells had TDS greater than 10,000 mg/L. An analysis of salinity versus depth for the North Belridge field by Gillespie and others (2017) noted a salinity reversal with decreasing salinity as depth increased below about –6,500 ft (7,000 ft bls). Although not readily apparent based on this report's analysis of combined TDS data from North and South Belridge, a similar effect is evident for the Cymric and Elk Hills fields, albeit at much shallower depths. Total dissolved solids concentrations in petroleum wells appear to peak at about –4,000 ft (5,000 ft bls) and –2,000 ft (3,000 ft bls) in Cymric and Elk Hills, respectively, and subsequently decline with increasing depth (fig. 14). Salinity reversals in other San Joaquin Valley oil fields beyond the scope of this study have been noted by other researchers and ascribed to differences in water origin (Gillespie and others, 2017).

No individual or aggregated field in the West Kern Valley Margin had median TDS concentrations less than 10,000 mg/L for petroleum wells (table 3). However, all fields did have median TDS less than 10,000 mg/L for water wells, including Elk Hills and Cymric with median TDS less than 3,000 mg/L (table 3). Petroleum wells with TDS greater than 10,000 mg/L were perforated over a broad range of altitudes between 500 and –8,600 ft (fig. 14). In comparison, all water wells with well-construction information that were used for mapping salinity in the subregion were perforated or completed at altitudes between 500 ft (less than 50 ft bls) and –800 ft (1,100 ft bls). Using the shallowest depth of TDS greater than 10,000 mg/L based on actual perforation depth, the approximate minimum depth of TDS greater than 10,000 mg/L ranges from an altitude of about 500 ft (100 ft bls) in the combined North and South Belridge fields to about –1,100 ft (1,800 ft bls) in Elk Hills field. Except for Elk Hills, the depths of the 3,000 and 10,000 mg/L thresholds were similar, owing to the lack of samples with TDS concentrations between 3,000 and 10,000 mg/L from wells shallower than the shallowest well having a TDS concentration greater than 10,000 mg/L.

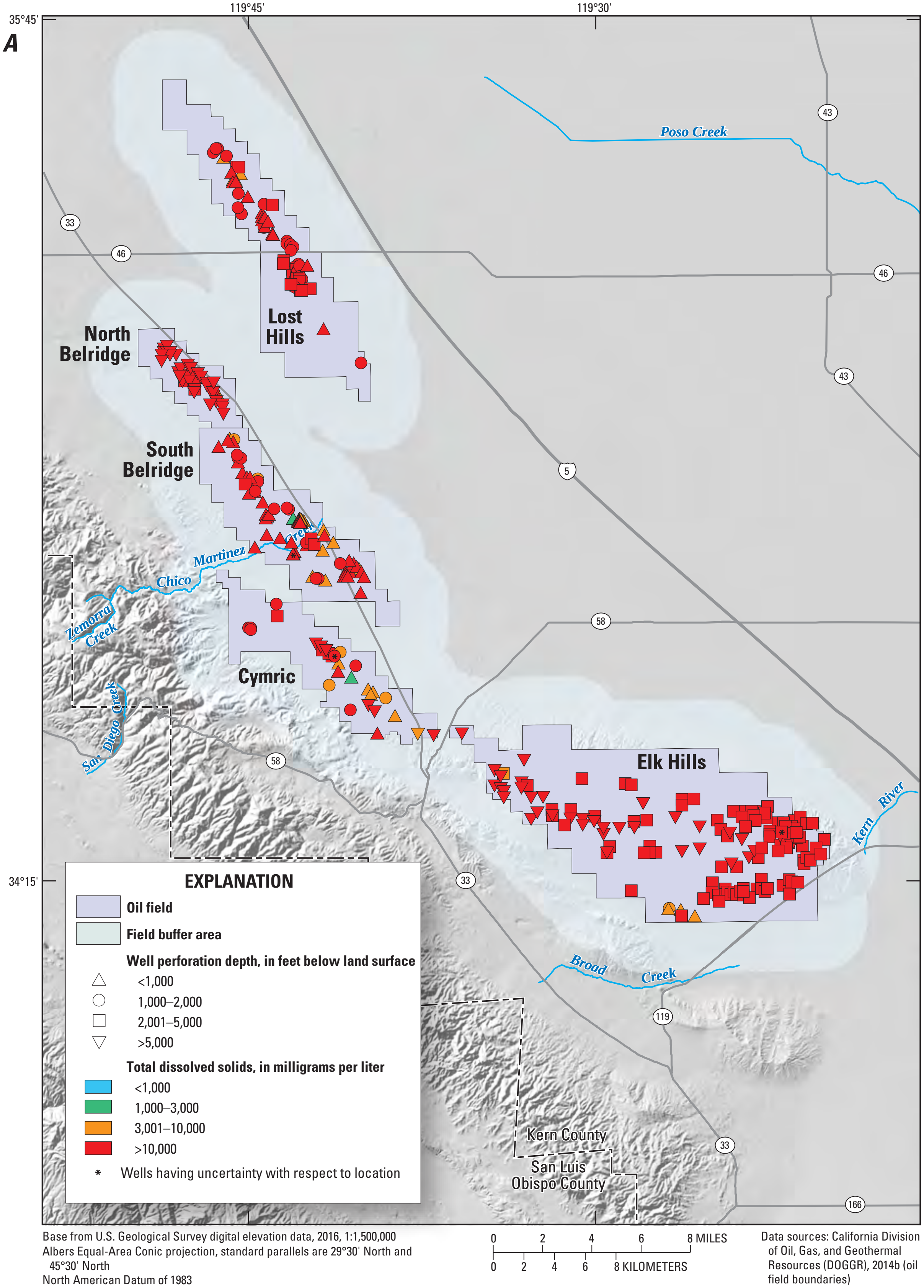
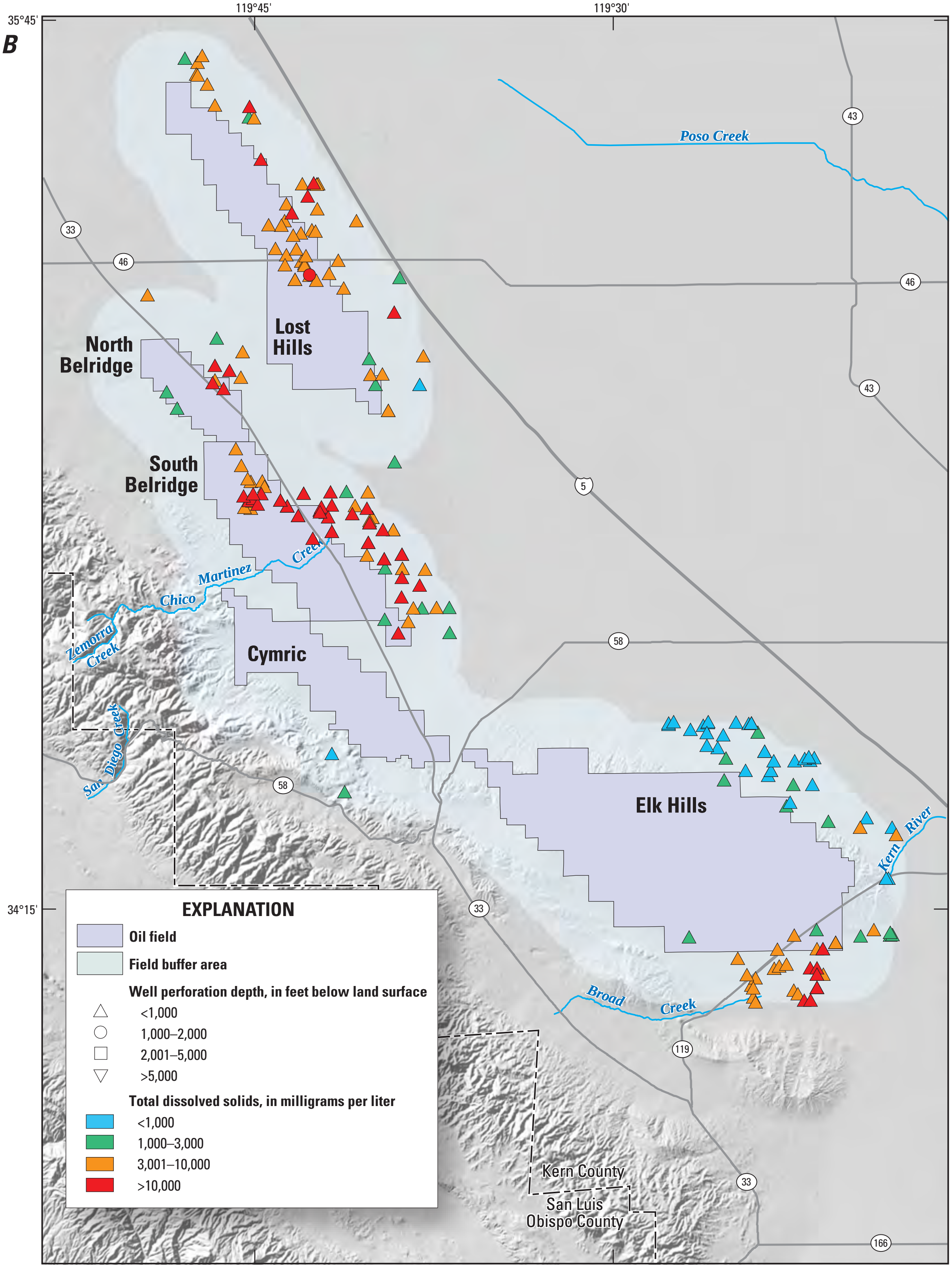


Figure 13. Distribution of total dissolved solids in *A,* produced water from petroleum wells, and *B*, water from water wells, for selected oil fields in the West Kern Valley Margin subregion, central California.



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014b (oil field boundaries)

Figure 13. —Continued

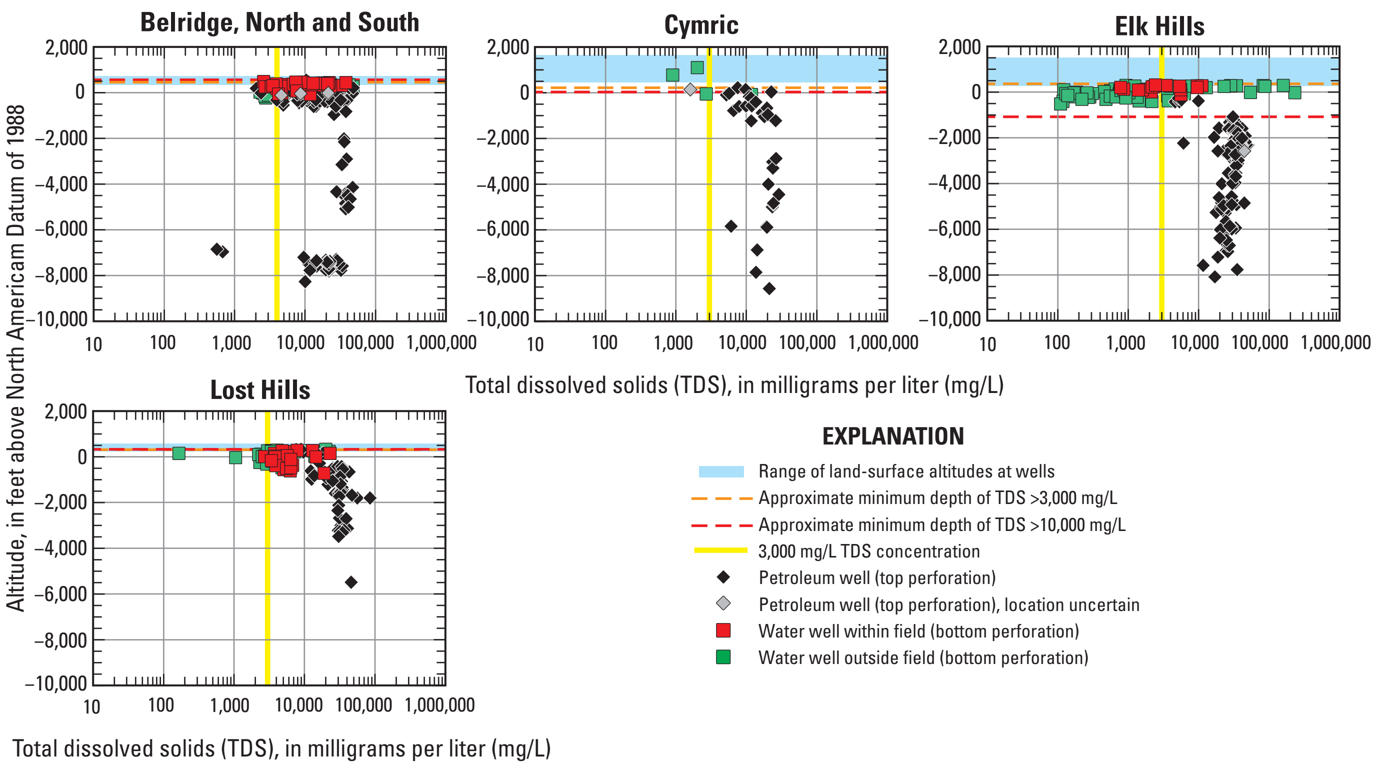


Figure 14. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the West Kern Valley Margin subregion, central California.

Los Angeles Basin

The Los Angeles Basin subregion occupies the relatively flat and broad expanse of central and southern Los Angeles County, extending from mountains of the Transverse and Selected Peninsular Ranges hydrogeologic province on the north and west to the Pacific Ocean on the south (fig. 1). Oil fields mapped as part of this reconnaissance salinity mapping effort included Montebello, Santa Fe Springs, and Wilmington. Wells used for mapping salinity across these 3 fields numbered between 3 (Montebello) and 118 (Wilmington) petroleum wells and between 202 (Santa Fe Springs) and 330 (Wilmington) water wells within or adjacent to each field (table 3). Petroleum wells in the Wilmington field identified as being located offshore were not included in salinity mapping. Water wells included in salinity mapping for the Wilmington field were limited to those located within 1 mile of the field's administrative boundaries, as opposed to the 2-mile buffer area used for all other mapped fields, to exclude what would have constituted a majority of water wells located within nearby unmapped fields to the north and west of Wilmington. The number of attributed wells ranged from 60 percent (Santa Fe Springs) to 100 percent (Montebello) of petroleum wells and 69 percent (Montebello) to 74 percent (Wilmington) of water wells (table 3).

Geologically, the Los Angeles Basin subregion can be characterized as a deep sedimentary basin surrounded by east-to-west trending hills and mountains that form the Transverse and Selected Peninsular Ranges and are composed of crystalline rocks (Bilodeau and others, 2007). The Los Angeles Basin subregion is divided into four structural blocks because of faulting: the Southwestern Block (SWB), the Northwestern Block (NWB), the Central Block (CB), and the Northeastern Block (NEB; Beyer, 1988, Yerkes and others, 1965). The three oil fields included in this report are located in the SWB (Wilmington), the CB (Santa Fe Springs), and the NEB (Montebello; fig. 2). Basement rock within the Los Angeles Basin subregion consists of metamorphic and igneous rock of Precambrian to Late Cretaceous age (Yerkes and others, 1965). The overlying strata consist of marine and nonmarine sedimentary and volcanic rock of Late Cretaceous to recent age with a maximum thickness of about 31,000 ft approximately midway between the Wilmington and Montebello fields, within the CB (Yerkes and others, 1965). The primary hydrocarbon reservoirs in the subregion are the Puente Repetto and Pico Formations (Division of Oil, Gas, and Geothermal Resources, 1992). In the Wilmington field, some oil production also occurs beneath the Puente Formation from fractured basement rock referred to as Catalina Schist (Beyer, 1988; Division of Oil, Gas, and Geothermal Resources, 1992). Above the Pico Formation resides non-hydrocarbon-bearing upper (San Pedro Formation) and lower (Lakewood Formation and recent alluvium) aquifer systems tapped by water-supply wells (Reichard and others, 2003).

Groundwater near the studied fields in the Los Angeles Basin subregion has a large contrast in TDS based on well depth and location, particularly within and adjacent to the Wilmington field. Total dissolved solids concentrations in produced-water samples from all 126 petroleum wells used for salinity mapping were greater than 10,000 mg/L (table 3; figs. 15*A*–*B*). These mapped petroleum wells all had top perforation depths greater than 2,000 ft bls (fig. 15*A*). In contrast, some of the highest TDS concentrations were associated with samples from water wells having either bottom perforation or completed well depth less than 1,000 ft bls and were located in or near the Wilmington field (fig. 15*B*). Total dissolved solids concentrations were greater than 10,000 mg/L in samples from 20 percent (66 of 330) of water wells in the Wilmington area used for salinity mapping. An additional 15 percent (50 of 330) of water wells in the Wilmington area had TDS concentrations between 3,000 and 10,000 mg/L. Median TDS concentrations in produced water ranged from 18,114 mg/L (Santa Fe Springs) to 30,957 mg/L (Wilmington). For water wells, median TDS concentrations in water samples ranged from 512 mg/L (Montebello) to 1,070 mg/L (Wilmington; table 3). These median values are somewhat higher than but still comparable to averages of upper and lower aquifer median TDS concentrations in the Central Groundwater Basin (401 mg/L), which includes the Montebello and Santa Fe Springs oil fields, and the West Coast Groundwater Basin (688 mg/L), which includes the Wilmington oil field, based on water supply and monitoring wells sampled as part of a study by Reichard and others (2003).

Profile plots of the vertical distribution of TDS show that produced-water samples generally had much higher TDS concentrations than water-well samples, as evidenced by limited overlap between the two well types (fig. 16). The exception is the Wilmington field, where the overall range of TDS concentrations in produced-water samples from petroleum wells overlaps the upper end of the range of TDS values in samples from water wells. Total dissolved solids concentrations in samples from about one-third (61 of 180) of water wells within the Wilmington field were similar (greater than 10,000 mg/L) to the TDS concentrations of produced water from petroleum wells, including samples from two water wells (one within the field and the other within the 1-mile buffer area) that exceeded the maximum TDS concentration of produced water, with TDS concentrations up to 48,250 mg/L (fig. 16; table 3). Among the three fields, Wilmington also had the smallest vertical separation, with a difference of about 2,800 ft between the median top perforation for petroleum wells and median bottom perforation, completed well depth, or hole depth for water wells. For Montebello and Santa Fe Springs, the vertical separation based on median depths was about 5,000 and 5,500 ft, respectively.

Top perforation depths for petroleum wells used for salinity mapping were all greater than 2,000 ft bls, ranging from 2,300 to 8,100 ft bls (fig. 16). In comparison, bottom perforation, completed well depth, or hole depth for within-field water wells were all less than 2,000 ft bls, ranging from about 10 to 1,900 ft bls.

Using either the shallowest depth of TDS greater than 10,000 mg/L based on the actual perforation depth, or predicted depth based on regression analysis (Santa Fe Springs), the approximate minimum depth of TDS greater than 10,000 mg/L ranges from an altitude of about 0 ft (approximately 0 ft bls) in Wilmington to about –4,200 ft (4,400 bls) in Santa Fe Springs (fig. 16; table 3). For the 3,000 mg/L and 10,000 mg/L thresholds, the approximate minimum depths in Wilmington were similar (the approximate minimum depth lines on fig. 16 overlap), owing to similar well depths over the entire range of TDS concentrations in samples from water wells. For the Montebello and Santa Fe Springs fields, the 3,000 mg/L threshold is much shallower than the 10,000 mg/L threshold, at about –1,100 ft (1,500 ft bls) and –900 ft (1,100 ft bls), respectively. Widespread elevated TDS concentrations at shallow depths in the Wilmington area, particularly in wells closest to the coast, is attributable at least in part to seawater intrusion as a result of groundwater pumping, which lowered water levels below sea level and induced the inland movement of seawater (Reichard and others, 2003; Land and others, 2004). Beginning in the 1950s, efforts were made to address seawater intrusion by injecting imported water into aquifers to create a hydraulic barrier. Over time, a combination of reduced groundwater pumping and artificial injection resulted in increasing water levels. However, despite these efforts, geophysical-log and water-quality analyses indicate that in parts of the West Coast Groundwater Basin, high salinity water persists in aquifers of the Lakewood Formation and overlying alluvium (above about 400 ft bls) and is increasing in parts of deeper aquifers (below about 700 ft bls) of the San Pedro Formation (Land and others, 2004). Additional possible sources of saline water include (1) disposal of oil-field brine water into sumps, natural channels, or onto the land surface, all common practices during the early development of oil in Wilmington and other fields in the West Coast Groundwater Basin; (2) groundwater contamination at depth from possible migration of contamination through abandoned or failed well casing; and (3) deep circulation of connate water (Land and others, 2004).

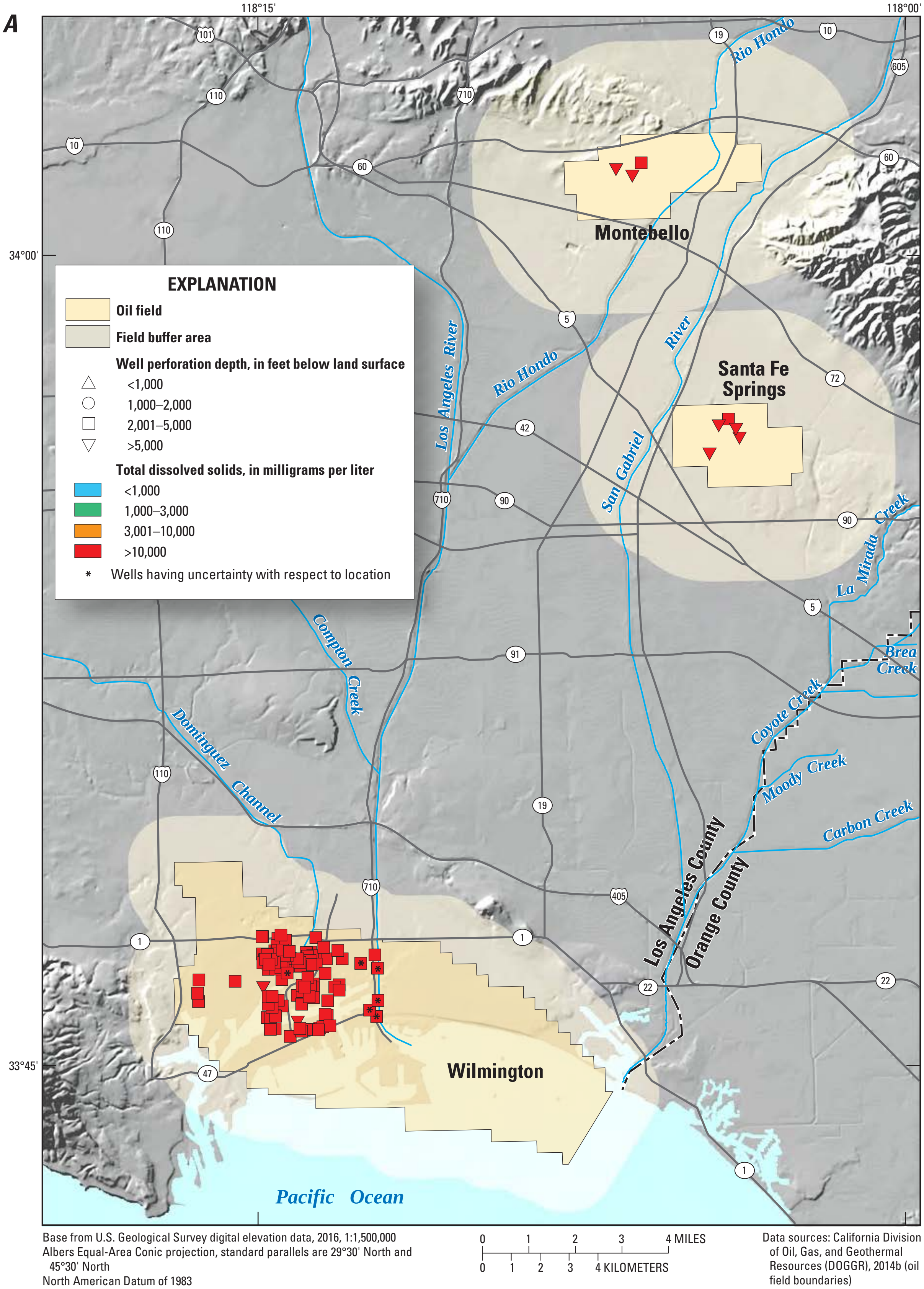
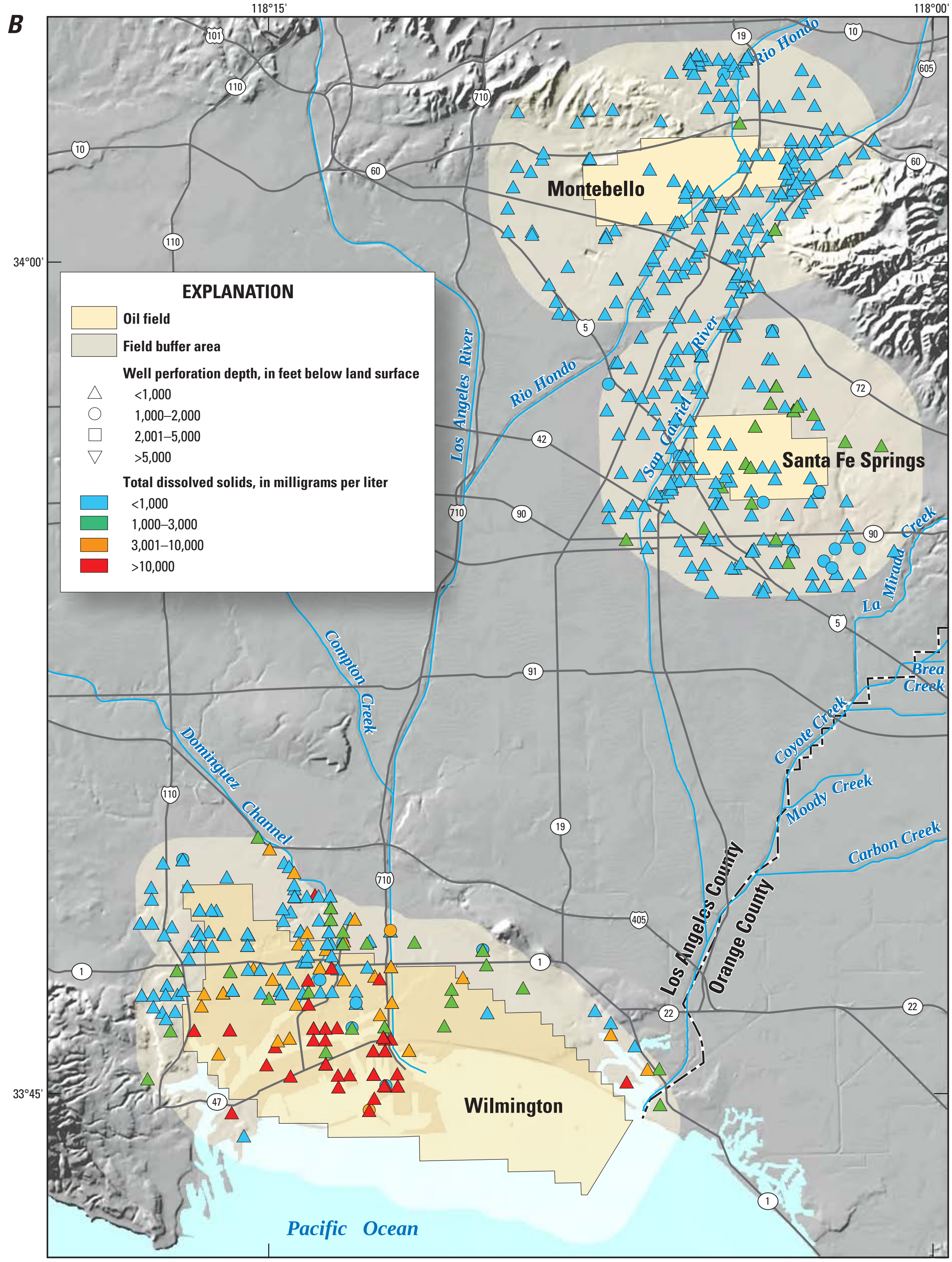


Figure 15. Distribution of total dissolved solids in *A*, produced water from petroleum wells, and *B*, water from water wells, for selected oil fields in the Los Angeles Basin subregion, southern California.



Base from U.S. Geological Survey digital elevation data, 2016, 1:1,500,000
Albers Equal-Area Conic projection, standard parallels are 29°30' North and 45°30' North
North American Datum of 1983

Data sources: California Division of Oil, Gas, and Geothermal Resources (DOGGR), 2014b (oil field boundaries)

Figure 15. —Continued

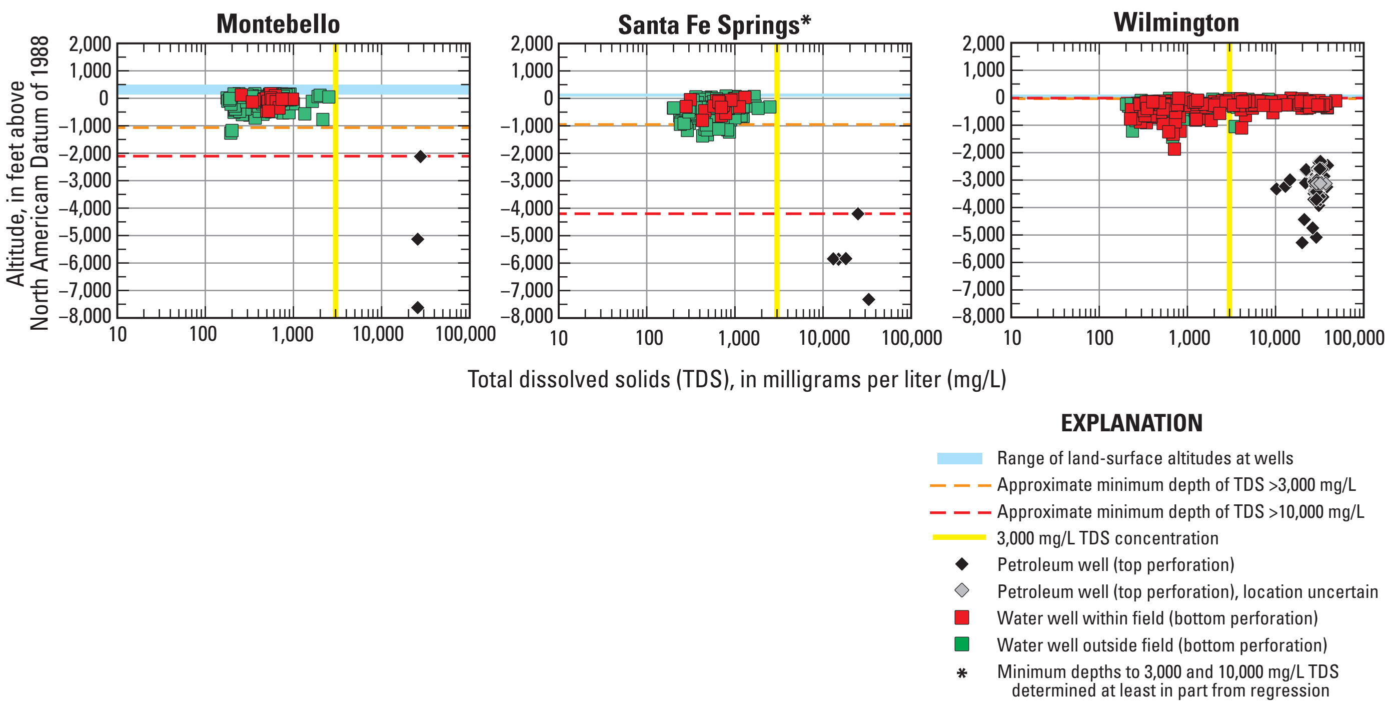


Figure 16. Vertical distribution of total dissolved solids concentrations for mapped oil fields in the Los Angeles Basin subregion, southern California. [The approximate minimum depths of TDS to 3,000 and 10,000 mg/L in Wilmington were similar, so the approximate minimum depth lines overlap.]

Central Coast Basin

The Central Coast Basin subregion is in Santa Barbara and San Luis Obispo Counties (fig. 1). This subregion contains a number of active oil fields, but for the reconnaissance salinity mapping, the Santa Maria Valley field was the sole focus. Wells used for salinity mapping in the Santa Maria Valley field included 6 petroleum wells and 471 water wells located either within the administrative field boundaries or the surrounding 2-mile buffer area. All petroleum wells and 79 percent of water wells were attributed with perforation and (or) well depth information (table 3).

Geologically, the Santa Maria Valley field in the Central Coast Basin subregion overlies a broad structural depression (syncline) bordered on all but the west side by hills that form the surface expression of regional uplift (anticlines; Worts, 1951). Basement consists of metamorphic and igneous rock of the Franciscan Formation (Worts, 1951). Overlying strata from older to younger are a combination of consolidated rock (the Monterey Formation and interbedded volcanics, the Sisquoc Formation, and Foxen Mudstone) and unconsolidated, water-bearing deposits (Careaga Sand, the Paso Robles Formation, the Orcutt Formation, and alluvium; Worts, 1951). The thickness of these consolidated and unconsolidated strata increases from northeast to southwest across the subregion, attaining a maximum thickness of about 10,000 ft along the axis of the Santa Maria Valley syncline, just north of but roughly parallel to Orcutt Creek (figs. 17*A*–*B*; Woodring and Bramlette, 1950; Worts, 1951). The principal hydrocarbon reservoirs include the Monterey, Sisquoc, and Foxen Formations, with additional production obtained from the Point Sal and Franciscan Formations (Division of Oil, Gas, and Geothermal Resources, 1992).

Median TDS concentrations near the Santa Maria Valley oil field ranged from 900 mg/L for samples from water wells to 24,742 mg/L in produced-water samples from petroleum wells (table 3). The majority of petroleum wells (five of six) had TDS concentrations greater than 10,000 mg/L (fig. 17*A*). The one exception had a TDS concentration between 3,000 and 10,000 mg/L and was the shallowest of the six petroleum wells, with a top perforation between 1,000 and 2,000 ft bls versus greater than 2,000 ft bls for all other mapped petroleum wells (fig. 17*A*). Total dissolved solids concentrations in samples from nearly all water wells (467 of 471) were less than 3,000 mg/L (fig. 17*B*). For the remaining four water wells (one within the field and three just outside of the administrative boundaries), TDS concentrations were between 3,000 and 10,000 mg/L. These particular wells were relatively shallow (well or hole depth instead of bottom perforation less than 200 ft bls) and were located in the western part of the Santa Maria Valley field.

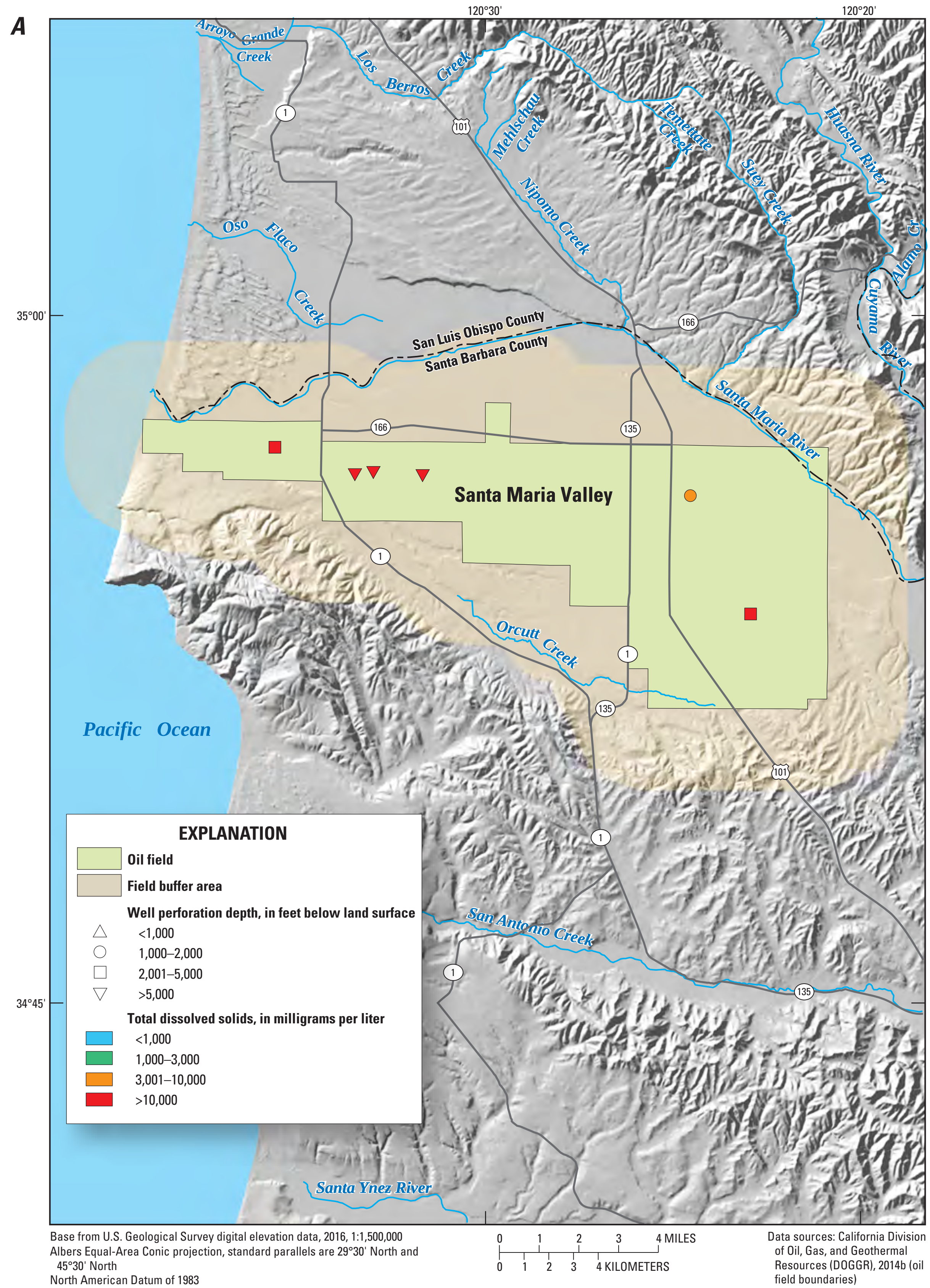


Figure 17. Distribution of total dissolved solids in *A*, produced water from petroleum wells, and *B*, water from water wells, for the Santa Maria Valley oil field, Central Coast Basin subregion, central California.

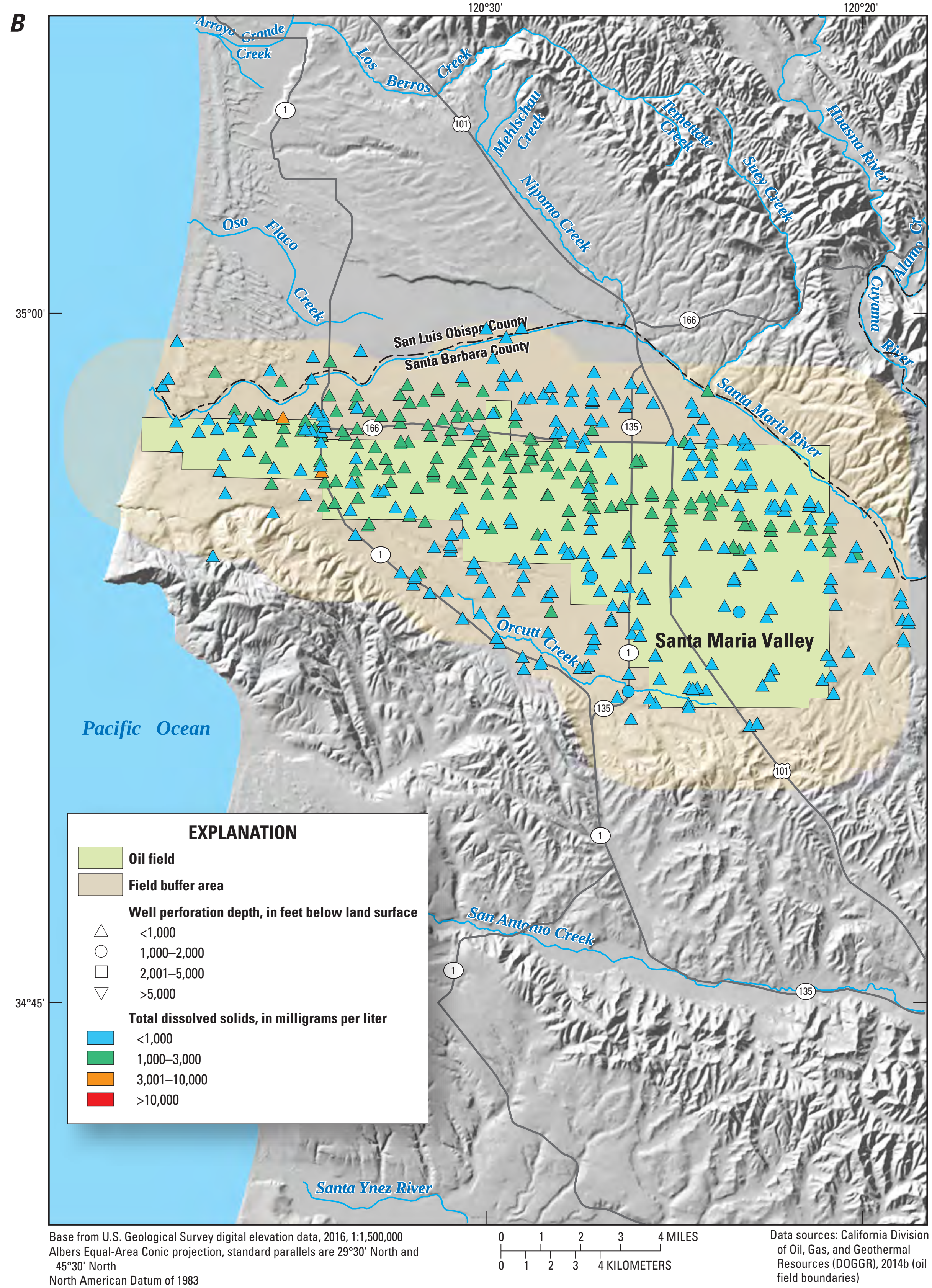


Figure 17. —Continued

A profile plot of the vertical distribution of TDS in the Santa Maria Valley field shows that concentrations in produced-water samples were higher than in water-well samples (fig. 18). The profile plot shows a significant vertical separation of about 4,600 ft based on the median altitude of top perforation for petroleum wells and median bottom perforation, completed well depth, and hole depth for water wells. The profile plot also shows a relatively small vertical separation, about 500 ft, between the shallowest top perforation for petroleum wells and deepest bottom perforation or completed well depth for within-field water wells. However, the TDS value of 8,000 mg/L in produced water from the shallowest mapped petroleum well was still less than the USDW threshold of 10,000 mg/L (table 3). The shallowest depth with TDS greater than 10,000 mg/L was at an altitude of –3,900 ft (4,100 ft bls). In comparison, the shallowest depth with TDS greater than 3,000 mg/L was at an altitude of about 0 ft (200 ft bls; table 3). Concentrations in excess of this threshold were limited to four water wells in the western part of the Santa Maria Valley field. Seawater intrusion is not believed to be a factor based on water-quality sampling of several monitoring wells along the western edge of the Santa Maria Valley field (GEI Consultants, 2013). Deep percolation of applied water for irrigation containing salts and nutrients flushed out of the root zone may be a source of elevated TDS concentrations (GEI Consultants, 2013).

Variation in Salinity Vertical Profiles Across Subregions

In general, TDS across the eight geographic subregions increased with depth, but the relation of TDS with depth varied regionally (fig. 19). The generalized depth profiles for each subregion shown in figure 19 are the best fit lines for the aggregated data for each subregion, plotted on a semi logarithmic scale (logarithmic x axis for TDS and linear y axis for depth). Because of differences in data availability, distributions, and uncertainties between the subregions, generalized profiles are presented to conceptualize relative differences in TDS-depth profiles between subregions. More precise and quantitative regional relations between TDS and depth will require more complete datasets.

In general, TDS values sharply increased over relatively small vertical depths near the land surface in the West Kern Valley Floor and West Kern Valley Margin subregions on the west side of the San Joaquin Valley and the Wilmington field part of the Los Angeles Basin subregion (fig. 19); relatively high TDS concentrations were present within the upper few hundred to several thousand feet of land surface. For these subregions, TDS concentrations were relatively high throughout the range of depths for which TDS data were available, including most of the shallowest produced waters and some overlying and adjacent well-water samples. The

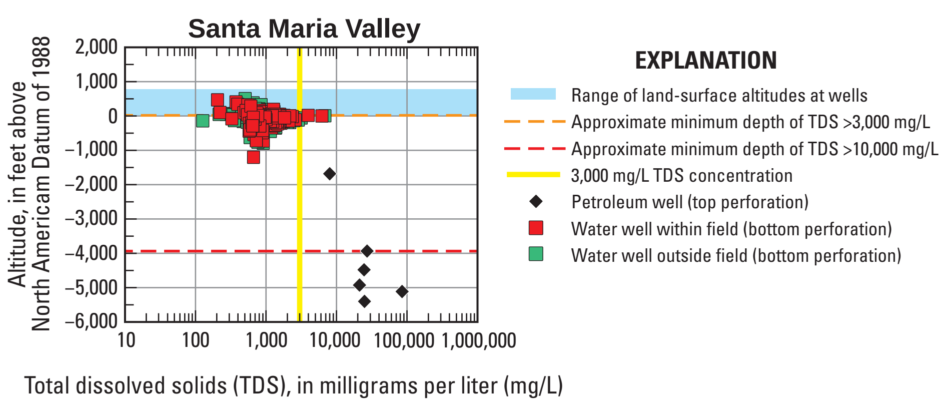


Figure 18. Vertical distribution of total dissolved solids concentrations for the Santa Maria oil field, Central Coast Basin subregion, central California.

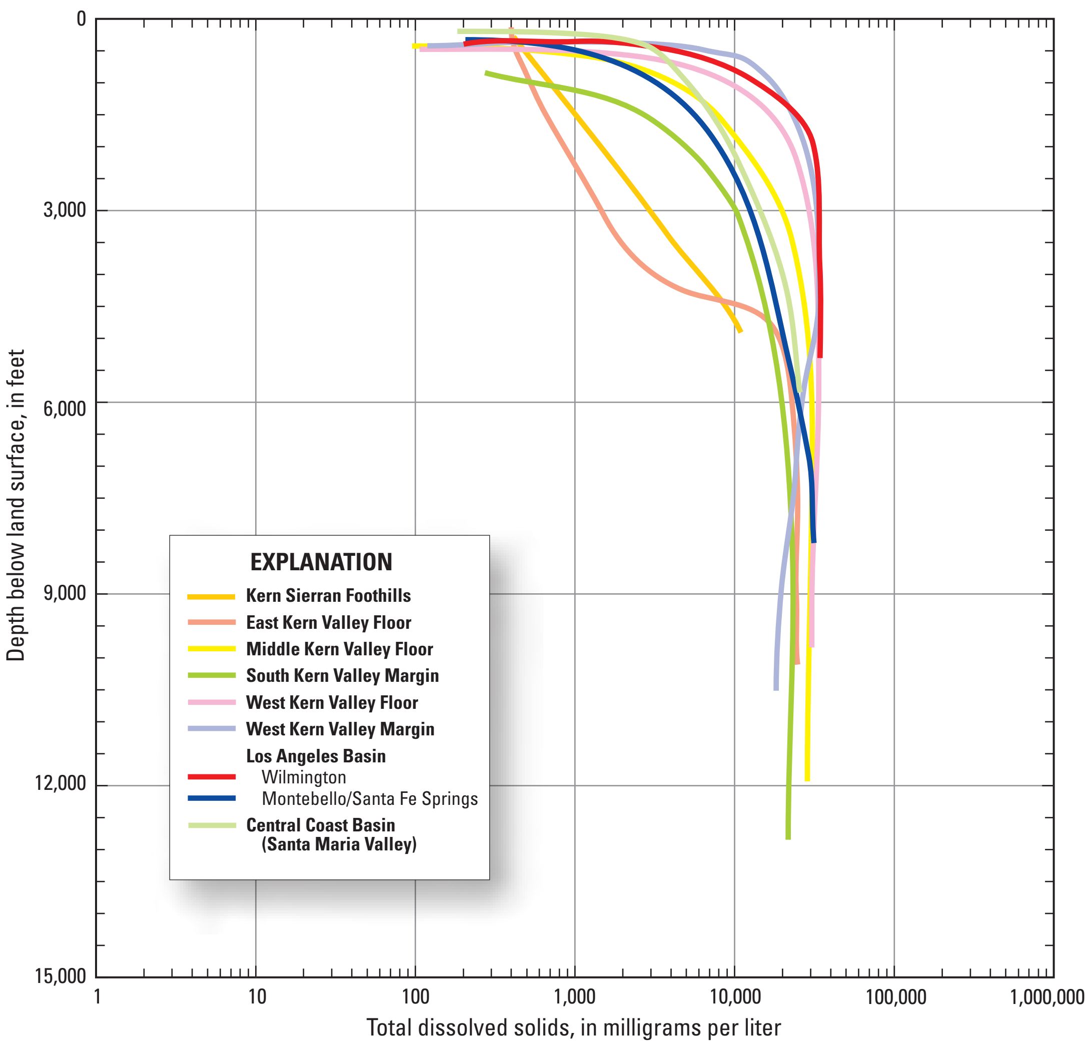


Figure 19. Generalized distribution of total dissolved solids versus depth for the eight geographic subregions, central and southern California.

depths of some well-water and produced-water samples in these subregions overlapped or had relatively little vertical separation. Some groundwater samples had TDS greater than 10,000 mg/L in western Kern County because of a combination of natural conditions and anthropogenic factors (Bean and Logan, 1983), and in the Wilmington field part of the Los Angeles subregion because of seawater intrusion and other factors (Land and others, 2004).

Total dissolved solids concentrations increased more gradually with depth, with intermediate slopes, in the Middle Kern Valley Floor and South Kern Valley Margin subregions, the Montebello and Santa Fe Springs fields in the Los Angeles Basin subregion, and Central Coast Basin subregion. In these areas, produced waters primarily had TDS concentrations greater than 10,000 mg/L, water-well samples primarily had TDS less than 3,000 mg/L, and groundwater and produced-water samples were generally thousands of feet apart vertically.

The Kern Sierran Foothills and East Kern Valley Floor subregions, on the east side of the San Joaquin Valley, had the most gradual increases in TDS with depth. Concentrations of TDS in available water samples were not typically greater than 10,000 mg/L even in the deepest petroleum wells sampled in the Kern Sierran Foothills subregion, consistent with the mapping results of Gillespie and others (2017), which showed maximum depths to 10,000 mg/L TDS on the east side of the southern San Joaquin Valley. Groundwater and produced-water samples were in relatively close vertical proximity in the Kern Sierran Foothills subregion. Fields in the East Kern Valley Floor subregion generally had groundwater and produced water with TDS less than 10,000 mg/L extending to a large depth compared to most other subregions, but most of the deeper produced-water samples had TDS more than 10,000 mg/L.

Overall, the west side of the San Joaquin Valley in Kern County and the Wilmington field in Los Angeles County, in proximity to the Pacific Ocean, generally had the highest TDS values and the shallowest depths to high TDS. Fields on the east side of the San Joaquin Valley in Kern County had the lowest TDS and greatest depths to TDS more than 10,000 mg/L because of their geologic setting adjacent to Sierra Nevada recharge areas (Gillespie and others, 2017). The San Joaquin Valley floor and southern margin settings in Kern County, Los Angeles Basin subregion inland oil fields (Montebello and Santa Fe Springs), and the Central Coast Basin subregion Santa Maria Valley oil field had intermediate TDS depth profiles with relatively low TDS in groundwater at shallow depths and relatively high TDS in produced water at large depths and varying degrees of vertical separation of these contrasting sample types.

The 10,000 mg/L threshold, representing the highest level of TDS concentration of water that could be considered as a potential source of drinking water (USDW), was present in all but 4 (Jasmin, Kern Bluff, Kern Front, and Mount Poso) of the 31 individual oil fields (29 aggregated fields). In some of the fields where the 10,000 mg/L threshold was encountered, it was at relatively shallow depths. For all five mapped fields in the West Kern Valley Margin subregion, TDS concentrations greater than 10,000 mg/L were present in wells within 2,000 ft of land surface, including within 200 ft of land surface in North and South Belridge (combined) and Lost Hills (fig. 20; table 3). Other than fields in the West Kern Valley Margin subregion, parts of the Wilmington field in the Los Angeles Basin subregion also had TDS concentrations greater than 10,000 mg/L within 200 ft of land surface. Selected fields in other subregions, including Kern River (Kern Sierran Foothills subregion), Rosedale (East Kern Valley Floor subregion), and Wheeler Ridge (South Kern Valley Margin subregion), had USDW thresholds that were within 2,000 ft bls (fig. 20; table 3).

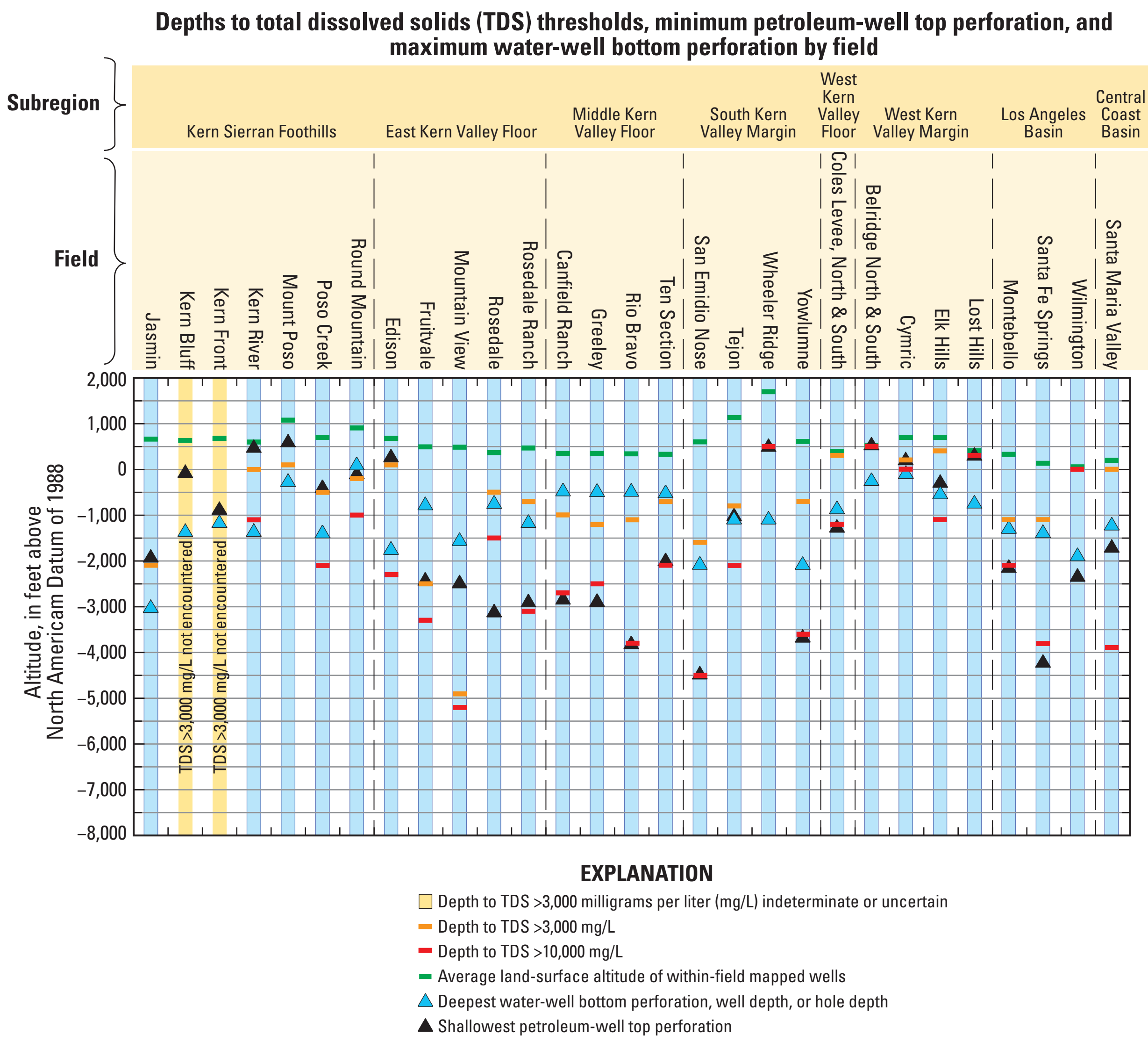


Figure 20. Altitudes of total dissolved solids (TDS) thresholds, minimum top perforation for petroleum wells, and maximum bottom perforation, well depth, or hole depth for water wells, by oil field, central and southern California.

The proximity of the depth interval where petroleum wells are perforated for production or injection to the depth of where water wells are perforated or completed varies substantially between different oil fields and thus indicates regional differences in the proximity of groundwater having TDS less than 10,000 mg/L and oil-field waters. The data compiled for this analysis differs from that of Davis and others (2018), who compared the depths of oil/gas and water wells, in that this analysis focuses only on those wells having TDS values. In a number of mapped fields in this analysis, the highest top perforation for petroleum wells is shallower than the deepest bottom perforation or completed well depth for water wells. A number of fields in the Kern Sierran Foothills, East Kern Valley Floor, South Kern Valley Margin, and West Kern Valley Margin subregions have petroleum wells perforated at comparable or even higher depths than where water wells, located both within and outside administrative field boundaries, are perforated or completed including Kern River, Poso Creek, Edison, North and South Belridge (combined), Elk Hills, and Lost Hills (fig. 20). Fields where this applies only to buffer wells, and thus the areal separation between petroleum wells and water wells used for salinity mapping may be upwards of 2 miles, include Jasmin, Kern Bluff, Kern Front, Mount Poso, Tejon, Wheeler Ridge, and Cymric (no within-field water wells for either Wheeler Ridge or Cymric). All of these fields may represent areas where oil and gas extraction activities are located in relative proximity to groundwater of potential beneficial use, consistent with conclusions of Davis and others (2018) using data sets that did not include water quality. As noted earlier in this report, vertical proximity of petroleum and water wells may be the result of perforation placement with respect to where recoverable oil is located. In some fields, petroleum well perforations do not necessarily coincide with where oil is structurally or stratigraphically trapped, but rather where oil may be present as a result of upward migration. Provided that oil has a pathway by which to migrate to the water table, it can reach altitudes corresponding with the perforation depths of water wells (Jan Gillespie, written commun., 2016).

Data Limitations and Future Work

The primary limitation of the reconnaissance salinity mapping was the lack of well-construction data for a substantial number of wells having salinity data. Bottom perforation, the key metric for water wells, was not readily available for 64 percent of wells used for salinity mapping. Instead of bottom perforation and for the purposes of this study, completed well depth or hole (drill) depth were acceptable alternatives. In combination with wells where depth to bottom perforation was estimated based on depth to top perforation plus screen length, the number of water wells lacking useful construction information (unattributed) was reduced to 35 percent (table 3). However, even with alternative values, five fields (Round Mountain, San Emidio Nose, Wheeler Ridge, Yowlumne, and Cymric) had less than 50 percent of water wells attributed (table 3). Construction data for petroleum wells was significantly more complete. Top perforation, the key metric for petroleum wells, was not readily available for just 3 percent of wells used for salinity mapping, with no field having less than 60 percent of wells attributed.

A second limitation of this study involved variability in data quality and selection of data used for mapping. Total dissolved solids and specific conductance data for both petroleum and water wells were compiled from a variety of data sources with varying amounts of documentation about sampling methodology ranging from comprehensive to very little or none. As a result, it was not always possible to assess how representative these data were of regional aquifer conditions. A few sample types were omitted, including injectate, tank, or composite samples from petroleum wells, because these samples could not be assigned to unique locations spatially. Analyses from drill stem test (DSTs) or Johnson formation testers (JFTs) in petroleum well boreholes collected during the drilling process were retained; in some cases, these sample results could be influenced by the presence of drilling fluids in the sample. Pore-water samples obtained from the unsaturated zone above the water table were omitted because they do not reflect saturated groundwater conditions and could be influenced by surface or soil processes. Other samples, particularly from relatively shallow water wells possibly representing perched groundwater or infiltration from surface impoundments, may not reflect regional groundwater conditions. However, given the uncertainty in being able to distinguish regional from local effects of salinity at the scales used for this report, samples from shallow water wells were retained as part of the salinity mapping effort.

Determination of depths in each field for TDS thresholds was a third data limitation. Both the 10,000 and 3,000 mg/L TDS thresholds should be considered as rough approximations given that, even within administrative field boundaries, TDS concentrations in samples from some petroleum and water wells with comparable depths were lower than the threshold concentrations. This indicates significant within-field variations, possibly attributable to factors such as geology; localized areas of wastewater injection; impacts from produced-water disposal ponds, irrigation return flow, or seawater intrusion; the assignment of median perforation or well depth to wells lacking construction information; or sample bias (samples that may represent a particular time period, data source, or may simply not be representative of the formation). Specifically, with respect to geology, variations in TDS concentrations may reflect water originating from different formations or mixtures of water from shallow and deeper sources. For example, the relatively shallow wells in the Kern River field of the Kern Sierran Foothills subregion may be drawing water from younger fluvial sediments with lower TDS versus deeper wells in other fields that may be predominantly drawing water from stratigraphically deeper units with higher TDS (Coburn and Gillespie, 2002).

This reconnaissance salinity analysis does not consider changes in salinity that may be occurring in the subsurface over time. Rather, for wells having TDS data (reported or converted from specific conductance) for multiple sample dates or multiple values on the same date, the median value was selected for salinity mapping, provided that the well perforation or sample depth was the same or a similar (within 100 ft vertical depth) for all analyses. Because the period of record is variable for each well (see data in Metzger and others, 2018), there is an implicit assumption that salinity is constant for time. Over a century of activities related to both oil production and groundwater pumping for beneficial use, older data may be more likely to reflect undisturbed formation conditions than recent analysis. In the absence of adequate documentation or information with respect to conditions at each well, TDS data were not screened on the basis of sample date.

Reconnaissance salinity mapping for additional priority fields using the approach applied for this study is continuing. These reconnaissance assessments may be refined through more detailed assessments for monitored oil fields or groups of oil fields in the future as part of the regional monitoring program. As part of ongoing and future salinity mapping, it is anticipated that well attribution will continue to be an important task in the ongoing effort to refine reconnaissance salinity maps through more detailed analysis as part of regional monitoring in and near priority oil fields or groups of fields. Additional efforts might also focus on acquiring more salinity data and applying more rigorous screening of available data to screen out values that may not be representative of regional aquifer conditions. Additional water-sample data exist that were not available in digital format at the time this study was conducted. More of these data may be available in numerical databases in the future. Future efforts to develop a more comprehensive understanding of the three-dimensional distribution of salinity near oil fields will need to incorporate a broader array of techniques, including analysis of oil and gas well borehole resistivity and ancillary logs, and surface and airborne geophysical (electromagnetic) data in selected areas to help fill in salinity patterns between locations of wells or boreholes with measured or modeled data. These additional approaches may become feasible as part of regional monitoring efforts at the scale of priority oil fields or groups of oil fields.

References Cited

Bartow, J.A., 1991, The Cenozoic evolution of the San Joaquin Valley, California: U.S. Geological Survey Professional Paper 1501, 40 p., https://pubs.er.usgs.gov/publication/pp1501.

Bartow, J.A., and Pittman, G.M., 1983, The Kern River Formation, southeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1529–D, 17 p., https://pubs.er.usgs.gov/publication/b1529D.

Bean, R.T., and Logan, J., 1983, Lower Westside water quality investigation, Kern County: prepared for California State Water Resources Control Board Under Contract No. 2–096–158–0, 128 p.

Belitz, K., Dubrovsky, N.M., Burow, K., Jurgens, BC.., and Johnson, T., 2003, Framework for a ground-water quality monitoring and assessment program for California: U.S. Geological Survey Water-Resources Investigations Report 2003–4166, 78 p., https://pubs.er.usgs.gov/publication/wri034166.

Beyer, L.A., 1988, Summary of geology and petroleum plays used to assess undiscovered recoverable petroleum resources of the Los Angeles Basin province, California: U.S. Geological Survey Open-File Report 88–450–L, 62 p., https://pubs.er.usgs.gov/publication/ofr88450L.

Bishop, J. [Chief Deputy Director, State Water Resources Control Board], 2014, Letter to Jared Blumenfeld, Regional Administrator, U.S. Environmental Protection Agency, Region IX, dated September 15, 2014, RE: Underground Injection Control Drinking Water Source Evaluation: State Water Resources Control Board, 5 p.

Blondes, M.S., Gans, K.D., Rowan, E.L., Thordsen, J.J., Reidy, M.E., Thomas, B., Engle, M.A., Kharaka, Y.K., and Thomas, B., 2017, U.S. Geological Survey National Produced Waters Geochemical Database v2.3 (provisional): U.S. Geological Survey web page, accessed March 1, 2018, at https://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data.

Blondes, M.S., Gans, K.D., Thordsen, J.J., Reidy, M.E., Thomas, B., Engle, M.A., Kharaka, Y.K., and Rowan, E.L., 2014, U.S. Geological Survey National Produced Waters Geochemical Database v2.1 (provisional): U.S. Geological Survey Web page, accessed April 22, 2015, at https://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data.

California Department of Water Resources, 2015a, California's groundwater update 2013—A compilation of enhanced content for California Water Plan Update 2013: California Department of Water Resources, 90 p., accessed May 2016 at http://www.water.ca.gov/waterplan/docs/groundwater/update2013/content/statewide/GWU2013_Combined_Statewide_Final.pdf.

California Department of Water Resources, 2015b, Water quality data reports: California Department of Water Resources web page, accessed June 2015 at http://wdl.water.ca.gov/waterdatalibrary/waterquality/index.cfm/.

California Department of Water Resources, 2017, San Joaquin Valley agricultural drainage—Shallow groundwater and electrical conductivity [digital spatial data, 2013]: California Department of Water Resources web page, accessed May 2017 at http://wdl.water.ca.gov/drainage/sgwec/index.cfm.

California Division of Oil, Gas, and Geothermal Resources, 1992, California oil and gas fields; Volume II—Southern, central coastal, and offshore California oil and gas fields: California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, 645 p., accessed February 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 February 2017 at ftp://ftp.consrv.ca.gov/pub/oil/publications/Datasheets/Dtasheet_vol_1.pdf.

California Division of Oil, Gas, and Geothermal Resources, 2014a, DOGGR GIS mapping: California Department of Conservation Division of Oil, Gas, and Geothermal Resources web page, accessed September 23, 2014, at http://www.conservation.ca.gov/dog/maps/Pages/GISMapping2.aspx.

California Division of Oil, Gas, and Geothermal Resources, 2014b, DOGGR GIS mapping: California Department of Conservation Division of Oil, Gas, and Geothermal Resources web page, accessed December 1, 2014, at http://www.conservation.ca.gov/dog/maps/Pages/GISMapping2.aspx.

California State Water Resources Control Board, 2015, Electronic data transfer library and water quality analyses data and download page [digital spatial water-quality data for public supply wells]: California State Water Resources Control Board web page, accessed February 2015 at http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/EDTlibrary.shtml.

California State Water Resources Control Board, 2016, GeoTracker [digital spatial environmental data for water-quality regulatory programs including those associated with oil and gas monitoring]: California State Water Resources Control Board database, accessed December 2016 at http://geotracker.waterboards.ca.gov/search.

Coburn, M.G., and Gillespie, J.M., 2002, A hydrogeologic study to optimize steamflood performance in a giant oilfield—Kern River field, California: American Association of Petroleum Geologists (AAPG) Bulletin 86, no. 8, p. 1489–1505, https://doi.org/10.1306/61EEDCD8-173E-11D7-8645000102C1865D.

Davis, T.A., Landon, M.K., and Bennett, G.L., 2018, 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: U.S. Geological Survey Scientific Investigations Report 2018–5065, 115 p., https://doi.org/10.3133/sir20185065.

Drever, J.I., 1982, The geochemistry of natural waters: 2nd Ed., Englewood Cliffs, N.J., Prentice-Hall, Inc., 388 p., https://hwbdocuments.env.nm.gov/Los%20Alamos%20National%20Labs/TA%2000/7181.pdf.

Eckis, R., 1940, The Stevens sand, southern San Joaquin Valley, California [abs.]: Bulletin of the American Association of Petroleum Geologists, v. 24, no. 12, p. 2195–2196.

Edwards, E.C., 1943, Kern Front area of the Kern River oil field, *in* Jenkins, O.P., ed., Geologic formations and economic development of the oil and gas fields of California: San Francisco, Calif., State of California, Department of Natural Resources, Division of Mines Bulletin No. 118, p. 571–574.

Fisher, J.B., and Boles, J.R., 1990, Water–rock interaction in Tertiary sandstone, San Joaquin Basin, California, U.S.A.—Diagenetic controls on water composition: Chemical Geology, v. 82, p. 83–101, https://doi.org/10.1016/0009-2541(90)90076-J.

Friedman, L.C., and Erdmann, D.E., eds., 1982, Quality assurance practices for the chemical and biological analyses of water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A6, 181 p., https://pubs.er.usgs.gov/publication/twri05A6.

GEI Consultants, Inc., 2013, Santa Maria Valley groundwater assessment: Submitted to Salt and Nutrient Planning Workgroup, Santa Barbara County IRWM Plan 2013, accessed April 1, 2016, at http://cosb.countyofsb.org/uploadedFiles/pwd/Water/IRWMP/2013_Plan/SM_GW_Assessment_SN_Report%2010_10_2013%20Final.pdf.

Gillespie, J., Kong, D., and Anderson, S.D., 2017, Groundwater salinity in the southern San Joaquin Valley: American Association of Petroleum Geologists (AAPG) Bulletin 101, no. 8, p. 1239–1261, https://doi.org/10.1306/09021616043.

Helsel, D.R., and Hirsh, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chapter A3, 523 p., https://pubs.er.usgs.gov/publication/twri04A3.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural waters, 3rd Ed.: U.S. Geological Survey Water Supply Paper 2254, 263 p., https://pubs.er.usgs.gov/publication/wsp2254.

Horsely Witten Group, 2011, California class II underground injection control program review: Submitted to Ground Water Office, U.S. Environmental Protection Agency Region 9, 490 p., accessed February 2016 at http://www.conservation.ca.gov/dog/Documents/DOGGR%20USEPA%20consultant%27s%20report%20on%20CA%20underground%20injection%20program.pdf.

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, accessed September 28, 2016, at https://pubs.usgs.gov/pp/pp1713/.

Land, M., Reichard, E.G., Crawford, S.M., Everett, R.R., Newhouse, M.W., and Williams, C.F., 2004, Ground-water quality of coastal aquifer systems in the West Coast Basin, Los Angeles County, California, 1999–2002: U.S. Geological Survey Scientific Investigations Report 2004–5067, 88 p., https://pubs.er.usgs.gov/publication/sir20045067.

Metzger, L.F., Davis, T.A., Peterson, M.F., Brilmeyer, C.A., and Johnson, J.C., 2018, Water and petroleum well data used for preliminary regional groundwater salinity mapping near selected oil fields in central and southern California: U.S. Geological Survey data release, https://doi.org/10.5066/F7RN373C.

Miller, R.H., and Bloom, C.V., 1939, Mountain View oil field, *in* Summary of operations, California oil fields: San Francisco, Calif., Annual Report of the State Oil and Gas Supervisor, v. 22, no. 4, p. 5–36.

Reichard, E.G., Land, M., Crawford, S.M., Johnson, T.D., Everett, R.R., Kulshan, T.V., Ponti, D.J., Halford, K.L., Johnson, T.A., Paybins, K.S., and Nishikawa, T., 2003, Geohydrology, geochemistry, and ground-water simulation-optimization of the Central and West Coast Basins, Los Angeles County, California: U.S. Geological Survey Water-Resources Investigations Report 2003–4065, 196 p., https://pubs.er.usgs.gov/publication/wri034065.

Stanton, J.S., Anning, D.W., Brown, C.J., Moore, R.B., McGuire, V.L., Qi, S.L., Harris, A.C, Dennehy, K.F., McMahon, P.B., Degnan, J.R., and Bohlke, J.K., 2017, Brackish groundwater in the United States: U.S. Geological Survey Professional Paper 1833, 185 p., https://doi.org/10.3133/pp1833.

Swain, W.C., and Duell, L.F. Jr., 1993, Water-quality data for shallow wells in the western and southern Tulare Basin, San Joaquin Valley, California, May to August 1989: U.S. Geological Survey Open-File Report 92–655, 30 p., https://pubs.er.usgs.gov/publication/ofr92655.

U.S. Environmental Protection Agency, 2017, General information about injection wells: U.S. Environmental Protection agency web page, accessed March 5, 2017, https://www.epa.gov/uic/general-information-about-injection-wells.

U.S. Geological Survey, 2015, National Water Information System—Web interface, USGS water data for California: U.S. Geological Survey web page, accessed February 3, 2015, at https://waterdata.usgs.gov/ca/nwis/.

Woodring, W.P., and Bramlette, M.N., 1950, Geology and paleontology of the Santa Maria district, California: U.S. Geological Survey Professional Paper 222, 185 p., https://pubs.er.usgs.gov/publication/pp222.

Worts, G.F., Jr., 1951, Geology and ground-water resources of the Santa Maria Valley area, California, with a section on surface-water resources: U.S. Geological Survey Water Supply Paper 1000, 169 p., https://pubs.er.usgs.gov/publication/wsp1000.

Yerkes, R.F., McCulloch, T.H., Schoellhamer, J.E., and Vedder, J.G., 1965, Geology of the Los Angeles Basin, California—An introduction: U.S. Geological Survey Professional Paper 420–A, 57 p., https://pubs.er.usgs.gov/publication/pp420A.

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Sacramento Publishing Service Center

For more information concerning the research of this report, contact the
Director, California Water Science Center
U.S. Geological Survey
6000 J Street, Placer Hall
Sacramento, California 95819
http://ca.water.usgs.gov

Metzger and Landon—**Preliminary Groundwater Salinity Mapping Near Selected Oil Fields Using Historical Water-Sample Data, Central and Southern California**—Scientific Investigations Report 2018–5082

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20185082