Prepared in cooperation with the California State Water Resources Control Board

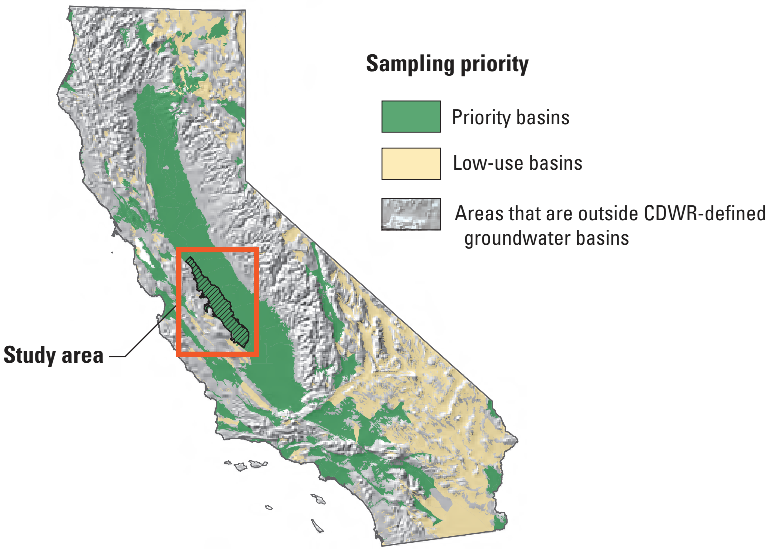
A product of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program

Groundwater Quality in the Western San Joaquin Valley Study Unit, 2010: California GAMA Priority Basin Project

Scientific Investigations Report 2017–5032

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

Front Cover Map: Groundwater basins categorized by sampling priority. Location of groundwater basin boundaries from California Department of Water Resources (CDWR, 2003).



Cover photographs:

Front cover: Alfalfa field, Five Points, California. (Photograph taken by Tyler Johnson, U.S. Geological Survey).

Back cover: Irrigation well, Gustine, California. (Photograph taken by Gregory Brewster, U.S. Geological Survey).

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By Miranda S. Fram

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

U.S. Geological Survey
William H. Werkheiser, Acting Director

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)

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

°F = (1.8 × °C) + 32.

Datum

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

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 either milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is equivalent to parts per million (ppm), and micrograms per liter is equivalent to parts per billion (ppb).

Activities for selected radioactive constituents in water are given in picocuries per liter (pCi/L).

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (iE) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

blsd	below land-surface datum
BQ	benchmark quotient
CDWR	California Department of Water Resources
DM	Delta–Mendota
DO	dissolved oxygen
EPA	U.S. Environmental Protection Agency
GAMA	Groundwater Ambient Monitoring and Assessment Program
HAL	lifetime health-advisory level
HBSL	health-based screening level
LLNL	Lawrence Livermore National Laboratory
MCL	maximum contaminant level
NAWQA	National Water Quality Assessment Program
NDMA	*N*-nitrosodimethylamine
NL	notification level
pmC	percent modern Carbon
RC	relative concentration
RSD5-US	U.S. Environmental Protection Agency risk-specific dose at a risk factor of 10^{-5}
SMCL	secondary maximum contaminant level
SWRCB	California State Water Resources Control Board
SWRCB-DDW	California State Water Resources Control Board Division of Drinking Water
TDS	total dissolved solids
THMs	trihalomethanes
TU	tritium units
USGS	U.S. Geological Survey
UST	leaking or formerly leaking underground storage tank
VOC	volatile organic compound
WS	Westside
WSJV	Western San Joaquin Valley

Acknowledgments

We especially thank the cooperating well owners and water purveyors for their generosity in allowing the U.S. Geological Survey to collect samples from their wells. Most of the funding for this work was provided by State of California bonds authorized by Proposition 50 and administered by the California State Water Resources Control Board. Additional funding was provided by U.S. Geological Survey Cooperative Matching Funds. This report is a product of the California State Water Resources Control Board Groundwater Ambient Monitoring and Assessment Program Priority Basin Project.

Groundwater Quality in the Western San Joaquin Valley Study Unit, 2010: California GAMA Priority Basin Project

By Miranda S. Fram

Abstract

Water quality in groundwater resources used for public drinking-water supply in the Western San Joaquin Valley (WSJV) was investigated by the USGS in cooperation with the California State Water Resources Control Board (SWRCB) as part of its Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. The WSJV includes two study areas: the Delta–Mendota and Westside subbasins of the San Joaquin Valley groundwater basin. Study objectives for the WSJV study unit included two assessment types: (1) a status assessment yielding quantitative estimates of the current (2010) status of groundwater quality in the groundwater resources used for public drinking water, and (2) an evaluation of natural and anthropogenic factors that could be affecting the groundwater quality. The assessments characterized the quality of untreated groundwater, not the quality of treated drinking water delivered to consumers by water distributors.

The status assessment was based on data collected from 43 wells sampled by the U.S. Geological Survey for the GAMA Priority Basin Project (USGS-GAMA) in 2010 and data compiled in the SWRCB Division of Drinking Water (SWRCB-DDW) database for 74 additional public-supply wells sampled for regulatory compliance purposes between 2007 and 2010. To provide context, concentrations of constituents measured in groundwater were compared to U.S. Environmental Protection Agency (EPA) and SWRCB-DDW regulatory and non-regulatory benchmarks for drinking-water quality. The status assessment used a spatially weighted, grid-based method to estimate the proportion of the groundwater resources used for public drinking water that has concentrations for particular constituents or class of constituents approaching or above benchmark concentrations. This method provides statistically unbiased results at the study-area scale within the WSJV study unit, and permits comparison of the two study areas to other areas assessed by the GAMA Priority Basin Project statewide.

Groundwater resources used for public drinking water in the WSJV study unit are among the most saline and most affected by high concentrations of inorganic constituents of all groundwater resources used for public drinking water that have been assessed by the GAMA Priority Basin Project statewide. Among the 82 GAMA Priority Basin Project study areas statewide, the Delta–Mendota study area ranked above the 90th percentile for aquifer-scale proportions of groundwater resources having concentrations of total dissolved solids (TDS), sulfate, chloride, manganese, boron, chromium(VI), selenium, and strontium above benchmarks, and the Westside study area ranked above the 90th percentile for TDS, sulfate, manganese, and boron.

In the WSJV study unit as a whole, one or more inorganic constituents with regulatory or non-regulatory, health-based benchmarks were present at concentrations above benchmarks in about 53 percent of the groundwater resources used for public drinking water, and one or more organic constituents with regulatory health-based benchmarks were detected at concentrations above benchmarks in about 3 percent of the resource. Individual constituents present at concentrations greater than health-based benchmarks in greater than 2 percent of groundwater resources used for public drinking water included: boron (51 percent, SWRCB-DDW notification level), chromium(VI) (25 percent, SWRCB-DDW maximum contaminant level (MCL)), arsenic (10 percent, EPA MCL), strontium (5.1 percent, EPA Lifetime health advisory level (HAL)), nitrate (3.9 percent, EPA MCL), molybdenum (3.8 percent, EPA HAL), selenium (2.6 percent, EPA MCL), and benzene (2.6 percent, SWRCB-DDW MCL). In addition, 50 percent of the resource had TDS concentrations greater than non-regulatory, aesthetic-based SWRCB-DDW upper secondary maximum contaminant level (SMCL), and 44 percent had manganese concentrations greater than the SWRCB-DDW SMCL.

Natural and anthropogenic factors that could affect the groundwater quality were evaluated by using results from statistical testing of associations between constituent concentrations and values of potential explanatory factors, inferences from geochemical and age-dating tracer results, and by considering the water-quality results in the context of the hydrogeologic setting of the WSJV study unit.

Natural factors, particularly the lithologies of the source areas for groundwater recharge and of the aquifers, were the dominant factors affecting groundwater quality in most of the WSJV study unit. However, where groundwater resources used for public supply included groundwater recharged in the modern era, mobilization of constituents by recharge of water used for irrigation also affected groundwater quality.

Public-supply wells in the Westside study area had a median depth of 305 m and primarily tapped groundwater recharged hundreds to thousands of years ago, whereas public-supply wells in the Delta–Mendota study area had a median depth of 85 m and primarily tapped either groundwater recharged within the last 60 years or groundwater consisting of mixtures of this modern recharge and older recharge.

Public-supply wells in the WSJV study unit are screened in the Tulare Formation and zones above and below the Corcoran Clay Member are used. The Tulare Formation primarily consists of alluvial sediments derived from the Coast Ranges to the west, except along the valley trough at the eastern margin of the WSJV study unit where the Tulare Formation consists of fluvial sands derived from the Sierra Nevada to the east. Groundwater from wells screened in the Sierra Nevada sands had manganese-reducing or manganese- and iron-reducing oxidation-reduction (redox) conditions. These redox conditions commonly were associated with elevated arsenic or molybdenum concentrations, and the dominance of arsenic(III) in the dissolved arsenic supports reductive dissolution of iron and manganese oxyhydroxides as the mechanism. In addition, groundwater from many wells screened in Sierra Nevada sands contained low concentrations of nitrite or ammonium, indicating reduction of nitrate by denitrification or dissimilatory processes, respectively.

Geology of the Coast Ranges westward of the study unit strongly affects groundwater quality in the WSJV. Elevated concentrations of TDS, sulfate, boron, selenium and strontium in groundwater were primarily associated with aquifer sediments and recharge derived from areas of the Coast Ranges dominated by Cretaceous-to-Miocene age, organic-rich, reduced marine shales, known as the source of selenium in WSJV soils, surface water, and groundwater. Low sulfur-isotopic values ($\delta^{34}S$) of dissolved sulfate indicate that the sulfate was largely derived from oxidation of biogenic pyrite from the shales, and correlations with trace element concentrations, geologic setting, and groundwater geochemical modeling indicated that distributions of sulfate, strontium, and selenium in groundwater were controlled by dissolution of secondary sulfate minerals in soils and sediments.

Elevated concentrations of chromium(VI) were primarily associated with aquifer sediments and recharge derived from areas of the Coast Ranges dominated by the Franciscan Complex and ultramafic rocks. The Franciscan Complex also has boron-rich, sodium-chloride dominated hydrothermal fluids that contribute to elevated concentrations of boron and TDS.

Groundwater from wells screened in Coast Ranges alluvium was primarily oxic and relatively alkaline (median pH value of 7.55) in the Delta–Mendota study area, and primarily nitrate-reducing or suboxic and alkaline (median pH value of 8.4) in the Westside study area. Many groundwater samples from those wells have elevated concentrations of arsenic(V), molybdenum, selenium, or chromium(VI), consistent with desorption of metal oxyanions from mineral surfaces under those geochemical conditions.

High concentrations of benzene were associated with deep wells located in the vicinity of petroleum deposits at the southern end of the Westside study area. Groundwater from these wells had premodern age and anoxic geochemical conditions, and the ratios among concentrations of hydrocarbon constituents were different from ratios found in fuels and combustion products, which is consistent with a geogenic source for the benzene rather than contamination from anthropogenic sources.

Water stable-isotope compositions, groundwater recharge temperatures, and groundwater ages were used to infer four types of groundwater: (1) groundwater derived from natural recharge of water from major rivers draining the Sierra Nevada; (2) groundwater primarily derived from natural recharge of water from Coast Ranges runoff; (3) groundwater derived from recharge of pumped groundwater applied to the land surface for irrigation; and (4) groundwater derived from recharge during a period of much cooler paleoclimate. Water previously used for irrigation was found both above and below the Corcoran Clay, supporting earlier inferences that this clay member is no longer a robust confining unit.

Recharge of water used for irrigation has direct and indirect effects on groundwater quality. Elevated nitrate concentrations and detections of herbicides and fumigants in the Delta–Mendota study area generally were associated with greater agricultural land use near the well and with water recharged during the last 60 years. However, the extent of the groundwater resource affected by agricultural sources of nitrate was limited by groundwater redox conditions sufficient to reduce nitrate. The detection frequency of perchlorate in Delta–Mendota groundwater was greater than expected for natural conditions. Perchlorate, nitrate, selenium, and strontium concentrations were correlated with one another and were greater in groundwater inferred to be recharge of previously pumped groundwater used for irrigation. The source of the perchlorate, selenium, and strontium appears to be salts deposited in the soils and sediments of the arid WSJV that are dissolved and flushed into groundwater by the increased amount of recharge caused by irrigation. In the Delta–Mendota study area, the groundwater with elevated concentrations of selenium was found deeper in the aquifer system than it was reported by a previous study 25 years earlier, suggesting that this transient front of groundwater with elevated concentrations of constituents derived from dissolution of soil salts by irrigation recharge is moving down through the aquifer system and is now reaching the depth zone used for public drinking water supply.

Introduction

This study is part of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, a statewide program which assesses the quality of drinking water sources at the scale of individual groundwater basins. Groundwater composed 46 percent of the water used for public and domestic drinking-water supply in California in 2010 (Maupin and others, 2014). GAMA Priority Basin Project studies are designed to: (1) provide more robust information about water quality in groundwater resources used for drinking water supply than do traditional drinking water quality source assessments; (2) identify constituents in the groundwater present at concentrations near or above drinking-water quality benchmarks; (3) establish a baseline for tracking changes in groundwater quality at basin scales; and (4) describe why observed water quality patterns exist and what natural process and human activities are responsible for constituent concentrations. The results from GAMA Priority Basin Project studies are intended for use by drinking water suppliers, entities managing groundwater under the Sustainable Groundwater Management Act (California Department of Water Resources, 2016) and other local programs, to support evaluations of regulatory programs being implemented by the California Regional Water Quality Control Boards and the California State Water Resources Control Board (SWRCB), and to expand the availability of data and information about groundwater quality to the public. In addition, because the project's design objectives overlap with those of the USGS National Water Quality Assessment (NAWQA) Project (Hirsch and others, 1988), GAMA Priority Basin Project results are used in national water quality assessments.

The GAMA Program was implemented by the SWRCB, in collaboration with the U.S. Geological Survey (USGS) and Lawrence Livermore National Laboratory (LLNL; website at http://www.waterboards.ca.gov/gama/) in 2000 in response to Legislative mandates (State of California, 1999, 2001a). Additional partners in the GAMA Priority Basin Project include the California Department of Pesticide Regulation, California Department of Water Resources (CDWR), and local water agencies and well owners (Kulongoski and Belitz, 2004).

In 2017, the statewide GAMA Program consisted of two active projects, the GAMA Priority Basin Project, carried out by the USGS (website at http://ca.water.usgs.gov/gama/), and the GeoTracker GAMA on-line groundwater information system, led by the SWRCB (website at http://geotracker.waterboards.ca.gov/gama/). The initial focus of the GAMA Priority Basin Project in 2004 to 2012 was on assessment of water quality in groundwater resources used for public drinking water supply (Belitz and others, 2015). The study described in this report is part of this initial phase of the project. In 2012, the GAMA Priority Basin Project began water-quality assessments of the groundwater resources used for individual, domestic and small-system drinking-water supplies. The groundwater resources used for domestic drinking-water supplies are typically shallower than the groundwater resources used for public drinking-water supplies, and therefore could be more vulnerable to contamination from human activities at the land surface. The trends assessment component of the GAMA Priority Basin Project began in 2007 and includes re-sampling of a subset of the wells sampled for the baseline assessments at 5-year intervals.

The project is called the "priority basin" project because California's groundwater basins were initially prioritized for assessment based primarily on the numbers of public supply wells in each basin (Belitz and others, 2003; California State Water Resources Control Board, 2003). Of the 472 basins designated by CDWR (California Department of Water Resources, 1980; 2003), 116 basins contained approximately 95 percent of the public-supply wells in groundwater basins. These 116 basins were defined as "priority basins," and the remaining 356 basins were defined as "low-use basins" (Belitz and others, 2003). All of the priority basins, selected low-use basins, and selected areas outside of groundwater basins were grouped into 87 study areas in 35 GAMA Priority Basin Project study units that together represent approximately 95 percent of all public-supply wells in California (Belitz and others, 2015). The Western San Joaquin Valley (WSJV) study unit is in the Central Valley hydrogeologic province (fig. 1) and includes two priority basins: the Westside and Delta–Mendota subbasins of the San Joaquin Valley Basin.

The purposes of this report are to provide a description of the hydrogeologic setting of the WSJV study unit, an assessment of the status of the quality of groundwater resources used for public drinking water in the study unit, and a general evaluation of natural and human factors that could be affecting groundwater quality in the study unit. Trends in groundwater quality are not discussed in this report. Water-quality data for samples collected by the USGS for the GAMA Priority Basin Project in the WSJV study unit and details of sample collection, analysis, and quality-assurance procedures are reported in Mathany and others (2013). Noble gas data provided by the Lawrence Livermore National Laboratory that were not available at the time of publication of the accompanying data-series report (Mathany and others, 2013) are presented in appendix 4 of this report.

Features of the hydrogeologic setting are described for the Delta–Mendota and Westside study areas, which compose the WSJV study unit. Geology, land-use patterns, and hydrology in the study areas are summarized. Characteristics of the part of the aquifer system containing groundwater resources used for public drinking water, including overlying land-use characteristics, depths of wells and hydrologic conditions, geologic characteristics, and groundwater age and geochemical conditions are described by using ancillary data compiled for the wells sampled by the USGS for the GAMA Priority Basin Project (USGS-GAMA) in the WSJV study unit.

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

Figure 1. Hydrogeologic provinces of California and the location of the Western San Joaquin Valley (WSJV) study unit in the Central Valley hydrogeologic province, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

The status assessment is designed to provide a statistically representative characterization of groundwater resources used for public drinking water at the study-area scale for the period of the assessment (Belitz and others, 2003, 2010, 2015). This report describes methods used to design the sampling networks for the status assessment and to estimate aquifer-scale proportions for constituents (Belitz and others, 2010). Aquifer-scale proportion is defined as the areal proportion of the groundwater resource where groundwater has a specified quality (Belitz and others, 2010). Water-quality data from 117 wells were used in the status assessment: 43 wells sampled by USGS-GAMA in the WSJV study unit (Mathany and others, 2013) and 74 other public-supply wells in the study unit for which water-quality data were available in the SWRCB Division of Drinking Water (SWRCB-DDW) database for samples collected from March 2007 through August 2010. The SWRCB-DDW compiles water-quality data from public-supply wells for regulatory compliance purposes. Aquifer-scale proportions for constituents and classes of constituents were computed for the WSJV study unit as a whole and for the two study areas in the study unit by using a spatially weighted method based on a 40-cell grid covering the WSJV study unit (Belitz and others, 2010, 2015).

To provide context, the water-quality data discussed in this report are compared to California and Federal regulatory and non-regulatory benchmarks for treated drinking water. Groundwater quality is defined in terms of relative concentrations, which are calculated by dividing the concentration of a constituent in groundwater by the concentration of the benchmark for that constituent. The assessments in this report characterize the quality of groundwater resources used for public drinking water in the study unit prior to any treatment, not the treated drinking water delivered to consumers by water purveyors. After withdrawal from the ground, water can be treated, disinfected, or blended with other waters to attain acceptable water quality. Regulatory benchmarks apply to treated water that is served to the consumer, not to untreated groundwater.

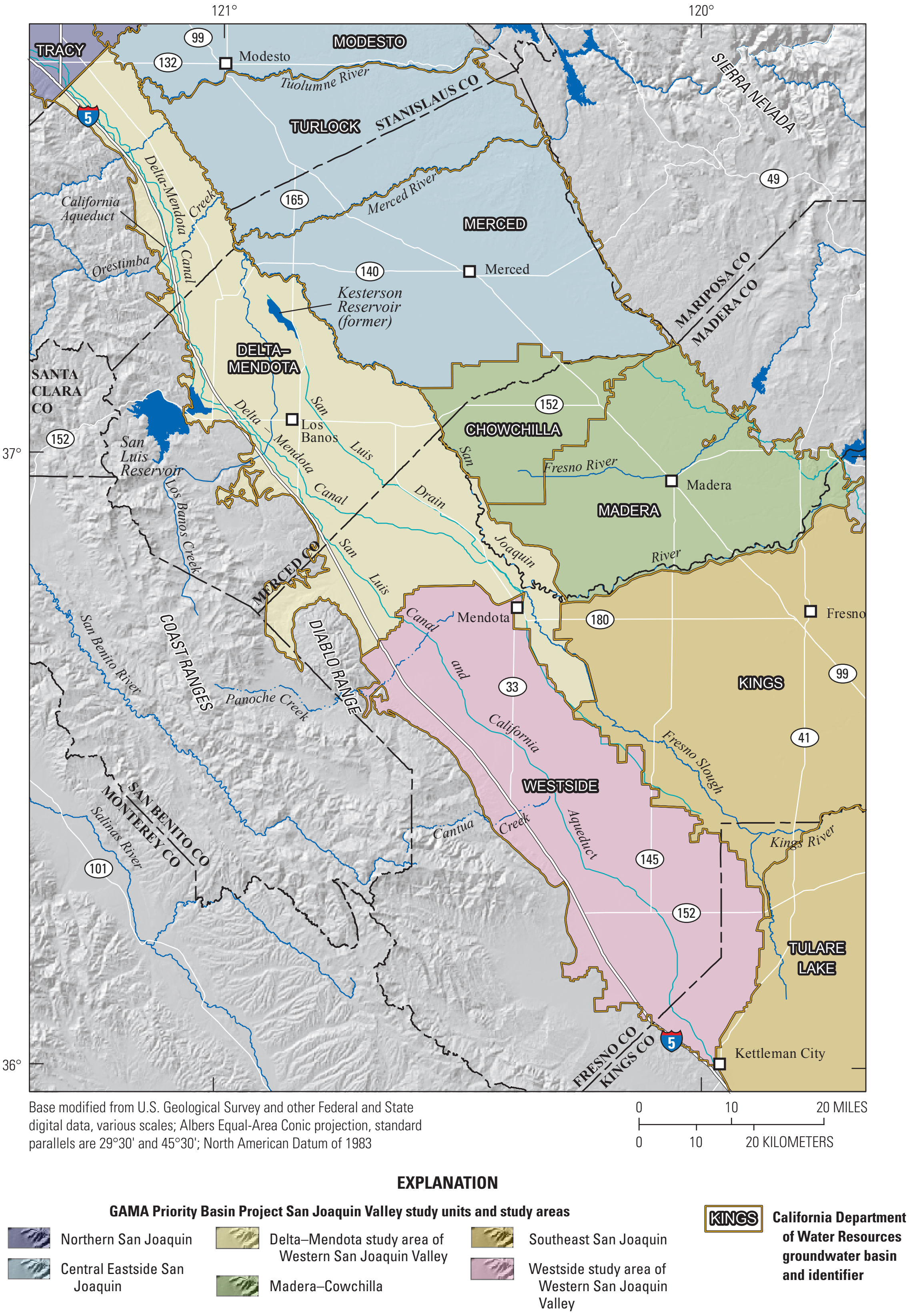
The evaluation of natural and human factors that could be affecting groundwater quality in the study unit used a variety of statistical, graphical, and geochemical approaches. Data for 17 potential explanatory factors in four categories were compiled: land-use characteristics (percentage of natural, urban, and agricultural land use and density of septic tanks and underground fuel tanks around the well site), location characteristics (study area, lateral position, depths to top and bottom of screened interval in well, and climate index), geologic features (aquifer lithology in the screened interval of the well, position relative to the Corcoran Clay, and dominant geologic unit in the inferred upgradient watershed), and groundwater age and geochemical conditions (age class, redox class, dissolved oxygen concentration, and pH). Relations between these potential explanatory factors and concentrations of constituents in groundwater were investigated by using statistical tests for association and correlation and by using inferences from graphical and spatial patterns. Stable isotopic composition of hydrogen and oxygen in water, groundwater-age tracers (tritium and carbon-14), and noble gas recharge temperatures were used to determine whether groundwater samples reflected recharge of water derived from Coast Ranges or Sierra Nevada watersheds, whether recharge resulted from natural processes or from water used for irrigation, and whether recharge occurred recently or long ago. Major-ion chemistry, stable isotopic compositions of nitrogen and oxygen in nitrate and of sulfur in sulfate, strontium isotopic ratios, arsenic redox species ratios, and PHREEQC modeling were used to infer the geochemical processes affecting salinity and concentrations of individual dissolved constituents. Results from these statistical, graphical, and geochemical evaluations are discussed in the context of the hydrogeologic setting of the study unit.

Hydrogeologic Setting

The WSJV study unit is in the southwestern part of the Central Valley (fig. 1) and includes two CDWR-defined San Joaquin Valley groundwater subbasins: Delta–Mendota and Westside (fig. 2; California Department of Water Resources, 2003). The WSJV study unit covers an area of approximately 5,620 square kilometers (km^2) in Stanislaus, Merced, Madera, Fresno, and Kings Counties in California. The study unit is bounded by the Diablo Range of the Southern Coast Ranges to the west, the San Joaquin River to the northeast, and the Kings and Tulare Lake groundwater basins to the southeast.

The Delta–Mendota study area is 3,030 km^2 and corresponds to the Delta–Mendota subbasin of the San Joaquin Valley groundwater basin (subbasin 5-22.07; California Department of Water Resources, 2006a; fig. 2). The Westside study area is 2,590 km^2 and corresponds to the Westside subbasin of the San Joaquin Valley groundwater basin (fig. 2; subbasin 5-22.09; California Department of Water Resources, 2006b). The only communities in the study unit with populations greater than 10,000 in the 2010 U.S. Census were Los Banos, Patterson, Mendota, and Newman (U.S. Census Bureau, 2010).

The WSJV study unit has a Mediterranean climate, with hot, dry summers and cool, damp winters; approximately 85 to 90 percent of annual precipitation falls as rain during November through April (Western Regional Climate Center, 2011). Average rainfall ranges from 15 centimeters (cm) in the southern part of the Westside study area to 30 cm in the northern part of the Delta–Mendota study area (PRISM Climate Group, Oregon State University, 2010).



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

Figure 2. Boundaries of California Department of Water Resources groundwater basins and selected hydrologic features in the San Joaquin Valley, California.

Most public supply wells in the WSJV study unit are screened in the unconsolidated, non-marine alluvial deposits of the Tulare Formation (Hotchkiss and Balding, 1971; Belitz and Heimes, 1990; California Department of Water Resources, 2006a, b). The Tulare Formation is composed of mostly unconsolidated clay, silt, sand, and gravel of Pliocene and Pleistocene age. The Corcoran Clay Member of the Tulare Formation (referred to as Corcoran Clay in this report) is found from about 30 to 260 meters (m) below land surface datum (m blsd) throughout most of the study unit and generally is 15 to 30 m thick (figs. 3, 4; California Department of Water Resources, 2006a, b; Faunt, 2009). The Corcoran Clay generally restricts the interaction between the underlying confined and overlying unconfined groundwater; however, well bores open to the aquifer above and below it (across the Corcoran Clay) have been shown to permit water exchange across the confining unit (Williamson and others, 1989). Groundwater in the upper part of the Tulare Formation, above the Corcoran Clay, can be unconfined, semi-confined, or confined as a result of many discontinuous lenses of clay and silt within the sequence of unconsolidated sediments (Hotchkiss and Balding, 1971). The lower part of the Tulare Formation, below the Corcoran Clay, is a confined hydrogeologic unit, and the depth to Corcoran Clay is deeper in the Westside study area than in the Delta–Mendota study area, particularly on the western edge of the study unit (Faunt, 2009). Parts of the Tulare Formation above and below the Corcoran Clay are used by public drinking-water supply wells.

Under pre-development conditions, groundwater in the study unit was recharged by infiltration of precipitation and seepage from stream channels, and groundwater was discharged primarily by evapotranspiration and to stream channels (Williamson and others, 1989; Belitz and Heimes, 1990). Groundwater mostly moved horizontally from the western margin of the San Joaquin Valley by the Coast Ranges toward the valley center, following the elevation trend of the valley (Hotchkiss and Balding, 1971; Faunt, 2009). Slight vertically downward hydraulic gradients were present in the alluvial fans near the Coast Ranges, and slight upward gradients were present at the valley trough (Williamson and others, 1989).

Under post-development conditions, groundwater in the study unit is recharged mostly by infiltration of groundwater and imported surface water used for irrigation, and groundwater is discharged mostly by pumping, evapotranspiration from crops, and engineered drainage (California Department of Water Resources, 2006a, b; Faunt, 2009). Groundwater-flow gradients are generally downward in much of the study unit because of application of water at the surface for irrigation coupled with pumping of groundwater at depth (Williamson and others, 1989; Belitz and Heimes, 1990). For the entire Central Valley, the rates of groundwater recharge and discharge under modern conditions were estimated to be 6 times greater than recharge and discharge under natural conditions (Williamson and others, 1989), and in parts of the WSJV study unit, rates may have increased by as much as 40 times (Belitz and Heimes, 1990). The change in direction of groundwater flow gradients and the increase in groundwater recharge and discharge rates due to irrigation and groundwater pumping results in rapid movement of modern groundwater downwards into the aquifer system. Because of human activities at the land surface, this modern recharge can have different water-quality characteristics than premodern recharge, and therefore, the quality of groundwater tapped by wells changes (for example, Jurgens and others, 2010).

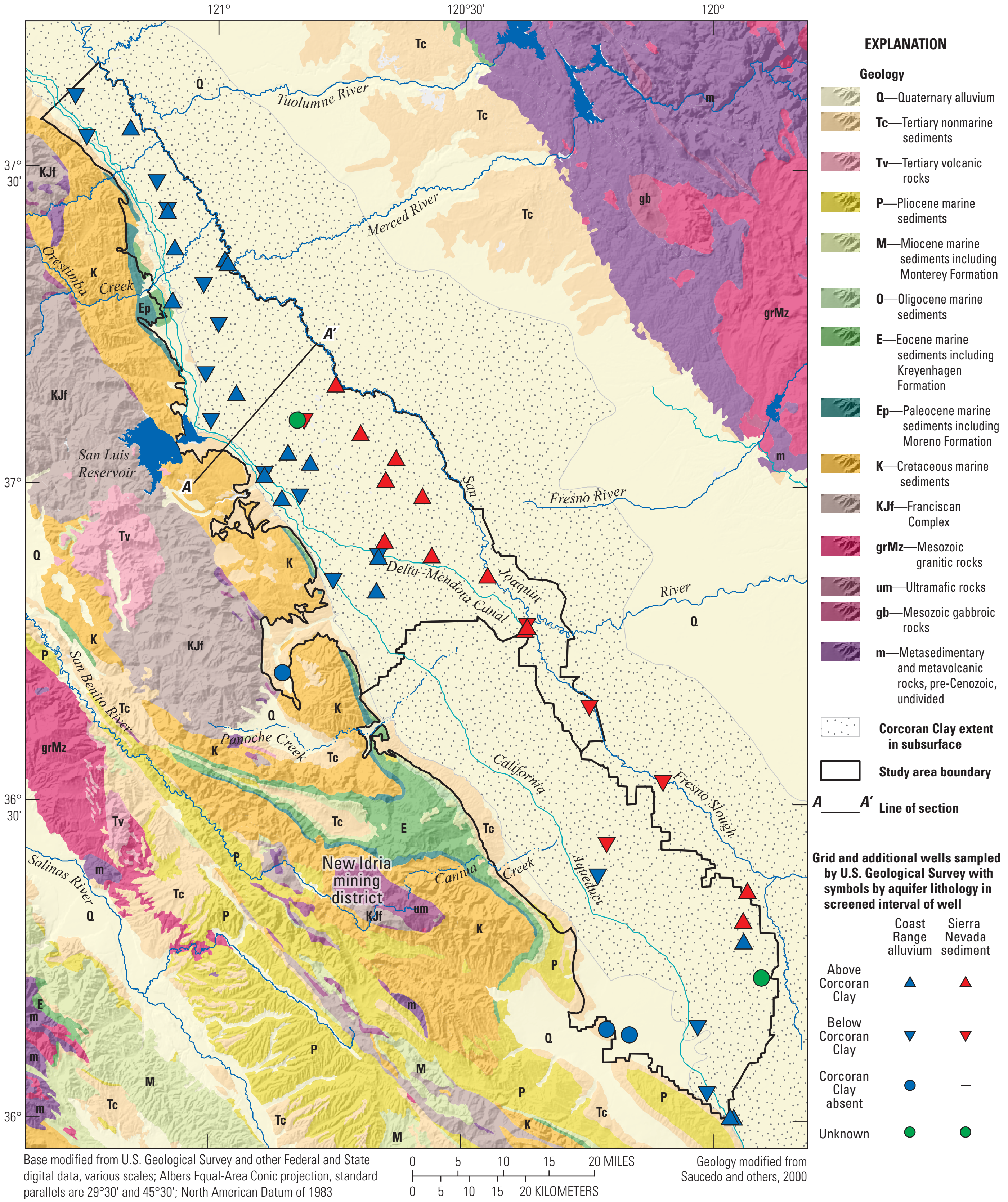
On the basis of differences in source of materials, textures, lithologic characteristics, hydrologic properties, and oxidation states, the unconsolidated deposits in the Tulare Formation are divided into two major lithologic types: Coast Ranges alluvium and Sierra Nevada sands (fig. 4; Hotchkiss and Balding, 1971; Belitz and Heimes, 1990; Dubrovsky and others, 1991). Previous studies have shown that wells screened in Coast Ranges alluvium yield groundwater with different water-quality characteristics than wells screened in Sierra Nevada sands (Deverel and Millard, 1988; Dubrovsky and others, 1991).

The Coast Ranges alluvium, derived from the Coast Ranges to the west, is generally oxidized and ranges in thickness from 260 m along the Coast Ranges to 0 m at the eastern edge of the study unit. The Coast Ranges alluvium was deposited in a series of coalescing alluvial fans (west fans) from streams draining the Coast Ranges. Sediments deposited near the fan heads, where the streams enter the San Joaquin Valley, are typically the coarsest, and sediment texture generally becomes finer with increasing distance from the fan head and stream channels (Belitz and Heimes, 1990).

The Sierra Nevada sands predominantly consist of well-sorted micaceous sand derived from the Sierra Nevada to the east. These deposits are up to 120–150 m thick in the San Joaquin Valley trough and thin to the west, where they interfinger with the Coast Ranges alluvium (fig. 4). The Sierra Nevada sands are highly permeable and predominantly chemically reduced in the valley trough (Belitz and Heimes, 1990).

The San Joaquin River, at the eastern edge of the Delta–Mendota study area, is the largest river in the study unit. Numerous small streams that flow intermittently after rainstorms drain from the Coast Ranges eastward into the study unit; however, only Orestimba and Los Banos Creeks (fig. 2) maintain perennial flows to the San Joaquin River. When flowing, tributary streams lose most of their water to seepage and evaporation before reaching the San Joaquin River (Hotchkiss and Balding, 1971).

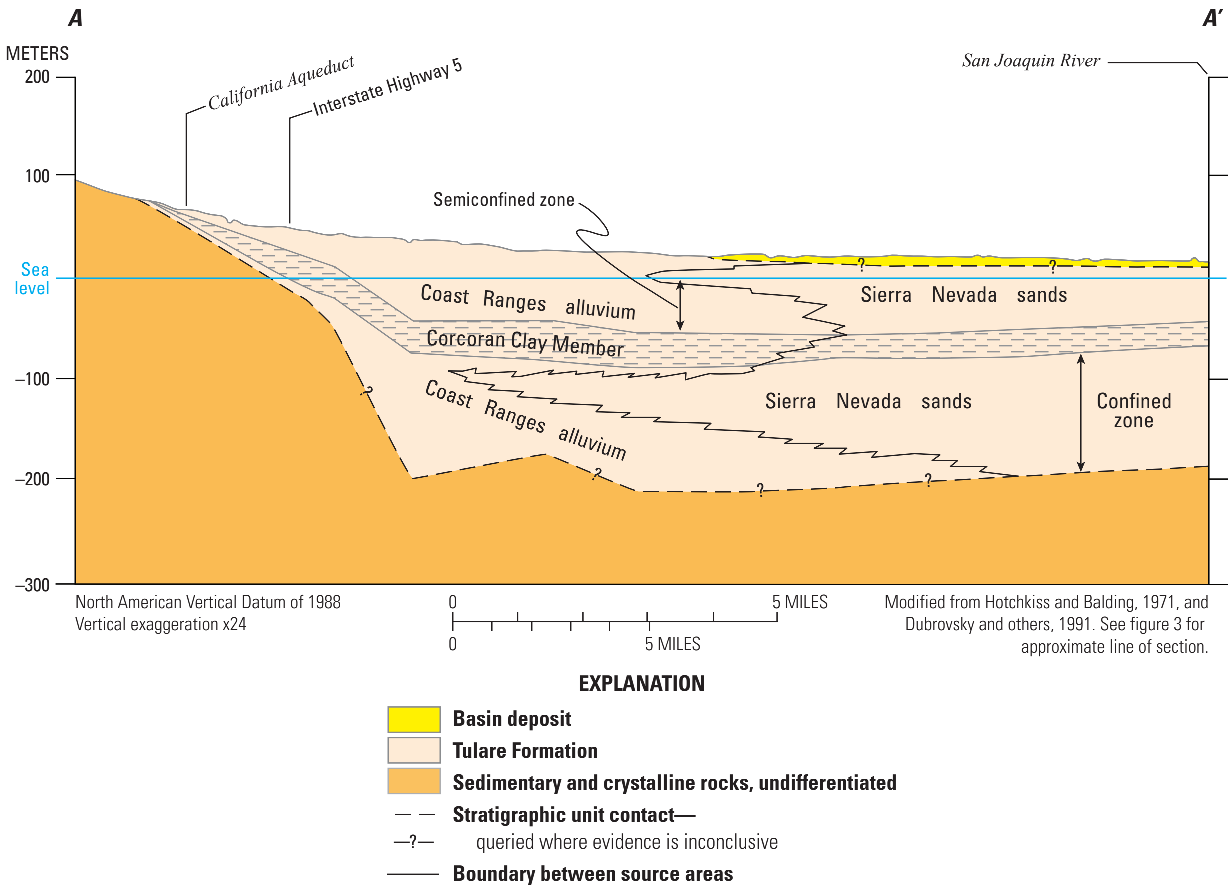
The largest surface-water features in the study unit are the reservoirs and canals of the Central Valley Project and the State Water Project. The State Water Project transports water from the Sacramento–San Joaquin Delta to the Central Valley and Southern California through the California Aqueduct (fig. 2). Surface water imported for irrigation in the WSJV study unit comes from the Bureau of Reclamation's Central Valley Project through the Delta–Mendota and San Luis Canals (fig. 2).



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

Geology modified from Saucedo and others, 2000

Figure 3. Geologic features of the San Joaquin Valley and adjacent mountains and the wells sampled for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



Modified from Hotchkiss and Balding, 1971, and Dubrovsky and others, 1991. See figure 3 for approximate line of section.

Figure 4. Generalized geologic cross section of the Western San Joaquin Valley (WSJV) study unit.

Between 1926 and 1970, extensive groundwater pumping for irrigation caused large declines in groundwater levels and 1–8 m of land subsidence in the WSJV study unit (Ireland and others, 1984). Starting in the 1950s, delivery of surface water from the Central Valley Project allowed for reversal of groundwater level declines, but curtailment of surface water deliveries during drought periods has renewed groundwater-level declines (Faunt, 2009). Increased groundwater pumping during the drought that began in 2011 has drawn groundwater levels below historic lows and has caused land subsidence in parts of the WSVJ study unit (Sneed and others, 2013). The effect of subsidence on groundwater quality has not yet been investigated.

In the early 1980s, a subsurface tile-drain system was constructed beneath a large part of the Westside study area to facilitate drainage of water from the root zone of crops (San Joaquin Valley Drainage Program, 1990). The drainage water from this system was intended to be discharged in the San Francisco Bay through the San Luis Drain, but the drain was only constructed as far north as Kesterson Reservoir (fig. 2). Deliveries of agricultural drainage water to Kesterson were halted in 1986, and the reservoir was drained and dewatered in 1988 after high rates of embryo deformities and mortalities in migratory birds were attributed to poisoning by selenium carried to the reservoir by agricultural drainage water (San Joaquin Valley Drainage Program, 1990; Ohlendorf and Santolo, 1994).

Methods

This section describes the methods used to select wells for sampling and compile water-quality data for this study, to assess the status of water quality in groundwater resources used for public drinking water, and to evaluate factors that could affect groundwater quality. Methods used to collect and analyze groundwater samples are described by Mathany and others (2013).

Well Selection and Data Compilation

The status assessment used data collected by the USGS-GAMA from 39 grid and 4 additional wells, and data compiled for 74 other public-supply wells in the SWRCB-DDW database. The evaluation of factors that could affect groundwater quality used data collected by the USGS-GAMA for 39 grid, 4 additional, and 16 monitoring wells.

The SWRCB-DDW database includes wells from systems that serve 25 or more people or have 15 or more service connections (California State Water Resources Control Board, 2015); these systems are classified as community (such as cities, towns, and mobile-home parks), non-transient, non-community (such as schools, workplaces, and restaurants), or transient, non-community (such as campgrounds, parks, and highway rest areas). The California Department of Public Health Drinking Water Program that regulated water quality in public-supply wells was transferred to the SWRCB Division of Drinking Water on July 1, 2014. Although data for this study were collected before this transfer date, the program is referred to as SWRCB-DDW in this report for consistency with current terminology.

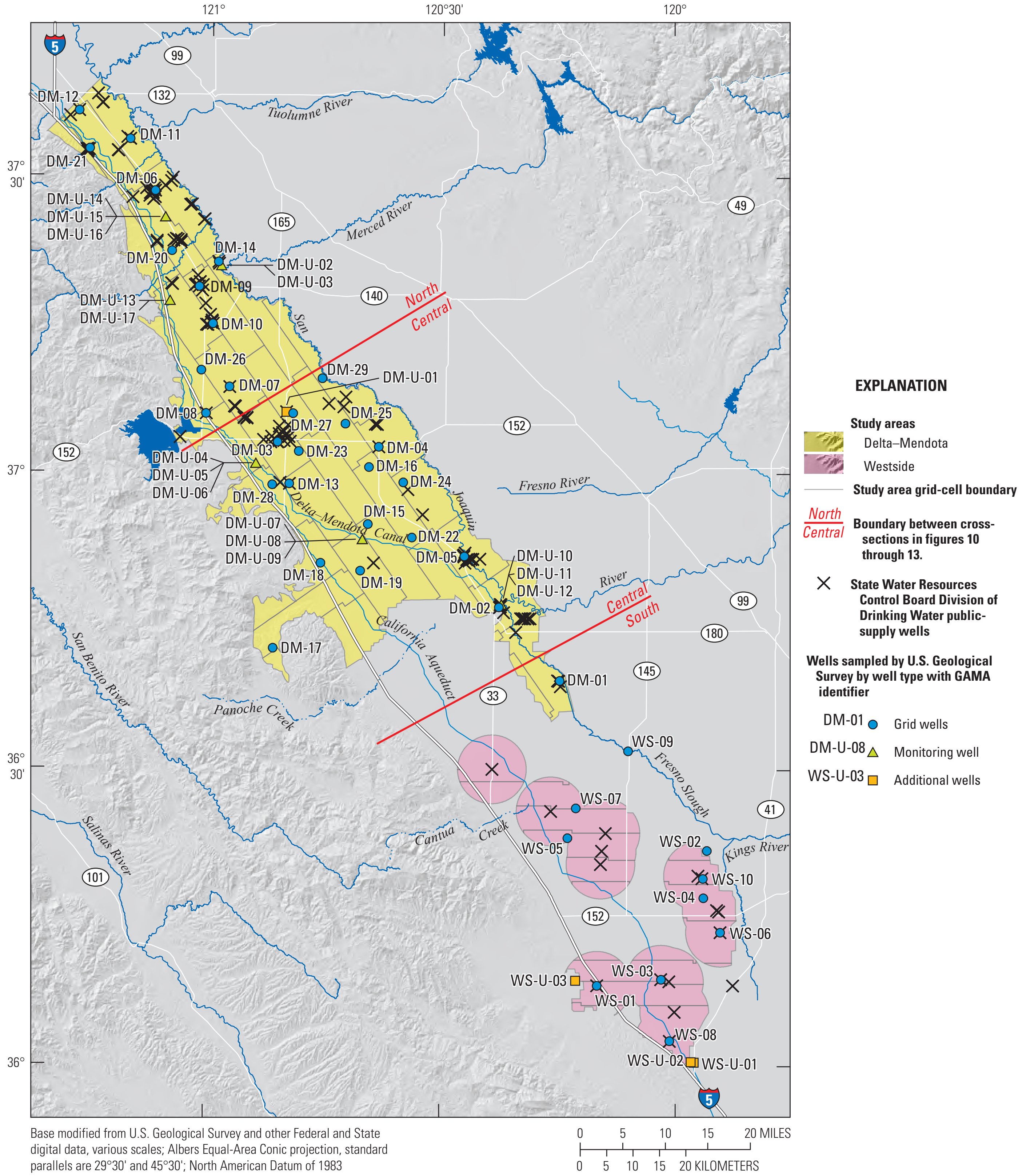
Wells Sampled by USGS-GAMA

Detailed descriptions of the methods used to identify wells for sampling are given in Mathany and others (2013). Briefly, each study area was divided into equal-area grid cells (Scott, 1990), and in each cell, one well was randomly selected to represent the groundwater resource in the cell. The design of the grid cells differed between the Delta–Mendota and Westside study areas because of the limited number of public-supply wells in the Westside study area. The 119 public-supply wells in the Delta–Mendota study area were distributed across most of the study area; thus, the entire study area was included in the gridded area (fig. 5). The Delta–Mendota study area was divided into 30 grid cells, each approximately 100 km^2 in area (table 1). In contrast, the Westside study area contained only 15 public-supply wells, which were not evenly distributed across the study area (fig. 5). Thus, if the entire study area were included in the gridded area, there would be many grid cells without any public-supply wells. To minimize the number of cells with no wells, only areas near public-supply wells were included in the gridded area. A 6.5-km radius circle was drawn around each public-supply well in the study area, and the aggregate area encompassed by those circles was divided into 10 grid cells, each approximately 100 km^2 in area (fig. 5).

All public-supply wells were assigned random rankings and the highest ranked well in each cell that met basic sampling requirements, and for which permission could be obtained, was sampled. Public-supply wells in 20 of the grid cells were selected for sampling by this method. For cells without accessible public-supply wells, door-to-door canvassing was used to identify irrigation or domestic wells that met basic sampling requirements and that had screened intervals at similar depths as the public-supply wells in the study area. The first appropriate well for which permission to sample could be obtained was selected for sampling. Irrigation wells were sampled in 11 cells, domestic wells in 7 cells, and an unused well in one cell. The two study units contained a total of 40 grid cells, and USGS-GAMA sampled wells representing 39 of those cells (grid wells; fig. 5). One Westside grid well (WS-09) was located outside of the boundary of the study area, but was considered representative because it was a public-supply well (although not listed in the SWRCB-DDW database as such) and was the closest public-supply well to a Westside grid cell in which the only public-supply well was not available for sampling. A suitable grid well could not be identified in or near one Delta–Mendota grid cell. The grid wells sampled by the USGS for the GAMA Priority Basin Project were owned by other organizations or individuals. The 39 grid wells were named with an alphanumeric GAMA_ID consisting of a prefix indicating the study area (DM or WS), followed by a number indicating the order of sample collection in each study area (appendix 1; fig. 5).

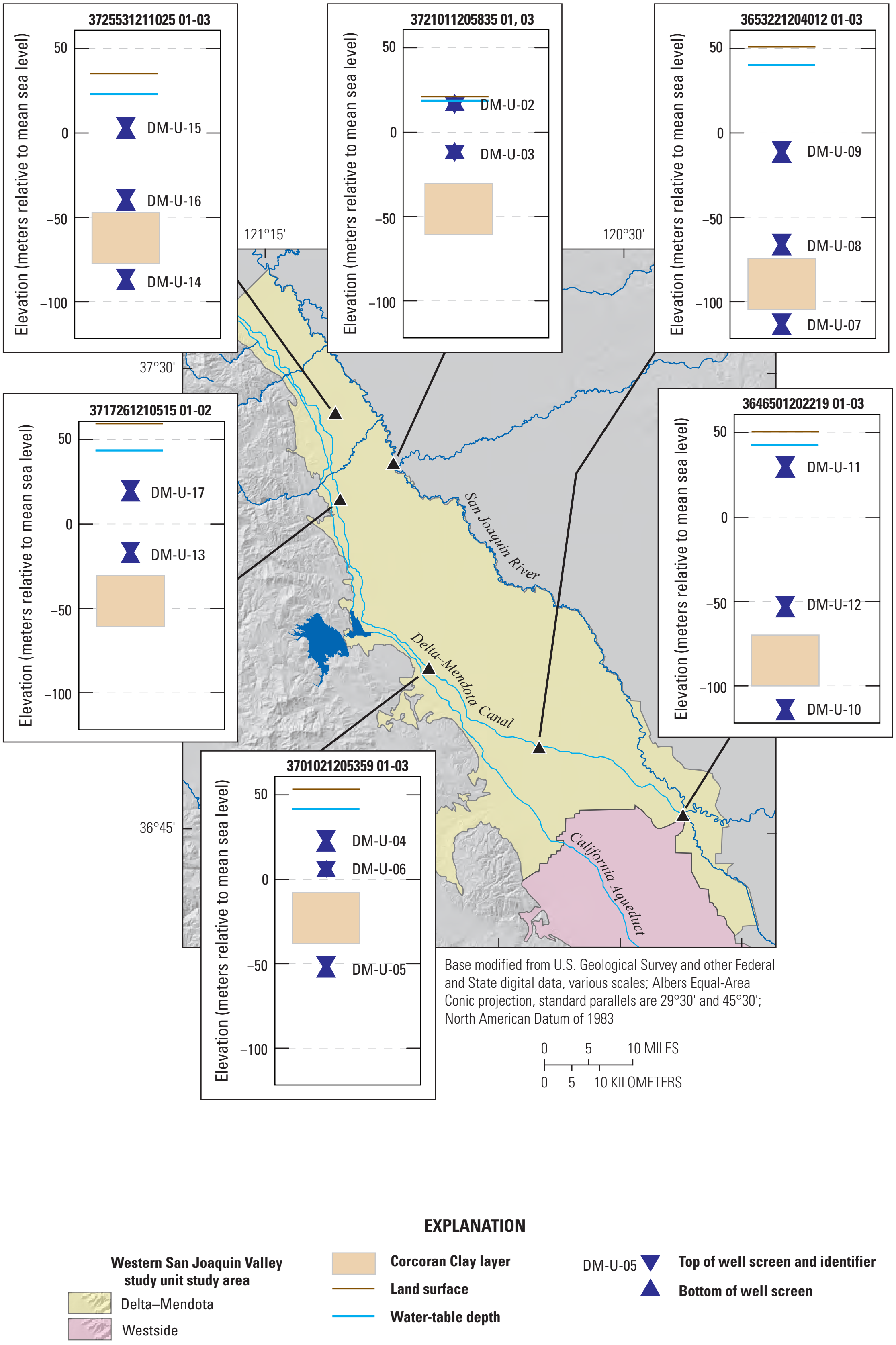
In addition to the 39 grid wells, a total of 20 other wells were sampled in the study unit by the USGS-GAMA (appendix table 1–1). These wells were selected to increase sampling density in certain areas and to help identify differences in water quality by depth in the aquifer system. These 20 wells were numbered in the order of collection with prefixes modified from those used for the grid wells: “DM-U” or “WS-U” (“U” indicates understanding; fig. 5; appendix table 1–1). Of these 20 wells, 4 were public-supply wells screened or open at similar depths as the grid wells; these 4 wells are referred to as “additional wells” and were included in the dataset for the status assessment. The other 16 wells were monitoring wells and might not be representative of the groundwater resources used for public drinking water in the study unit; therefore, data from the monitoring wells were not used for the status assessment.

The 16 monitoring wells were sampled from 6 multi-level monitoring-well sites. The USGS constructed five of the sites in 2010 as part of a project to monitor groundwater conditions along the Delta–Mendota Canal (http://ca.water.usgs.gov/projects/central-valley/delta-mendota-canal-groundwater-monitoring.html). At each site along the Delta–Mendota Canal, a borehole was completed to a depth of about 150 m below land surface, and multiple piezometers were installed in each borehole—generally, one just below the water table, one just above the Corcoran Clay, and one just below the Corcoran Clay (fig. 6). The sixth site was constructed for an earlier USGS project and was near the San Joaquin River. It had two piezometers above the Corcoran Clay (fig. 6).



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

Figure 5. Grid cells and wells sampled by the U.S. Geological Survey (USGS) in each study area, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



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

Figure 6. Locations and depth of monitoring wells from which samples were collected for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Groundwater from wells sampled by USGS-GAMA was analyzed for up to 236 constituents (table 2). Water-quality data collected by USGS-GAMA are tabulated in Mathany and others (2013) and also are available from the SWRCB's publicly accessible internet-database GeoTracker GAMA (http://geotracker.waterboards.ca.gov/gama/) and the USGS's publically accessible internet-database NWIS Web (http://waterdata.usgs.gov/ca/nwis/). Because all samples from grid wells were analyzed for major and minor ions, trace elements, and nutrients, it was not necessary to supplement the grid-well dataset with data from the SWRCB-DDW database for these constituent groups, as was done in the status assessments for many other GAMA Priority Basin Project study units (for example, Landon and others, 2010; Burton and others, 2012).

Data Compiled for SWRCB-DDW Wells

The SWRCB-DDW database lists 89 public-supply wells for which water-quality data were collected between March 2007 and August 2010. Of these 89 wells, 15 were sampled by the USGS as grid or additional wells, and for these wells, only the USGS-GAMA data were used (table 1). For many of the remaining 74 wells, SWRCB-DDW data were available only for a limited number of constituents, commonly just nitrate. For example, the SWRCB-DDW database contained nitrate data for all of the remaining 74 wells, whereas arsenic data only were reported for 53 wells. Water-quality data in the SWRCB-DDW database are available from the SWRCB's publically accessible online groundwater-information system GeoTracker GAMA (website at http://geotracker.waterboards.ca.gov/gama/).

Status-Assessment Methods

The status assessment was designed to determine which water-quality constituents are present at concentrations that may be of concern at the study-area scale, and to establish a baseline with which comparisons between study areas and assessments of water-quality trends could be made. The statistical design of the status assessment represents a balance between the statewide scale of the GAMA Priority Basin Project and the many study area-specific and site-specific processes and characteristics affecting groundwater quality.

The status assessment involved quantifying the areal proportion of the groundwater resource used for public drinking-water supplies containing groundwater of a specified quality. The depth of this groundwater resource is defined by the depth intervals in which public-supply wells are screened or open. The groundwater resource used for public drinking-water supply generally does not correspond to a single, discrete aquifer unit in a study unit. In most groundwater basins, public drinking-water supply wells typically are screened or open at greater depths than are domestic wells (for example, Burow and others, 2008; Burton and others, 2012). This section describes the methods used for defining groundwater quality, selecting constituents for evaluation, and calculating aquifer-scale proportions.

Groundwater Quality Defined by Relative Concentrations

The primary purpose of the GAMA Priority Basin Project is to develop information on the quality of groundwater resources that are used for drinking water supply. Therefore, a system for comparing measured constituent concentrations to drinking-water benchmark concentrations is needed to help distinguish constituents that may be of concern for drinking-water quality from those that are not. In this study, groundwater-quality data are presented as relative concentrations (RCs). An RC is the ratio of a constituent's concentration measured in a groundwater sample to the concentration of that constituent's regulatory or non-regulatory benchmark used to evaluate drinking-water quality. Regulatory and non-regulatory benchmarks apply to treated water that is served to the consumer, not to untreated groundwater. However, untreated groundwater that does not meet regulatory standards must be treated before it is used for public drinking water supply; thus, the RC provides a quick comparative tool for identifying groundwater resources that may require treatment before use as drinking water supplies. The use of RCs is similar to the approaches used in other studies to place the concentrations of constituents in groundwater in a toxicological context (for example, Toccalino and others, 2004; Toccalino and Norman, 2006; Rowe and others, 2007; U.S. Environmental Protection Agency, 2014).

An RC less than 1 indicates a sample concentration less than the benchmark, and an RC greater than 1 indicates a sample concentration greater than the benchmark. The use of RCs permits comparison on a single scale of constituents present at a wide range of concentrations. The RCs can only be computed for constituents with water-quality benchmarks; therefore, constituents without water-quality benchmarks were not included in the status assessment. Benchmarks established by the U.S. Environmental Protection Agency (EPA; U.S. Environmental Protection Agency, 2012) and the SWRCB-DDW (California State Water Resources Control Board, 2015) were selected in the following order of priority:

1. Regulatory, health-based levels established by the SWRCB-DDW and the EPA, which are maximum contaminant levels (MCL) and EPA action levels (AL).

2. Non-regulatory SWRCB-DDW and EPA secondary maximum contaminant levels (SMCL). The salinity indicators chloride, sulfate, and total dissolved solids (TDS) have recommended and upper SWRCB-DDW SMCL levels; the values for the upper levels were used.

3. Non-regulatory, health-based SWRCB-DDW notification levels (NL), EPA lifetime health advisory levels (HAL), and EPA risk-specific doses for 1 in 100,000 lifetime risk of cancer (RSD5).

Note that for constituents with multiple types of benchmarks, this hierarchy does not always result in selection of the benchmark with the lowest concentration. Additional information about the types of benchmarks used and lists of the benchmark values for all constituents analyzed are provided by Mathany and others (2013).

Toccalino and others (2004), Toccalino and Norman (2006), and Rowe and others (2007) used the ratio of measured sample concentration to the benchmark concentration, either the EPA MCL or the EPA and USGS health-based screening level (HBSL), and defined this ratio as the benchmark quotient (BQ). Because different water-quality benchmarks were used to calculate the RCs and BQs, the terms are comparable, but not interchangeable.

For ease of discussion, the RCs of constituents were classified into low, moderate, and high categories (table 3). The RC values greater than 1.0 were defined as “high” for all constituents. For inorganic constituents (trace elements, nutrients, radioactive constituents, and inorganic constituents having SMCL benchmarks), RC values greater than 0.5 and less than or equal to 1.0 were defined as “moderate,” and RC values less than or equal to 0.5 were defined as “low.” For organic and special-interest constituents, RC values greater than 0.1 and less than or equal to 1.0 were defined as “moderate,” and RC values less than or equal to 0.1 were defined as “low.” Although more complex classifications could be devised based on the properties and sources of individual constituents, use of a single moderate/low threshold value for each of the two major groups of constituents provided consistent objective criteria for distinguishing constituents present at moderate, rather than low, concentrations.

Other studies have used the same boundary value between low and moderate RCs for inorganic and organic constituents—either 0.5 (for example, U.S. Environmental Protection Agency, 1999) or 0.1 (for example, Toccalino and others, 2010). The primary reason for using a higher boundary value for inorganic constituents in this study was to focus attention on the inorganic constituents most prevalent at concentrations closest to benchmark concentrations. In a national survey of water quality in aquifers used for public drinking-water supply, Toccalino and others (2010) found that organic constituents (pesticides and volatile organic compounds) were present at BQs greater than 0.1 in approximately 10 percent of the samples and that inorganic constituents (nutrients, trace elements, and radioactive constituents) were present at BQs greater than 0.1 in approximately 80 percent of the samples. By setting the boundary between low and moderate BQs at 0.1, Toccalino and others (2010) produced a conservative assessment of water quality that is protective of human health and provides an early indication of potential groundwater contamination issues. Organic constituents generally are anthropogenic and enter groundwater as a result of human activities (both intentional, such as pesticide applications, and unintentional, such as leaks and spills) at the land surface. Concentrations of the organic constituents can change rapidly in groundwater; therefore, early warning (as given by using an RC of 0.1) could be vital for planning and implementing measures to protect aquifer systems from further contamination and to mitigate existing contamination. Inorganic constituents, on the other hand, typically are naturally present in groundwater, and their concentrations usually are stable or change slowly compared to those of organic constituents. Assigning a boundary between low and moderate RCs (or BQ) at 0.5 (rather than 0.1) allows identification of those inorganic constituents—from among the many that could be present—that are most common at concentrations close to benchmarks and could therefore warrant more immediate attention from water-resource managers.

The boundary between low and moderate RCs is not intended as a demarcation of the presence of contamination from anthropogenic sources. For this study, nitrate and the other nutrient constituents were categorized as inorganic constituents, and the boundary between low and moderate RCs was set at 0.5. Unlike the other classes of inorganic constituents, however, concentrations of nutrients in groundwater can be strongly affected by contamination from anthropogenic sources. Concentrations of nitrate in groundwater greater than 1 milligram per liter (mg/L) generally are considered to indicate contamination from anthropogenic sources (Nolan and others, 2002; Dubrovsky and others, 2010). Setting the boundary between low and moderate RCs at 0.5 for nitrate (which corresponds to 5 mg/L for nitrate), therefore, results in some groundwater samples that likely are contaminated by anthropogenic sources to be categorized as having a low RC for nitrate. Similarly, groundwater containing anthropogenic organic constituents at RCs less than 0.1 was classified as having a low RC for organic constituents, despite presumptive contamination from anthropogenic sources.

Selection of Constituents

All constituents with benchmarks were evaluated for this study. Aquifer-scale proportions are presented for individual constituents that were present at high or moderate RCs in the 39 grid wells, the 4 additional wells, or in the SWRCB-DDW database for any sample collected between March 2007 and August 2010. Aquifer-scale proportion results also are presented for individual organic constituents detected in more than 10 percent of the grid-well samples dataset. These criteria identified 18 inorganic constituents, 5 organic constituents, and 1 special-interest constituent (table 4).

An additional 27 inorganic constituents and 26 organic constituents were detected by the USGS-GAMA, but they either had no drinking-water quality benchmarks or were only detected at low RCs (table 5). Aquifer-scale proportions are not presented for constituents only detected at low RCs because the proportion of the groundwater resource with low RCs for those constituents was 100 percent. All of the 21 geochemical and age-dating tracers examined also were detected (table 2). The remaining 139 constituents were not detected by the USGS-GAMA in the samples from wells used in the status assessment (6 of these 139 constituents were detected in samples from the monitoring wells, which were not considered representative of groundwater resources used for public drinking water). A complete list of the constituents analyzed by the USGS-GAMA in the WSJV study unit can be found in the data-series report by Mathany and others (2013).

The SWRCB-DDW database was also used to identify constituents that have been reported at high RCs historically, but not at the time of the study (table 6). The historical period, March 1980 through February 2007, was defined as the period starting at the date of the earliest record maintained in the SWRCB-DDW electronic database and ending just before the period used for this status assessment. Constituents could have been present at high concentrations during the historical period, but not during the study period, because of improved groundwater quality over time or because wells that pumped groundwater with high concentrations of constituents had been abandoned. Constituents reported at high RCs historically, but not present at moderate or high RCs during the study period were not considered potential water-quality concerns for the groundwater resources used for public drinking water during the study period.

In the WSJV study unit, historically, 13 constituents were measured at high concentrations in groundwater (table 6). Of these 13 constituents, 3—aluminum, chromium, and perchlorate—were detected at moderate RCs during the 3-year period of the status assessment or were detected at moderate RCs in samples from the grid wells (table 4). One constituent, *tert*-butyl-alcohol, was not analyzed by the USGS-GAMA. Of the remaining 9 historically high constituents, 7 were detected at high concentrations in samples from less than 2 percent of the wells tested (table 6).

Calculation of Aquifer-Scale Proportions

The status assessment characterized groundwater quality in three areas of the groundwater resource used for public drinking-water supplies: the Delta–Mendota study area, the Westside study area, and the WSJV study unit as a whole. The proportions of these areas with high, moderate, and low RCs of constituents were calculated using the spatially weighted approach of Belitz and others (2010). For ease of discussion, these proportions are referred to as “high-RC,” “moderate-RC,” and “low-RC” aquifer-scale proportions. Calculations of aquifer-scale proportions were made for individual constituents and for classes of constituents. Aquifer-scale proportions for constituent classes were calculated using the maximum RC for any constituent in the class to represent the class. Such an approach is conservative for protection of human health. For example, a well where the groundwater had a high RC of arsenic, a moderate RC of fluoride, and low RCs of molybdenum, boron, selenium, and other trace elements would be counted as having a high RC for the class of trace elements with health-based benchmarks.

High-RC aquifer-scale proportion was estimated for each constituent by calculating the proportion of wells where high RCs were detected for each cell and then calculating the average proportion for the cells in each study area (equation 1; Isaaks and Srivastava, 1989; Belitz and others, 2010). The moderate-RC aquifer-scale proportion was calculated similarly.

$$P_s^{high} = \frac{\sum \frac{W_n^{high}}{W_n}}{n} \tag{1}$$

where

P_s^{high} is the spatially weighted high-RC aquifer-scale proportion for the study area,

W_n^{high} is the number of wells in cell n of the study area in which the constituent was detected at high RC,

W_n is the number of wells in cell n of the study area that have data for the constituent,

n is the number of cells in the study area or study unit having data for the constituent (29 for the Delta–Mendota study area, 10 for the Westside study area, and 39 for the WSJV study unit as a whole).

Area-weighting was not required for calculation of proportions for the WSJV study unit as a whole because the size of the cells in the two study areas was the same.

In addition, the raw detection frequencies of high and moderate RCs for individual constituents were calculated using the same dataset of wells as used for the spatially weighted calculations. These raw detection frequencies were not spatially unbiased, however, because the wells in the SWRCB-DDW database were not uniformly distributed (fig. 5). For example, if a constituent was present at high RCs in a small region of the aquifer that had a high density of wells, the raw detection frequency of high RCs would be greater than the high aquifer-scale proportion. Raw detection frequencies of high and moderate RCs are provided for in the aquifer-scale proportion results table , but were not used to assess aquifer-scale proportions.

The detection frequencies of organic constituents for each study area and the study unit as a whole were calculated using only the grid-well dataset.

Methods for Evaluating Factors Affecting Water Quality

The GAMA Priority Basin Project uses statistical tests of associations between potential explanatory factors and water quality to infer processes that could affect water quality in a study unit. For the WSJV study unit, 17 potential explanatory factors describing land-use characteristics, location characteristics, geology, and groundwater age and geochemical conditions were evaluated. These 17 factors were selected because they were found to be causative factors in previous water-quality studies in the San Joaquin Valley and because values for the factors could be obtained for all WSJV study-unit sites, either from data collected at the site or from available Geographic Information System (GIS) coverages. Associations among these factors that could explain apparent relations between the factors and water quality are also described. Associations were explored using data from the 43 grid and additional wells used in the status assessment. The other SWRCB-DDW wells were not used for evaluating potential explanatory factors because the SWRCB-DDW database did not include data for the potential explanatory factors. Data from the 16 monitoring wells not used in the status assessment were not used in the statistical analyses, but were used in graphical evaluation of potential processes affecting groundwater quality. This section describes the methods used for selecting constituents for evaluation, and for assessing the strength, direction, and significance of associations between the potential explanatory factors and constituents of interest.

Selection of Constituents

A subset of the constituents for which aquifer-scale proportion results were presented was selected for evaluation of relations between potential explanatory factors and groundwater quality and for discussion of those relations in the context of the hydrogeologic setting of the WSJV study unit. This subset included individual constituents present at high RCs in greater than approximately 2 percent of the groundwater resource used for public drinking water and organic constituent classes and special-interest constituents detected at any concentration in greater than 10 percent of the resource. These criteria resulted in selection of 14 individual constituents and 2 organic constituent classes (table 4). These constituents have the greatest potential to be present at concentrations above benchmark concentrations in groundwater resources used for public drinking water supply in the WSJV study unit.

Statistical Analysis

Nonparametric statistical methods were used to assess the strength, direction, and significance of associations among the factors and between the factors and water-quality constituents. Nonparametric statistics are robust techniques that generally are not sensitive to outliers and do not require that the data follow any particular distribution (Helsel and Hirsch, 2002). The WSJV study-unit dataset included a few samples that had sufficiently different water chemistry compared to the rest of the samples that they behaved as outliers in parametric tests and strongly influenced the results of such tests. The significance level (p) used for hypothesis testing for this report was compared to a threshold value (α) of 5 percent ($\alpha = 0.05$) to evaluate whether the relation was statistically significant ($p < \alpha$).

Three statistical tests were used because the set of potential explanatory factors included categorical and continuous variables. Groundwater-age class, study area, aquifer lithology, position relative to Corcoran Clay, and oxidation-reduction (redox) status were treated as categorical variables, each with two nominal classification categories; for example, for redox, wells were classified as anoxic or oxic. Land use, septic-tank density, density of leaking or formerly leaking underground storage tanks, aridity index, lateral position, depths to top and bottom of screened interval, and groundwater pH and dissolved oxygen concentration were treated as continuous variables; for example, land use was represented by percentages of land-use types. Concentrations of water-quality constituents were treated as continuous variables. Specific statistical methods (Helsel and Hirsch, 2002) used for each tested combination of variable types were as follows.

Relations between categorical variables and continuous variables were evaluated by using the Wilcoxon rank-sum test in cases for which the categorical variable had two subsets or the Kruskall-Wallace test in cases for which the categorical variable had more than two subsets. This test assesses whether the median values for the continuous variable are significantly different between the subsets of samples, as defined by the categorical variable.

Relations between continuous variables were evaluated using Spearman's rank-order correlation analysis, which gives the rank correlation coefficient, rho (ρ), and the significance level of monotonic relations (p). Rho was used to assess the strength and direction of the relation. Because the rank correlation test only evaluates monotonic relations, each continuous variable was plotted against all other continuous variables, and the graphs were visually examined to identify non-monotonic relations.

Relations between categorical variables were evaluated by using contingency tables. For a contingency-table analysis, the data are recorded as a matrix of counts. One variable is assigned to the columns, and the other to the rows, and the entries in the cells of the matrix are the number of observations that are in the categories corresponding to the i^{th} row and j^{th} column of the matrix. A test statistic is computed by comparing the observed counts to the counts expected if the two variables are independent, and significance is determined by comparing the test statistic to the 1–α quantile of a *chi*-squared distribution (Helsel and Hirsch, 2002). If the contingency-table test yielded a result of significance, then the locations of the most important relations were determined by comparing magnitudes of the components of the test statistic.

Description and Evaluation of Potential Explanatory Factors

The 17 potential explanatory factors examined in this study were grouped into 4 classes: land-use characteristics (percentages of natural, urban, and agricultural land use and densities of septic tanks and underground storage tanks around the well site), location characteristics (study area, lateral position, depths to top and bottom of screened interval in well, and climate index), geologic features (aquifer lithology in the screened interval of the well, position relative to the Corcoran Clay, and dominant geologic unit in the inferred upgradient watershed from the well), and groundwater age and geochemical conditions (age classification, redox classification, dissolved oxygen concentration, and pH). The following discussion is divided into four parts, one for each of the four classes of potential explanatory factors. For each class of factors, the discussion includes explanations of why the factors were selected, how the data were compiled and values assigned to the wells, and what the values of the factors are for the grid wells in the context of the hydrogeologic setting of the WSJV study unit. Relations among the factors are discussed on the basis of results of statistical tests of associations among the factors (tables 7*A–C*) and in the context of the hydrogeologic setting of the WSJV study unit.

A result of significance on a statistical test does not necessarily mean that there is a causal relation between the two variables (two explanatory factors, an explanatory factor and a water-quality constituent, or two water-quality constituents). Correlation between two variables could be a spurious relation that reflects the causal relations of those two variables to a third variable. Similarly, a result of not significant does not necessarily mean that there is no causal relation between the two variables: there could be confounding factors that obscure relations.

Land-Use Characteristics

Human activities at the land surface can affect groundwater quality because they can be sources of contaminants and because they can alter the groundwater-flow system. Fertilizers and amendments applied to agricultural and urbanized lands, livestock, septic and wastewater systems, runoff from urbanized areas, industrial activities, leaking fuel and chemical storage tanks, landfill leachates, and other anthropogenic sources can contribute nitrate, salts, pesticides, VOCs, and other constituents to groundwater recharge. These anthropogenic factors have long been part of drinking water source assessment and protection programs (for example California Department of Health Services, 2000) and water-quality evaluations, including those by the USGS NAWQA Program and the GAMA Priority Basin Project (for example, Gilliom and others, 2006; Zogorski and others, 2006; Landon and others, 2010; Burton and others, 2012; Shelton and others, 2013). In addition, irrigation and groundwater pumping can alter the sources, rates, and flow directions of groundwater recharge. Such changes to the groundwater flow system can cause changes in groundwater chemistry that may have deleterious effects on groundwater quality (for example, Jurgens and others, 2010).

Development of the region containing the WSJV study unit for agricultural use began in the late 1800s (Mendenhall and others, 1916), and the region's land use has been dominated by irrigated agriculture since the mid-1900s (Bull and Miller, 1975). If a WSJV study-unit well dominantly taps groundwater recharged during the last 80 years, approximately, then the groundwater quality could reflect human activities at the land surface. If a well dominantly taps older groundwater, then the water quality should be little influenced by human activities at the land surface.

Land use was classified using an enhanced version of the satellite-derived (30-meter pixel resolution) USGS National Land Cover Dataset (Nakagaki and others, 2007). This dataset has been used in previous national and regional studies relating land use to water quality (Gilliom and others, 2006; Zogorski and others, 2006). The data represent land use during the early 1990s. The imagery is classified into 25 land-cover classes (Nakagaki and Wolock, 2005). These 25 land-cover classes were condensed into 3 principal land-use categories—urban, agricultural, and natural—and land use was then expressed as a percentage urban, agricultural, and natural. Land-use statistics for the study unit, study areas, and areas within a 500-m radius around each study well (500-m buffers) were calculated. A 500-m radius centered on the well has been shown to be effective for correlating land use with detections of VOCs or pesticides, or with occurrence of elevated concentrations of nitrate in groundwater (for example, Rupert, 2003; Johnson and Belitz, 2009). Land-use data for USGS-GAMA wells are listed in appendix table 1–2.

Land use in the WSJV study unit was 78 percent agricultural, 20 percent natural, and 2 percent urban (figs. 7, 8*A*). Approximately 60 percent of the agricultural land use in the late 1990s was for cotton, tomatoes, grains, and alfalfa (California Department of Water Resources, 1998). Changes in agricultural land-use patterns in the last couple of decades have increased acreage of high-value crops, such as almonds, pistachios, and other tree crops, and decreased acreage of lower value crops, such as cotton (California Department of Water Resources, 2010). In addition, some land was taken out of agricultural production to limit the volume of agricultural drainage water with poor water quality or because of insufficient availability of water for irrigation (San Joaquin Valley Drainage Program, 1990; California Department of Water Resources, 2014). Natural areas were predominantly grasslands and wetlands.

The average amounts of urban land use in the 500-m buffers around all of the SWRCB-DDW wells (30 percent) and around the grid wells (13 percent) are greater than the average amount of urban land use in the study unit as a whole (fig. 8*A*) because public-supply wells typically are preferentially located where people are living. The difference between the average land use around all the SWRCB-DDW wells and around the grid wells reflects the spatially distributed nature of the grid wells. The SWRCB-DDW wells are biased toward urban land use because urbanized areas typically have more public-supply wells.

Septic tanks and leaking (or formerly leaking) underground storage tanks (USTs) can be useful markers of land-use patterns because they are generally associated with areas where people live and work, and they can be sources of anthropogenic contamination of groundwater recharge. Septic-tank density was determined from housing characteristics data from the 1990 U.S. Census (U.S. Census Bureau, 1992). The density of septic tanks in each housing census block (block density) was calculated from the number of tanks in the block and census block area. The density of septic tanks around each well was then calculated from the area-weighted mean of the block densities for blocks intersecting the 500-m buffer around the well. (Tyler Johnson, U.S. Geological Survey, written commun., 2009). The density of septic tanks in the 500-m buffers around the grid wells in the study unit ranged from 0.1 to 13.2 tanks per square kilometer (tanks/km^2; appendix table 1–2), with a median density of 0.8 tanks/km^2. Septic-tank density was greater in the Delta–Mendota study area than in the Westside study area (table 7*A*).

The density of leaking or formerly leaking underground fuel tanks (USTs) was determined from the locations of tanks in the SWRCB's GeoTracker database of environmental cleanup sites (California State Water Resources Control Board, 2007). The density of USTs was calculated using Theissen polygons (Tyler Johnson, U.S. Geological Survey, written commun., 2007). The boundary of the Theissen polygon around a particular UST was created by bisecting the linear distances between the UST and all the surrounding USTs. The density of USTs in the polygon was the number of tanks in the polygon (nearly always one) divided by the area of the polygon in square kilometers. A well was assigned the UST density of the Theissen polygon in which it was located. The density of USTs in the grid wells in the study unit ranged from 0 to 3.38 tanks/km^2 (appendix table 1–2), with a median density of 0.02 tanks/km^2. The density of USTs was positively correlated with the percentage of urban land use and with the density of septic tanks (table 7*B*).

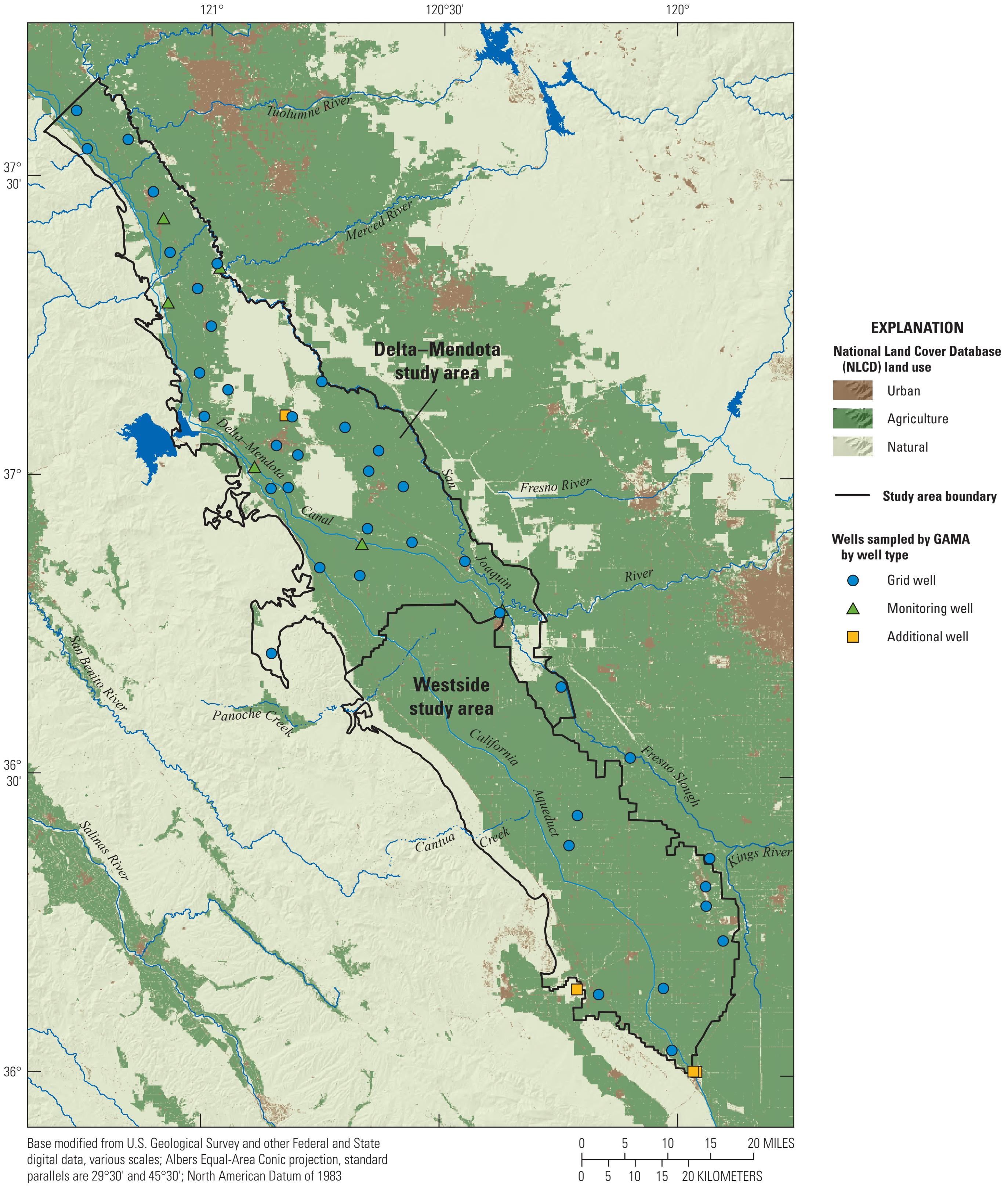
The percentages of agricultural and urban land use around grid wells used for the WSJV study were similar to those in adjacent GAMA Priority Basin Project study units, the Southeast San Joaquin Valley and Madera–Chowchilla (fig. 2; Burton and others, 2012; Shelton and others, 2013), but densities of septic tanks and USTs were lower in the WSJV study unit, which likely reflects the lower population density in the WSJV study unit compared to the Southeast San Joaquin Valley and Madera–Chowchilla study units.

Location Characteristics

Five potential explanatory factors were used to represent the locations of wells in the WSJV study unit hydrologic system: study area, climate index, lateral position, and depths to top and bottom of screened interval in well.

As discussed in the "Hydrogeologic Setting" section, there are many differences between the Delta–Mendota and Westside study areas. The "study area" factor combines all of those differences in one variable. It was selected as a potential explanatory factor because the fundamental units for the GAMA Priority Basin Project were the 87 study areas statewide (Belitz and others, 2015). These 87 study areas were grouped into 35 study units to facilitate sampling wells and organizing, interpreting, and publishing the resulting data. By using study area as a potential explanatory factor, the differences and similarities between the component study areas in the study unit could be evaluated.

For this study, the climate at each well site was represented by calculating the United Nations Educational, Scientific, and Cultural Organization (UNESCO) aridity index (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997). The aridity index is the average annual precipitation divided by the average annual evapotranspiration. The aridity index summarizes one potential effect of climate on groundwater quality: the degree to which concentrations of dissolved constituents in groundwater could be decreased by input of dilute water from precipitation or could be increased by evaporative concentration.



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

Figure 7. Land use and locations of sampled wells for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

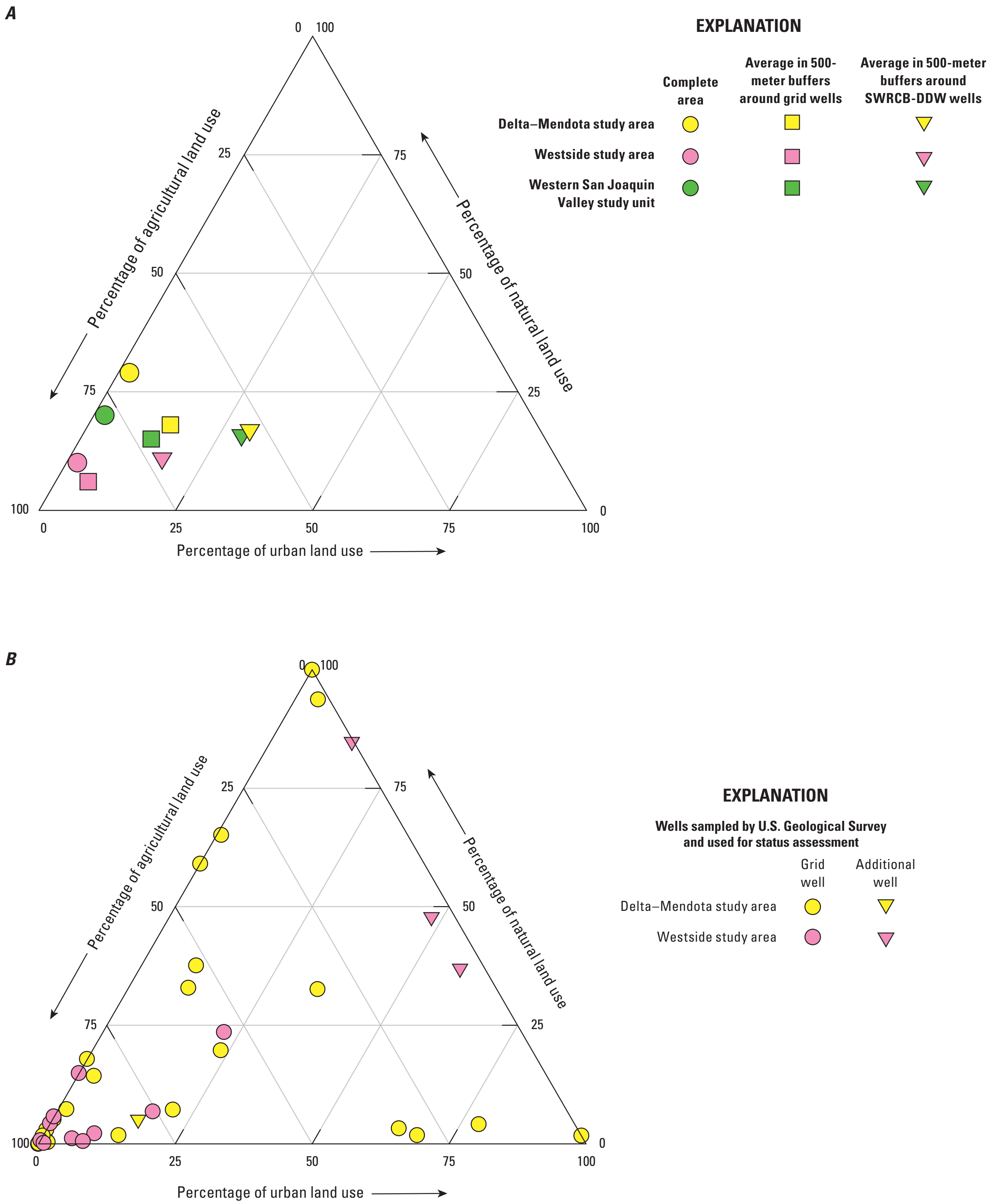


Figure 8. Percentages of urban, agricultural, and natural land use in the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project for *A*, the study unit and study areas, and averages for areas within 500-meter buffer around grid wells sampled by the U.S. Geological Survey (USGS), and public-supply wells inventoried by the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) and *B*, individual wells sampled by the U.S. Geological Survey (USGS) and used for the status assessment.

Average annual precipitation for each well site was extracted from the PRISM average annual precipitation for 1971–2000 GIS coverage (PRISM Group, Oregon State University, 2010). Average annual evapotranspiration for each well site was extracted from a GIS coverage modified from Flint and Flint (2007). The modification consisted of calibrating the evapotranspiration values to the measured California Irrigation Management Information System evapotranspiration reference values (California Irrigation Management Information System, 2005; Alan Flint, U.S. Geological Survey California Water Science Center, oral commun., 2009). Greater values of aridity index correspond to wetter conditions. Values less than 0.05 are defined as hyper-arid, 0.05 to less than 0.20 as arid, 0.20 to less than 0.50 as semi-arid, 0.50 to less than 0.65 as dry sub-humid, 0.65 to less than 1.00 as humid, and greater than or equal to 1.00 as wet (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997). Most of the WSJV study unit has an arid climate (aridity index of less than 0.20; appendix table 1–1). Sites in the Westside study area were significantly more arid than sites in the Delta–Mendota study area (table 7*A*).

The potential explanatory factor "lateral position" summarizes several variables that can vary systematically with distance between the Coast Ranges at the western side of the WSJV study unit and the San Joaquin River and Fresno Slough at the eastern side. As discussed in the "Hydrogeologic Setting" section, the lateral component of groundwater movement in the WSJV study unit under pre-development conditions was generally from the western margin of the study unit toward the San Joaquin River and Fresno Slough; therefore, a normalized distance from the margin can be representative of relative position in the groundwater-flow system. Relative position in the groundwater-flow system could affect groundwater quality because the progress of geochemical reactions that can consume dissolved oxygen or dissolve minerals in the aquifer sediments depends, in part, on the length of time the groundwater has been in contact with aquifer materials. The composition of the aquifer sediments also varies from west to east (fig. 4); thus, a relation between sediment composition and groundwater quality could show up as a relation between lateral position and groundwater quality. Finally, the source of recharge varies from west to east. Recharge derived from the Coast Ranges has different water quality than recharge derived from the Sierra Nevada (see discussion in the "Total Dissolved Solids, Sulfate, and Chloride" section).

The lateral position of each well was calculated as the ratio of the distance from the well to the valley trough to the total distance from the valley trough to the west edge of the valley. The west edge of the valley was represented by the western boundary of the valley-fill deposits and by definition has a lateral position of 1. The valley trough was represented by the position of the San Joaquin River in the Delta–Mendota study area and by the position of the Fresno Slough in the Westside study area, and by definition has a lateral position of 0. Greater values of lateral position indicated the upgradient or proximal portion of the groundwater-flow system, and lower values of lateral position indicated the downgradient or distal portion of the flow system. Wells located at lateral positions of greater than 0.34 generally were in alluvial fan deposits composed of Coast Ranges alluvium and wells located at lateral positions less than 0.34 generally were in basinal deposits composed of either Coast Ranges alluvium or Sierra Nevada sands. The wells sampled by the USGS-GAMA were distributed across the full range of normalized lateral positions (appendix table 1–1).

Water quality can be related to depth in the aquifer system for many reasons. Groundwater age generally increases with depth. Older groundwater could have had more geochemical reactions with aquifer materials, and the quality of younger groundwater could have been affected by human activities at the land surface. In the WSJV study unit, aquifer lithology varies by depth (fig. 4), and different lithologies could be associated with different groundwater quality. For this study, depth in the aquifer system was defined as the depth from land surface to the top and to the bottom of the screened interval in the well. Because the thickness of the unsaturated zone at the top of aquifer system varied (Belitz and Heimes, 1990; Faunt, 2009), it might have been more appropriate to define depth in the aquifer system as the depth from the water table to the top and the bottom of the screened interval in the well (for example, Jurgens and others, 2010). However, the depth of the water table in the WSJV study unit has varied over time, as a result of irrigation and groundwater pumping (for example, Belitz and Heimes, 1990; Faunt, 2009); thus, the choice of a water table configuration would have been arbitrary. Groundwater levels were not measured for this study.

Well-construction information was available for 41 of the 43 grid and additional wells sampled in the WSJV study unit, but not all information was available for every well (appendix table 1–1). Well-construction data were obtained primarily from drillers' logs. For wells where drillers' logs were not available, well-construction data were obtained from ancillary records of well owners or from the USGS National Water Information System database. Well depth data were available for 15 wells for which data for depth to the bottom of the screened interval were not. For these wells, depth to the bottom of the screened interval was assumed to be equal to well depth. This assumption was based on relations between well depth and depth to the bottom of the screened interval for the 26 wells having data for both parameters. The difference between well depth and depth to the bottom of the screened interval ranged from 0 m to 7.6 m, with a median of 0 m, a mode of 0 m, and a mean of 1.1 m. This difference was deemed too small to be important for the purposes of this study; therefore, well depth was assumed to equal depth to the bottom of the screened interval for wells lacking data for depth to the bottom of the screened interval.

For 11 wells, data for well depth or depth to the bottom of the screened interval were available, but not data for depth to the top of the screened interval. The depth to the top of the screened interval was estimated from the relation between the depths to the top and bottoms of the screened interval using the data from the 30 wells that had data for both parameters. The estimated depths to the top of the screened intervals were used for plotting wells on figures, but were not used in the statistical tests.

The median depth to the bottom of the screened interval in grid and additional wells was 85 m blsd in the Delta–Mendota study area and was 233 m blsd in the Westside study area (figs. 9, 10; appendix table 1–1). Depths to the bottom of the screened interval for the three additional wells in the Westside study area were not significantly different from the depths of the grid wells in the study area (Wilcoxon rank-sum test, $p = 0.228$). The median depth to the top of the screened interval was 53 m blsd in the Delta–Mendota study area and was 122 m blsd in the Westside study area. Screened intervals in wells in the Delta–Mendota study area were significantly shallower than those in the Westside study area (table 7*A*). Because septic tanks were less dense and it was more arid in the Westside study area as well, depths to the top and bottom of screened interval were inversely correlated with aridity index and tank density (table 7*B*).

Geologic Factors

Geologic factors were represented by three variables: depth relative to the Corcoran Clay, aquifer lithology in the screened interval of the well, and dominant geologic unit in the inferred upgradient watershed from the well. Depth relative to the Corcoran Clay was chosen as a potential explanatory factor to test whether the confined groundwater system below the Corcoran Clay has different water quality than the semi-confined to unconfined system above the clay layer. Aquifer lithology was considered an important explanatory factor because the chemical composition of sediments derived from the Coast Ranges and from the Sierra Nevada differs. Sediment chemistry can affect groundwater geochemical conditions, thus differences in sediment chemistry could result in differences in the solubility of some constituents in the groundwater. Dominant geologic unit in the inferred upgradient watershed from the well was considered an important explanatory factor because the Coast Ranges adjacent to the WSJV study unit includes a wide variety of geologic units. Investigations of surface water in the area of the WSJV study unit found that that the concentrations of many constituents of interest in surface water were strongly correlated with watershed geologic characteristics (Davis, 1961; Presser and others, 1990).

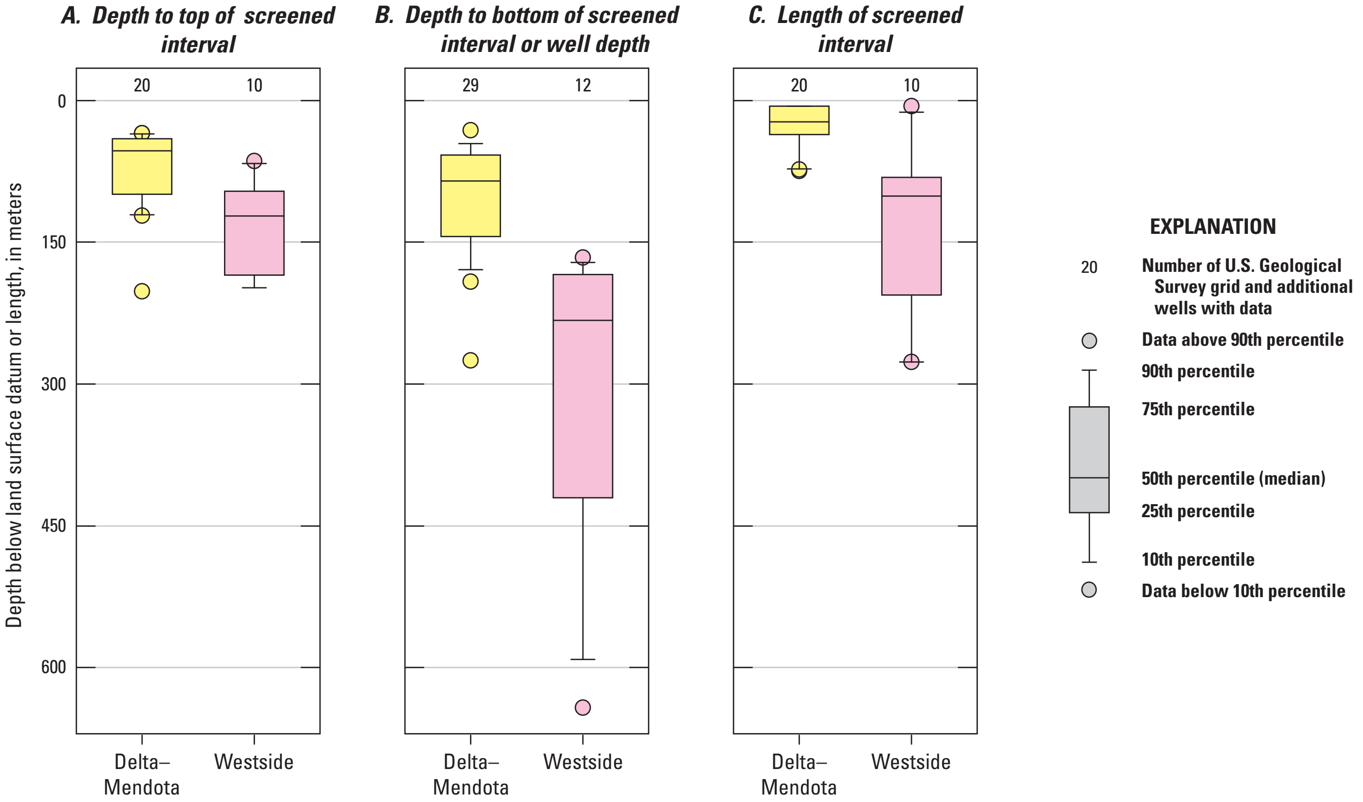


Figure 9. Depth and length of screened intervals in grid and additional wells sampled by the U.S. Geological Survey (USGS) by study area, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project: *A*, depth to top of screened interval, *B*, depth to bottom of screened interval, and *C*, length of screened interval.

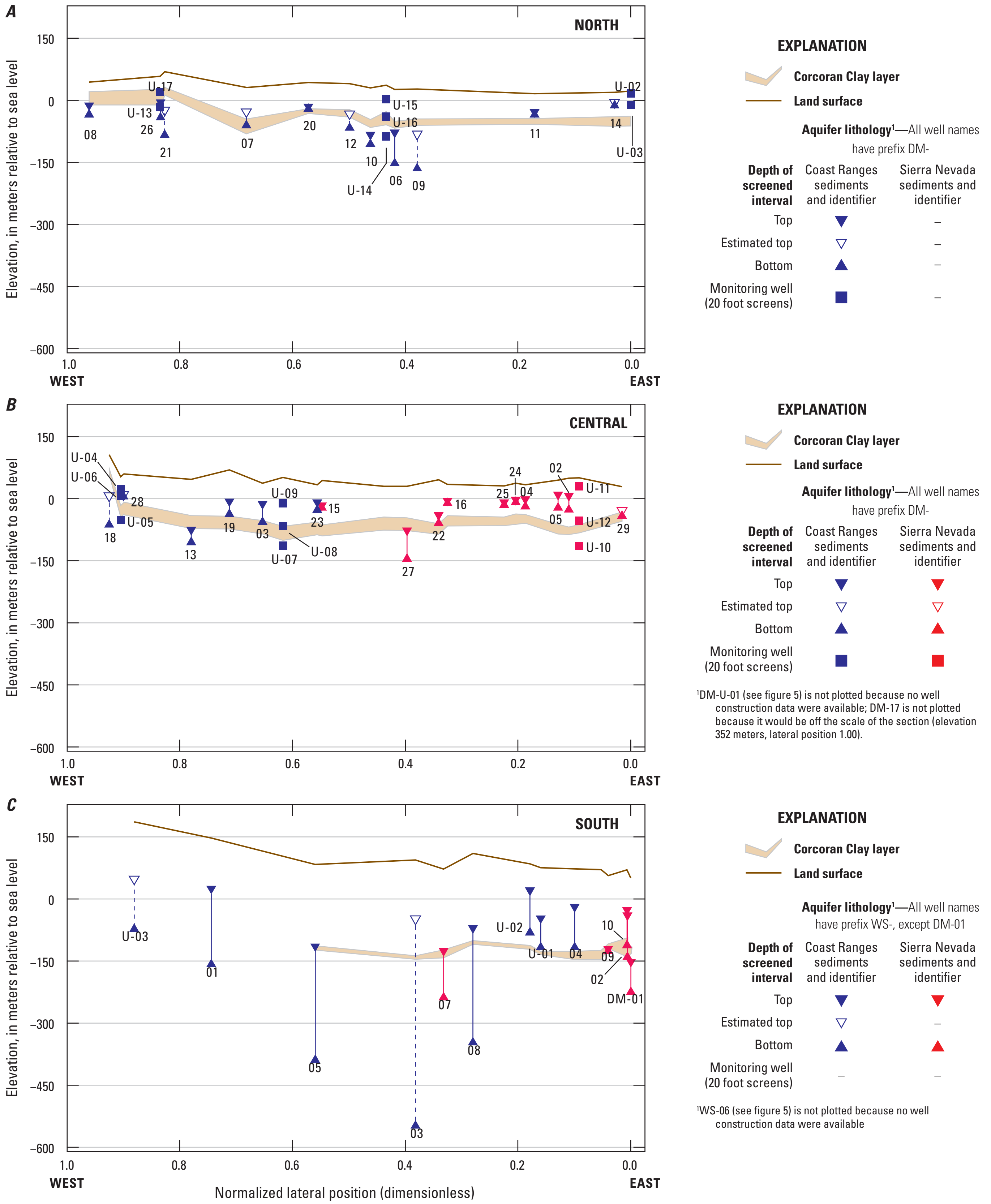


Figure 10. Depths to the tops and bottoms of screened interval in wells, aquifer lithology at the depth of the screened interval in the wells, and depth of the wells relative to the depth of the Corcoran Clay horizon for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, North; *B*, Central; and *C*, South. (Boundaries between North, Central, and South regions are shown in figure 5.)

The freshwater aquifer system in the WSJV study unit is roughly divided into two levels by the Corcoran Clay (fig. 4), and there are public-supply wells screened in the upper and lower aquifer systems. The elevations of the top and bottom of the Corcoran Clay horizon at the wells sampled by USGS-GAMA were estimated from Faunt (2009) and compared to the elevations at the top and bottom of the screened interval in the wells to determine whether the wells were screened above or below the Corcoran Clay. Of the 40 grid and additional wells in the area where Corcoran Clay was in the subsurface, 15 had screened intervals entirely below the Corcoran Clay, 21 had screened intervals entirely above, 2 had screened intervals both above and below (referred to as “across”), and 2 had no well-construction data from which to determine depth relative to the Corcoran Clay (figs. 3, 10; appendix table 1–3). Of the 16 monitoring wells, 12 were screened above and 4 were screened below the Corcoran Clay (figs. 6, 10; appendix table 1–3).

Wells were classified on the basis of the aquifer lithology in the screened interval of the well: either Coast Ranges alluvial sediments or Sierra Nevada sands (Dubrovsky and others, 1991). The presence or absence of Sierra Nevada sediments at the screened interval of wells was estimated from maps of the extent and thickness of the Sierra Nevada sands (Miller and others, 1971; Belitz and Heimes, 1990). Of the 41 grid and additional wells with depth information, 15 were screened in Sierra Nevada sands and 26 were screened in Coast Ranges alluvium (figs. 3, 10; appendix table 1–3). The Sierra Nevada sands are thickest along the valley trough and are both above and below the Corcoran Clay (fig. 4; Belitz and Heimes, 1990; Dubrovsky and others, 1991); thus, aquifer lithology was not correlated with study area or position relative to the Corcoran Clay (table 7*C*).

Wells also were classified on the basis of the dominant geologic unit in the inferred upgradient watershed from the well. Davis (1961) classified the geologic units within the drainage basin for 31 ephemeral and perennial creeks on the eastern slope of the Coast Ranges adjacent to the San Joaquin Valley. The geology of each drainage basin was defined by the percentage of area occupied by five generalized geologic unit: Franciscan Complex, ultramafic intrusive rocks, marine sedimentary rocks of Cretaceous age, marine sedimentary rocks of Tertiary age, and continental deposits of Tertiary and Quaternary age (Davis, 1961). For this study, drainage basins for which the sum of the percentages of Franciscan Complex and ultramafic intrusive rocks was greater than 50 percent were defined as dominated by Franciscan Complex, and drainage basins for which the sum of the percentages of Cretaceous and Tertiary marine sedimentary rocks was greater than 50 percent were defined as dominated by marine sediments. The drainage basins of Davis (1961) were matched with subbasin Hydrologic Unit Code (HUC_10) polygons (U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service, 2013) on the basis of map location and name. Wells generally were assigned to the HUC_10 in which they were located. In some cases, wells that were located in a HUC_10 on the floor of the San Joaquin Valley, but immediately adjacent to a HUC_10 of a Coast Ranges creek were assigned to the HUC_10 of the creek. Of the 59 USGS grid, additional, and monitoring wells, 49 were assigned to a HUC_10 that had been matched to a Davis (1961) drainage basin: 32 wells to drainage basins dominated by marine sediments and 17 to drainage basins dominated by Franciscan Complex (appendix table 1–3).

Groundwater Age and Geochemical Conditions

Groundwater age was selected as a potential explanatory factor because longer contact time between groundwater and aquifer sediments generally results in greater opportunity for reactions that can alter the groundwater quality. Groundwater “age” refers to the length of time that the water has resided in the aquifer system, which is the amount of time elapsed since the water was last in contact with the atmosphere. Data for the age-dating tracers tritium and carbon-14 were used to classify groundwater ages into three categories: modern, mixed, and premodern. Samples with tritium activities less than 0.5 tritium units (TU) and ^{14}C values less than 90 percent modern carbon (pmC) were classified as “premodern” groundwater; samples with tritium activities greater than 0.5 TU and ^{14}C values greater than 90 pmC were classified as “modern” groundwater. Samples with tritium activities greater 0.5 TU and ^{14}C values less than 90 pmC were assigned to the “mixed” groundwater age class.

The threshold levels of 0.5 TU and 90 pmC were selected based on expected tritium values in premodern groundwater and the relation between tritium and ^{14}C values in the WSJV study unit groundwater samples. At the latitudes and longitudes corresponding to the parts of the Sierra Nevada and Coast Ranges of California that are sources of recharge for groundwater in the WSJV study unit, background tritium values in precipitation are approximately 4 to 6 TU (Michel, 1989; Jurgens and others, 2012). Aboveground nuclear testing resulted in a large increase in tritium values in precipitation beginning in about 1952, which in the northern hemisphere, peaked at values of over 1,000 TU in 1963 (Michel, 1989). Radioactive decay of tritium in water with a tritium value of 6 TU in 1952 would result in a tritium value of 0.25 TU in 2010. The threshold between premodern and modern or mixed groundwater was set at 0.50 TU because the two samples with tritium values between 0.25 and 0.50 TU also had ^{14}C values less than 10 pmC (WS-02 and DM-17; appendix table 1–4), indicating dominance by old groundwater. The atmospheric ^{14}C value in 1950 is defined as 100 pmC (Clark and Fritz, 1977), and aboveground nuclear testing resulted in the ^{14}C values of greater than 100 pmC in atmospheric carbon dioxide and dissolved inorganic carbon in precipitation. Radioactive decay of ^{14}C from the background value of 100 pmC in 1952 would result in a ^{14}C value of 99 pmC in 2010 in dissolved inorganic carbon in precipitation.

The threshold between premodern and modern groundwater was defined as 90 pmC because the ^{14}C pmC values in this study were "uncorrected." Bexfield and others (2012) corrected ^{14}C values in groundwater samples from Albuquerque, New Mexico, by using geochemical modeling to account for reactions with sedimentary carbonates and oxidation of sedimentary organic matter, yielding corrected values of ^{14}C that were 1 to 9 pmC greater than the measured values. It was assumed that correction of ^{14}C values for the WSJV samples would result in changes similar in magnitude to the greatest changes determined for the Albuquerque samples, because many of the WSJV samples had low dissolved oxygen concentrations (appendix table 1–5) and because the Coast Ranges alluvium contains some carbonate minerals. In other words, it was assumed that WSJV samples with uncorrected ^{14}C values greater than 90 pmC would have corrected values greater than 99 pmC, and therefore indicate modern groundwater.

Although more sophisticated lumped-parameter models that incorporate mixing could have been used to analyze groundwater-age distributions (for example, Cook and Böhlke, 2000; Jurgens and others, 2012), use of these alternative models to understand age mixtures was beyond the scope of this report. Instead, classification of groundwater age as modern (primarily recharged after 1952), mixed, or premodern (primarily recharged before 1952) was deemed an appropriate and useful characterization for assessment of groundwater quality at the study area and study-unit scales.

Of the 43 grid and additional wells, 23 were classified as having premodern groundwater, 9 as having mixed groundwater, and 10 as having modern groundwater (fig. 11; appendix table 1–4). One well was classified as having modern or mixed groundwater because ^{14}C data were not available. Modern and mixed categories were combined for the purpose of statistical tests. Wells pumping premodern groundwater had greater depths to the top and bottom of the screened interval than wells pumping modern or mixed groundwater (table 7*A*). All the wells in the Westside study area pumped premodern groundwater, whereas only 40 percent did in the Delta–Mendota study area (table 7*C*; fig. 11). Wells pumping modern or mixed groundwater were associated with greater densities of septic tanks and USTs (table 7*A*), but there was no causal relation between tank densities and groundwater age. The association reflects characteristics strongly related to study area: wells pumping modern or mixed groundwater were only in the Delta–Mendota study area (table 7*C*), which also had greater septic tank densities (table 7*A*). In the northern part of the Delta–Mendota study area, all grid wells screened above or below the Corcoran Clay pumped mixed or modern age groundwater (fig. 11). Dubrovsky and others (1991) concluded that tritiated water below the Corcoran Clay in this area of the WSJV study unit indicated that the Corcoran Clay was no longer an intact confining unit because of perforation by well bores and that the tritiated water below the clay was recharged by water applied to the surface as irrigation, not natural recharge.

Groundwater geochemical conditions are important potential explanatory factors because the solubility of many constituents of interest varies as a function of pH or oxidation-reduction conditions. Redox conditions were classified on the basis of dissolved oxygen (DO), nitrate, manganese, and iron concentrations using a modified version of the classification scheme of McMahon and Chapelle (2008) and Jurgens and others (2009). The modification was that the DO threshold for separating oxic from anoxic groundwater was increased from 0.5 mg/L to 1 mg/L. Of the 43 grid and additional wells, 29 (67 percent) had anoxic groundwater and 14 (33 percent) had oxic groundwater (appendix table 1–5). Anoxic conditions were further subdivided into suboxic, nitrate-reducing, manganese-reducing, and iron-reducing conditions (fig. 12; appendix table 1–5).

Correlations between redox status and other potential explanatory factors were tested with redox status represented by a continuous variable (DO concentration) and by a categorical variable (redox class). Oxic conditions and higher DO concentrations showed positive correlations with aridity index, lateral position, and modern/mixed groundwater (tables 7*A*–*C*). Previous investigations have noted that groundwater typically becomes more reducing toward the trough of the San Joaquin Valley (Davis and others, 1959; Bertoldi and others, 1991; Dubrovsky and others, 1993; Chapelle and others, 1995; Burow and others, 1998). Redox conditions were not correlated with depths to the top or bottom of the screened interval or position relative to the Corcoran Clay (tables 7*A*–*C*). Redox conditions were more closely related to aquifer lithology than to depth: DO concentrations were significantly lower in groundwater from wells screened in Sierra Nevada sands than in groundwater from wells screened in Coast Range alluvium (figs. 10, 12; tables 7*A*, *C*). Of the 15 grid and additional wells screened in the Sierra Nevada Sands, 14 had anoxic manganese- or manganese- and iron-reducing conditions. Among the 26 grid and additional wells screened in Coast Range alluvium, anoxic conditions were associated with premodern groundwater (contingency table test, $p < 0.001$), higher values of pH (Wilcoxon test, $p = 0.002$), and deeper wells (Wilcoxon test, $p = 0.020$) (figs. 10–13; appendix tables 1–3, 1–5).

Values of pH in samples from the Westside study area were greater than those in samples from the Delta–Mendota study area (fig. 13; table 7*A*). The negative correlations between pH and aridity index and septic tank density (table 7*B*) likely do not reflect causal relations, but rather reflect that aridity-index and septic-tank density values were lower for Westside study-area sites than for Delta–Mendota study-area sites (table 7*A*). Values of pH were greater in premodern than in modern groundwater and in deep wells than in shallow wells (table 7*A*), and pH showed a negative correlation with DO (table 7*B*).

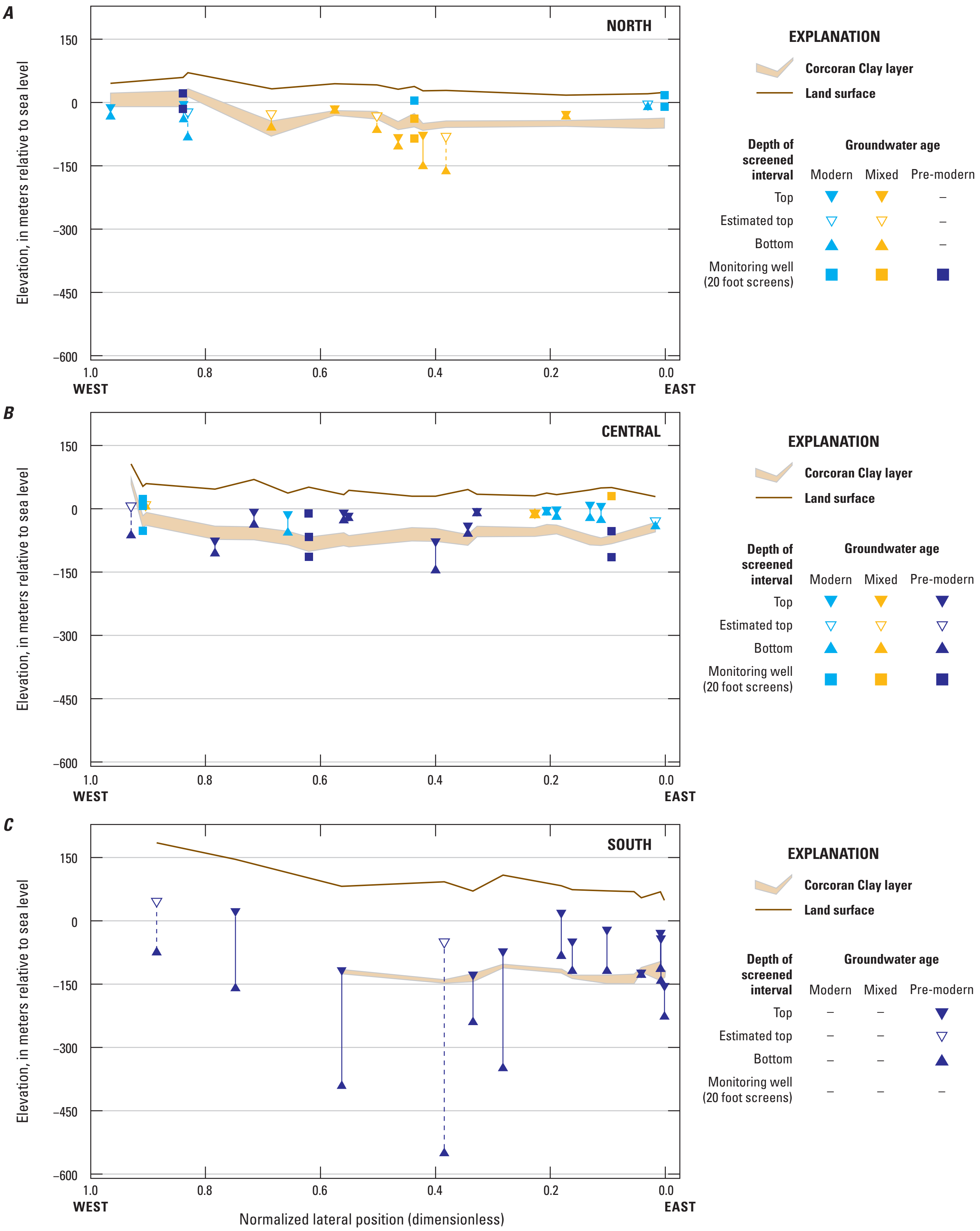


Figure 11. Depth to screened interval, groundwater-age classification, and position of the Corcoran Clay, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project: *A*, North; *B*, Central; and *C*. South. (Boundaries between North, Central, and South regions are shown in figure 5.)

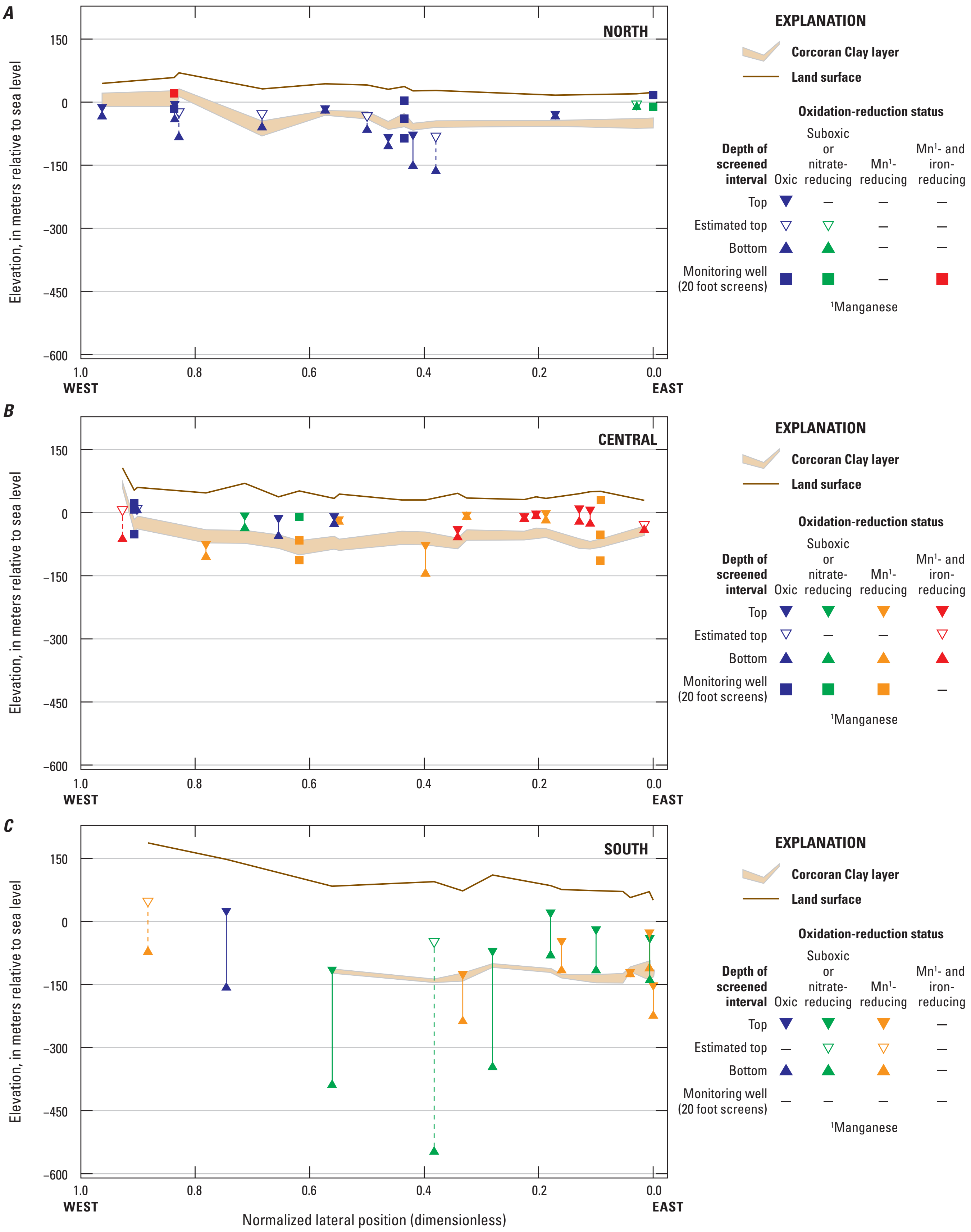


Figure 12. Depth of screened interval, oxidation-reduction classification of groundwater, and position of the Corcoran Clay, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project: *A*, North; *B*, Central; and *C*, South. (Boundaries between North, Central, and South regions are shown in figure 5.)

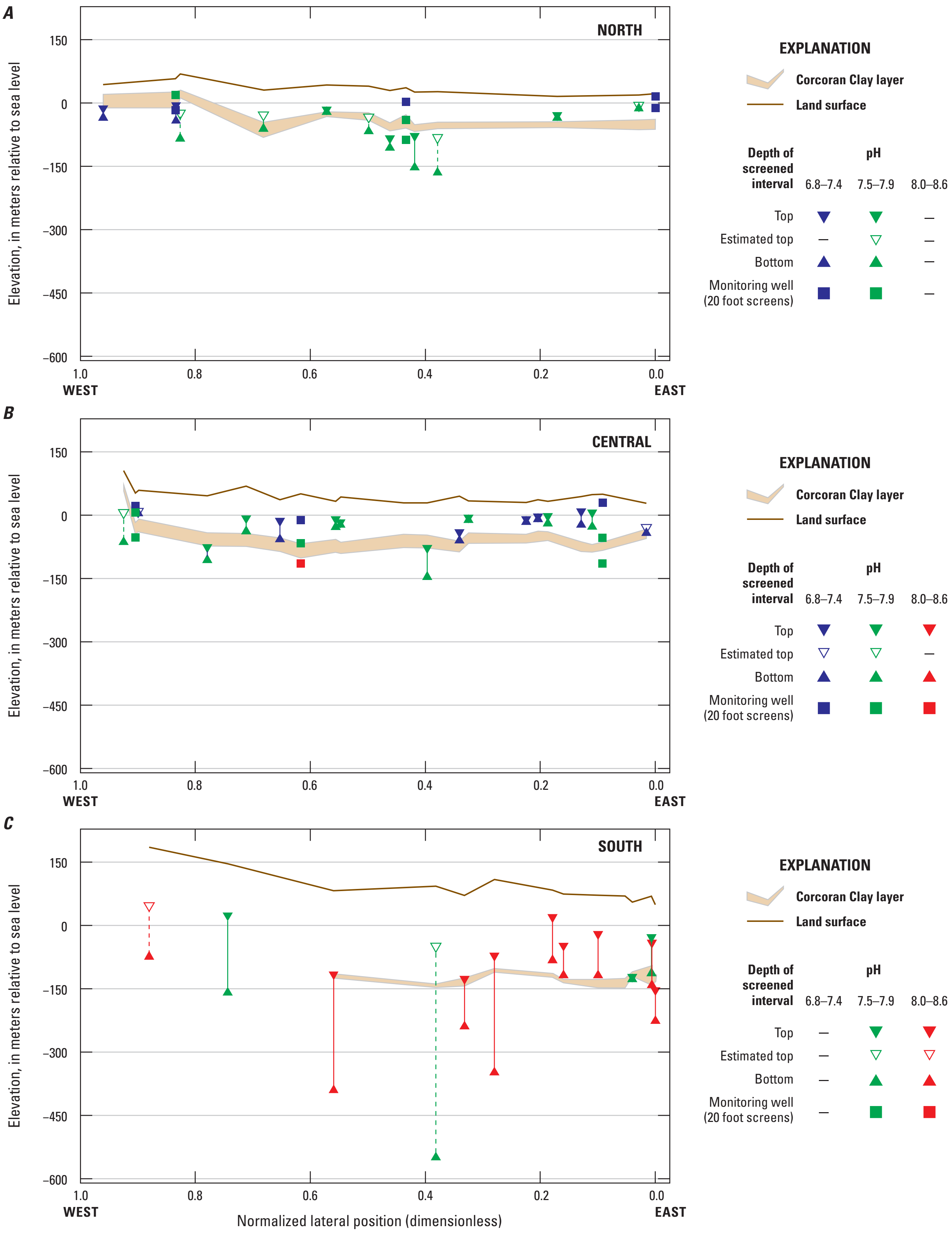


Figure 13. Depth of screened interval, pH values of groundwater, and position of the Corcoran Clay, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project: *A*, North; *B*, Central; and *C*, South. (Boundaries between North, Central, and South regions are shown in figure 5.)

Assessment of Groundwater Quality

The following discussion of the assessment results is divided into two parts, one for inorganic constituents and the other for organic constituents, and each part has a tiered structure. Each part begins with a survey of how many constituents were detected at any concentration in the USGS-GAMA well samples compared to the number analyzed and includes a graphical summary of the RCs of constituents detected in the USGS-GAMA wells. Aquifer-scale proportions then are presented for individual constituents and constituent classes. For constituents that met criteria for evaluation of potential natural and anthropogenic factors affecting water quality, results of those evaluations are discussed following the status-assessment results for that constituent.

Inorganic Constituents

Inorganic constituents generally are naturally present in groundwater, although their concentrations can be influenced by human activities as well as by natural factors (Hem, 1985). USGS-GAMA analyzed samples from the WSJV study unit for 44 inorganic constituents (table 2), and data were available from the SWRCB-DDW database for 2 additional inorganic constituents (gross alpha-particle and radium activities). Of these 46 inorganic constituents, 24 had regulatory or non-regulatory health-based benchmarks, 8 had non-regulatory aesthetic-based secondary maximum contaminant level (SMCL) benchmarks, and 14 had no established benchmarks (Mathany and others, 2013; tables 4, 5). Of the 32 inorganic constituents that had benchmarks, 19 were detected at moderate or high RCs in the WSJV study unit (table 4).

Fifteen inorganic constituents were detected at moderate or high RCs in the grid wells: the nutrient nitrate; the trace elements arsenic, boron, chromium(VI), chromium, molybdenum, selenium, strontium, and vanadium; and the SMCL constituents chloride, sulfate, total dissolved solids (TDS), specific conductance, iron, and manganese (table 4; fig. 14). The majority of these 15 constituents were detected at moderate or high RCs in more than 20 percent of the grid wells (figs. 15*A*, *B*). Aluminum, uranium, gross alpha-particle activity, and radium activity were reported at moderate or high RCs in the SWRCB-DDW database between March 2007 and August 2010 (table 4), but not in groundwater samples from USGS-GAMA grid or additional wells.

Aquifer-scale proportions for individual inorganic constituents are summarized in table 8 for the WSJV study unit as a whole and in appendix tables 2–1*A* and 2–1*B* for the two study areas. Aquifer-scale proportions for inorganic constituent classes are summarized in table 9*A* for the WSJV study unit as a whole and in appendix table 2–2*A* for the two study areas. Results of statistical tests for relations between water quality and potential explanatory factors are presented in tables 10*A*, *B*, and 11 for the 13 inorganic constituents present at high RCs in more than 2 percent of the groundwater resource (table 4). Inorganic constituents that have health-based benchmarks (trace elements, nutrients, radioactive constituents) were present at high RCs in 53 percent of the area of groundwater resource used for public drinking-water supplies and at moderate RCs in 30 percent (table 9*A*). Inorganic constituents that have SMCL benchmarks (manganese, iron, and salinity indicators), as a group, were present at high RCs in 70 percent of the groundwater resource and at moderate RCs in 27 percent (table 9*A*).

The GAMA Priority Basin Project assessed the quality of groundwater resources used for public drinking water in 87 study areas statewide (Belitz and others, 2015). Because consistent methods were used for the status assessment in all study areas, results for aquifer-scale proportions of constituents in different study areas can be directly compared. Figure 16 shows the proportion of the groundwater resources used for public drinking water with high RCs of selected constituents in the 82 study areas for which water-quality data were available for 10 or more wells. Results for the Delta–Mendota and Westside study areas of the WSJV study unit are shown as points superimposed on the box plots of results for all study areas.

Constituents with Secondary Maximum Contaminant Level (SMCL) Benchmarks

The class of constituents with SMCL benchmarks includes salinity indicators (TDS, sulfate, and chloride) and the trace elements iron and manganese. These constituents can affect the aesthetic properties of water, such as taste, color, and odor, or create technical problems, such as scaling and staining. SMCL benchmarks are based on these aesthetic and technical concerns and are not health-based benchmarks (table 4). About 52 percent of the groundwater resources used for public drinking water had high RCs of TDS, chloride, or sulfate, and 46 percent had high RCs of iron or manganese (table 9*A*). High RCs of all five constituents were found in the Delta–Mendota study area, and high RCs of all but chloride were found in the Westside study area (figs. 17*A*–*E*).

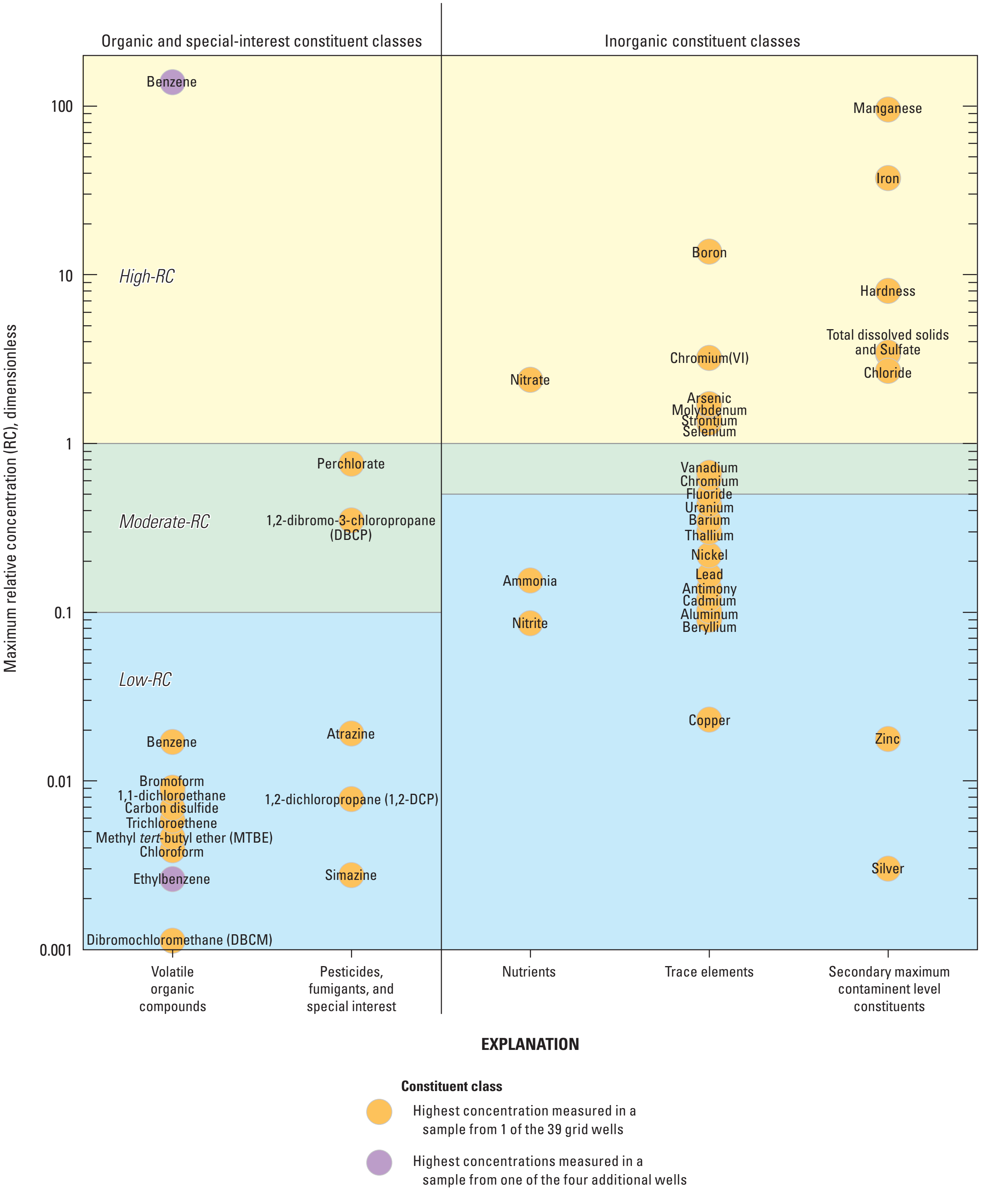


Figure 14. Maximum relative concentrations of constituents, by constituent class, in samples collected from grid and additional wells by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

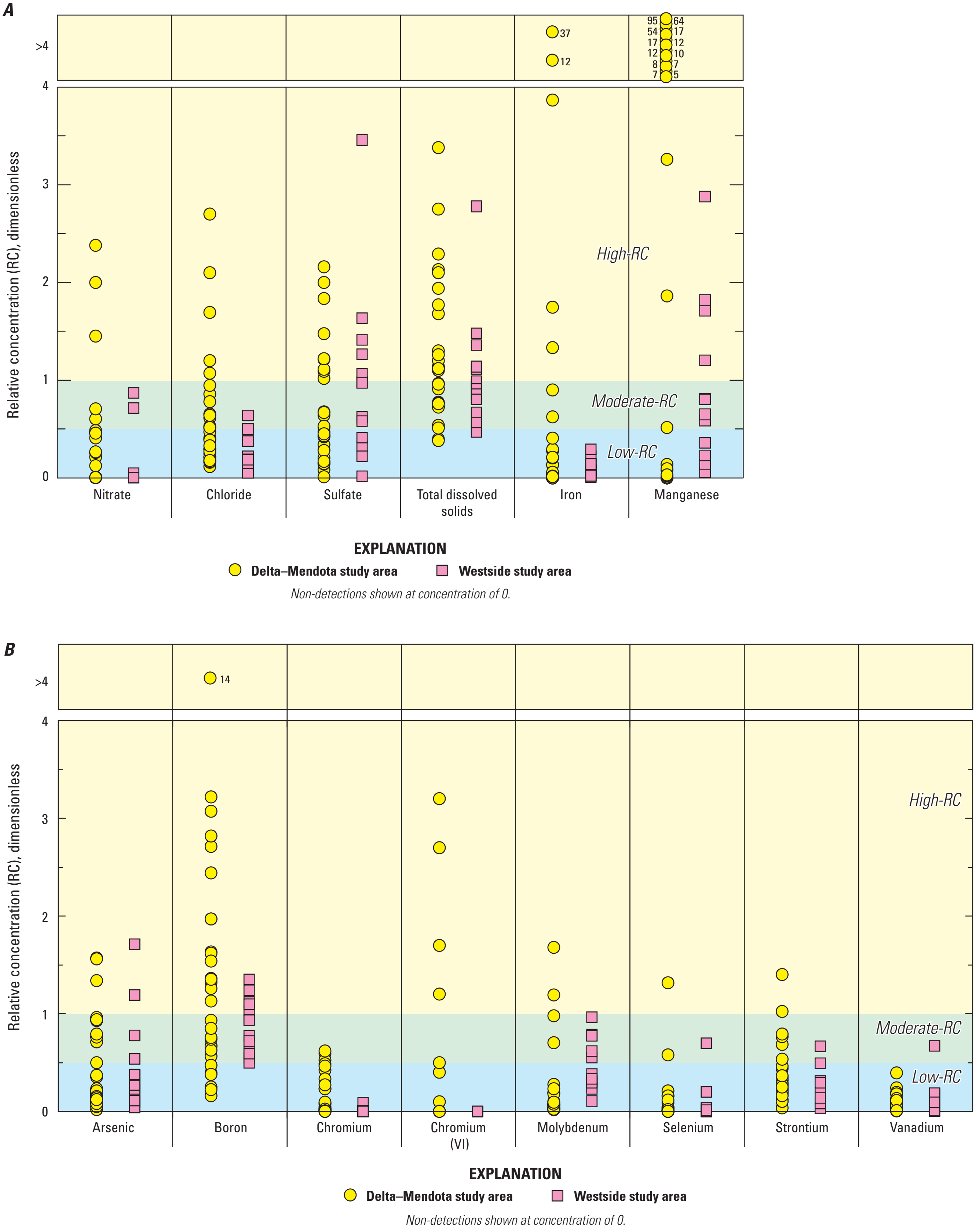


Figure 15. Relative concentrations of selected constituents by study area in samples collected from grid and additional wells by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, nitrate, with health-based benchmark and trace elements and salinity indicators with aesthetic-based benchmarks and *B*, trace elements with health-based benchmarks.

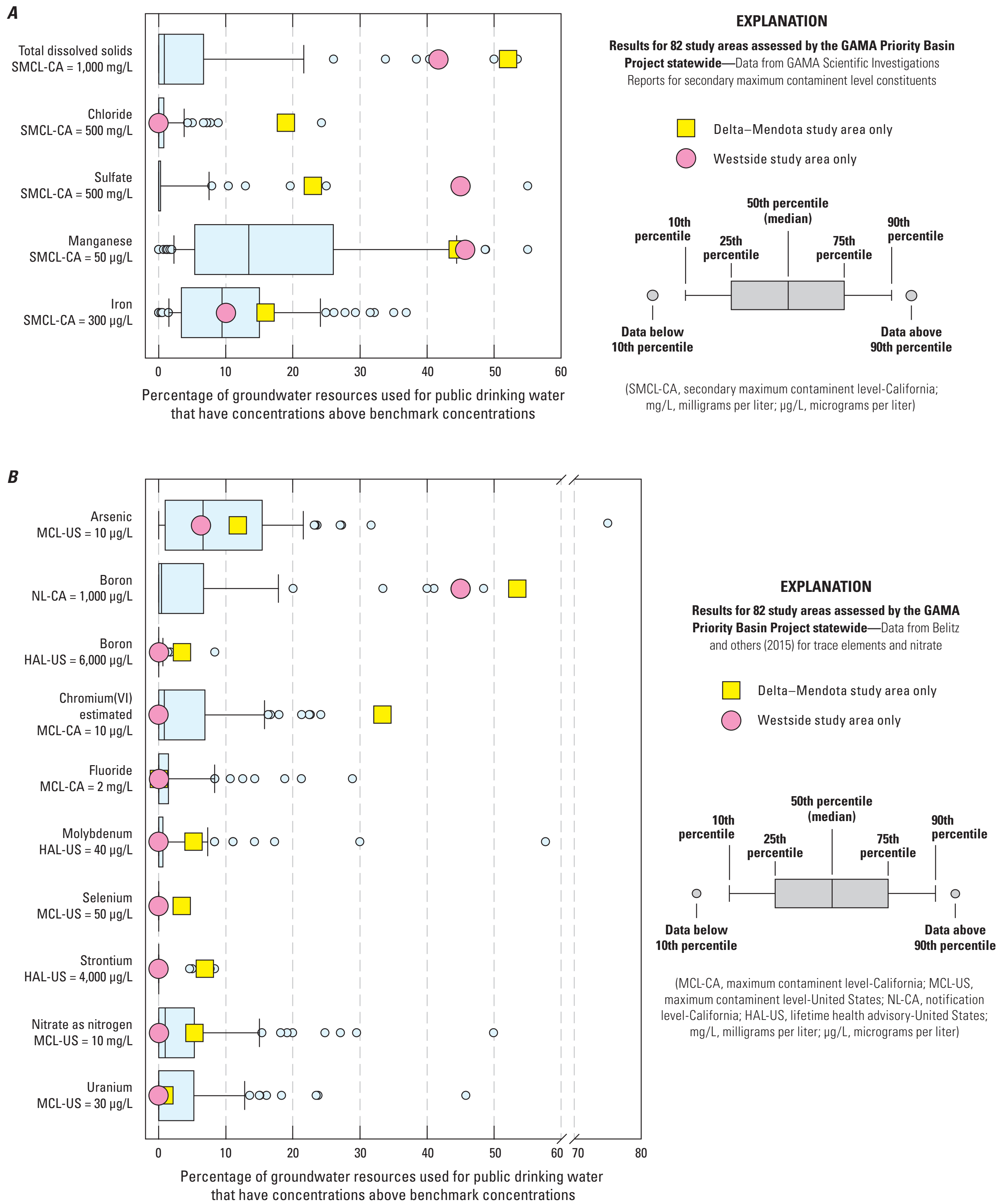
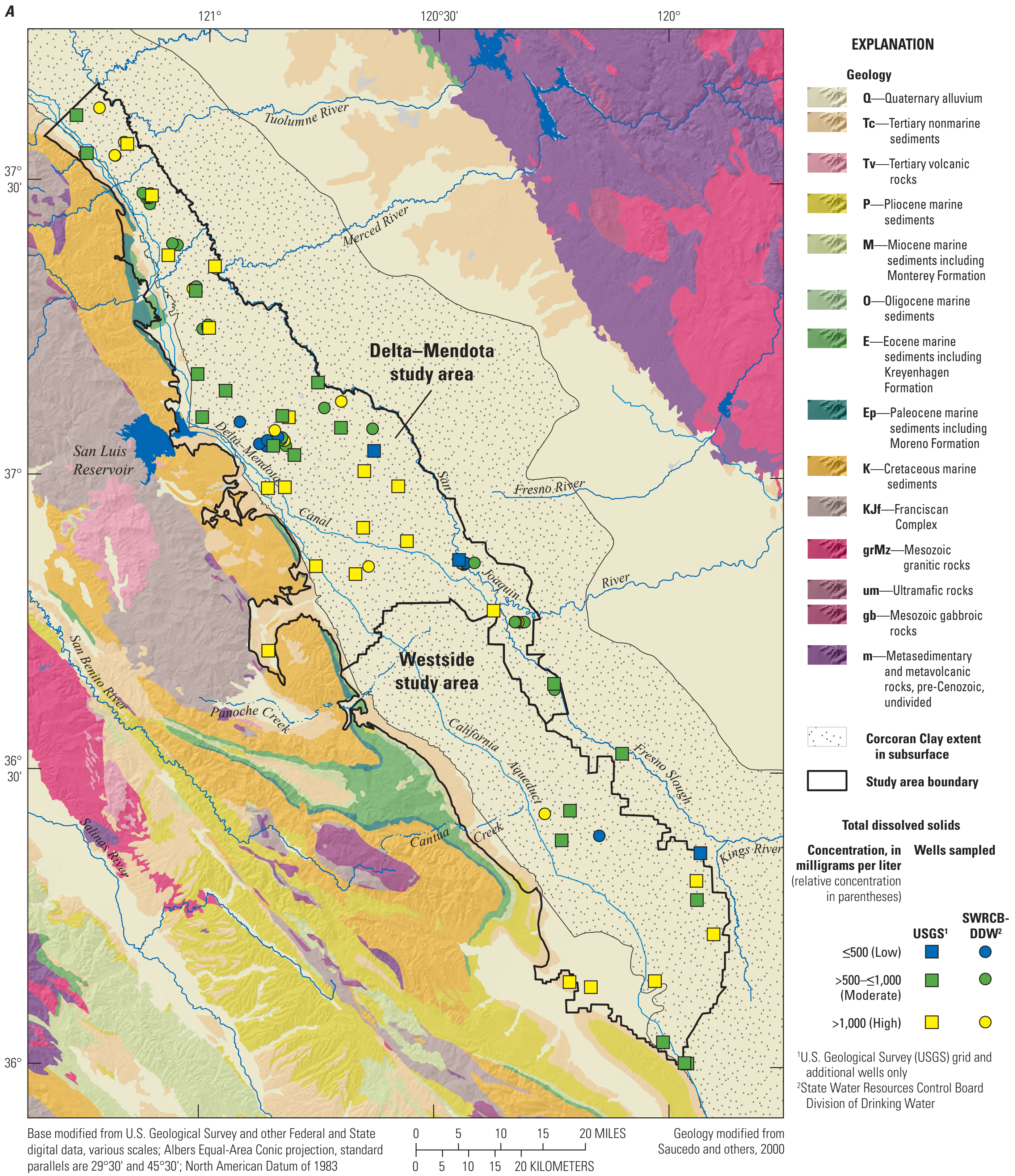


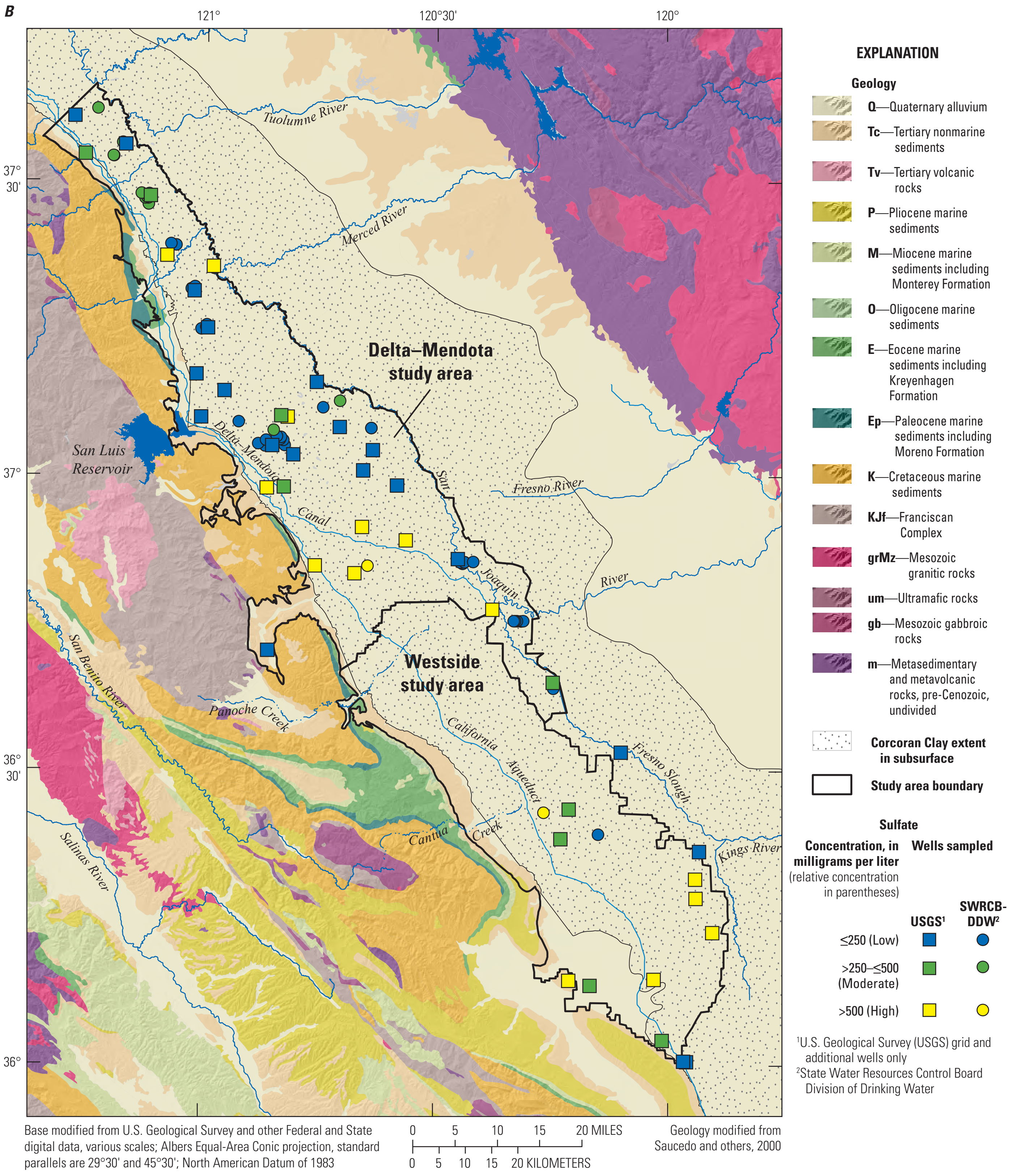
Figure 16. Proportion of groundwater resources that have high relative concentrations of selected constituents for 82 study areas statewide assessed by the California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, 2004–2012: *A*, constituents with aesthetic-based benchmarks and *B*, constituents with health-based benchmarks.



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

Geology modified from Saucedo and others, 2000

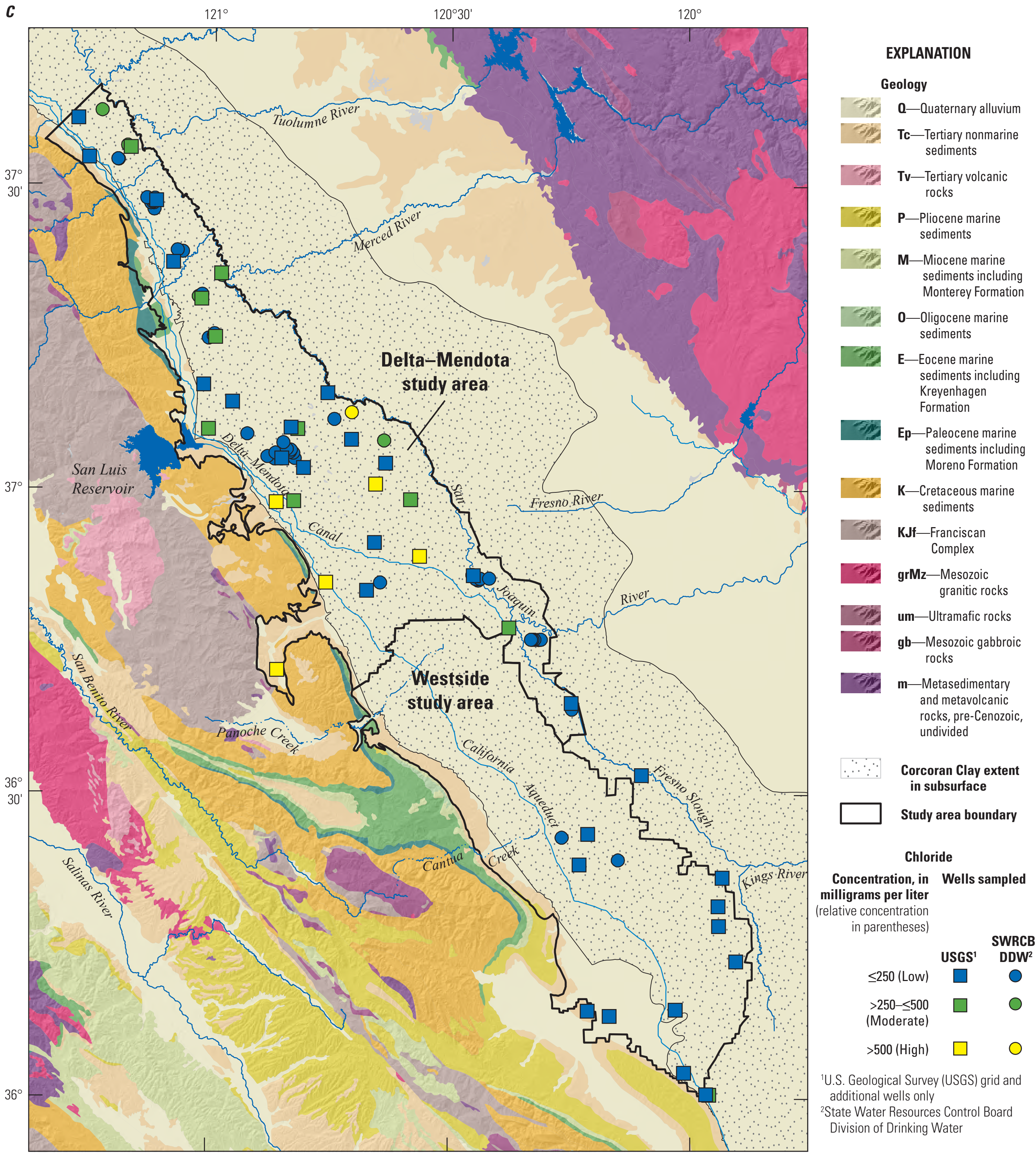
Figure 17. Relative concentrations of selected constituents in groundwater from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project and from public-supply wells that have data in the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database for samples collected from March 2007 through August 2010: *A*, total dissolved solids; *B*, sulfate; *C*, chloride; *D*, manganese; and *E*, iron.



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

Geology modified from Saucedo and others, 2000

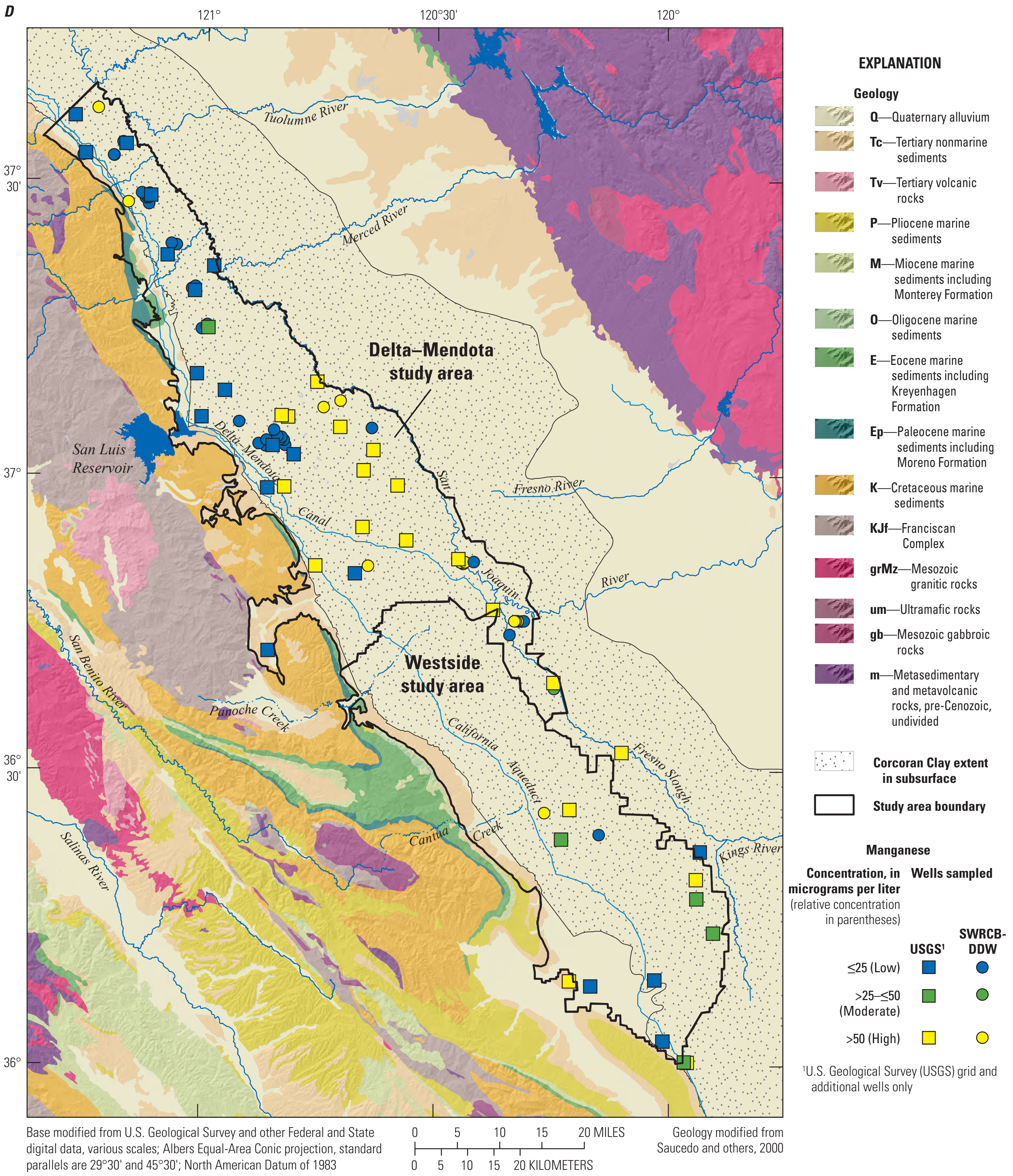
Figure 17. —Continued



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

Geology modified from Saucedo and others, 2000

Figure 17. —Continued



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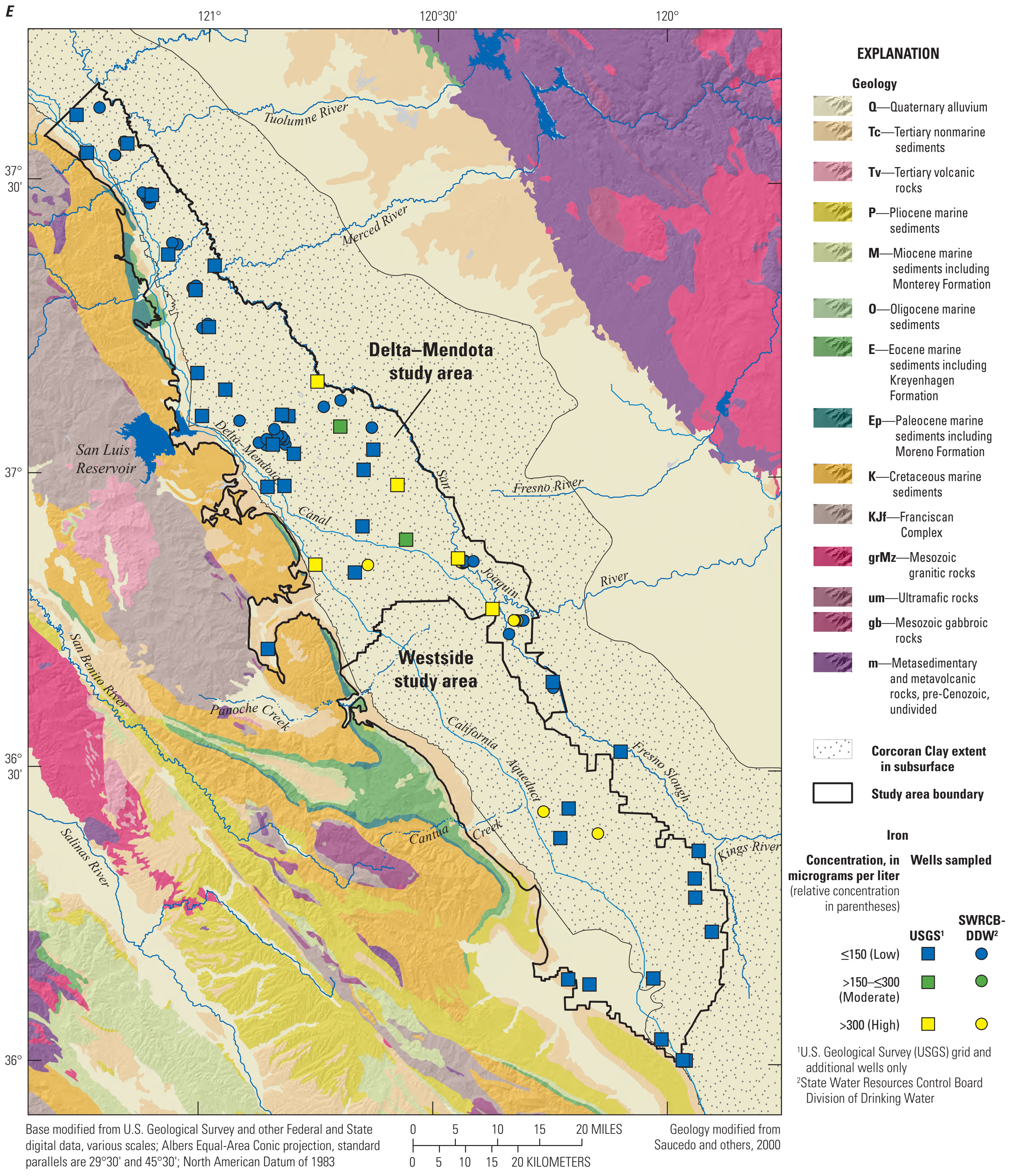
Geology modified from Saucedo and others, 2000

Figure 17. —Continued



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

Geology modified from Saucedo and others, 2000

Figure 17. —Continued

Total Dissolved Solids, Sulfate, and Chloride

Natural sources of TDS to groundwater include dissolution of minerals in soils, sediments, and rocks; concentration of solutes in shallow groundwater by evapotranspiration; mixing with hydrothermal fluids; mixing with connate fluids from marine or lacustrine sediments; and mixing with saline or brackish waters from the ocean, estuaries, or saline lakes (Hem, 1985). Potential anthropogenic sources of TDS to groundwater include recharge of water used for irrigation, wastewater discharge, and evaporative concentration. Data collected for this study indicated that the dominant sources of TDS in groundwater used for public supply in the WSJV study unit are the dissolution of minerals from marine sediments and mixing with hydrothermal fluids. Shallow groundwater that has high TDS from concentration of solutes by evapotranspiration (for example, Fujii and Swain, 1995) had not reached the depth zone used for public supply at the time of this study (2010).

Half of the groundwater resources used for public drinking water in the WSJV study unit had TDS concentrations above the upper SMCL (high RC), and 44 percent had TDS concentrations between the recommended and upper SMCL (moderate RC) (table 8). Both study areas had groundwater with low and moderate RCs of TDS (appendix tables 2–1*A*, *B*; figs. 15*A*, 16*A*), and the median concentrations of TDS in the two study areas were not significantly different (table 10*A*). Wells where groundwater had low RCs of TDS were primarily along the eastern edge of the study unit in the valley trough or in an area near the valley margin east of San Luis Reservoir (fig. 17*A*). The TDS concentrations showed positive correlation with sulfate and chloride concentrations (table 11), and all samples with high RCs of TDS had high or moderate RCs of sulfate, chloride, or both (Mathany and others, 2013).

Sulfate and chloride were present at high RCs in 29 and 14 percent, respectively, of the groundwater resources used for public drinking water in the WSJV study unit (table 8). High and moderate RCs of sulfate were common in both study areas; wells in which groundwater had low RCs of sulfate were primarily along the eastern edge of the study unit in the valley trough or near the valley margin east and northeast of San Luis Reservoir (fig. 17*B*). High and moderate RCs of chloride were common in the Delta–Mendota study area, but rare in the Westside study area (fig. 17*C*; appendix tables 2–1*A*, *B*).

Groundwater resources used for public drinking water supply in the WSJV study unit were among the most saline of groundwater resources used for public drinking water supply statewide. Of 82 study areas assessed statewide by the GAMA Priority Basin Project, only 8 study areas had high RCs of TDS in greater than 25 percent of the groundwater resources, and the Delta–Mendota (52.1 percent) and Westside (41.7 percent) study areas had two of the highest percentages (fig. 16*A*),

The TDS concentrations were not correlated with any potential explanatory factors (tables 10*A*, *B*). The absence of statistically significant correlations likely reflects the complexity of sources and processes affecting TDS concentrations, not the absence of systematic behavior of TDS concentrations in response to hydrologic processes and conditions in the WSJV study unit. Statistical correlations—or the absence of statistical correlations—between groundwater quality parameters and potential explanatory factors are just one tool for evaluating relations between groundwater quality and hydrologic processes and conditions. This study also used inferences from major-ion compositions, isotopic tracers, age-dating tracers, and geology.

Groundwater quality in the area of the WSJV study unit has been extensively investigated as part of several USGS efforts during the past century (for example, Mendenhall and others, 1916; Davis and others, 1959; Deverel and Millard, 1988; Davis and Coplen, 1989; Dubrovsky and others, 1991). Previous investigations of groundwater quality in the area of the WSJV study unit identified numerous compositional types of groundwater on the basis of major-ion compositions, TDS concentrations, and δ^2H and δ^{18}O ratios of water (Davis and Coplen, 1989; Dubrovsky and others, 1991).

Fujii and Swain (1995), Dubrovsky and others (1991), and Davis and Coplen (1989) used δ^2H and δ^{18}O values to infer whether groundwater samples represented recharge derived from Sierra Nevada precipitation, Coast Range precipitation, or mixtures of those two sources. The δ^2H and δ^{18}O values in precipitation in California vary systematically by distance from the Pacific Ocean and elevation (Davis and Coplen, 1989). The San Joaquin and Kings Rivers are the major Sierra Nevada rivers providing water to the WSJV study unit under natural conditions and also are the primary sources of imported surface water used for irrigation. Groundwater δ^{18}O values less than about –9.5 per mil indicated that most of the recharge was derived from the San Joaquin or Kings Rivers, and higher groundwater δ^{18}O values indicated that the recharge was mostly derived from the Coast Range streams (Davis and Coplen, 1989; Dubrovsky and others, 1991; Fujii and Swain, 1995). Among the WSJV study-unit samples, groundwater with isotopic characteristics consistent with a Sierra Nevada origin was found only in wells located near the center of the San Joaquin valley (lateral position less than 0.34) (fig. 18). Groundwater that had isotopic characteristics consistent with a Sierra Nevada origin had lower TDS concentrations than groundwater derived from recharge to Coast Ranges watersheds dominated by marine sediments, but had TDS concentrations similar to groundwater derived from recharge to Coast Ranges watersheds dominated by Franciscan Complex rocks (fig. 19).

Tritium activities and calculated recharge temperatures provided additional information about the source of recharge. Tritium activities greater than 0.5 TU indicated groundwater containing a large proportion of modern recharge (post-1952).

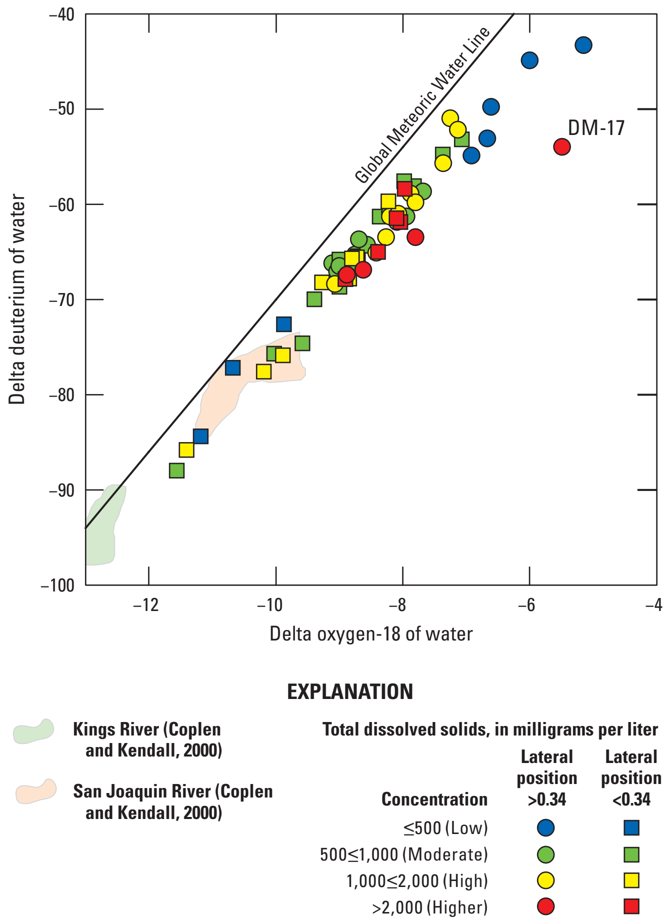


Figure 18. Relation between stable-isotope ratios of water, lateral position, and total dissolved solids concentrations for groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

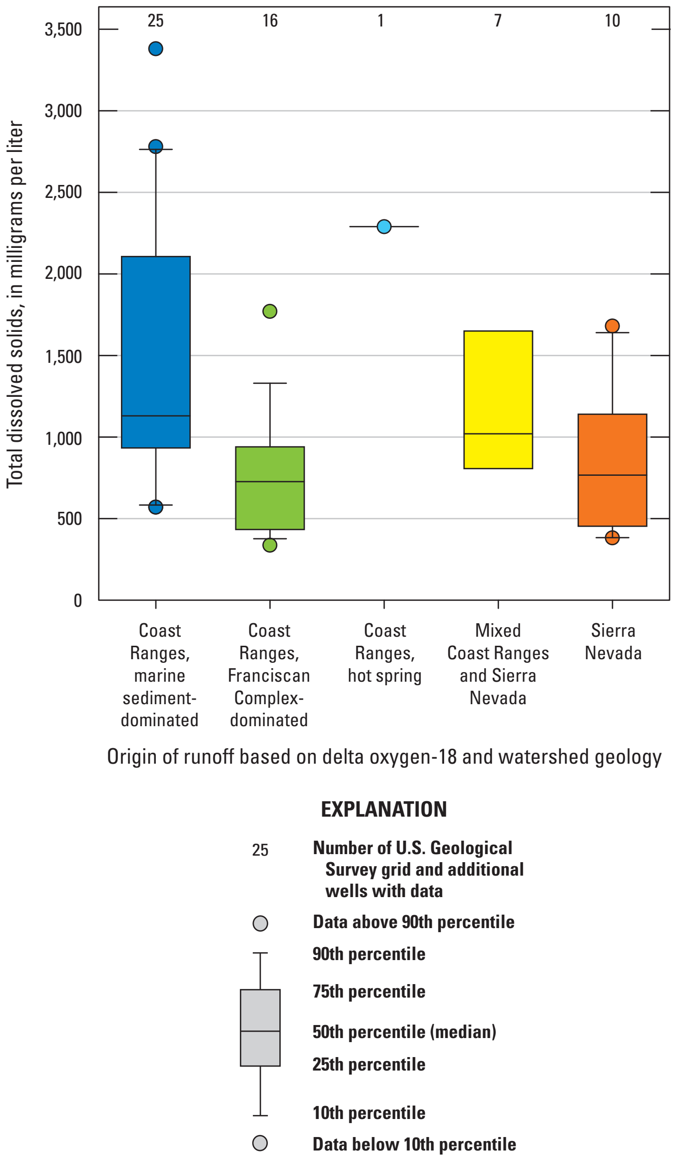


Figure 19. Box plots comparing total dissolved solids (TDS) concentrations in five groups of groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Recharge temperatures were calculated from dissolved noble-gas concentrations (appendix 4). Under natural hydrologic conditions, groundwater was mostly recharged during the cool, winter season because precipitation amounts and stream flows are much greater during the winter, rainy season than the summer, dry season. In contrast, under modern hydrologic conditions, irrigation provides most of the water for groundwater recharge, and irrigation is used mostly during the growing season, which is generally the warmer spring and summer seasons. Irrigation with imported surface water would recharge groundwater having the isotopic characteristics of Sierra Nevada water, modern tritium values, and relatively warm recharge temperatures. In contrast, natural recharge by Sierra Nevada water would have either modern or premodern tritium values, depending on whether it was recharged in modern times or in the distant past, but would have relatively cold recharge temperatures. Groundwater samples from the WSJV study unit with Sierra Nevada isotopic characteristics included samples with modern and premodern tritium values, and all have relatively cold recharge temperatures, indicating the water was recharged under natural conditions (fig. 20). The WSJV study-unit samples with isotopic characteristics of Sierra Nevada water were all from wells along the valley trough near the San Joaquin River or the Fresno Slough, an area most likely to be dominated by natural recharge from Sierra Nevada-derived runoff. The absence of groundwater with Sierra Nevada isotopic characteristics in other WSJV study-unit samples indicated that imported surface water applied for irrigation had not recharged to the depths used for public supply wells to a large extent.

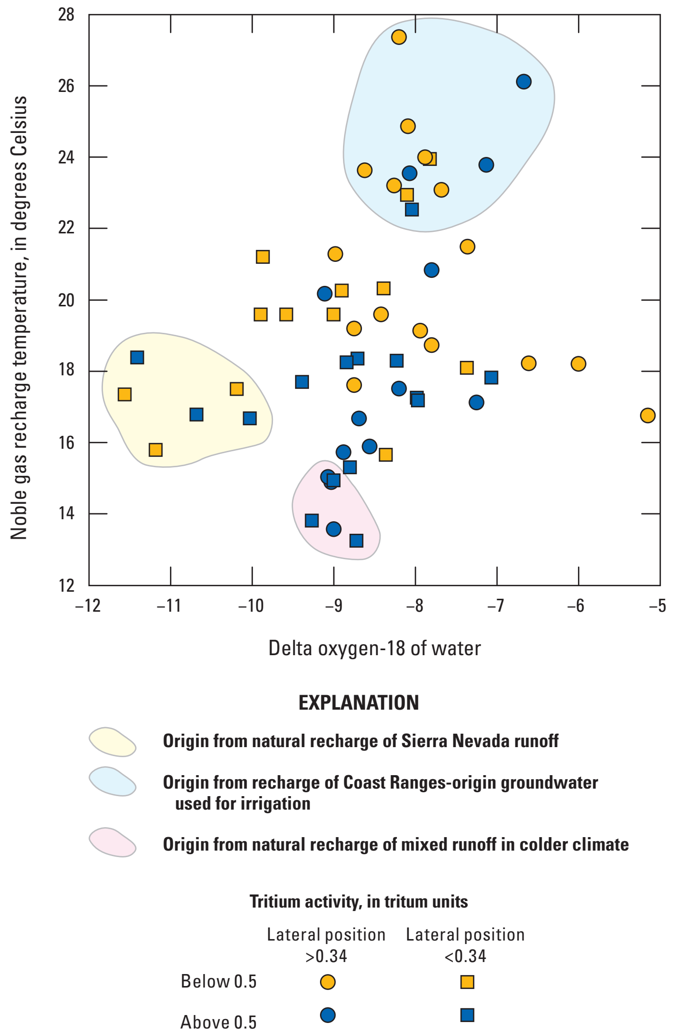


Figure 20. Calculated groundwater-recharge temperatures, oxygen stable isotopic composition of water, and tritium activity in groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Groundwater has been extensively used for irrigation in the WSJV, both before and after imported surface water started being used for irrigation in the 1960s. Groundwater composed of recharge from irrigation with pumped groundwater would have isotopic characteristics consistent with Coast Ranges runoff; relatively warm recharge temperatures; and either modern or premodern tritium activities, depending on the age of the groundwater pumped for irrigation. The 12 samples that had recharge temperatures greater than 22 degrees Celsius (°C) and $\delta^{18}O$ values greater than –9.0 per mil (fig. 20), therefore, likely were groundwater composed of recharge from irrigation with pumped groundwater. Of these 12 samples, 8 were from the northern part of the Delta–Mendota study area and included wells screened above (DM-07, -U-03, -U-13, and -U-16) and below (DM-06, -08, -21, and -U-14) the Corcoran Clay (figs. 6, 10). These results confirm the conclusion of Dubrovsky and others (1991) that tritiated water below the Corcoran Clay in this area of the WSJV study unit indicated that the Corcoran Clay was no longer an intact confining unit because of perforation by well bores and that the tritiated water below the clay was recharged by water applied to the surface as irrigation, not natural recharge.

Among the subset of samples that were oxic, suboxic, or nitrate-reducing, nitrate concentrations positively correlated with recharge temperature (Spearman's rho = +0.56, $n = 33$, $p < 0.001$), which is consistent with leaching of agricultural nitrogen from soils by irrigation-water recharge. Despite the evidence for use in agricultural irrigation, the groundwater samples with elevated recharge temperatures and nitrate concentrations did not show evidence of evaporative concentration based on the water's stable-isotope ratios (fig. 18), and TDS was not correlated with recharge temperature. Evaporation of surface water or shallow groundwater concentrates solutes in the water and can be identified by systematic change in δ^2H and $\delta^{18}O$ to produce a shallower slope than the Global Meteoric Water Line (GMWL). Fujii and Swain (1995) and Deverel and Fujii (1988) found extensive areas of the southern San Joaquin Valley where groundwater within 6 m of land surface that showed evidence of evaporation, both based on the shallow slopes of the relation between δ^2H and $\delta^{18}O$ and on TDS concentrations up to 100,000 mg/L. Groundwater with TDS concentrations greater than 5,000 mg/L was not sampled in the WSJV study unit or in the datasets of Davis and Coplen (1989) and Dubrovsky and others (1991), all of which sampled relatively deep wells primarily used for drinking-water supply or for irrigation.

Davis and Coplen (1989) identified a compositional type of groundwater generally found below the Corcoran Clay that had lower TDS concentrations than groundwater above it and that had $\delta^{18}O$ values of approximately –9 per mil. They inferred that this groundwater represented recharge during the early and mid-Pleistocene epoch from floodwaters that mixed Sierra Nevada and Coast Range runoff. In the WSJV study unit, seven samples had $\delta^{18}O$ values around –9 per mil and recharge temperatures of less than 16 °C (fig. 20). All seven had tritium activities less than 0.10 TU and carbon-14 activities of 1 to 6 pmC, corresponding to uncorrected carbon-14 ages of 23,000 to 37,000 years before present (note that corrected carbon-14 ages would likely be several thousand years younger). Based on these estimated late-Pleistocene epoch ages, the groundwater could represent recharge during or prior to the Last Glacial Maximum in the Sierra Nevada (about 19,000 years before present; Rood and others, 2011).

The TDS concentrations in these six samples generally were greater than TDS concentrations in groundwater derived solely from Sierra Nevada sources (fig. 19). Five of the samples were from wells near the southern end of the Delta–Mendota study area (DM-01, -15, -19, -U-07, and -U-10; fig. 5). This group included wells screened above and below the Corcoran Clay (figs. 6, 10). The other two samples were from wells at the southern tip of the Westside study area (WS-U-01 and -U-02), which were both screened above the Corcoran Clay (fig. 10).

The TDS concentrations in the WSJV study-unit samples for which isotopic characteristics were consistent with recharge from Coast Range runoff ranged from less than 400 mg/L to greater than 2,000 mg/L (fig. 18). A large part of this range can be attributed to differences in geology among the Coast Range watersheds that are the sources of the runoff. Davis (1961) mapped the outcrop geology of 31 drainage basins along the eastern slope of the Coast Ranges, expressing drainage-basin geology as the percentage of the area occupied by 5 geologic units: Franciscan Complex, ultramafic intrusive rocks, Cretaceous marine sedimentary rocks, Tertiary marine sedimentary rocks, and Tertiary and Quaternary non-marine sediments. The WSJV study unit wells were in or directly downslope from 16 of these drainage basins (appendix table 1–3). Samples from wells in drainage basins composed of more than 50-percent Franciscan Complex and ultramafic intrusive rocks had significantly lower TDS concentrations than samples from wells in drainage basins dominated by Cretaceous and Tertiary marine sedimentary rocks (fig. 19). The Franciscan Complex in the Coast Ranges adjacent to the WSJV study unit is dominated by arkosic sandstone, with lesser amounts of mafic volcanic rocks, radiolarian cherts, and thin shale layers (Davis, 1961). The Franciscan Complex and serpentinized, ultramafic intrusive rocks have relatively low solubility and, therefore, yield runoff having relatively low TDS concentrations. The Cretaceous and Tertiary marine sedimentary rocks of the Coast Range adjacent to the WSJV study unit contain thick sequences of organic-rich, siliceous shales of the Moreno (upper Cretaceous to Paleocene age), Kreyenhagen (Eocene to Oligocene age), and Monterey (Miocene age) Formations (fig. 3; Anderson and Pack, 1915; Davis, 1961; Presser and others, 1990). These rocks are more soluble and yield runoff with high TDS concentrations (Davis, 1961; Presser and others, 1990).

Not all groundwater associated with the Franciscan Complex had relatively low TDS concentrations, however. The sample collected from grid-well DM-17 at the site of a hot spring that is associated with hydrothermal alteration and faulting in the Franciscan Complex (Anderson and Pack, 1915; Presser and others, 1990) had a TDS concentration of 2,200 mg/L and a water temperature of 43 °C. The stable-isotope composition of the groundwater from well DM-17 also indicated hydrothermal activity. Water-rock interaction at elevated temperatures generally results in a systematic increase in $\delta^{18}O$ of the water with little change in the $\delta^{2}H$, because rocks contain abundant oxygen and relatively little hydrogen. On a plot of stable isotope composition, the sample from DM-17 is displaced to the right of the rest of the samples that lie along a local trend parallel to the GMWL (fig. 18).

Major-ion composition was closely related to the TDS concentration and to source of the groundwater. Groundwater with isotopic characteristics consistent with Sierra Nevada runoff or groundwater from Coast Ranges watersheds dominated by Franciscan Complex rocks generally had anion compositions with greater proportions of bicarbonate than groundwater from other sources (fig. 21). The greater proportion of bicarbonate in the anion composition, coupled with the generally lower TDS concentrations, reflected the absence of relatively soluble, sulfate-rich and chloride-rich rocks in the Sierra Nevada and in the Franciscan Complex areas of the Coast Ranges. Among groundwater samples in which the isotopic composition indicated origin from Sierra Nevada runoff, tritium activities less than 0.50 TU generally were associated with cation compositions that had greater proportions of sodium than those with tritium activities greater than 0.5 TU (Wilcoxon test, $n = 10$, $p = 0.028$; fig. 20). This is consistent with an exchange of calcium for sodium after long contact with clays in aquifer sediments (for example, Stumm and Morgan, 1996; Appelo and Postma, 2005). Groundwater samples consistent with origin from runoff from Coast Ranges watersheds dominated geologically by the Franciscan Complex mostly had modern tritium activities and had cation compositions with relatively low proportions of sodium.

Groundwater samples from Coast Ranges watersheds dominated by Cretaceous and Tertiary marine sedimentary rocks generally had anion compositions dominated by sulfate or sulfate plus chloride (fig. 21). The greater proportion of sulfate and chloride in the anion composition, coupled with the generally higher TDS concentrations, reflects the relatively soluble sulfate-rich and chloride-rich rocks in the Cretaceous and Tertiary marine sedimentary rocks. Groundwater samples from Coast Ranges watersheds dominated by Cretaceous and Tertiary marine sedimentary rocks had a wide range of cation compositions, which is consistent with having modern and premodern groundwater sources and with the diverse geology of the watersheds. Groundwater samples representing recharge from an earlier, colder climatic period (fig. 20) had cation compositions dominated by sodium, low ^{14}C (less than 6 pmC), and low tritium (less than 0.10 TU) activities that indicated long periods for cation exchange with clays in the aquifer sediments.

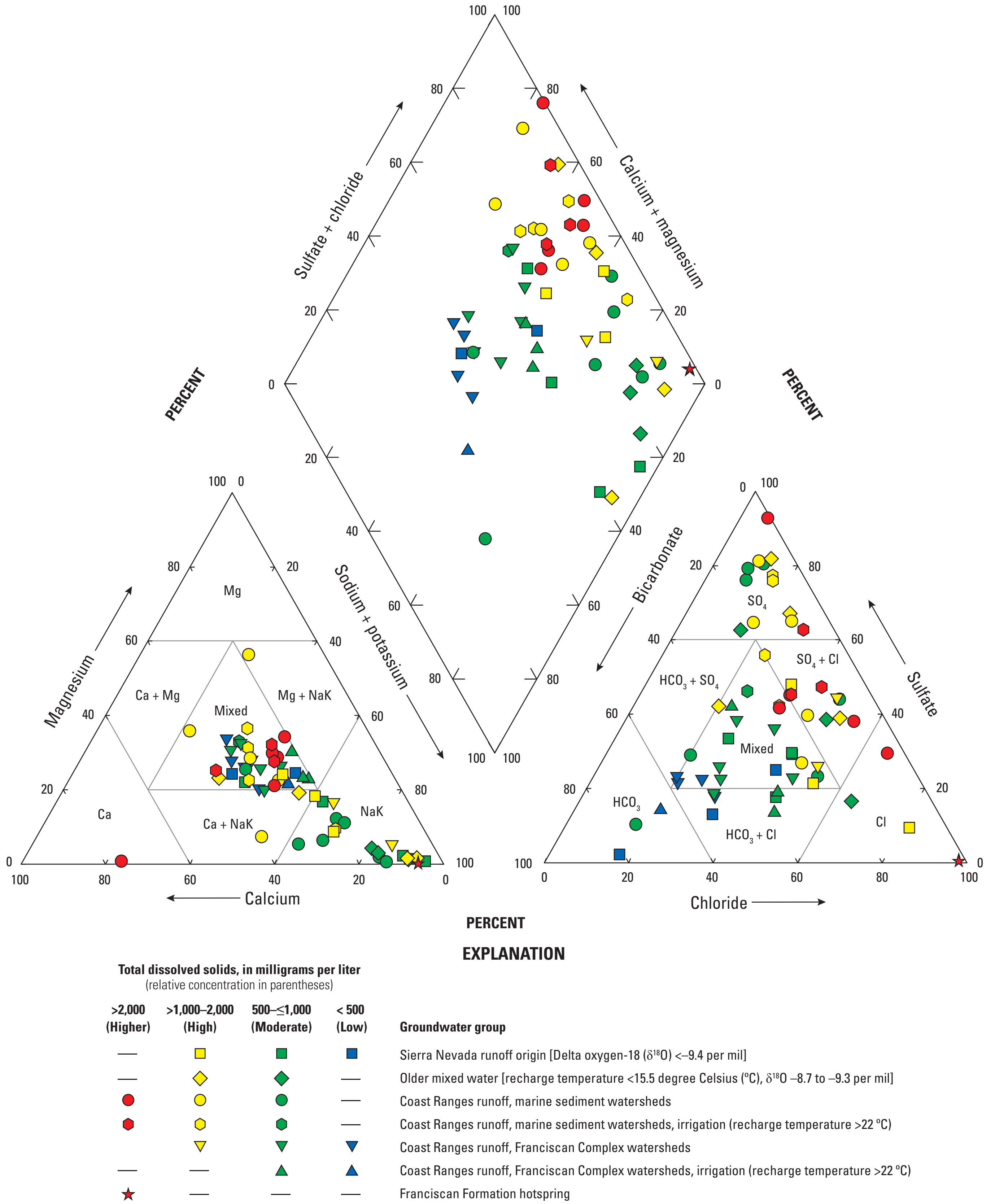
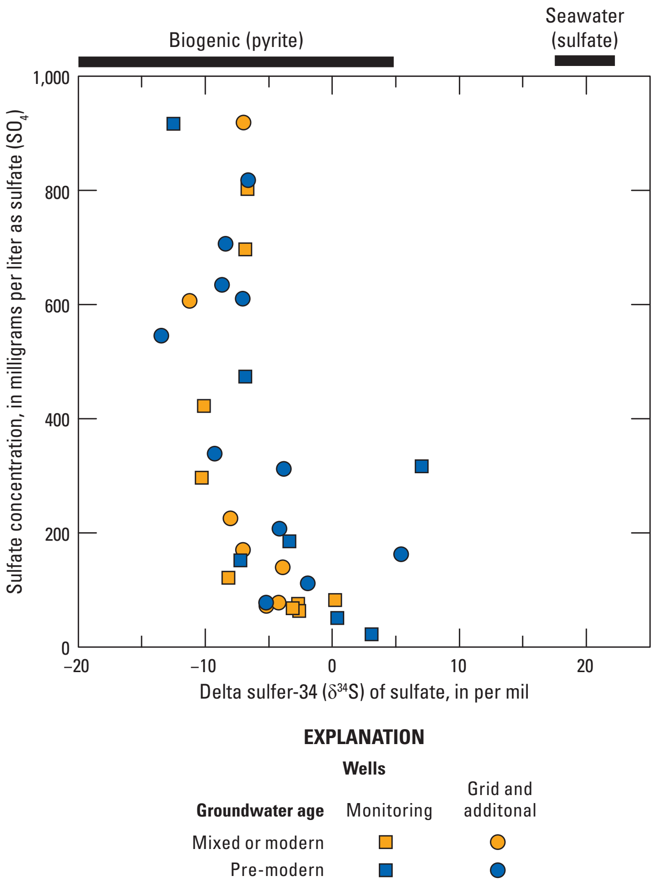


Figure 21. Piper diagram and total dissolved solids concentrations for groundwater samples from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Geological data indicated sulfate in the WSJV study-unit groundwater originated from the oxidation of pyrite in marine shales, primarily the Tertiary marine sedimentary rocks (Davis, 1961; Presser and others, 1990). The late Cretaceous through Miocene stratigraphic section includes organic-rich, pyrite-bearing, siliceous marine shales (Moreno, Kreyenhagen, and Monterey Formations) that are exposed on the eastern slope of the Coast Ranges (formations not distinguished in fig. 3; Anderson and Pack, 1915; Davis, 1961; Presser and others, 1990). These units are the source rocks for petroleum deposits in the San Joaquin Valley, Southern Coast Ranges, and Los Angeles Basins (Peters and others, 2007). Subaerial exposure of the shales results in oxidation of the pyrite to sulfate. In the arid environment of the WSJV study unit, the sulfate re-precipitates in the soils and sediments as a panoply of calcium, magnesium, and sodium sulfate minerals (Presser and others, 1990). These sulfate salts are then dissolved by the intermittent precipitation and streamflow and enter groundwater recharge.

The sulfur-isotope composition of the sulfate supported the conclusion that sulfate in the groundwater water came from dissolution of sulfate salts derived from pyrite oxidation, rather than from dissolution of primary marine sulfate deposits. The sulfate-isotope composition of seawater has ranged between +17 and +22 per mil during the Cenozoic era (Paytan and others, 1998), and there is only a small positive isotopic fractionation during precipitation of sulfate minerals from seawater sulfate (Krouse and Mayer, 2000). The δ^{34}S compositions of sulfate in WSJV samples ranged from –15 to +9 per mil—all values outside the range expected from primary sulfate minerals in marine sediments (fig. 22). Microbial reduction of sulfate to sulfide proceeds with a large negative sulfur-isotope fractionation, resulting in pyrite with δ^{34}S that can be 15 to 40 per mil more negative than the δ^{34}S of the initial dissolved sulfate (Clark and Fritz, 1997; Krouse and Mayer, 2000). Oxidation of pyrite to sulfate proceeds with little to no fractionation. The samples with the highest sulfate concentrations (and TDS concentrations) had δ^{34}S between –15 and –5 per mil (fig. 22), indicative of oxidation of biogenic pyrite as the origin of the sulfate.

Large amounts of gypsum have been applied as a soil amendment to reclaim sodic soils in the WSJV study unit (Natural Resources Conservation Service, 2006). The western San Joaquin Valley and the adjacent Coast Ranges have gypsum deposits that are a source of gypsum used as soil amendments in the San Joaquin Valley (California Division of Mines, 1956; Holloway Gypsum, 2016). These gypsum deposits are in shallow sediments and soils and were formed by evaporative concentration of shallow groundwater or water in the margins of periodic lakes (Hess and Steiger, 1910; California Division of Mines, 1956). Isotopic data were not available for San Joaquin Valley gypsum deposits, but given the mechanism of formation, it is likely that gypsum from these deposits would have δ^{34}S values similar to those of sulfate in the groundwater; thus, although the δ^{34}S data indicated that the source of the sulfate was dissolution of sulfate salts derived from oxidation of biogenic pyrite, the isotopic data would not be able to distinguish between dissolution of sulfate salts naturally present in the aquifer materials and sulfate salts mined from the local aquifer materials and applied as soil amendments.



Ranges in δ^{34}S in environments from Clark and Fritz (1997); Paytan and others (1998); Krouse and Mayer (2000); Coplen and others (2002).

Figure 22. Sulfur isotope ratio of dissolved sulfate and sulfate concentrations for groundwater samples from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

The cation composition of the WSJV study-unit groundwater samples indicated that gypsum applied as soil amendments was not the primary source of sulfate, however. If gypsum applied as soil amendments were a dominant source of sulfate, then the groundwater samples identified as recharge of groundwater pumped for irrigation would have major-ion compositions dominated by calcium sulfate. Groundwater samples for which recharge temperatures were greater than 22 °C did not have systematically different major-ion compositions or TDS concentrations from those of other groundwater samples (fig. 21). Except in areas where the sulfate salts have been re-deposited as gypsum deposits, the sulfate salts in western San Joaquin Valley soils and sediments are dominated by sodium and magnesium sulfate minerals (Presser and others, 1990).

Manganese and Iron

Natural sources of manganese and iron to groundwater include weathering and dissolution of minerals in soils, sediments, and rocks. Manganese and iron oxyhydroxide minerals commonly coat mineral and sediment grains. In addition, iron-bearing silicate, sulfide, or oxide minerals are present in most rocks and sediments, and manganese commonly substitutes for iron in silicate and oxide minerals. In the range of geochemical conditions generally found in groundwater environments, manganese and iron can be either reduced or oxidized—that is, manganese(II) or (VI) and iron(II) or (III), respectively. The solubilities of manganese and iron are strongly dependent on oxidation-reduction conditions: the more reduced species are much more soluble (Hem, 1985).

Manganese was found at high RCs in 44 percent of the groundwater resources used for public drinking water in the WSJV study unit and at moderate RCs in 8.3 percent; iron was found at high RCs in 14 percent of the groundwater resources used for public drinking water and at moderate RCs in 4.4 percent (table 8). High RCs of manganese and iron were present in both study areas (figs. 16*A*, 17*D*, *E*; appendix tables 2–1*A*, *B*), and the concentrations in samples from the two study areas were not significantly different (table 10*A*).

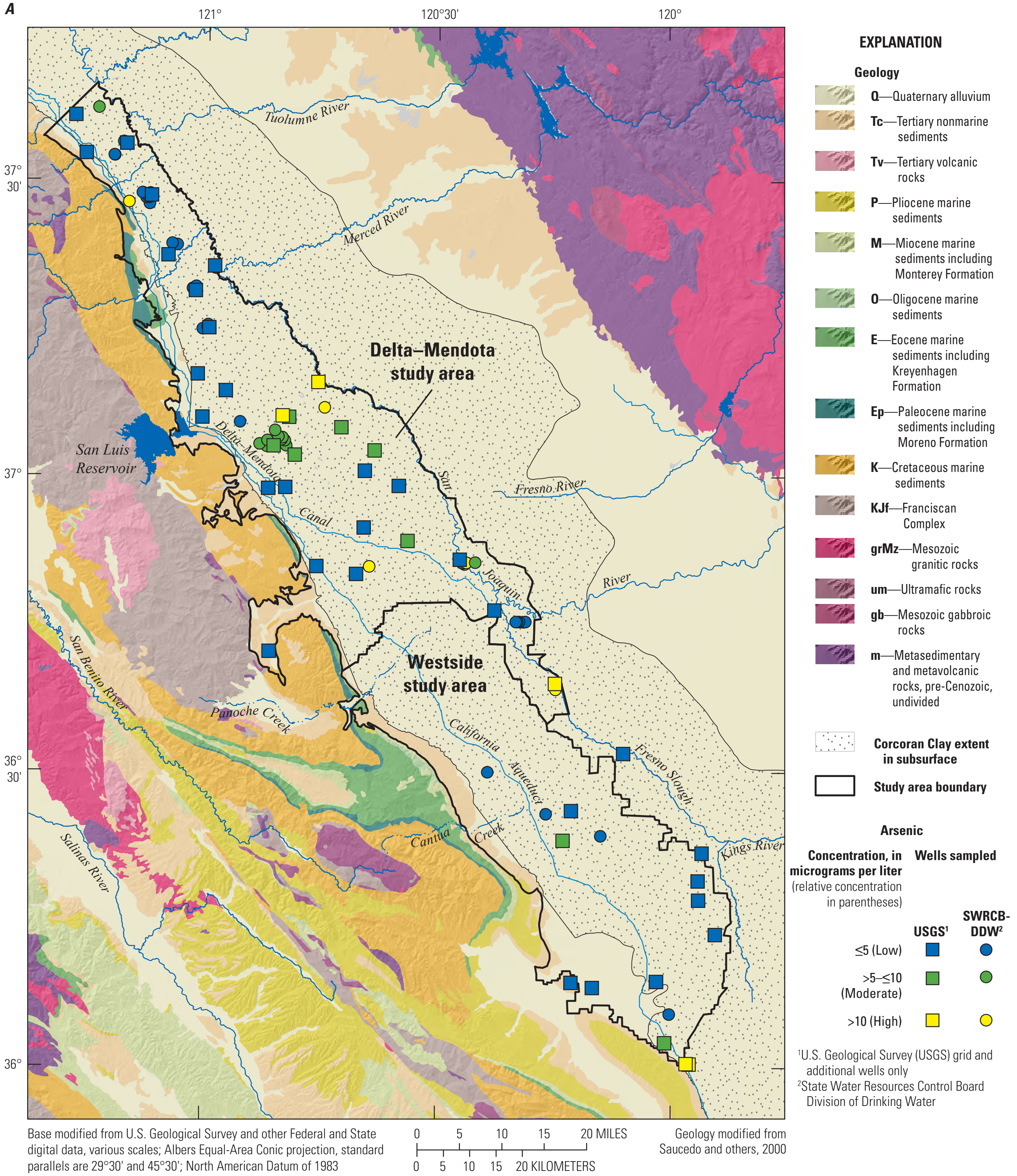
The most important explanatory factor for manganese and iron was aquifer lithology. Most of the wells with manganese-reducing or manganese- and iron-reducing conditions were screened in Sierra Nevada sands (compare figs. 10 and 12; table 10*A*), reflecting the more reduced Sierra Nevada sands compared to the Coast Range alluvium (Belitz and Heimes, 1990; Dubrovsky and others, 1991). Because the Sierra Nevada sands are above and below the Corcoran Clay (fig. 4), manganese and iron were not correlated with depth or groundwater age (tables 10*A*, *B*), contrary to observations in other GAMA Priority Basin Project San Joaquin Valley study units (Landon and others, 2010; Burton and others, 2012; Shelton and others, 2013). Manganese and iron concentrations showed negative correlations with nitrate, chromium(VI), selenium, and perchlorate (table 11)—constituents associated with oxic conditions. Manganese showed positive correlation with arsenic and molybdenum, but iron did not (table 11). This difference is discussed in the sections on arsenic and molybdenum.

Groundwater resources used for public drinking water supply in the WSJV study unit were among the more reduced of groundwater resources used for public drinking water supply statewide. The Delta–Mendota and Westside study areas were in approximately the 90th percentile of study areas for proportion of the groundwater resources that have high RCs of manganese (fig. 16*A*).

Trace Elements

The trace-elements constituent class includes a variety of metallic and non-metallic constituents that typically are present in groundwater at concentrations less than 1 mg/L (Hem, 1985). Trace elements that had health-based benchmarks, as a class, were at high RCs in 52 percent of the groundwater resources used for public drinking water and at moderate RCs in 27 percent (table 9*A*).

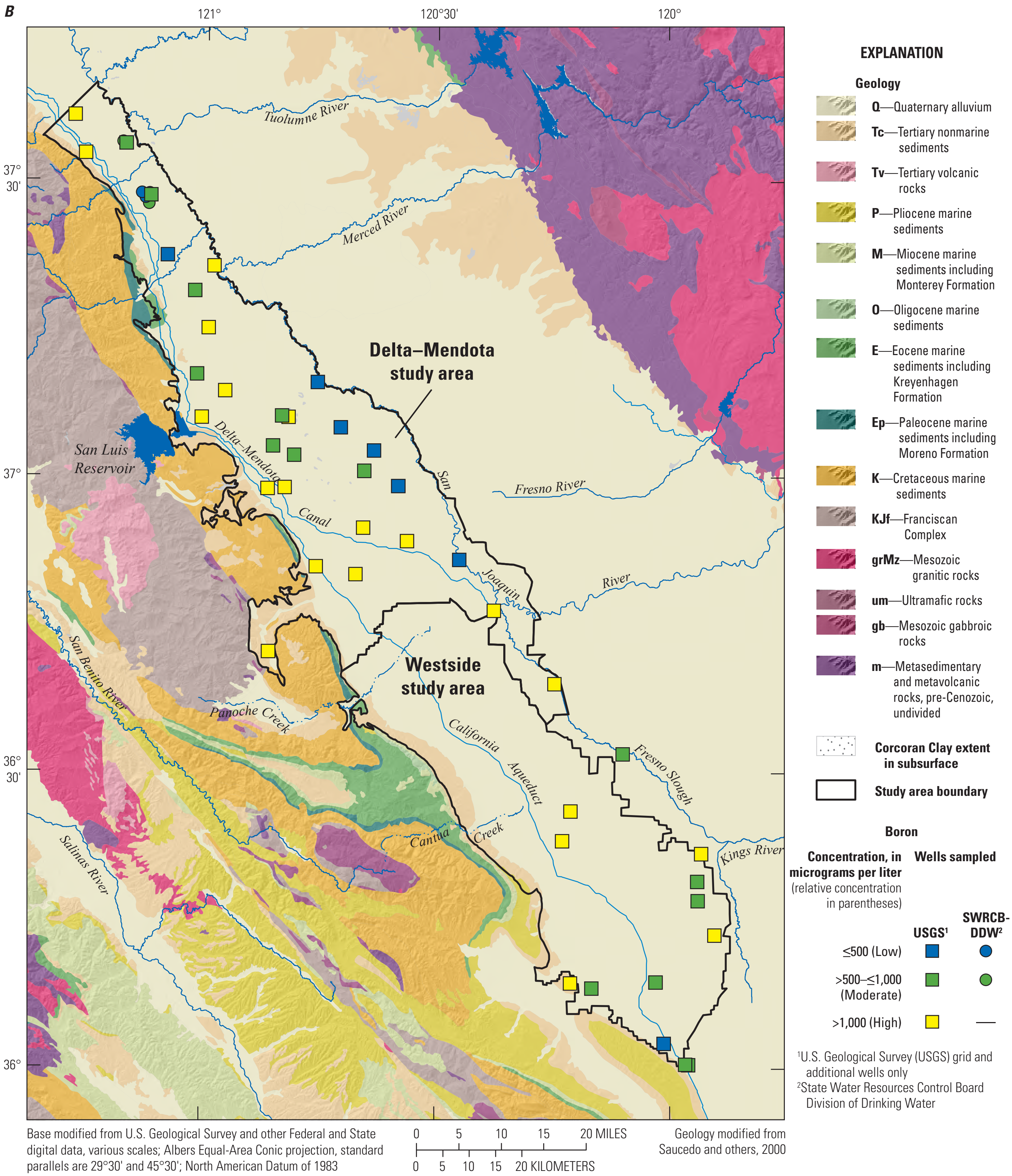
Boron was present at high RCs in 51 percent of the groundwater resources used for public drinking water, and arsenic, chromium(VI), molybdenum, selenium, and strontium each were present at high RCs in between 2.6 percent and 10.1 percent (table 8). Arsenic, boron, chromium(VI), molybdenum, selenium, and strontium all were present at high RCs in the Delta–Mendota study area, whereas only arsenic and boron were present at high RCs in the Westside study area (figs. 15*A*, 23*A*–*G*). Three other trace elements (aluminum, chromium, and vanadium) were present only at moderate RCs (table 8).



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

Geology modified from Saucedo and others, 2000

Figure 23. Relative concentrations of selected constituents in groundwater from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project and from public-supply wells that have data in the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database for samples collected from March 2007 through August 2010: *A*, arsenic; *B*, boron; *C*, measured chromium(VI); *D*, estimated chromium(VI); *E*, molybdenum; *F*, selenium; and *G*, strontium.



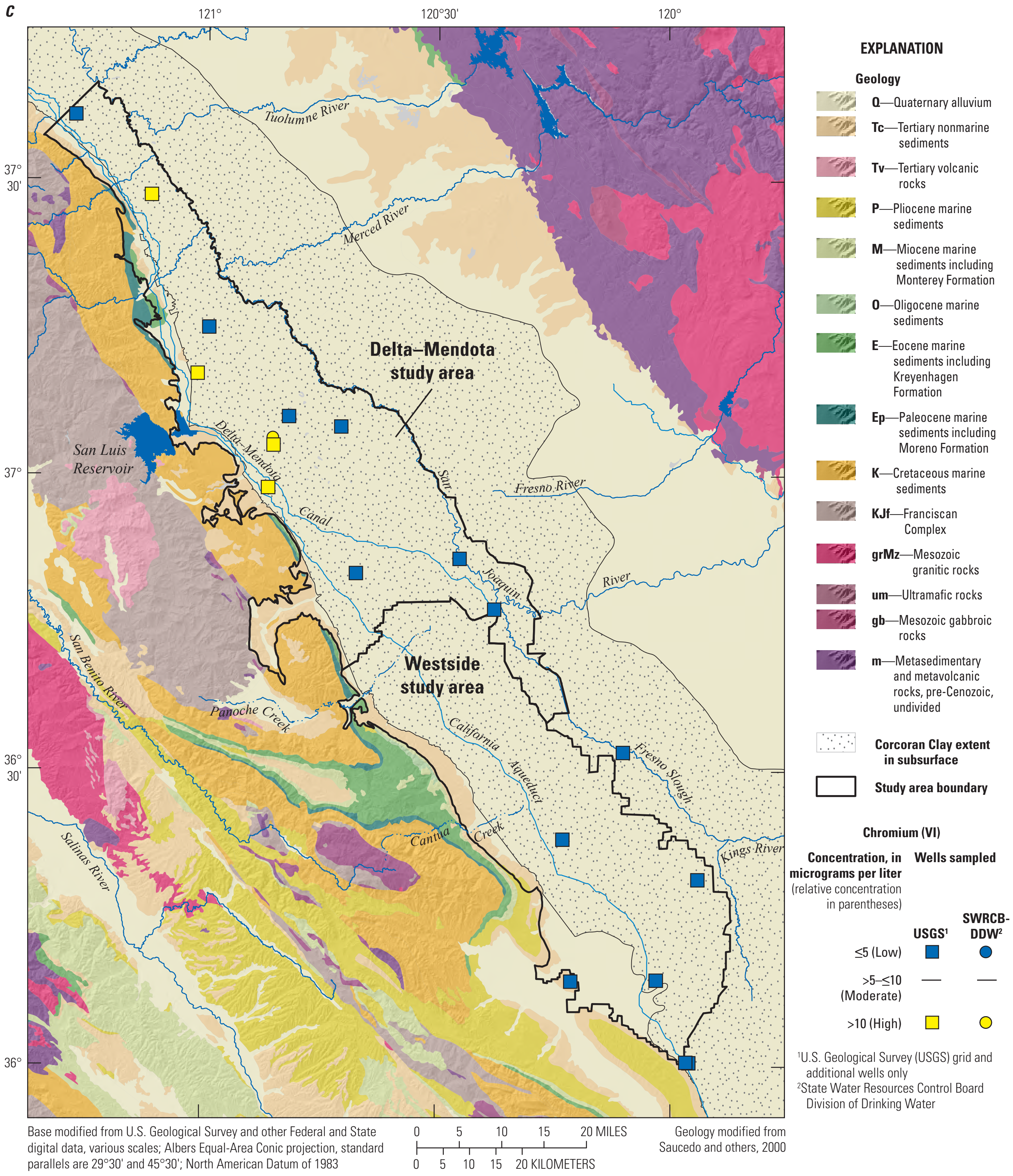
[1]U.S. Geological Survey (USGS) grid and additional wells only

[2]State Water Resources Control Board Division of Drinking Water

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

Geology modified from Saucedo and others, 2000

Figure 23. —Continued



¹U.S. Geological Survey (USGS) grid and additional wells only
²State Water Resources Control Board Division of Drinking Water

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Geology modified from Saucedo and others, 2000

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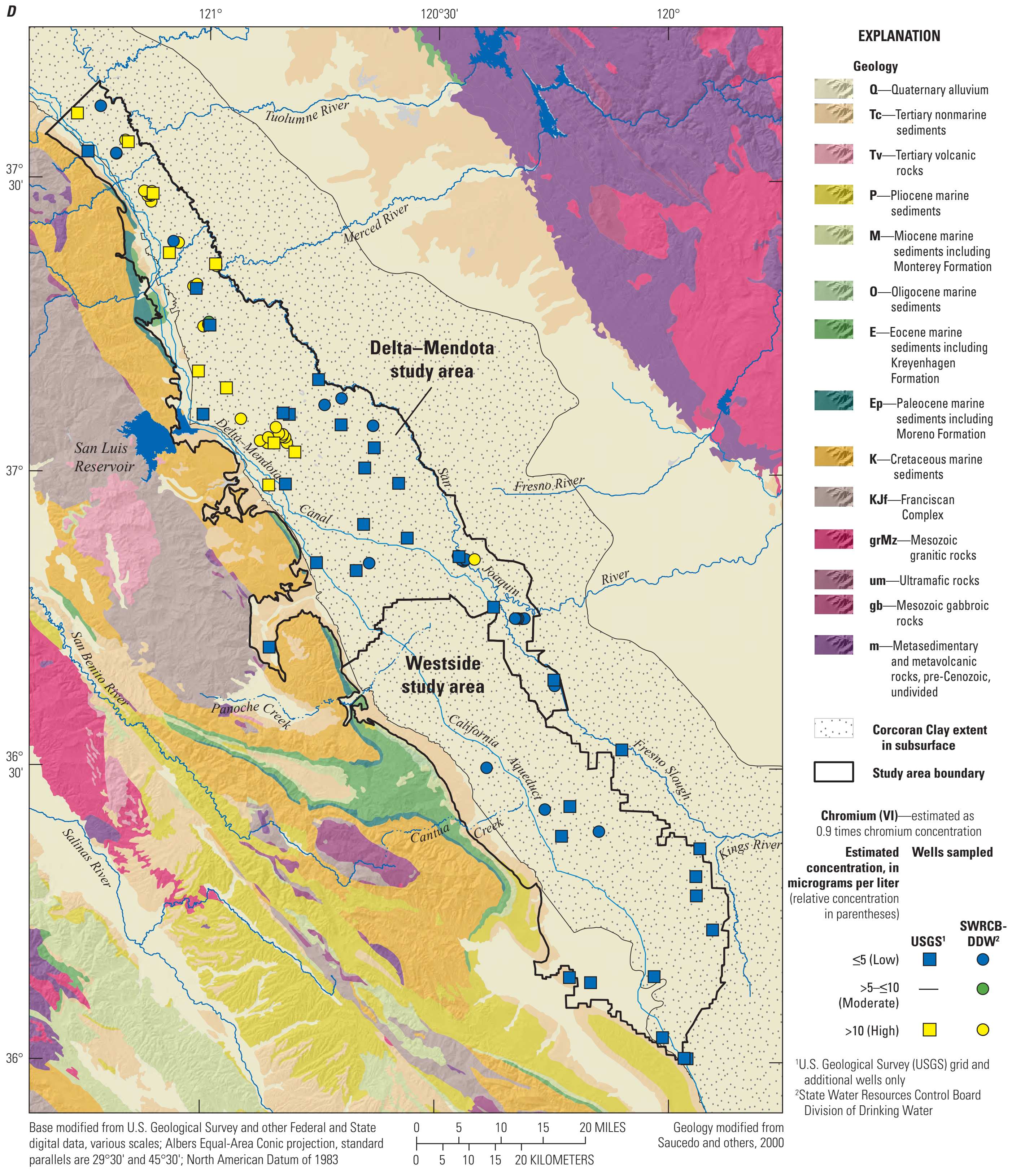

[1]U.S. Geological Survey (USGS) grid and additional wells only

[2]State Water Resources Control Board Division of Drinking Water

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Geology modified from Saucedo and others, 2000

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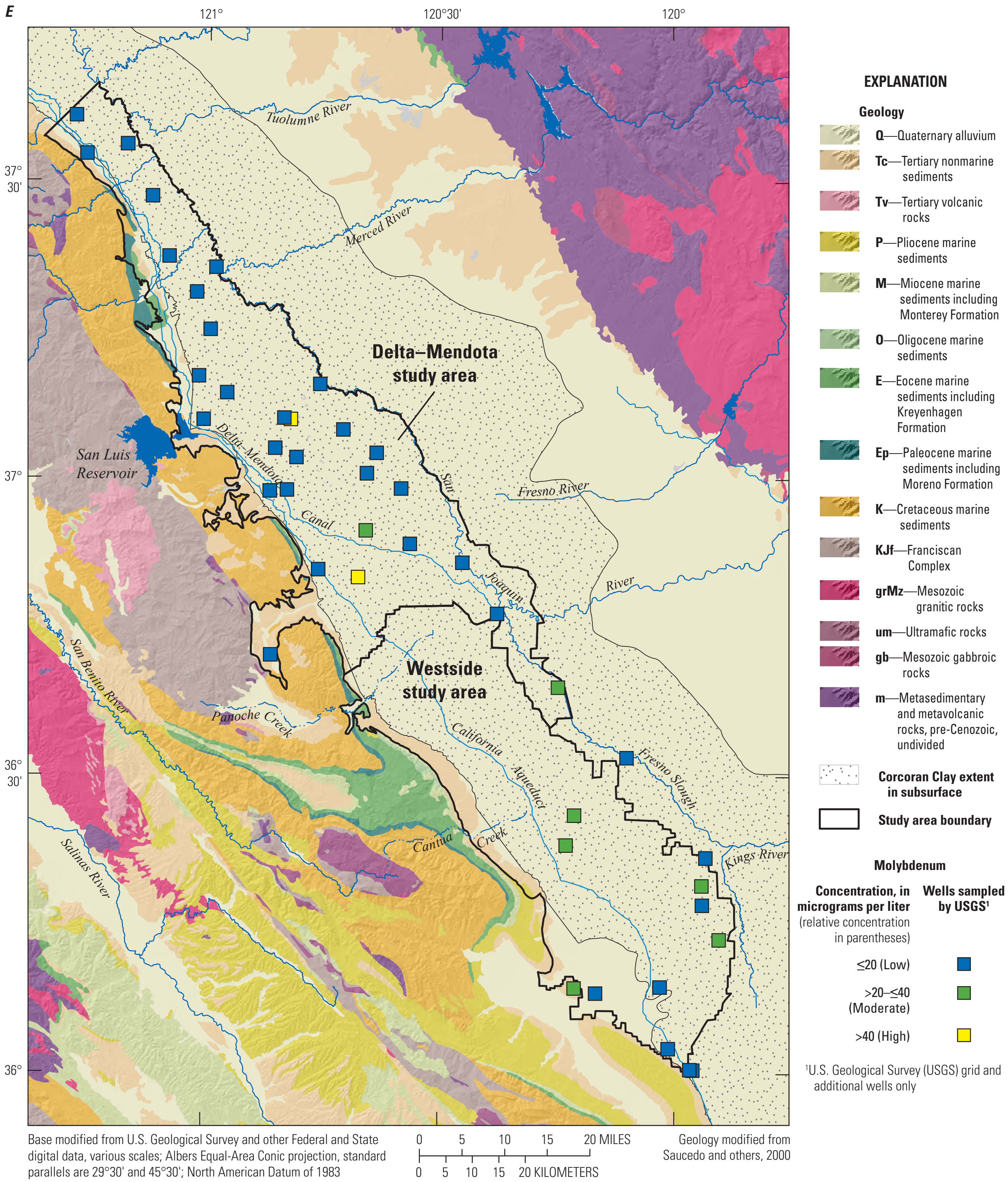

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Figure 23. —Continued

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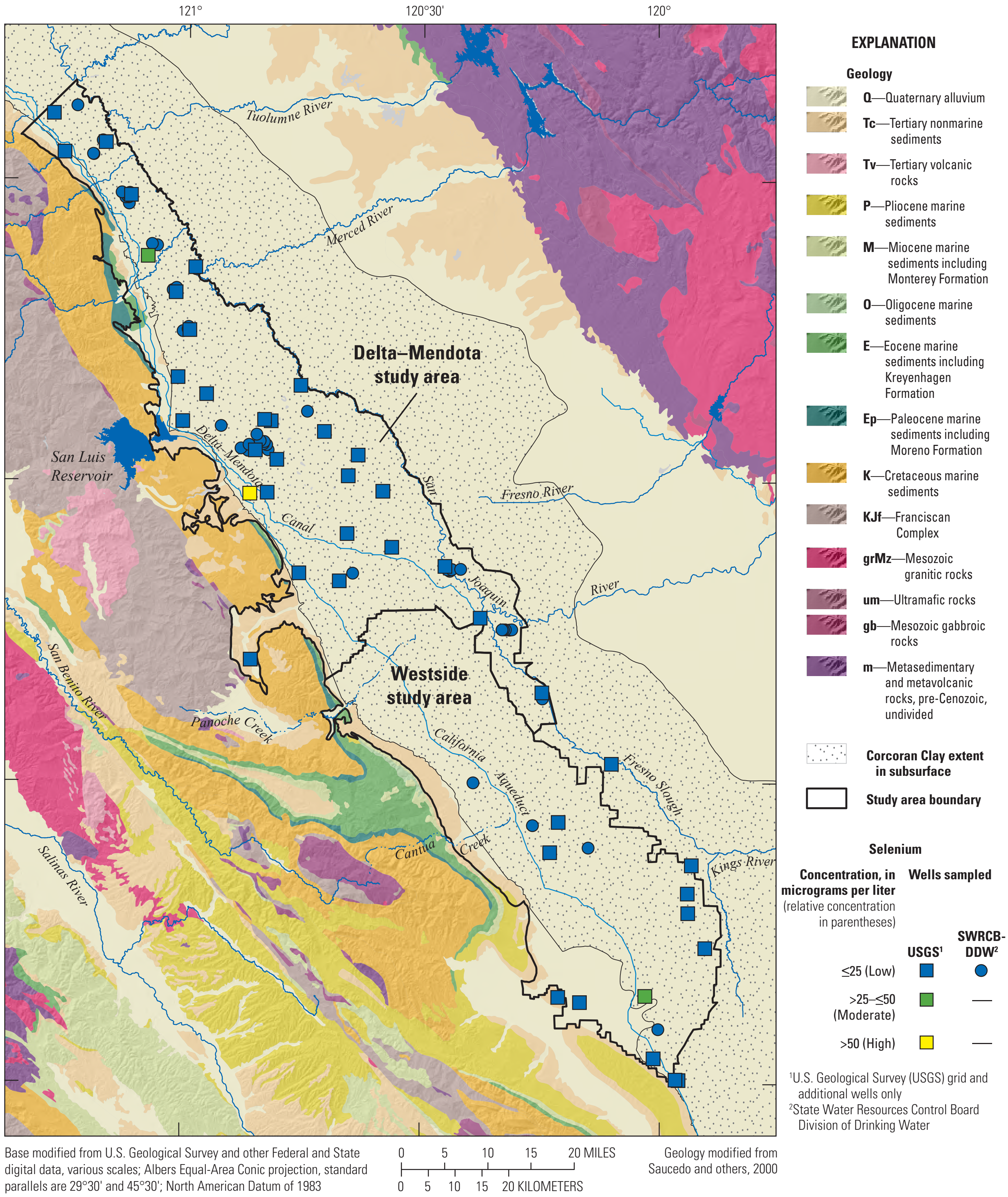

[1]U.S. Geological Survey (USGS) grid and additional wells only

[2]State Water Resources Control Board Division of Drinking Water

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Geology modified from Saucedo and others, 2000

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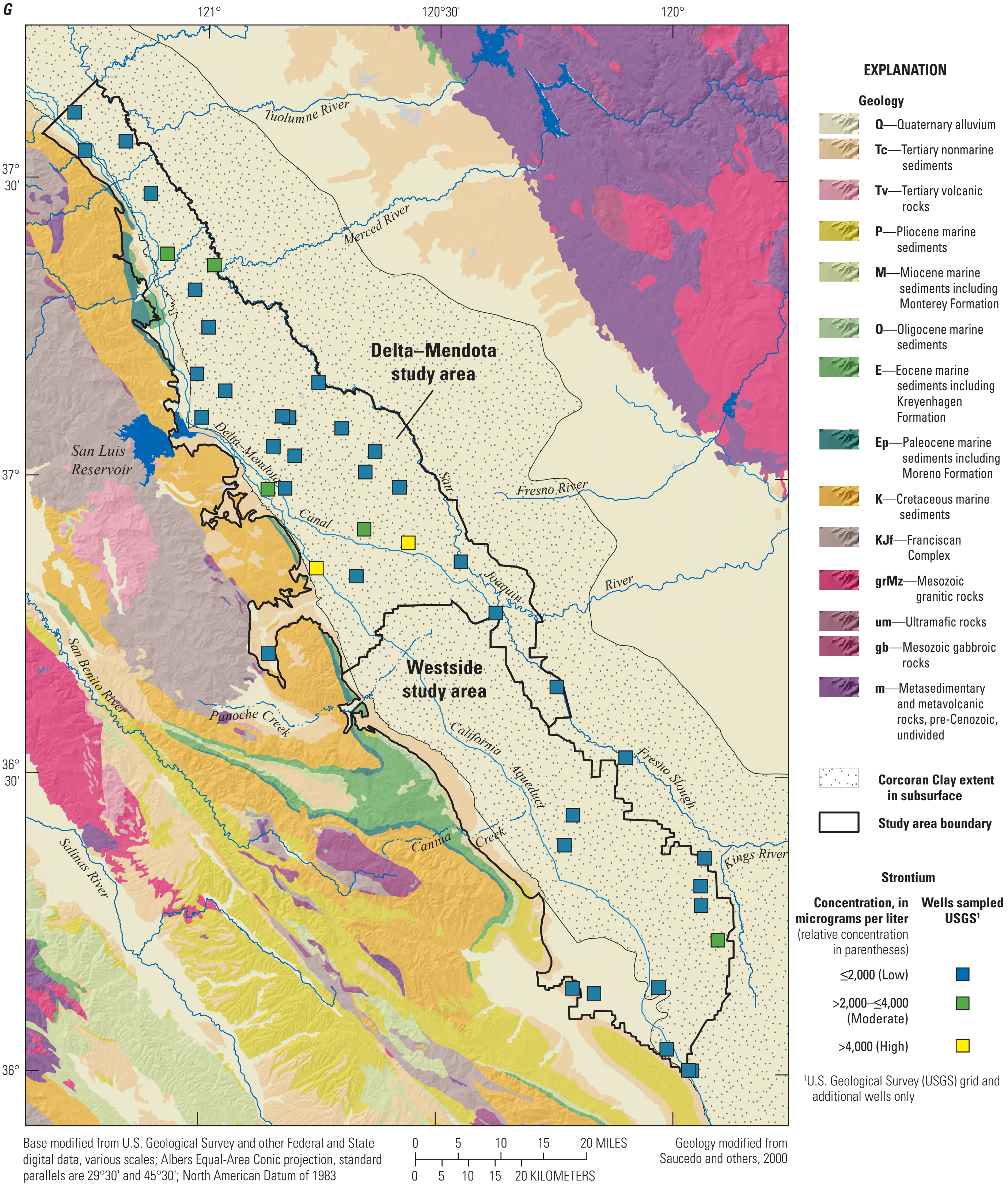

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Geology modified from Saucedo and others, 2000

Figure 23. —Continued

Arsenic

Natural sources of arsenic in groundwater include dissolution of arsenic-bearing minerals, desorption of arsenic from mineral surfaces, and mixing with hydrothermal fluids (Smedley and Kinniburgh, 2002; Welch and Stollenwerk, 2003; Barringer and Reilly, 2013). Pyrite, an iron-sulfide mineral that can contain up to several percent by weight of arsenic, and arsenopyrite (FeAsS) are common accessory minerals in aquifer materials (Welch and others, 2000; Smedley and Kinniburgh, 2002). Anthropogenic sources of arsenic can include atmospheric deposition from coal combustion, base-metal smelting and application of arsenical pesticides and wood preservatives (Welch and Stollenwerk, 2003). In addition, mining for copper, gold, and other metals can increase the rate of dissolution of arsenic-bearing minerals present in the rocks (Smedley and Kinniburgh, 2002). The New Idria Mercury Mining District is in the Coast Ranges next to the WSJV study unit (fig. 3); however, drainage from the mine has relatively low arsenic concentrations (4 µg/L; Presser and others, 1990), so mining activity is unlikely to contribute to high arsenic concentrations in groundwater in the WSJV study unit. Arsenical pesticides, such as cacodylic acid and MSMA, were used extensively as defoliants on cotton in the WSJV study unit, although usage has declined as the acreage devoted to cotton has decreased in recent years (California Department of Pesticide Regulation, 2013).

The EPA MCL for arsenic was decreased from 50 to 10 micrograms per liter (µg/L) in 2002. Chronic exposure to arsenic concentrations between 10 and 50 µg/L in drinking water has been linked to increased cancer risk and to non-cancerous effects, including skin damage and circulatory problems (National Research Council, 2001; U.S. Environmental Protection Agency, 2001). An estimated 8 percent of groundwater resources used for drinking water in the United States have high RCs of arsenic (greater than 10 µg/L; Focazio and others, 2000; Welch and others, 2000; Ayotte and others, 2011), and high concentrations of arsenic in groundwater used for drinking water are a worldwide concern (Smedley and Kinniburgh, 2002; Welch and others, 2006).

Arsenic was present at high RCs in 10.1 percent of the groundwater resources used for public drinking water in the WSJV study unit and at moderate RCs in 16.3 percent (table 8). High and moderate RCs of arsenic were present in both study areas (appendix tables 2–1*A*, *B*; figs. 15*B*, 23*A*), and the median concentrations of arsenic in the two study areas were not significantly different (table 10*A*). The percentage of the groundwater resources that had high RCs of arsenic in the Westside study area (6.3 percent) was approximately the median percentage among 82 study areas statewide, and the percentage in the Delta–Mendota study area (11.8 percent) was greater, but within the inter-quartile range of the median (fig. 16*B*).

Previous investigations of arsenic in the San Joaquin Valley (Belitz and others, 2003; Welch and others, 2006; Izbicki and others, 2008) and literature reviews (Smedley and Kinniburgh, 2002; Welch and Stollenwerk, 2003; Barringer and Reilly, 2013) have indicated two primary mechanisms for elevated arsenic concentrations in groundwater. The first is the release of arsenic from reductive dissolution of iron or manganese oxyhydroxides under iron- or manganese-reducing conditions. The second is desorption of arsenic from aquifer sediments under oxic, high-pH conditions.

In the WSJV study unit, arsenic concentrations were positively correlated with manganese concentrations (table 11), negatively correlated with DO (table 10*B*) and arsenic(V)/arsenic(III) ratio (fig. 24; Spearman's rho = –0.46, $n = 37$, $p = 0.004$), and showed no significant correlation with pH (table 10*B*). These relations are consistent with reductive dissolution being the primary mechanism for elevated arsenic concentrations. All samples with manganese-reducing or manganese- and iron-reducing conditions and arsenic concentrations greater than 2 µg/L had arsenic(V)/arsenic(III) ratios less than 1 (fig. 24), consistent with increased solubility of the reduced form of arsenic, arsenic(III), during reductive dissolution of manganese and iron oxyhydroxide minerals. Manganese-reducing and manganese- and iron-reducing conditions were more common in samples from wells screened in Sierra Nevada sands (14 of 15 wells) than in samples from wells screened in Coast Ranges alluvium (4 of 26 wells) (figs. 10, 12; contingency table test, $p < 0.001$), and accordingly, most of the samples with manganese-reducing or manganese- and iron-reducing conditions and high or moderate RCs of arsenic were from wells screened in Sierra Nevada sands. However, of the 19 USGS grid and additional wells with manganese-reducing or manganese- and iron-reducing conditions, only 8 (42 percent) had high or moderate RCs of arsenic, indicating that although manganese-reducing and manganese- and iron-reducing conditions favor elevated arsenic concentrations in groundwater, they are not sufficient to cause high or moderate RCs of arsenic in all such samples.

Previous investigation of groundwater quality in mostly domestic wells in a part of the Delta–Mendota study area found that arsenic concentrations were significantly greater in samples from wells in the Sierra Nevada sands than in wells in the Coast Range alluvium, because manganese-reducing and manganese- and iron-reducing conditions were significantly more common in the Sierra Nevada sands and reductive dissolution was the primary mechanism responsible for elevated arsenic concentrations (Dubrovsky and others, 1991). In this study, arsenic concentrations were not significantly related to aquifer lithology (table 10*A*), indicating that other mechanisms also were important causes of arsenic concentrations in groundwater.

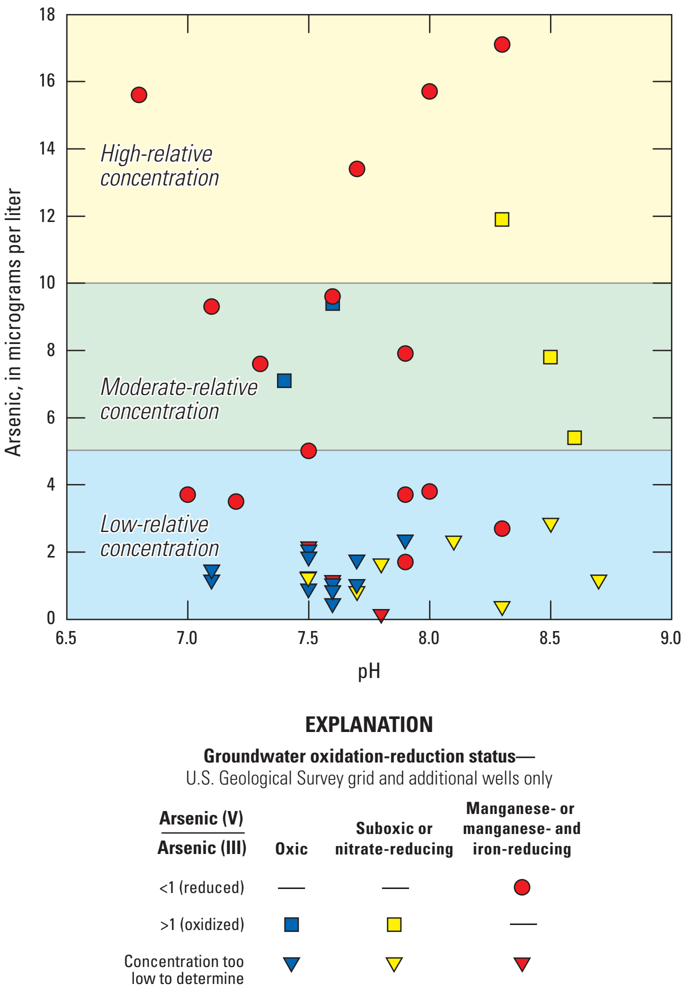


Figure 24. Concentration of arsenic as a function of pH, oxidation-reduction condition, and As(V)/As(III) ratio for samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Relations between arsenic concentrations and explanatory factors for the wells that did not have manganese-reducing conditions suggest that pH-dependent sorption processes (for example, Stollenwerk, 2003) also were important in the WSJV study unit. Arsenic(V)/arsenic(III) ratios were greater than 1 in all samples with nitrate-reducing, suboxic, or oxic redox conditions and high or moderate RCs of arsenic (fig. 24), indicating dominance of the more oxidized arsenate (arsenic(V)) species. Leaching experiments on Western San Joaquin Valley soil samples found that a large component of the total arsenic was phosphate-extractable arsenate, indicating that sorption-desorption reactions of arsenate would be an important factor controlling arsenic concentrations in groundwater (Fujii and Swain, 1995). Among samples with nitrate-reducing, suboxic, or oxic redox conditions, arsenic concentrations were not significantly correlated with pH (Spearman's rho = +0.23, $n = 24$, $p = 0.274$), however nearly all samples with nitrate-reducing, suboxic, or oxic redox conditions had pH values greater than or equal to 7.5 (fig. 24), values that are high enough to promote pH-dependent desorption of arsenate. In addition, arsenate can sorb to oxides, clays, and organic matter (Fujii and Swain, 1995), and the mineral proportions and arsenic concentrations in Western San Joaquin Valley sediments are variable (for example, Tidball and others, 1986); thus, the absence of significant correlation between pH and arsenic in samples in which the dominant arsenic species was arsenate was not surprising.

Arsenic concentrations were not significantly correlated with percentage of agricultural land use (table 10*B*) and were negatively correlated with nitrate concentrations (table 11). These relations suggested that arsenical pesticides were not a significant source of arsenic to groundwater in the depth interval used by public supply wells at present. Contributions of arsenic to individual groundwater samples from arsenical pesticides could not be ruled out (Fujii and Swain, 1995).

Boron

Elevated boron and TDS concentrations in the San Joaquin River led to establishment of total maximum daily loads (TMDL) for TDS and boron in the San Joaquin River watershed, and many of the implementation options rely on control of drainage from agricultural lands in the WSJV study unit (Central Valley Regional Water Quality Control Board, 2004). The comparison benchmark used for boron in this study was the SWRCB-DDW notification level (NL) of 1,000 µg/L. Boron is an essential nutrient for plants, but is toxic to many plants at concentrations above the SWRCB-DDW NL (Grieve and others, 2011). At concentrations greater than the EPA HAL of 6,000 µg/L, boron can adversely affect fetal development (U.S. Environmental Protection Agency, 2008).

Boron was present at high RCs in 51 percent and at moderate RCs in 32 percent of the groundwater resources used for public drinking water (table 8). High and moderate RCs of boron were present in both study areas (appendix tables 2–1*A*, *B*; fig. 23*B*), and the median concentrations of boron in the two study areas were not significantly different (table 10*A*). Only 2.5 percent of the groundwater resources used for public drinking water had boron concentrations greater than the EPA HAL of 6,000 µg/L.

The percentages of groundwater resources in the Delta–Mendota and Westside study areas that had boron concentrations greater than the SWRCB-DDW NL (53.4 and 45.0 percent, respectively; appendix tables 2–1*A*, *B*), and the percentage of the Delta–Mendota study area that had boron concentrations greater than the EPA HAL (3.4 percent) were greater than in nearly all of the other GAMA Priority Basin Project study areas statewide (fig. 16*B*).

Based on the geologic setting of the WSJV study unit, the likely primary natural sources of boron to groundwater are hydrothermal fluids and marine shales. Hydrothermal fluids can contain high concentrations of boron because boron is a volatile element, especially at higher temperatures (Hem, 1985; Leeman and Sisson, 1996). The only sample with boron concentration above the EPA HAL, DM-17, had a water temperature of 43°C and was from the site of a hot spring associated with hydrothermal alteration and faulting in the Franciscan Complex (Anderson and Pack, 1915; Presser and others, 1990). Seawater has a boron concentration of 4,500 µg/L. Compared to other types of marine sediments, organic-rich marine shales are highly enriched in boron because boron is preferentially absorbed onto clays and incorporated into organic matter (for example, Vengosh and Spivack, 2000; Williams and others, 2001). Boron-concentration data were not available for the Cretaceous and Tertiary marine sedimentary rocks of the Coast Range next to the WSJV study unit, but it is likely that the organic-rich siliceous shales of the Moreno, Kreyenhagen, and Monterey Formations contain abundant boron.

Boron concentrations in groundwater were positively correlated with lateral position (table 10*B*), consistent with the primary sources of boron to groundwater being marine shales and hydrothermal fluids from the Coast Ranges. Groundwater from wells along the San Joaquin River in the Delta–Mendota study area had the lowest boron concentrations (fig. 23*B*) and had δ^2H and δ^{18}O values indicative of origin as Sierra Nevada runoff (fig. 18). Boron concentrations in runoff from the Sierra Nevada are generally less than a few hundred µg/L (Westcot and others, 1990). Despite the relation between lateral position and boron concentration, boron concentrations were not significantly correlated with aquifer lithology (table 10*B*), indicating that whether the source of the groundwater is Sierra Nevada water or Coast Ranges water is more important than whether the aquifer lithology is Sierra Nevada sands or Coast Ranges alluvium for controlling boron concentrations in groundwater.

Streams, seeps, and springs issuing from the Coast Ranges next to the WSJV study unit have a wide range of chemical compositions (for example, Davis, 1961; Presser and others, 1990; Westcot and others, 1990), and these compositions are correlated with the geology of the source watershed (Davis, 1961). The TDS concentrations in the streams, seeps, and springs range from less than 100 mg/L to more than 50,000 mg/L, and the higher TDS concentrations are associated with surface water and shallow groundwater affected by evapotranspiration (Davis, 1961; Presser and others, 1990). In surface-water samples with TDS concentrations less than 4,000 mg/L, boron concentrations greater than the EPA HAL were associated with cation compositions dominated by sodium and two different anion compositions: in samples from watersheds dominated by marine sediments, boron concentrations greater than the EPA HAL were associated with anion compositions dominated by sulfate; whereas, in surface water samples from watersheds dominated by Franciscan Complex rocks, boron concentrations greater than the EPA HAL were associated with anion compositions dominated by chloride (fig. 25). This indicates that the source of boron was likely different in the two types of watersheds.

Among surface-water samples with TDS concentrations less than 4,000 mg/L, those from watersheds dominated by Franciscan Complex rocks exhibited a linear relation between TDS and boron concentrations (green field in fig. 26; linear regression, $n = 45$, $r^2 = 0.96$). This relation is consistent with a mixing line between relatively dilute waters with composition similar to DM-U-13 and hydrothermal fluids with composition similar to DM-17 (fig. 26). Hypothetical mixing calculations between DM-17 and DM-U-13 waters indicated that mixtures containing 0–12 percent DM-17 water accounted for the boron and chloride concentrations in the rest of the WSJV study-unit groundwater samples from the watersheds dominated by Franciscan Complex (not shown). The TDS concentrations of the mixed samples were greater than predicted by the mixing calculations, however, largely because the mixed samples had higher sulfate concentrations than solely from mixing of those two endmembers.

Surface-water samples from watersheds dominated by marine sediments (blue field in fig. 26) generally had lower ratios of boron concentration to TDS concentration and a weaker relation between boron and TDS concentrations than surface-water samples from watersheds dominated by Franciscan Complex rocks (green field in fig. 26). The WSJV study-unit groundwater samples from watersheds dominated by Coast Ranges marine sediments, samples in the group recharged during a colder paleoclimate period, and samples with isotopic ratios indicating Sierra Nevada origin all had boron and TDS concentrations in the range for surface-water samples from Coast Ranges watersheds dominated by marine sediments (fig. 26). If DM-17 was removed from the dataset, boron concentrations showed a positive correlation with sulfate concentrations (Spearman's rho = +0.49, $n = 42$, $p < 0.001$). For surface water and groundwater samples from watersheds dominated by marine sediments, higher boron concentrations were generally associated with anion compositions with a higher proportion of sulfate (fig. 25). As discussed previously, the origin of the sulfate is dissolution of sulfate salts that formed from oxidation of pyrite in the marine sediments.

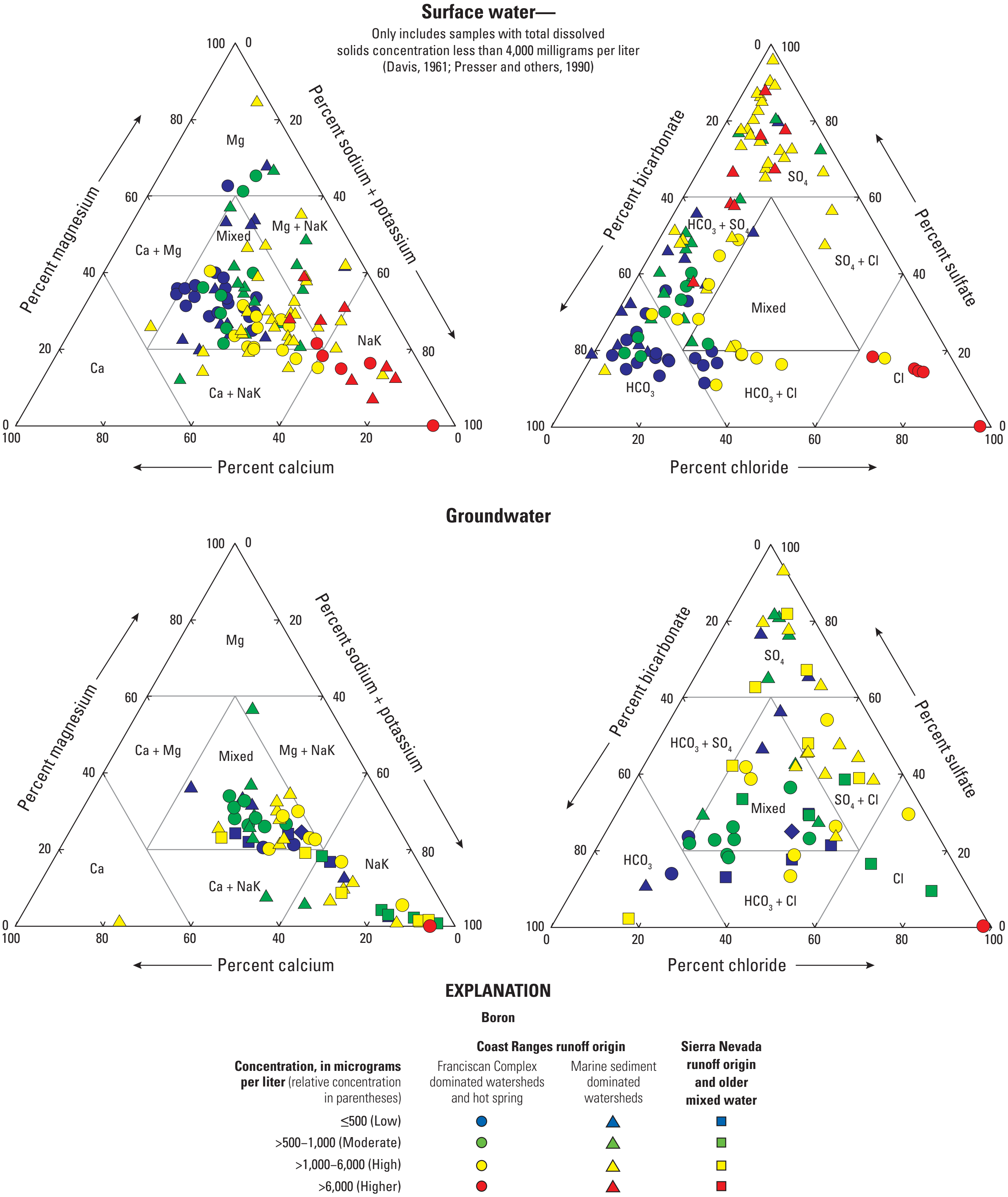
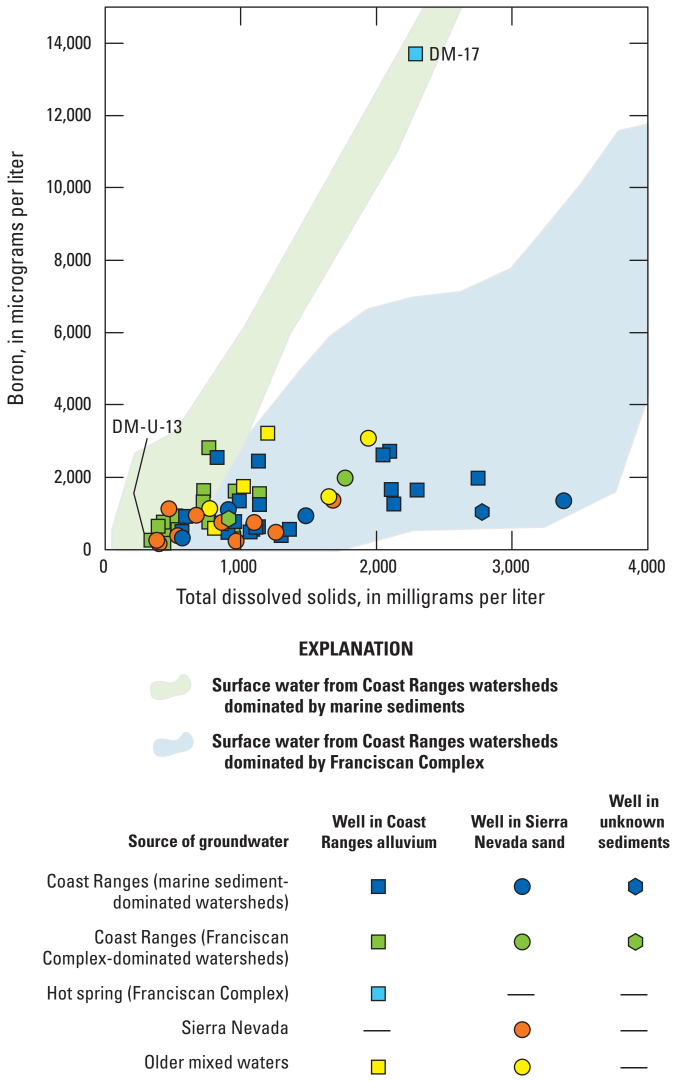


Figure 25. Piper diagrams and boron concentrations from the 2010 California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project for, *A*, surface-water samples from Coast Ranges adjacent to the Western San Joaquin Valley (WSJV) study unit with total dissolved solids concentrations less than 4,000 mg/L, 1952–89; and *B*, for groundwater samples from wells sampled by the U.S. Geological Survey (USGS) for the WSJV study unit.



Surface-water data from Davis, 1961, and Presser and others, 1990

Figure 26. Relation between boron and total dissolved solids concentrations for surface-water samples from Coast Ranges adjacent to the Western San Joaquin Valley (WSJV) study unit with total dissolved solids concentrations less than 4,000 µg/L,1952–89, and for groundwater samples from wells sampled by the U.S. Geological Survey (USGS) for the WSJV study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Chromium(VI)

Chromium is present naturally in the environment in two oxidation states, reduced as chromium(III) and oxidized as chromium(VI). The most common chromium mineral is chromite ($FeCr_2O_4$), and chromium is found in lesser amounts as a substituent in ferromagnesian silicates and other spinels (Reimann and de Caritat, 1998). Chromite can be in mafic and ultramafic rocks and alluvium derived from these rocks. In California, these rocks are found in the Klamath Mountains, the Coast Ranges, the northern Sierra Nevada foothills, and the San Gabriel Mountains (Kruckeberg, 1984; Izbicki and others, 2008; Morrison and others, 2009; Smith and others, 2014). Chromium(III), the dominant form in most minerals, is only sparingly soluble in water and strongly sorbed in mineral surfaces (Nriagu and Nieboer, 1988; Kotas and Stasicka, 2000). In the presence of manganese oxides, chromium(III) is oxidized to chromium(VI) , which under oxic, alkaline conditions, can desorb from mineral surfaces and become soluble in groundwater as an oxyanion (Eary and Rai, 1987; Kotas and Stasicka, 2000; Izbicki and others, 2008). The concentration of chromium(VI) in groundwater from natural sources generally is greatest where the combination of all the following conditions exist: abundant, easily weathered chromium-bearing minerals; manganese oxides on surfaces of aquifer materials; oxic, alkaline groundwater; and long residence times (Izbicki and others, 2008, 2015; Morrison and others, 2009; Mills and others, 2011). The primary anthropogenic source of chromium(VI) to groundwater is leaching from hazardous waste sites (California State Water Resources Control Board, 2014). An SWRCB-DDW MCL of 10 µg/L was established for chromium(VI) in 2014.

Measured chromium(VI) data were only available for samples from 30 wells located in 15 of the 39 cells in the WSJV study unit (fig. 23*C*); thus, the data were supplemented with chromium(VI) concentrations estimated from total dissolved chromium concentrations. Samples from a total of 96 USGS-grid and additional wells and SWRCB-DDW wells had data for total dissolved chromium. Chromium was not found at high RCs and was present at moderate RCs in 7.3 percent of the groundwater resources used for public drinking water (table 8). In the 918 wells analyzed for chromium(VI) by USGS-GAMA statewide, approximately 90 percent of the total dissolved chromium was chromium(VI) (Izbicki and others, 2015); in the WSJV study unit, for 30 samples with data for both total chromium and chromium(VI), 73–100 percent of the total dissolved chromium was chromium(VI) (fig. 27). Based on this relation, estimated chromium(VI) concentrations were calculated from total dissolved chromium by assuming that 90 percent of total dissolved chromium was chromium(VI). All of the wells with high or moderate RCs of measured chromium(VI) were in the DM study area (fig. 23*C*), and all of the wells with total dissolved chromium concentrations greater than 11 µg/L (estimated chromium(VI) greater than 10 µg/L) were also in the DM study area (fig. 23*D*).

In the WSJV study unit as a whole, high RCs of estimated chromium(VI) were present in 25 percent of the groundwater resources used for public drinking water, and moderate RCs of estimated chromium(VI) were present in less than 1 percent (table 8).The Delta–Mendota study area had a higher percentage of groundwater resources that had estimated high RCs of chromium(VI) (33.4 percent; appendix table 2–1*A*) than all other GAMA Priority Basin Project study areas statewide (fig. 16*B*).

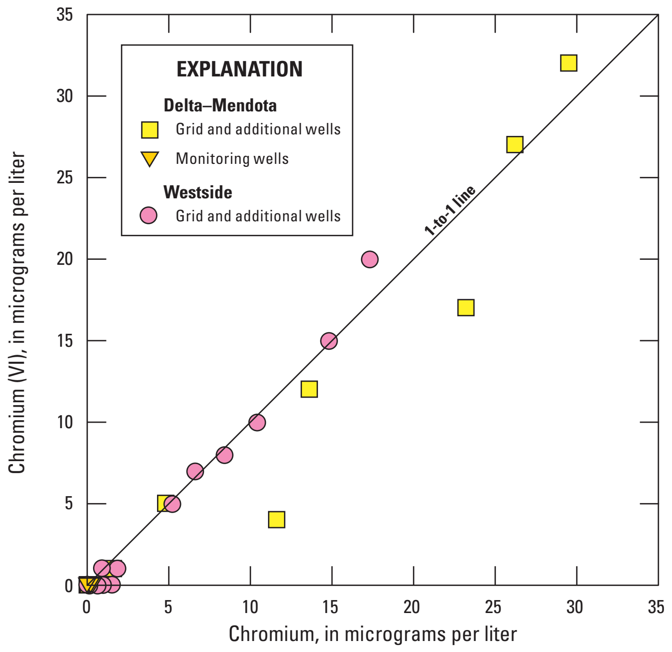


Figure 27. Relation between concentrations of chromium and chromium(VI) in samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

The spatial distribution of samples that had high RCs of chromium(VI) (measured and estimated) was consistent with natural sources of chromium(VI) to groundwater. The presence of elevated chromium(VI) concentration in groundwater requires groundwater geochemical conditions—redox status and pH—that favor chromium(VI) formation and solubility and requires a source of chromium. WSJV study unit groundwater samples were divided into four groups by redox status, aquifer lithology, and study area. Samples with manganese-reducing or manganese- and iron-reducing redox conditions from wells in either Sierra Nevada sands or Coast Ranges alluvium had median chromium concentrations of less than 1 µg/L (fig. 28), because chromium would be in the relatively insoluble chromium(III) form under those redox conditions. Because nearly all samples from wells screened in Sierra Nevada sands had manganese-reducing or manganese- and iron-reducing redox conditions (figs. 10, 12), chromium and chromium concentrations were lower in samples from wells screened in Sierra Nevada sands than in samples from wells screened in Coast Ranges alluvium (table 10*A*).

Among samples with oxic, suboxic, or nitrate-reducing redox conditions that would favor formation of chromium(VI), chromium concentrations in samples from wells located in the Delta–Mendota study area and screened in Coast Ranges alluvium (median of 13 µg/L) were much greater than concentrations in samples from wells located in the Westside study area and screened in Coast Ranges alluvium (median of less than 1 µg/L) (fig. 28). The Coast Ranges adjacent to the Delta–Mendota study area contains abundant Franciscan Complex rocks, whereas the Coast Ranges adjacent to the Westside study area contains fewer outcrops of Franciscan Complex rocks (figs. 3, 23*D*). The Franciscan Complex contains serpentinite bodies and ultramafic plutonic rocks (Kruckeburg, 1984) and soils and sediments derived from serpentinite bodies and ultramafic plutonic rocks have elevated chromium concentrations (Morrison and others, 2009).

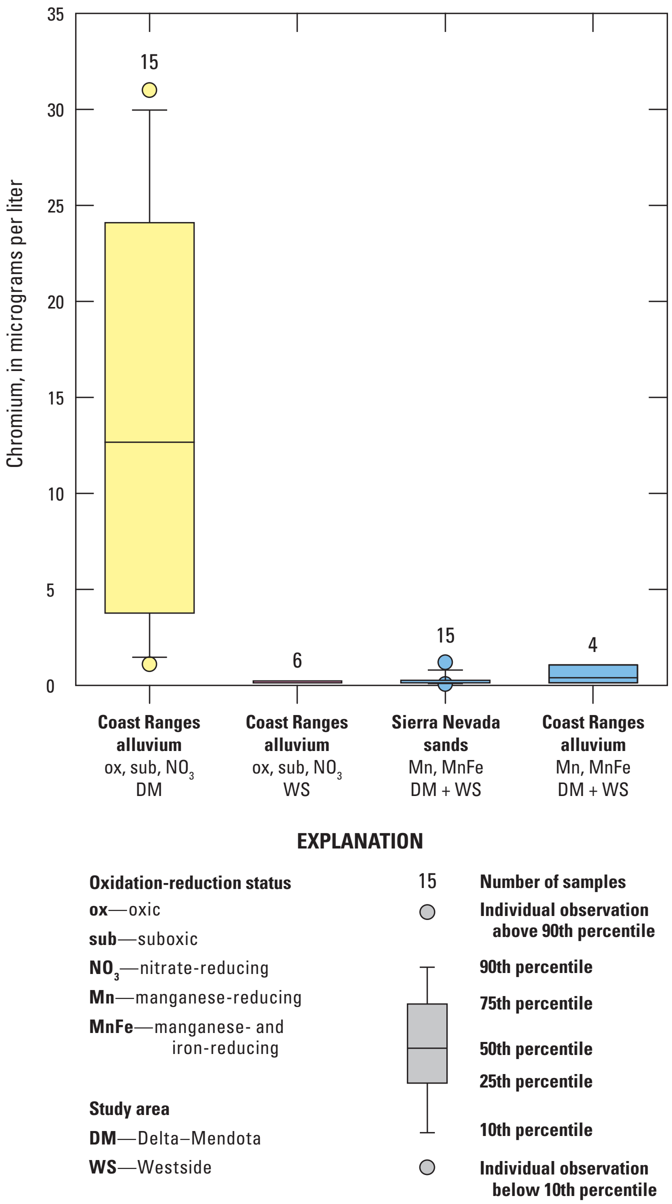


Figure 28. Chromium concentrations in samples grouped by aquifer lithology class, study area, and oxidation-reduction (redox) status, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Chromium and chromium(VI) both showed negative correlation with pH (table 10*B*), which was unusual because the solubility of chromium(VI) generally is greater in alkaline groundwater (Rai and Zachara, 1984; Rai and others, 1989; Izbicki and others, 2008). However, the pH values in oxic groundwater from wells screened in Coast Range alluvium and in areas near outcrops of Franciscan Complex in the Coast Ranges ranged from 7.1 to 7.9, which is sufficient for solubility of chromium(VI) (Rai and Zachara, 1984; Izbicki and others, 2008). The maximum chromium concentration in the USGS-GAMA WSJV samples with pH values greater than or equal to 8 was 0.24 µg/L. These low-chromium values reflect the fact that all 11 wells with pH values greater than or equal to 8 were in the southern part of the study unit (fig. 13). The absence of elevated chromium concentrations in samples from the Westside study area, despite geochemical conditions favorable to chromium solubility, illustrates the great importance of aquifer sediment provenance to the distribution of high RCs of chromium(VI) in groundwater.

Chromium(VI) and chromium concentrations showed significant positive correlations with DO, nitrate, selenium, and perchlorate concentrations and significant negative correlations with molybdenum, iron, and manganese concentrations (tables 10*B*, 11). These relations reflect that concentrations of chromium and chromium(VI) generally are greater in oxic groundwater compared to anoxic groundwater (Izbicki and others, 2015).

Molybdenum

Most molybdenum ore deposits are associated with porphyry granite or quartz monzonite plutons, and the primary ore mineral is molybdenite (MoS_2; for example, Misra, 2000). However, high concentrations of molybdenum also are found in organic-rich sediments and sedimentary rocks deposited in sulfidic environments (Crusius and others, 1996). Potential anthropogenic sources to groundwater include industrial sources and surface application of biosolids (Evans and Barabash, 2010). Molybdenum has an EPA HAL of 40 µg/L in drinking water and is on the EPA's Contaminant Candidate List 3 (U.S. Environmental Protection Agency, 2009). High levels of molybdenum in animals (including humans) can interfere with uptake of copper. Molybdenum is an essential trace nutrient for some plants for nitrogen fixation and can even be a limiting nutrient in molybdenum-poor environments (Goldman, 1960; Evans and Barabash, 2010).

Molybdenum was present at high RCs in 3.8 percent and at moderate RCs in 17 percent of the groundwater resources used for public drinking water (table 8). High RCs of molybdenum only were present in the Delta–Mendota study area (appendix tables 2–1*A*, *B*; fig. 23*E*); however, the median concentration of molybdenum in the Westside study area was significantly greater than that in the Delta–Mendota study area (table 10*A*). The percentage of the groundwater resources used for public drinking water in the Delta–Mendota study area that had high RCs of molybdenum (5.2 percent) was greater than in most of 82 study areas assessed by the GAMA Priority Basin Project statewide (fig. 16*B*).

Molybdenum concentrations in groundwater primarily are controlled by groundwater redox conditions, pH, and availability of molybdenum from aquifer materials (for example, Smedley and others, 2014). At pH values greater than about 4.5, dissolved molybdenum is present primarily as the molybdate oxyanion, MnO_4^{-2} over a wide range of redox conditions (Evans and Barabash, 2010). Concentrations of molybdenum in groundwater are limited at acidic and neutral pH values by sorbtion of the molybdate oxyanion to oxides, organic matter, and clays (Evans and Barabash, 2010). Alkaline conditions inhibit sorbtion of molybdate to mineral surfaces, thus resulting in higher concentrations of molybdenum in groundwater at higher pH values. Molybdenum also can be released into groundwater by reductive dissolution of manganese and iron oxyhydroxide minerals under manganese-reducing or manganese- and iron-reducing conditions (Smedley and others, 2014). However, under sulfate-reducing conditions, the solubility of molybdenum is strongly limited by solid solution of molybdenum in iron sulfide minerals (Crusius and Thompson, 2000), sorption of molybdenum thiosulfide complexes to mineral surfaces (Erickson and Helz, 2000), and perhaps precipitation of molybdenite.

Relations between molybdenum concentrations and potential explanatory factors in the WSJV study unit are consistent with operation of both mechanisms for enhanced molybdenum solubility in groundwater. Samples from USGS grid and additional wells were divided into 4 groups on the basis of groundwater redox conditions (fig. 29*A*). Median concentrations of molybdenum in samples classified as manganese-reducing and in samples classified as nitrate-reducing or suboxic were significantly greater than median molybdenum concentrations in samples classified as manganese- and iron-reducing or in samples classified as oxic (multi-stage Kruskall-Wallis, $p < 0.001$).

Elevated molybdenum concentrations in samples classified as manganese-reducing were consistent with reductive dissolution of manganese oxyhydroxide minerals, releasing molybdate oxyanions that were sorbed onto the surfaces of those minerals. Molybdenum concentrations were greater in samples from wells screened in Sierra Nevada sands than in samples from wells screened in Coast Ranges alluvium (table 10*A*; Dubrovsky and others, 1991), largely because manganese-reducing conditions were more common in wells screened in Sierra Nevada sands. Among wells with manganese-reducing conditions, molybdenum concentrations were not significantly different between wells screened in Sierra Nevada sands and wells screened in Coast Ranges alluvium (Wilcoxon rank-sum, $n = 11$, $p = 0.414$), indicating that both types of sediments contain sources of molybdenum.

The lower concentrations of molybdenum in samples classified as manganese- and iron-reducing may indicate removal of molybdenum from solution by precipitation of sulfide minerals. Dissolved sulfide concentrations were not measured consistently in WSJV study unit samples. Reduction of iron(III) to iron(II) can proceed concurrently with reduction of sulfate to sulfide (for example, Appelo and Postma, 2005), thus it is possible that samples that were iron-reducing also contained sulfide.

The greater molybdenum concentration in samples classified as nitrate-reducing or suboxic compared to concentrations in samples classified as oxic (fig. 29*A*) are not the result of anoxic conditions in the former: Nitrate-reducing and suboxic conditions, while anoxic, are too oxidizing to promote reductive dissolution of manganese or iron oxyhydroxides. Values of pH in the nitrate-reducing and suboxic samples (median 8.3) were significantly higher than pH values in the oxic samples (median 7.55; fig. 29*B*; multi-stage Kruskall-Wallis, $p < 0.001$), and were high enough to inhibit sorption of molybdate to mineral surfaces (Smedley and others, 2014). The high pH values in nitrate-reducing and suboxic samples likely are not a consequence of the redox conditions, but rather the high pH values and slightly reducing conditions are likely related to groundwater age. Samples with nitrate-reducing or suboxic conditions had significantly lower tritium activities than samples with oxic conditions (fig. 29*C*; Wilcoxon rank-sum test, $p < 0.001$). Greater contact time between groundwater and sediments commonly results in consumption of dissolved oxygen by reactions with sedimentary organic matter or minerals containing reduced iron and in increased pH due to silicate mineral dissolution. All wells with high or moderate RCs of molybdenum had premodern groundwater, indicating that whether the mechanism for molybdenum mobilization was reductive dissolution or inhibition of sorption under less reducing, alkaline conditions, long contact times between groundwater and aquifer materials favor molybdenum mobilization. Similar geochemical behavior was observed in groundwater used for public drinking water in the Sierra Nevada study units: moderate and high RCs of molybdenum were found in premodern age groundwater that was either from wells in granitic rocks with manganese-reducing conditions or from wells in sedimentary basins with oxic, alkaline conditions (Fram and Belitz, 2012).

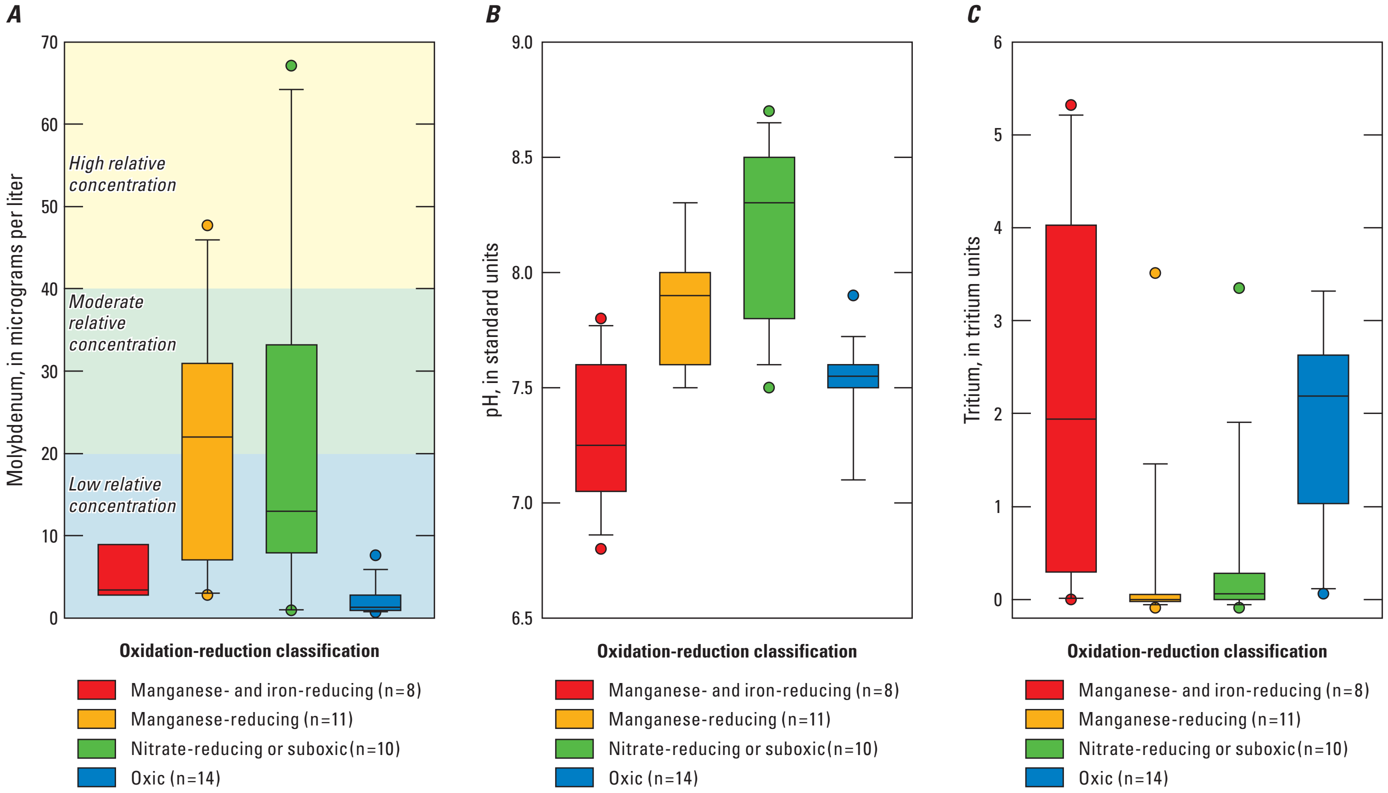


Figure 29. Relations for samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, between oxidation-reduction class and *A*, molybdenum concentration, *B*, pH, and *C*, tritium activity.

Samples classified as oxic had lower molybdenum concentrations (fig. 29*A*), lower pH values (fig. 29*B*), modern or mixed age groundwater (fig. 29*C*), and were from wells in the Delta–Mendota study area (fig. 12). This association between low molybdenum concentrations and oxic, relatively low pH conditions observed groundwater resources used for public drinking water also was observed in domestic wells from the Delta–Mendota study area (Dubrovsky and others, 1991) and shallow groundwater from the Tulare Basin just south of the Westside study area (Fujii and Swain, 1995). Under these geochemical conditions, the molybdate oxyanion likely is largely adsorbed onto ferric oxyhydroxides in the Coast Ranges alluvium (Dubrovsky and others, 1991; Fujii and Swain, 1995).

Reductive dissolution of manganese and iron oxyhydroxide minerals and desorption of metal oxyanions from mineral surfaces under alkaline conditions both are relatively common processes, as evidenced by the widespread occurrence of elevated concentrations of arsenic in groundwater (Smedley and Kinniburgh, 2002; Welch and others, 2006; Focazio and others, 2000; Ayotte and others, 2011; Belitz and others, 2015). In contrast, elevated concentrations of molybdenum are relatively less common in groundwater (Ayotte and others, 2011; Belitz and others, 2015; Smedley and others, 2014). Arsenic and molybdenum concentrations were positively correlated in USGS grid and additional wells from the WSJV study unit; however, the correlation (rho = 0.33) was less strong than the correlation between either trace element and manganese (table 11).

Both the Sierra Nevada sands and the Coast Ranges alluvium appear to be sources of molybdenum to WSJV groundwater (Deverel and Millard, 1988; Dubrovsky and others, 1991). Factor analysis of element concentration data for soils from a part of the WSJV study unit identified five groups of elements, and inferred that each group represented elements derived primarily from one the five potential sources of materials to WSJV soils: Sierra Nevada arkosic sediments, Franciscan Complex serpentinite, seleniferous sediments, carbonates and sulfates, and organic carbon (Tidball and others, 1986). None of the five groups included molybdenum (Tidball and others, 1986), indicating that molybdenum was not preferentially associated with one of the five potential sources of materials to WSJV soils.

Selenium

Selenium is an essential nutrient at low concentrations, but long-term exposure to concentrations above the EPA MCL of 50 µg/L can cause damage to nervous and circulatory systems, hair and fingernail loss, and damage to kidney and liver tissue (U.S. Environmental Protection Agency, 1995).

Selenium was present at high RCs in 2.6 percent and moderate RCs in 1.7 percent of the groundwater resources used for public drinking water (table 8). High RCs of selenium were present only in the Delta–Mendota study area and moderate RCs were present in both study areas (appendix tables 2–1*A*, *B*; figs. 15, 23*F*). The median concentrations of selenium in the two study areas were not significantly different (table 10*A*). The percentage of the groundwater resources in the Delta–Mendota study area that had high RCs of selenium (3.4 percent, appendix table 2–1*A*) was the highest of any study area assessed by the GAMA Priority Basin Project statewide (fig. 16*B*).

The source of selenium in groundwater in the WSJV study unit was intensively investigated in the late 1980s after selenium in agricultural drainage water was determined to have toxic effects on aquatic birds in Kesterson National Wildlife Refuge (National Research Council, 1989; Dubrovsky and others, 1993; Frankenberger and Benson, 1994). Starting in about 1980, the primary source of water for Kesterson was the San Luis Drain (fig. 2), which transported water from subsurface tile-drain systems in irrigated agricultural fields in parts of the WSJV. The drainage water contained high concentrations of selenium because some WSJV soils have high concentrations of selenium from geologic sources, and irrigation and drainage of those soils vastly accelerated mobilization of the selenium (Deverel and Millard, 1988; Fujii and others, 1988; Dubrovsky and others, 1993).

The following mechanism for selenium mobilization in the WSJV was described by Deverel and others (1984), Presser and others (1990), and Dubrovsky and others (1993). Oxidative weathering of pyritic shales in the Coast Ranges releases selenium substituted for sulfur in pyrite, as well as other metals. Alkaline soils buffer the pH, resulting in precipitation of most metals, except for the highly soluble, oxidized form of selenium, selenium(VI). The selenium(VI) oxyanion, selenate, substitutes for sulfate in sodium and magnesium sulfate salts that precipitate in the arid soils. Under natural conditions, the selenium then moves slowly through the hydrologic system by redistribution of sediment in episodic mass-wasting events and by dissolution of the selenium-bearing salts by the sparse precipitation and ephemeral stream flows. Natural recharge rates were very low (Williamson and others, 1989; Belitz and Heimes, 1990), resulting in limited transport of selenium to deeper parts of the system. Irrigation greatly increased the amount of recharge and resulted in dissolution of selenium-bearing salts from the soils (Dubrovsky and others, 1993). Dissolution of salts by recharge of applied irrigation water was a transient process; highest concentrations of selenium generally were observed in the “first flush” of the soils and later recharge through the leached soils had lower selenium concentrations (Dubrovsky and others, 1993). In areas where the water table was within a couple of meters of the land surface, evapotranspiration also increased selenium concentrations in groundwater (Dubrovsky and others, 1993; Fujii and Swain, 1995).

The solubility of selenium depends on redox conditions. Selenium(VI) is highly soluble, whereas selenium(IV) is strongly adsorbed to the WSJV soils and sediments (Fio and others, 1991). At a pH value if 7.5 selenium(V) (selenate) is reduced to selenium(IV) (selenite) at approximately the same oxidation-reduction potential as reduction of manganese(IV) to manganese(II) therefore, groundwater with manganese-reducing conditions, as indicated by high RCs of manganese, has low concentrations of selenium (Fujii and Swain, 1995). As indicated by these geochemical mechanisms and relations, in the WSJV study unit, selenium concentrations were correlated positively with DO, nitrate, chromium(VI), and perchlorate concentrations and were correlated negatively with arsenic, iron, and manganese concentrations (tables 10*B*, 11). Selenium concentrations were significantly greater in samples from wells screened in Coast Ranges alluvium compared to wells screened in Sierra Nevada sands (table 10*A*), because the source of selenium is in the Coast Ranges (Presser and others, 1990) and because most of the wells screened in Sierra Nevada sands had manganese-reducing conditions (figs. 10, 12).

In groundwater samples from USGS grid, additional, and monitoring wells with oxic, suboxic, or nitrate-reducing conditions, selenium concentrations were positively correlated with sulfate concentration (Spearman's rho = +0.53, $n = 34$, $p = 0.001$) and negatively correlated with $\delta^{34}S$ of the sulfate (Spearman's rho = –1.00, $n = 20$, $p < 0.001$) (fig. 30). This close association between elevated selenium concentrations, elevated sulfate concentrations, and $\delta^{34}S$ values of sulfate indicative of sulfur biogenic pyrite confirms the mechanism for selenium mobilization presented by Deverel and others (1984), Presser and others (1990), and Dubrovsky and others (1993).

The highest selenium concentrations in western San Joaquin Valley soils are in the interfan area between the Panoche and Cantua Creek fans, where the neighboring Coast Ranges are dominated by outcrops of the Eocene marine shale (Kreyenhagen Formation) (fig. 3; Tidball and others, 1986; Presser and others, 1990). No WSJV study-unit wells were in this area (fig. 3). The three USGS grid and additional wells with high or moderate RCs of selenium (DM-20, DM-28, and WS-03) were in the northern, central, and southern parts of the WSJV study unit, respectively (fig. 23*F*). The Kreyenhagen, Tumey, and Moreno Formations are all seleniferous shales (Presser and others, 1990; Martens and Suarez, 1997) that outcrop sporadically in the Coast Ranges along the entire length of the WSJV study unit (Anderson and Pack, 1915; Peters and others, 2007).

Positive correlations between selenium concentrations and noble gas recharge temperatures, nitrate concentrations, and perchlorate concentrations suggest that elevated selenium concentrations in groundwater resources used for public drinking water could be related to enhanced mobilization of selenium from aquifer sediments by recharge of water applied for irrigation. These relations are discussed in the section "Perchlorate".

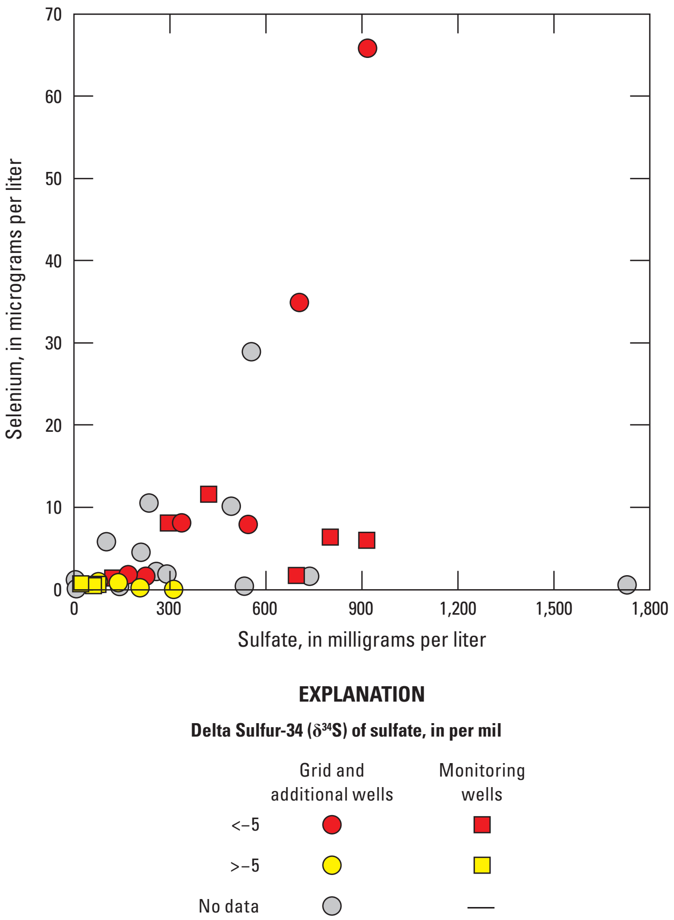


Figure 30. Relation between sulfate and selenium concentrations for two ranges of $\delta^{34}S$ of sulfate in samples with oxic, suboxic, and nitrate-reducing oxidation-reduction conditions, and for two groups of wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Strontium

The trace element strontium has geochemical behavior similar to the major ion calcium (Hem, 1985). The most common natural sources of strontium to groundwater are weathering of silicate minerals, particularly feldspars, dissolution of carbonate and sulfate minerals, and mixing with seawater (contains 7,750 µg/L strontium) or with brines (McNutt, 2000; Faure and Mensing, 2005). The EPA HAL for strontium in drinking water is 4,000 µg/L; over a lifetime, consumption of drinking water that has concentrations greater than the EPA HAL can affect bone and tooth growth (Alfredo and others, 2014). This study only examined stable strontium, which constitutes more than 99.9 percent of natural strontium. A radioactive isotope of strontium, ^{90}Sr, is in radioactive waste and can be in discharge from nuclear power plants; it is regulated separately (U.S. Environmental Protection Agency, 2012).

Strontium was present at high RCs in 5.1 percent and at moderate RCs in 13 percent of the groundwater resources used for public drinking water (table 8). High RCs of strontium were present only in the Delta–Mendota study area, and moderate RCs were present in both study areas (appendix tables 2–1*A*, *B*; figs. 15*B*, 23*G*). The median concentration of strontium in the Delta–Mendota study area was significantly greater than that in the Westside study area (table 10*A*). The Delta–Mendota study area was one of only six study areas statewide in which strontium was present at high RCs (fig. 16*B*). Strontium concentrations showed significant positive correlations with nitrate, chromium, selenium, sulfate, chloride, TDS, and perchlorate concentrations (table 11) and negative correlation with pH (table 10*B*). The strongest correlation was between strontium and calcium (Spearman's rho = 0.91, $p < 0.001$).

The factors and processes potentially affecting strontium concentrations in the WSJV study-unit groundwater were explored using aqueous geochemical modeling. The program PHREEQC (Parkhurst and Appelo, 2013) was used to calculate saturation indices (SI) for a large suite of minerals for WSJV water-quality analyses: a negative SI value indicates that a water is under-saturated with respect to a mineral and has the capacity to dissolve more of that mineral; a positive SI value indicates that a water is supersaturated with respect to a mineral; and an SI value near zero indicates equilibrium between the water and that mineral. Strontium concentrations were correlated with SI for gypsum ($CaSO_4 \cdot 2H_2O$) (fig. 31) and celestite ($SrSO_4$) (not shown), such that higher strontium concentrations were found in waters closer to equilibrium with those minerals. In contrast, strontium concentrations were not correlated with SI for calcite ($CaCO_3$) and strontianite ($SrCO_3$), and nearly all samples were close to equilibrium with calcite (fig. 31). These modeling results indicate that the distribution of strontium in the WSJV study-unit groundwater primarily reflects distribution of soluble sulfate minerals in aquifer materials. Salt crusts and efflorescences composed mostly of sodium and magnesium sulfate minerals, such as mirabilite, thenardite, and bloedite, are common in areas of the WSJV study unit (Presser and others, 1990; Natural Resources Conservation Service, 2006), and the area also has gypsum deposits (California Division of Mines, 1956).

Strontium concentrations were negatively correlated with the $\delta^{34}S$ in sulfate (fig. 32*A*; Spearman's rho = –0.71, $n = 33$, $p < 0.001$), and strontium concentrations greater than 1,200 µg/L (equal to an RC of 0.3) were only found in samples that had sulfate with $\delta^{34}S$ values less than –6 per mil. As discussed in the section on total dissolved solids, these $\delta^{34}S$ values are indicative of sulfate derived from oxidation of biogenic pyrite in Coast Ranges marine shale units. The association between elevated strontium concentrations and sulfate $\delta^{34}S$ values indicative of oxidation of biogenic pyrite supports the hypothesis that sulfate formed from pyrite oxidation is redeposited as sulfate salts that are then dissolved into groundwater recharge.

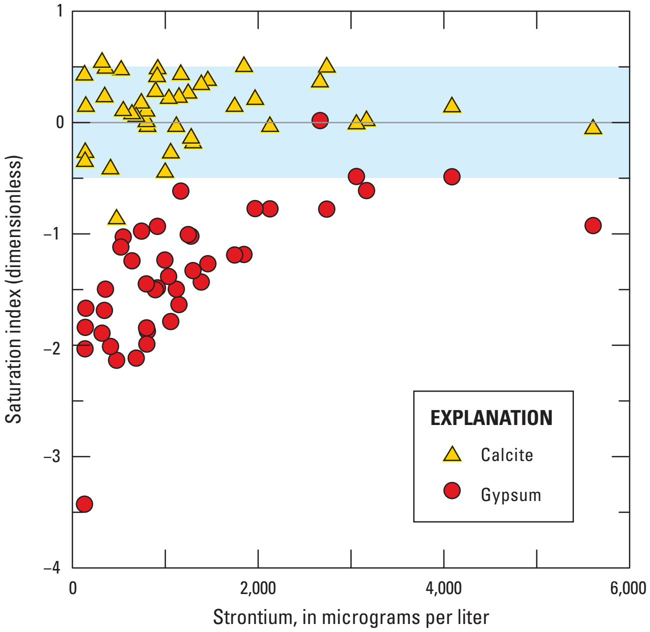


Figure 31. Relations of strontium concentration to calculated saturation indices of calcite and gypsum for groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Isotopic data also provided clues to the source of the strontium itself. The $^{87}Sr/^{86}Sr$ ratio is not fractionated during precipitation and dissolution processes; thus, $^{87}Sr/^{86}Sr$ values for groundwater samples are representative of the sources—or mixture of sources—of the strontium (Kendall and others, 1995). Over the range of ages of marine sediments in the Coast Ranges (late Cretaceous to Pliocene), the strontium-isotope composition of seawater increased from about 0.7075 to about 0.7090 (Peterman and others, 1970; Ravizza and Zachos, 2014). The strontium-isotope ratio, $^{87}Sr/^{86}Sr$, of strontium in groundwater samples from the WSJV study unit varies from 0.70467 to 0.70789, which is generally less than the seawater $^{87}Sr/^{86}Sr$ values (fig. 32*B*). This indicates that the strontium in the groundwater is a mixture of strontium derived from the marine sediments and strontium derived from other sources that have lower $^{87}Sr/^{86}Sr$ values.

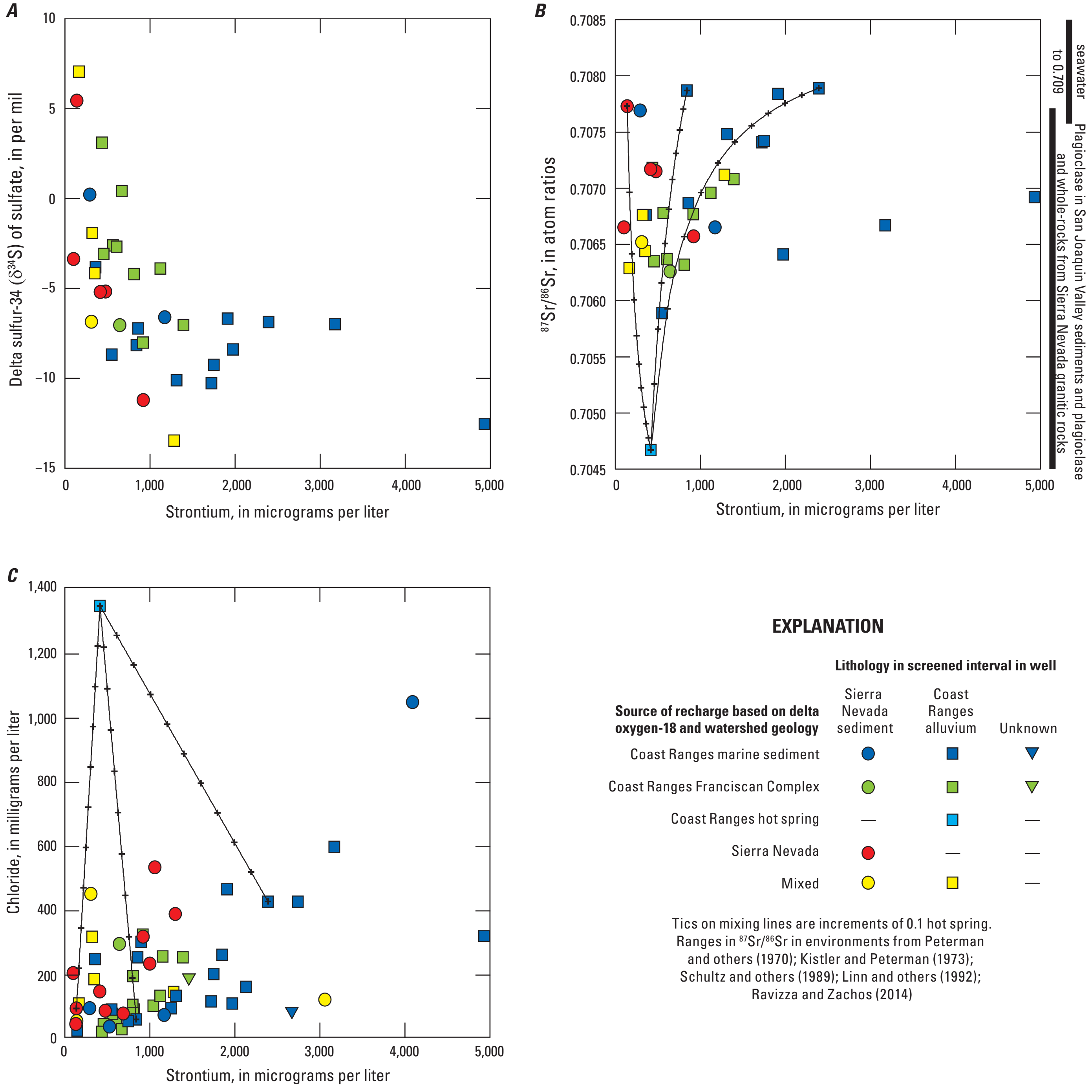


Figure 32. Strontium concentrations and isotopic compositions of dissolved constituents for groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. *A*, $\delta^{34}S$ of dissolved sulfate, *B*, $^{87}Sr/^{86}Sr$ of dissolved strontium, *C*, chloride.

There are two possible sources of strontium with low $^{87}Sr/^{86}Sr$ values to the WSJV groundwater: hydrothermal fluids and dissolution of plagioclase feldspar. The sample with the lowest $^{87}Sr/^{86}Sr$ was from well DM-17, the hot spring associated with hydrothermal alteration and a fault zone in Franciscan Complex rocks. Hypothetical mixing calculations between DM-17 and other WSJV groundwater samples that had high $^{87}Sr/^{86}Sr$ values indicated most of the WSJV sample values could not be produced by these mixtures: the high proportion of DM-17 required in mixtures to match the strontium isotopic ratios would result in mixtures that had higher chloride concentrations than most WSJV study-unit samples (figs. 32*B, C*). Moreover, most WSJV study-unit samples had $\delta^{18}O$ and $\delta^{2}H$ of water compositions that plotted along a line parallel to the global meteoric water line and did not appear to lie along mixing lines toward the sample from well DM-17 (fig. 18).

The other potential source of strontium that has low $^{87}Sr/^{86}Sr$ values is plagioclase feldspar in the aquifer sediments. Plagioclase grains from arkosic sandstones which are petroleum reservoirs in the southern San Joaquin Valley and plagioclase grains and whole-rock samples from the Sierra Nevada granitic rocks have $^{87}Sr/^{86}Sr$ values as low as 0.704, with many values around 0.705 to 0.707 (fig. 32*B*; Kistler and Peterman, 1973; Schultz and others, 1989; Linn and others, 1992). No data are available for plagioclase in rocks of the Coast Ranges; however, they are assumed to have similar $^{87}Sr/^{86}Sr$ values on the basis of the $^{87}Sr/^{86}Sr$ of hydrothermal fluids emanating from the Coast Ranges (DM-17) and the oceanic provenance of the igneous rocks in the Franciscan Complex. Plagioclase (solid solution of $CaAl_2Si_2O_8$ and $NaAlSi_3O_8$) can contain a large amount of strontium substituted for calcium. Dissolution of plagioclase results in release of this strontium.

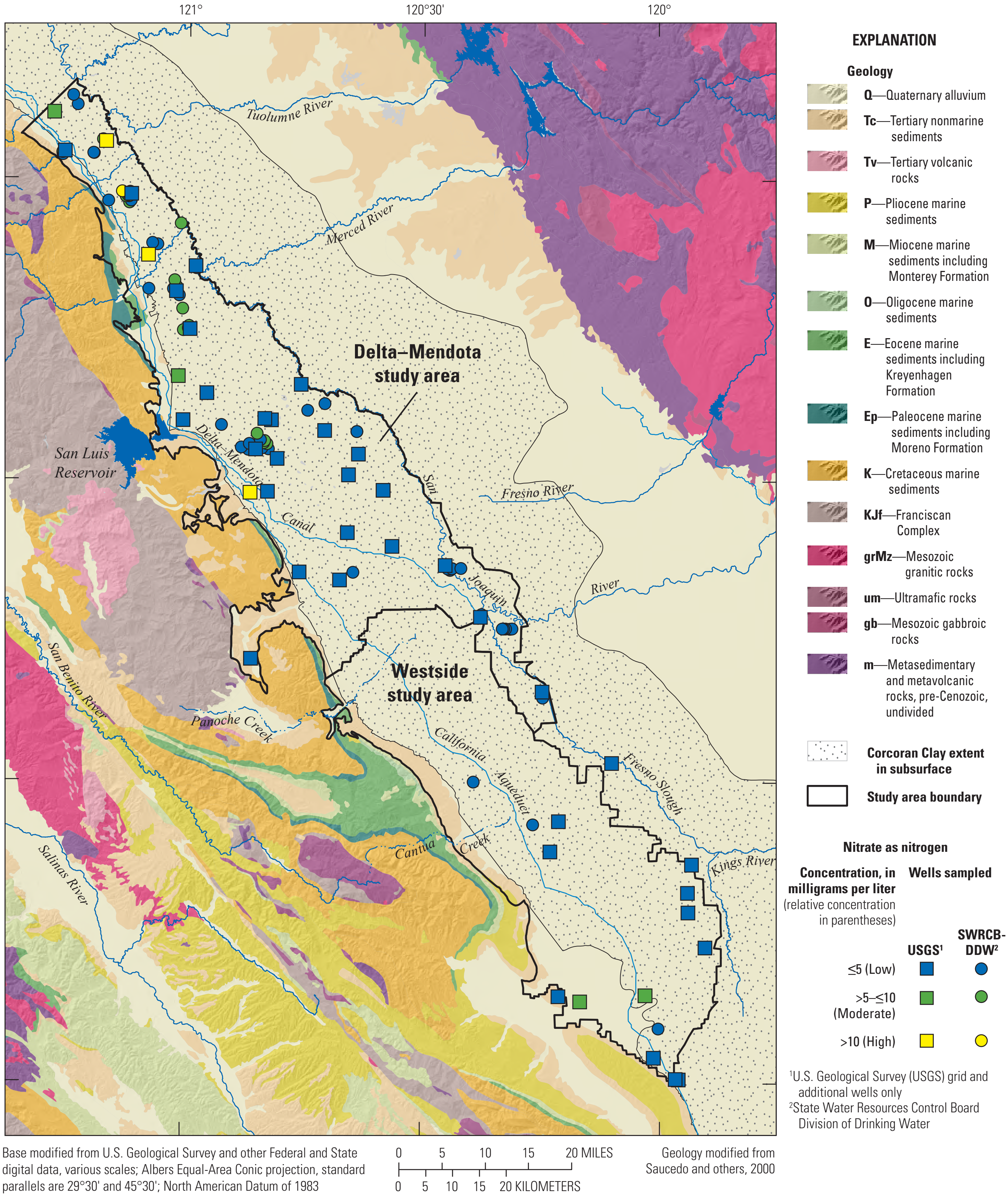
In the North Coles Levee petroleum reservoir in Kern County (not shown), arkosic sandstones contain carbonate cements formed during progressive diagenesis of the sandstone. The $^{87}Sr/^{86}Sr$ of the strontium in the cements changes progressively from initial values near the seawater value to lower values, close to the values in the plagioclase grains (Schultz and others, 1989). The $^{87}Sr/^{86}Sr$ of strontium in the pore water evolved as plagioclase dissolution proceeded during diagenesis. The North Coles Levee pore waters are found at much greater depths in the aquifer system than the groundwater sampled for the WSJV study unit, and likely reflect diagenesis at higher temperatures than would be encountered in the shallower freshwater aquifer system. However, Feldman and others (1993) identified groundwater in other San Joaquin Valley oil fields that had $\delta^{18}O$ and $\delta^{2}H$ characteristics consistent with meteoric origin without substantial interaction with rocks at elevated temperatures (compositions along a line parallel to the GMWL) and that had $^{87}Sr/^{86}Sr$ values like those of the WSJV study unit samples (intermediate between seawater values and values in plagioclase). They inferred that diagenetic processes must have affected dissolved strontium even in these lower temperature groundwater systems.

Nitrate

Nutrients in groundwater have natural and anthropogenic sources (Dubrovsky and others, 2010). Natural sources include atmospheric deposition or fixation, animal waste, and dissolution of organic material in soils. Anthropogenic sources include fertilizer application, animal waste, sewage and septic effluents, and combustion of fossil fuels (emits nitrogen oxides to the atmosphere). The most common forms of dissolved nitrogen in groundwater are nitrate, nitrite, ammonia/ammonium, and dissolved nitrogen gas, and which form dominates depends on redox conditions (for example, McMahon and Chapelle, 2008). Nitrate, nitrite, and ammonia/ammonium have health-based benchmarks (tables 4, 5). Although evapotranspiration from shallow groundwater can increase concentrations of nutrients in groundwater, concentrations of nitrate greater than about 1 mg/L (corresponds to an RC of 0.1) generally are the result of anthropogenic inputs (Nolan and Hitt, 2006; Dubrovsky and others, 2010).

Nutrients, as a class, were present at high RCs in 3.9 percent of the groundwater resources used for public drinking water and at moderate RCs in 15 percent (table 9*A*). Nitrate was the only nutrient present at high or moderate RCs (table 8). High RCs of nitrate were found only in the Delta–Mendota study area, and moderate RCs were found in both study areas (appendix tables 2–1*A*, *B*; figs. 15, 33). The median concentrations of nitrate in the two study areas were not significantly different (table 10*A*). The percentage of groundwater resources in the Delta–Mendota study area that had high RCs of nitrate (5.3 percent) was at the 75th percentile among all study areas assessed by the GAMA Priority Basin Project statewide (fig. 16*B*).

Nitrate has been extensively studied in the eastern San Joaquin Valley as part of the GAMA Priority Basin Project (Landon and others, 2010, 2011; Burton and others, 2012; Shelton and others, 2013) and as part of the USGS NAWQA program (Burow and others, 1998, 2008; Dubrovsky and others, 1998; McMahon and others, 2008). In these studies, nitrate concentrations generally were inversely correlated with depth to top of well screen, positively correlated with agricultural land use, and higher in modern groundwater than in premodern groundwater. Elevated nitrate concentrations are thus associated with shallow, recently recharged groundwater affected by agricultural sources of nitrate.



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

Geology modified from Saucedo and others, 2000

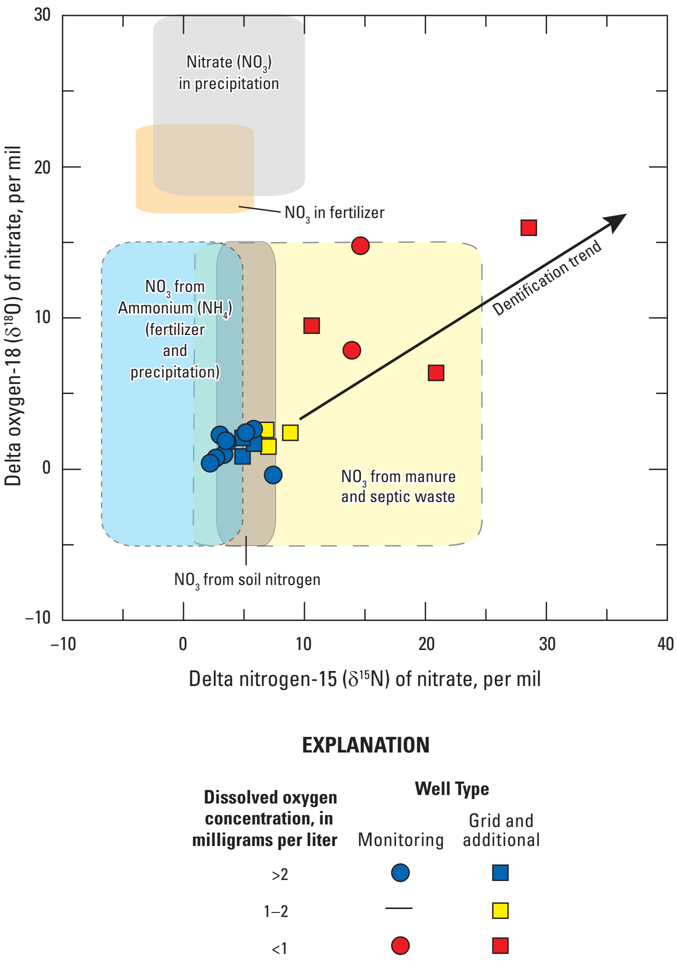
Figure 33. Relative concentrations of nitrate in groundwater from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, and from public-supply wells that have data in the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database for samples collected from March 2007 through August 2010.

In this study, nitrate concentrations were greater in modern or mixed age groundwater than in premodern age groundwater and were greater in oxic than anoxic groundwater, but were not significantly correlated with depth to the top or bottom of screened interval or with land-use parameters (tables 10*A*, *B*). The lack of correlation with well depth could be because nitrate degrades under anoxic conditions. The primary mechanism of nitrate degradation generally is denitrification, the bacterial reduction of nitrate to nitrogen gas through a series of intermediate stages including nitrite (for example, Kendall, 1998). In samples from the seven wells classified as nitrate-reducing or suboxic, nitrate was detected at concentrations ranging from 0.048 mg/L to 8.69 mg/L, and of those, nitrite was detected in four (0.006 to 0.086 mg/L; WS-03, -04, -08, U-02). The presence of nitrate and nitrite together is evidence for denitrification.

Nitrate stable-isotope data support the inference of denitrification in some WSJV study-unit samples, similar to the pattern observed in samples from the east side of the San Joaquin Valley (Landon and others, 2010). In samples with DO concentrations less than 1 mg/L, $\delta^{15}N$ and $\delta^{18}O$ values of nitrate increased with a slope of approximately 0.5 (fig. 34), which was consistent with denitrification (Kendall, 1998). Samples with DO concentrations greater than 2 mg/L showed no evidence of denitrification and had $\delta^{15}N$ and $\delta^{18}O$ values of nitrate that were within the ranges typically observed for nitrate derived from soil nitrogen, from ammonium fertilizers, or from manure and septic sources of nitrogen. It is not possible to distinguish among these potential sources of nitrate on the basis of the data available.

Nitrate can also be reduced to ammonium through dissimilatory pathways (for example, Appelo and Postma, 2005; Rütting and others, 2011). Reduction to ammonium rather than nitrogen gas can be more favorable under conditions of low nitrate concentrations and presence of sulfide (Rütting and others, 2011). In the WSJV study unit, 17 of the 19 wells with manganese-reducing or manganese- and iron-reducing conditions had groundwater with detections of ammonium (0.12–1.05 mg/L), but no nitrate was detected in any of the wells. In contrast, most of the wells sampled in the three GAMA Priority Basin Project eastern San Joaquin Valley study units had oxic groundwater conditions, and the reduced forms of nitrogen (ammonium and nitrite) were rarely detected (Landon and others, 2010; Burton and others, 2012; Shelton and others, 2013).

As expected from the relation between nitrate and redox conditions, nitrate concentrations were correlated positively with chromium, selenium, and perchlorate concentrations and were correlated negatively with arsenic, molybdenum, iron, and manganese (table 11). Nitrate concentrations were higher in groundwater samples from wells screened in Coast Range alluvium than in Sierra Nevada sands (table 10*A*) and were positively correlated with lateral position (table 10*B*), because anoxic conditions are more common in the Sierra Nevada sands than in the Coast Range alluvium (table 7*C*, figs. 10, 12).



Fields modified from Kendall (1998)

Figure 34. Relation between isotopic compositions of nitrogen and oxygen in dissolved nitrate in groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Nitrate concentrations were not correlated with percentage of agricultural land use (table 10*B*); however, when only wells with oxic, suboxic, or nitrate-reducing conditions were considered, some relations emerged. In wells with mixed- or modern-age groundwater and oxic, suboxic, or nitrate-reducing conditions, nitrate concentrations were significantly greater in groundwater samples from wells surrounded by more than 80-percent agricultural land use than in samples from wells surrounded by less agricultural land use (Wilcoxon rank-sum test, $p = 0.017$; fig. 35). Most of these wells had oxic, rather than suboxic or nitrate-reducing, conditions; thus, the relation was likely not confounded by nitrate degradation.

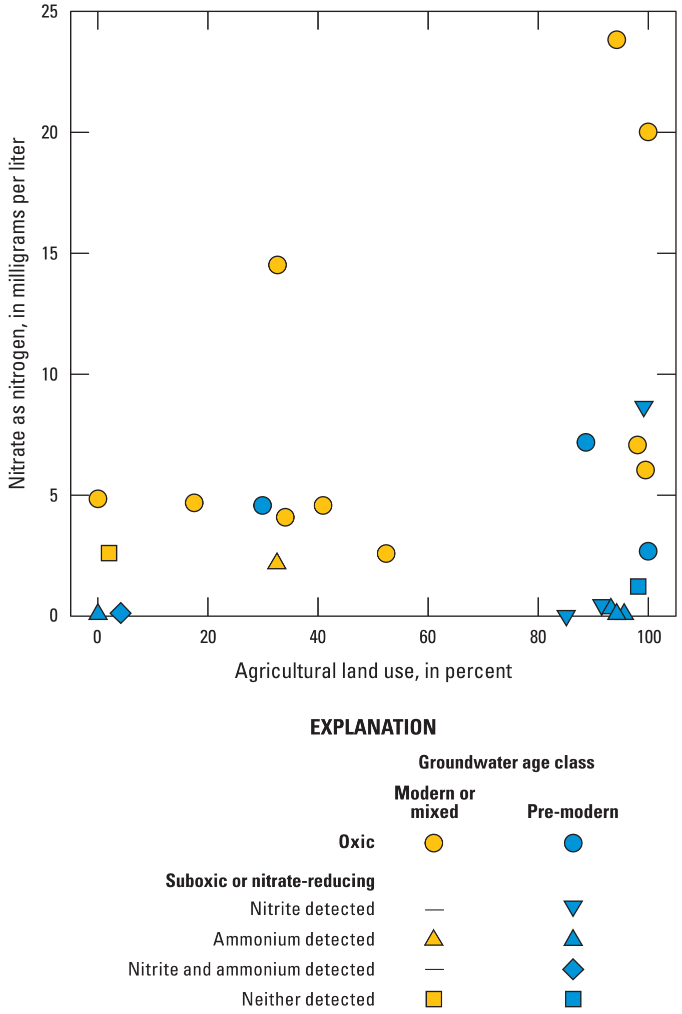


Figure 35. Relation between nitrate concentration in groundwater and percentage of agricultural land use within a 500-meter radius around the well for samples grouped by redox condition and groundwater age, for groundwater samples collected by the U.S. Geological Survey (USGS) from wells with oxic, suboxic, or nitrate-reducing redox (oxidation-reduction) conditions, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

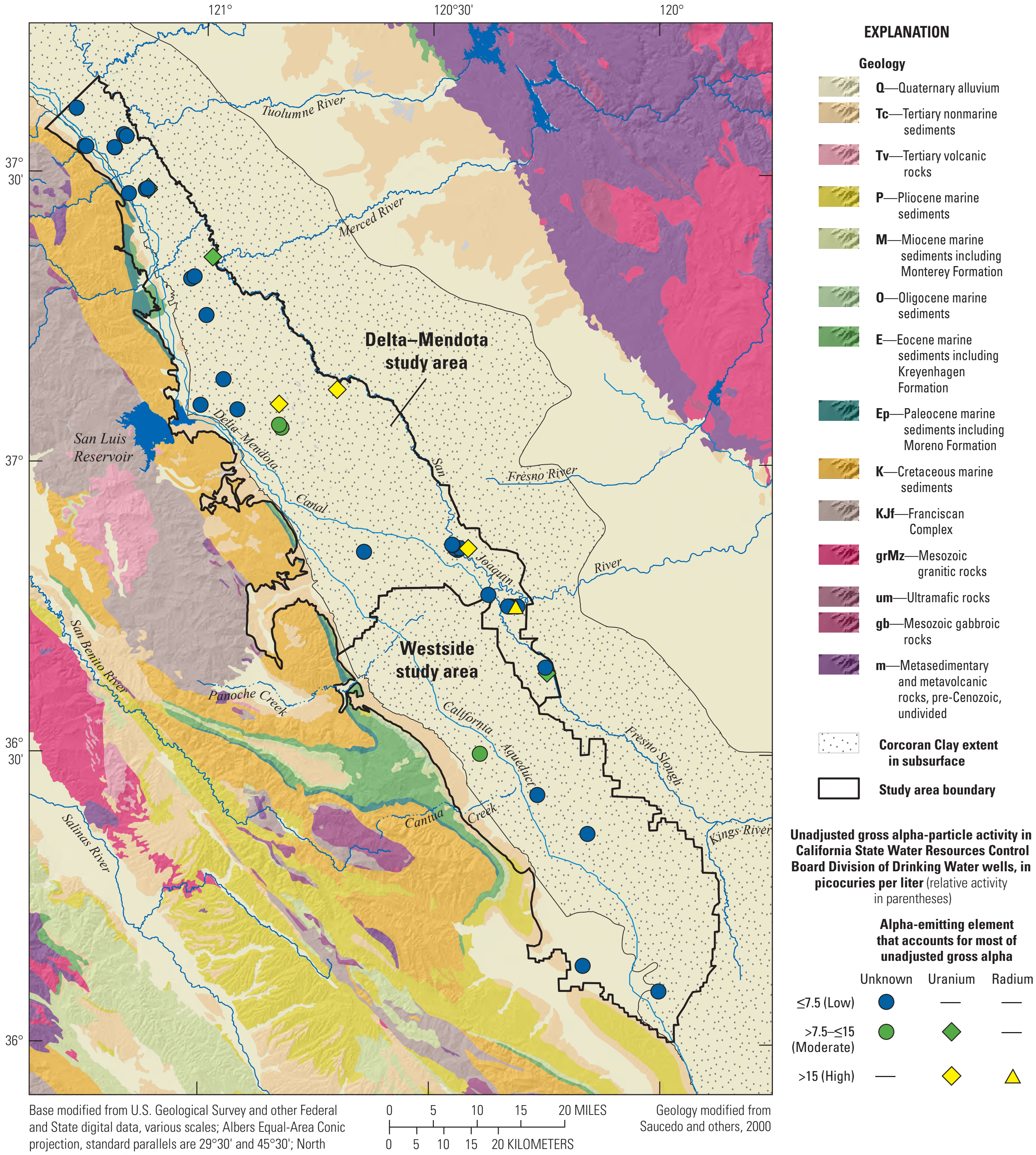
In wells with premodern age groundwater and oxic, suboxic, or nitrate-reducing conditions, the highest nitrate concentrations were found in samples from wells surrounded by more than 80-percent agricultural land use (fig. 35); however, the relation between land use and nitrate concentrations was not significant. Most of these wells had suboxic or nitrate-reducing conditions and nitrite or ammonium were detected in the groundwater, indicating nitrate degradation, so the relation was likely confounded by nitrate degradation.

The paucity of significant relations between nitrate concentrations and land use could also reflect the age of the groundwater sampled for this study. Many of the samples were classified as premodern or mixed age, indicating that a large amount of the groundwater used for public supply could have been recharged prior to the beginning of intensive agricultural activities in the WSJV study unit, so the quality of the groundwater would not be affected yet by modern agricultural land use. Elevated nitrate concentrations in a few wells with premodern groundwater could be from agricultural activities prior to 1950.

Uranium and Radioactive Constituents

Most of the radioactivity in groundwater is from the decay of uranium and thorium in the rocks or sediments of the aquifers. Radioactive decay of uranium and thorium isotopes produces long series of radioactive daughter products, including isotopes of radium, uranium, and radon. These elements have different chemical properties, and their solubility in groundwater varies with geochemical conditions, water chemistry, and aquifer mineralogy (Hem, 1985). This study assessed data for the individual constituents uranium and radium, and for gross alpha activity, which is a measure of the activities of all non-volatile radioactive elements in a water sample that decay by alpha-particle emission. Radium and gross alpha-particle activity were not measured in samples collected by the USGS-GAMA, and there were data for these constituents from only a limited number of wells listed in the SWRCB-DDW database. Uranium concentrations were compared to the EPA MCL of 30 µg/L rather than to the SWRCB-DDW MCL of 20 picocuries per liter (pCi/L), and gross alpha-particle activities were not adjusted for uranium activity (see appendix 3).

Radioactive constituents were present at high RCs in 3.3 percent and at moderate RCs in 5.1 percent of the groundwater resources used for public drinking water (table 9*A*). High RCs of uranium, radium, and unadjusted gross alpha-particle activity were found only in the Delta–Mendota study area (fig. 36; appendix tables 2–1*A*, *B*). The spatial distribution of wells for which there were data for radium or gross alpha-particle activity was insufficient to calculate aquifer-scale proportions for these constituents. Uranium was present at high RCs in 0.6 percent and at moderate RCs in 2.1 percent of the groundwater resources used for public drinking water in the WJSV study unit (table 8).



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

Geology modified from Saucedo and others, 2000

Figure 36. Relative-activities of gross alpha-particle activity in groundwater from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, and from public-supply wells that have data in the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database for samples collected from March 2007 through August 2010.

Four SWRCB-DDW public-supply wells had unadjusted gross alpha-particle activities greater than the benchmark for adjusted gross alpha-particle activity (15 pCi/L). Measured uranium activity was equal to or greater than the unadjusted gross alpha-particle activity in three of the wells, and measured radium activity accounted for most of the unadjusted gross alpha-particle activity in the fourth well (fig. 36). All four wells were located near to USGS-GAMA wells that were screened in Sierra Nevada sands, thus it is likely that the four SWRCB-DDW wells also were screened in Sierra Nevada sands and had manganese-reducing or manganese- and iron-reducing redox conditions. Elevated uranium concentrations typically are associated with oxic groundwater (Hem, 1985); however, groundwater with manganese-reducing conditions and high RCs of uranium was commonly found in wells in granitic and metamorphic rocks of the Central and Southern Sierra Nevada (California Department of Water Resources, 1990; Fram and Belitz, 2012).

The Sierra Nevada sands were derived primarily from weathering of Sierra Nevada granitic rocks. Mineralogical observations of the granitic rocks suggested that weathering of uraniferous titanite or biotite with zircon inclusions could be sources of uranium to groundwater in Sierra Nevada granites (Wollenberg and Smith, 1968; Thomas and others, 1993), and the same minerals would be present in sands derived from those granites. Isotopes of radium are produced by decay of uranium and thorium in minerals. In a national study of radium in groundwater, Szabo and others (2012) found that elevated concentrations of radium in groundwater were most commonly associated with manganese- and iron-reducing redox conditions and acidic pH values. Acidic pH values (less than 6.8) were not observed in samples collected by USGS-GAMA for the WSJV study unit (fig. 13), and pH data were not available for the SWRCB-DDW sample that had high RCs of radium.

Organic and Special-Interest Constituents

The organic constituents measured in this study included two constituent classes: volatile organic compounds (VOCs), which are characterized by their tendency to volatilize, and pesticides (table 4). There are VOCs in paints, solvents, fuels, fuel additives, refrigerants, and disinfected water (for example, Zogorski and others, 2006). Typically, VOCs persist longer in groundwater than in surface water because groundwater is relatively isolated from the atmosphere. Pesticides include herbicides, fumigants, insecticides, and fungicides and are used to control unwanted vegetation (weeds), insects, fungi, and other pests in agricultural, urban, and suburban settings (for example, Gilliom and others, 2006). Fumigants were grouped with the other pesticides on the basis of primary use; chemically, they behave as VOCs.

The GAMA Priority Basin Project included analyses of a large number of organic constituents, many of which were not subject to regulation in California drinking water as of 2016. The USGS-GAMA analytical methods for organic constituents had lower reporting limits than required for sampling for compliance with SWRCB-DDW regulations for monitoring drinking-water quality (table 5). In the WSJV study unit, half of the organic constituents detected were subject to regulation in California drinking water. Of the 168 organic constituents analyzed (table 2), 31 were detected at least once, and of these, 16 had an MCL benchmark, 6 had a non-regulatory health-based benchmark, and 9 had no benchmark (tables 4, 5).

The special-interest constituent class included three chemically unrelated constituents: perchlorate, 1,2,3-trichloropropane (1,2,3-TCP), and *N*-nitrosodimethylamine (NDMA). At the inception of the GAMA Priority Basin Project in 2003, these constituents were of special interest to State of California drinking-water-quality agencies because they had recently been detected in groundwater at concentrations that could be relevant to human health concerns (Belitz and others, 2003). The constituents 1,2,3-TCP and NDMA were not detected in the groundwater resources used for public drinking water in the WSJV study unit. Although perchlorate is an inorganic constituent, it was classified as a special-interest constituent in this report for consistency with other GAMA Priority Basin Project reports.

Figure 14 summarizes the maximum RCs for individual organic constituents and perchlorate detected in the 43 grid and additional wells sampled for the WSJV study unit. The fumigant 1,2-dibromo-3-chloropropane (DBCP) was detected at moderate RCs in grid wells, and the gasoline hydrocarbon benzene was detected at high RCs in samples from additional wells. High and moderate RCs of the solvent tetrachloroethene (PCE) were reported in the SWRCB-DDW database for samples collected between May 2007 and August 2010, but PCE was not detected in samples collected by USGS-GAMA. The detection frequencies and maximum RCs of organic constituents and perchlorate in grid wells are shown in figure 37. Because PCE detections were reported only in samples from SWRCB-DDW wells and not in samples from WSJV study unit grid wells, PCE does not appear in figures 14 or 37. The maximum RC for benzene in grid wells was 0.02 (figs. 14, 37); high RCs of benzene were detected only in additional wells (fig. 14). The trihalomethane chloroform and the herbicide simazine were the only individual organic constituents detected at frequencies greater than 10 percent. The special interest constituent perchlorate was detected at low and moderate RCs and had a detection frequency of 39 percent.

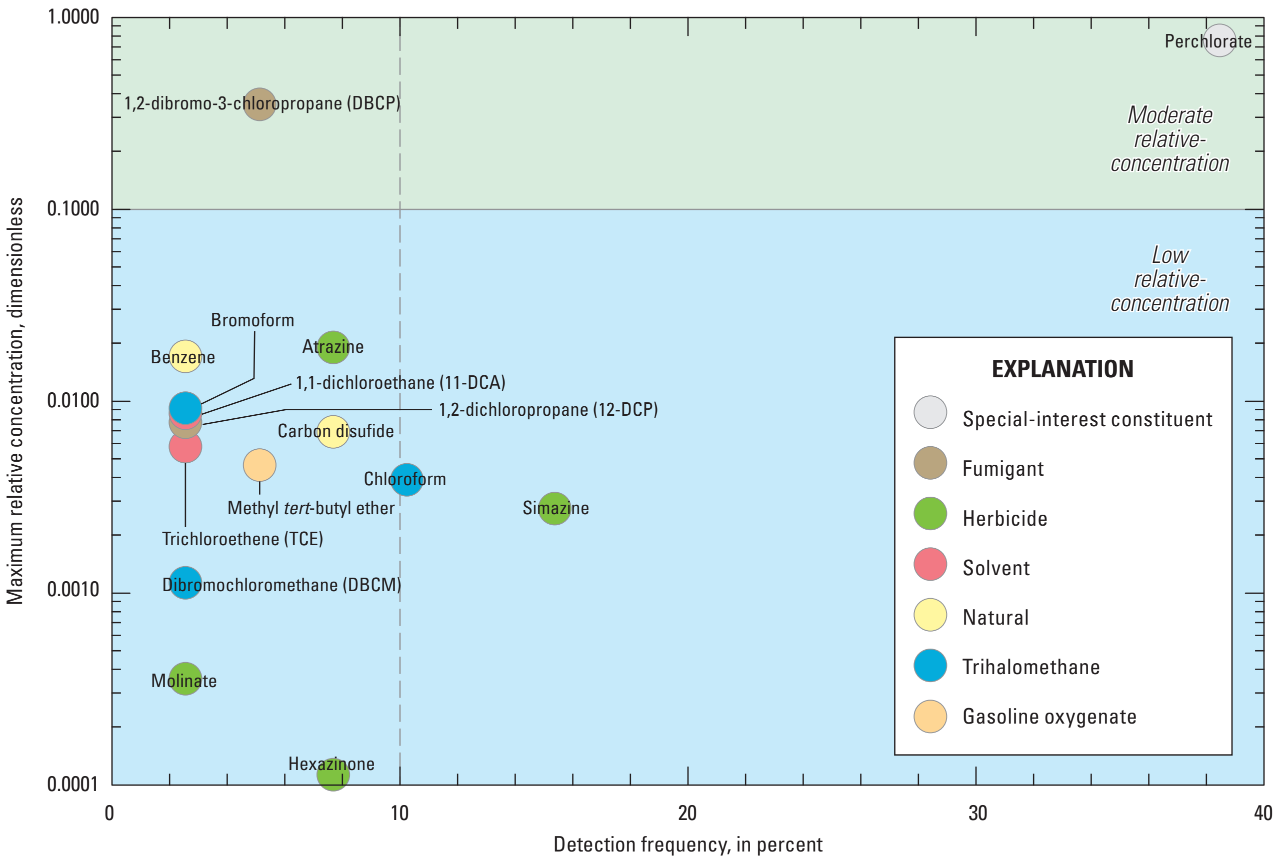


Figure 37. Detection frequencies and maximum relative concentrations of classes of organic and special-interest constituents detected in grid wells, Western San Joaquin Valley (WSJV), 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

One or more organic constituents with a health-based benchmark were present at high RCs in 3.1 percent of the groundwater resources used for public drinking water, at moderate RCs in 3.1 percent, and at low RCs in 30 percent (table 9*B*). Organic constituents were not present at concentrations above the analytical detection levels in about 64 percent of the groundwater resources used for public drinking water. Benzene was present at high RCs in 2.6 percent and PCE in 0.5 percent of the groundwater resources used for public drinking water (table 8). The organic constituents detected at moderate RCs in the groundwater resources used for public drinking water were DBCP and PCE (table 8).

Relations between water quality and potential explanatory factors were evaluated for benzene, the only organic constituent with a health-based benchmark that was present at high RCs in more than 2 percent of the groundwater resources used for public drinking water; for the two organic constituent classes (herbicides and trihalomethanes) that included an individual constituent with detection frequency greater than 10 percent in the study unit as a whole; and for the special interest constituent perchlorate. For the herbicide and trihalomethane constituent classes, the RCs of the individual constituents detected in each sample were calculated and then summed to represent the RC for the class in that sample.

Benzene

Benzene is an organic constituent that has potential natural and anthropogenic sources to groundwater. Benzene is a natural constituent of petroleum, and its presence in groundwater can sometimes be attributed to subsurface petroleum reservoirs (Fram and others, 2012; Landon and Belitz, 2012). The most common anthropogenic sources of benzene to groundwater are leakage from gasoline storage tanks and landfills and discharges from industrial operations (Zogorski and others, 2006).

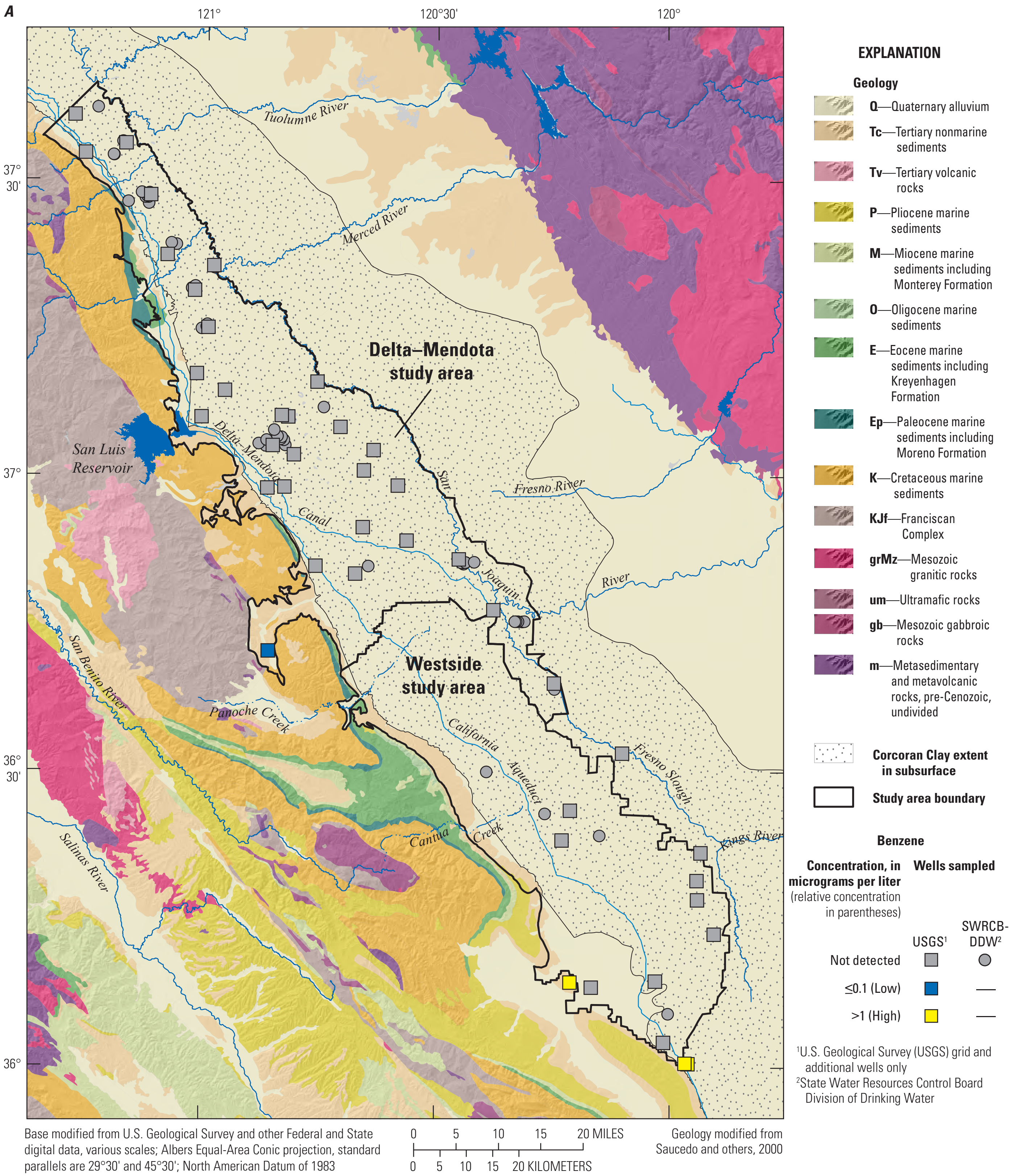
Benzene was not detected at high or moderate RCs in the grid wells, but was detected at high RCs in three additional wells (fig. 38*A*). High RCs of benzene were detected only in the Westside study area (fig. 38*A*; appendix tables 2–1*A*, *B*). Benzene concentrations were positively correlated with the percentage of natural land use and pH and were negatively correlated with the percentage of agricultural land use and aridity index (table 10*B*); these were spurious correlations that did not reflect causal relations, however. It is likely that the high RCs of benzene can be attributed to specific conditions in a part of the Westside study area.

The three wells with groundwater that had high RCs of benzene are at the southern end of the Westside study area. Wells WS-U-01 and WS-U-02 are between the Kettleman City oil field and the southeast side of the Kettleman North Dome oil field in an area where there was oil exploration in the 1920s and 1930s (California Division of Oil, Gas, and Geothermal Resources, 2016a; fig. 39). Economic amounts of petroleum were not found, and the exploration wells were either abandoned or converted to groundwater wells (California Division of Oil, Gas, and Geothermal Resources, 2016a). Well WS-U-03 is in the Guijarral Hills oil field (fig. 39) in an area where formerly productive oil wells were plugged or converted to groundwater wells in the 1970s (California Division of Oil, Gas, and Geothermal Resources, 2016a).

Wells WS-U-01, WS-U-02, and WS-U-03 had premodern groundwater, anoxic conditions, and depths of 166–253 m blsd (appendix tables 1–1, 1–3, 1–4), characteristics associated with geogenic benzene in groundwater in California (Landon and Belitz, 2012). Landon and Belitz (2012) and Landon and others (2014) used statewide data from the GAMA Priority Basin Project, the SWRCB-DDW database, and the USGS NWIS database to evaluate the sources of hydrocarbons to groundwater aquifers used for public supply in California and found higher concentrations and detection frequencies of benzene with increasing well depth, groundwater age, and proximity to oil and gas fields. The authors concluded that this represented a geogenic (natural) source of benzene from petroleum hydrocarbons. It is not possible to determine whether activities related to oil exploration and extraction created pathways for migration of the hydrocarbons to the groundwater resources used for public drinking water or whether the pathways were natural.

The ratios of hydrocarbons in the samples with high RCs of benzene supported the inference that the high RCs of benzene were from geogenic rather than anthropogenic sources of hydrocarbons. Fram and others (2012) compared the ratios of the concentrations of benzene, ethylbenzene, *o*-xylene, styrene, and 1,2,4-trimethylbenzene to the concentration of *m*- and *p*-xylenes in groundwater samples collected for the GAMA Priority Basin Project. The concentration ratios among the hydrocarbons in most of the groundwater samples were similar to concentration ratios observed in ambient air of urban areas in California (Daisey and others, 1994). Air in urban areas contains hydrocarbons primarily derived from incomplete combustion and volatilization of fuels. Groundwater samples that had high RCs of benzene—all of which were from the WSJV study unit or adjacent areas in the Southeast San Joaquin study unit—had concentration ratios that were markedly different from the ratios in ambient air of urban areas, indicating different sources for the hydrocarbons.

The correlation between anoxic conditions and benzene was expected, because benzene readily biodegrades under oxic or aerobic conditions, whereas benzene biodegration rates are much lower under reducing or anaerobic conditions (Kauffman and Chapelle, 2010).



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

Geology modified from Saucedo and others, 2000

Figure 38. Relative concentrations of selected constituents in groundwater from wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, and from public-supply wells that have data in the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database for samples collected from March 2007 through August 2010: *A*, benzene; *B*, total herbicides; *C*, total trihalomethanes; and *D*, perchlorate.

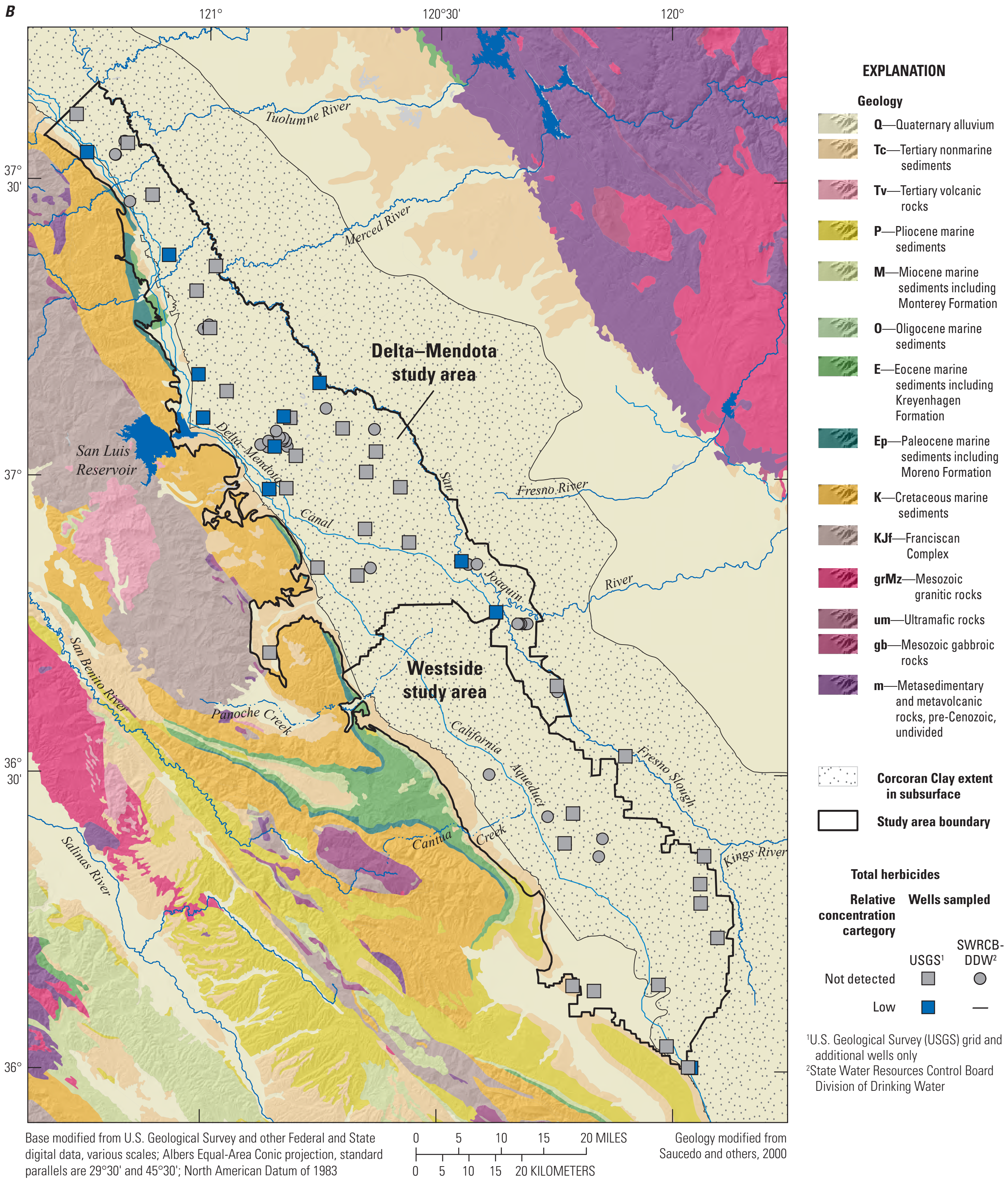


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Figure 38. —Continued

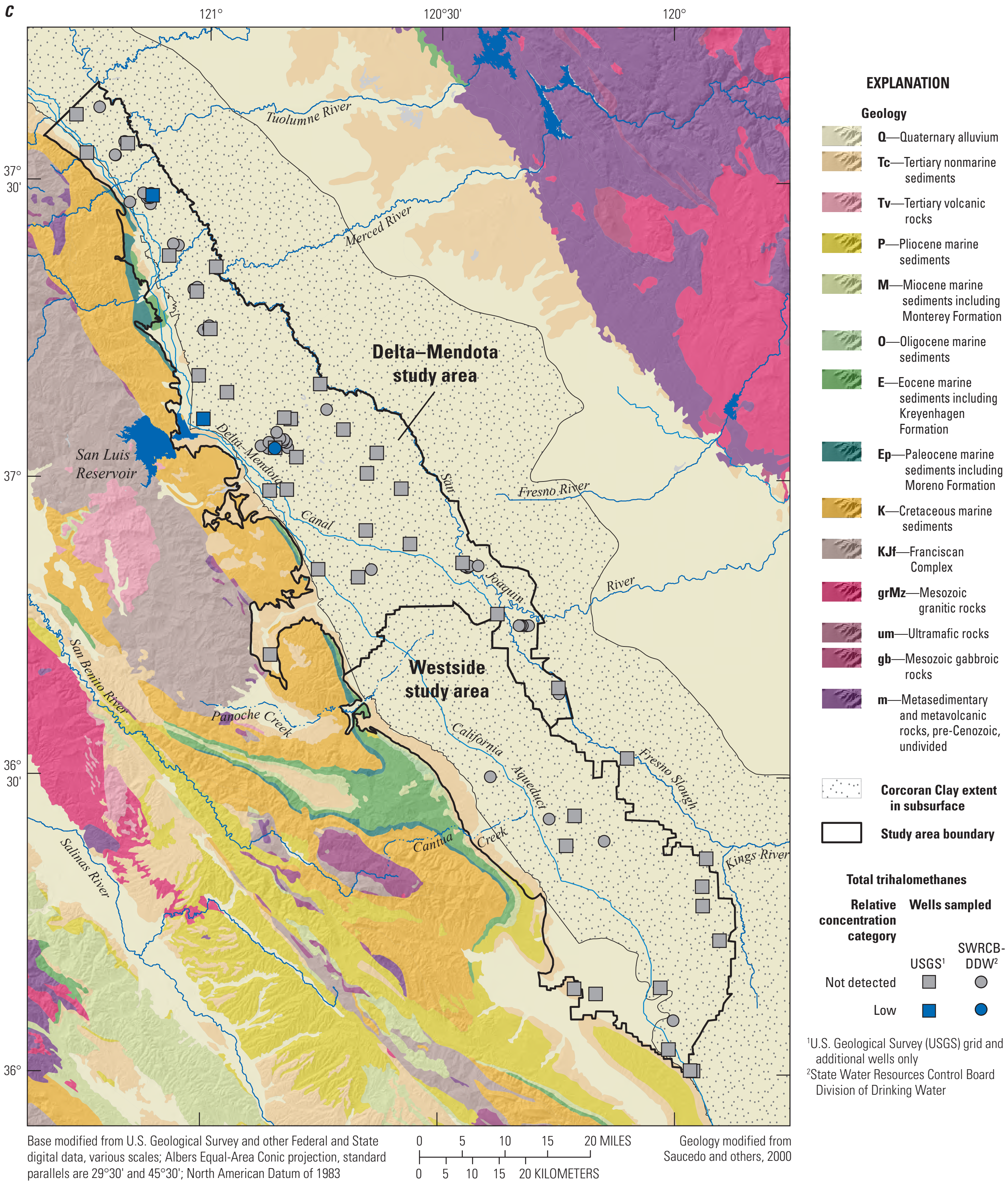

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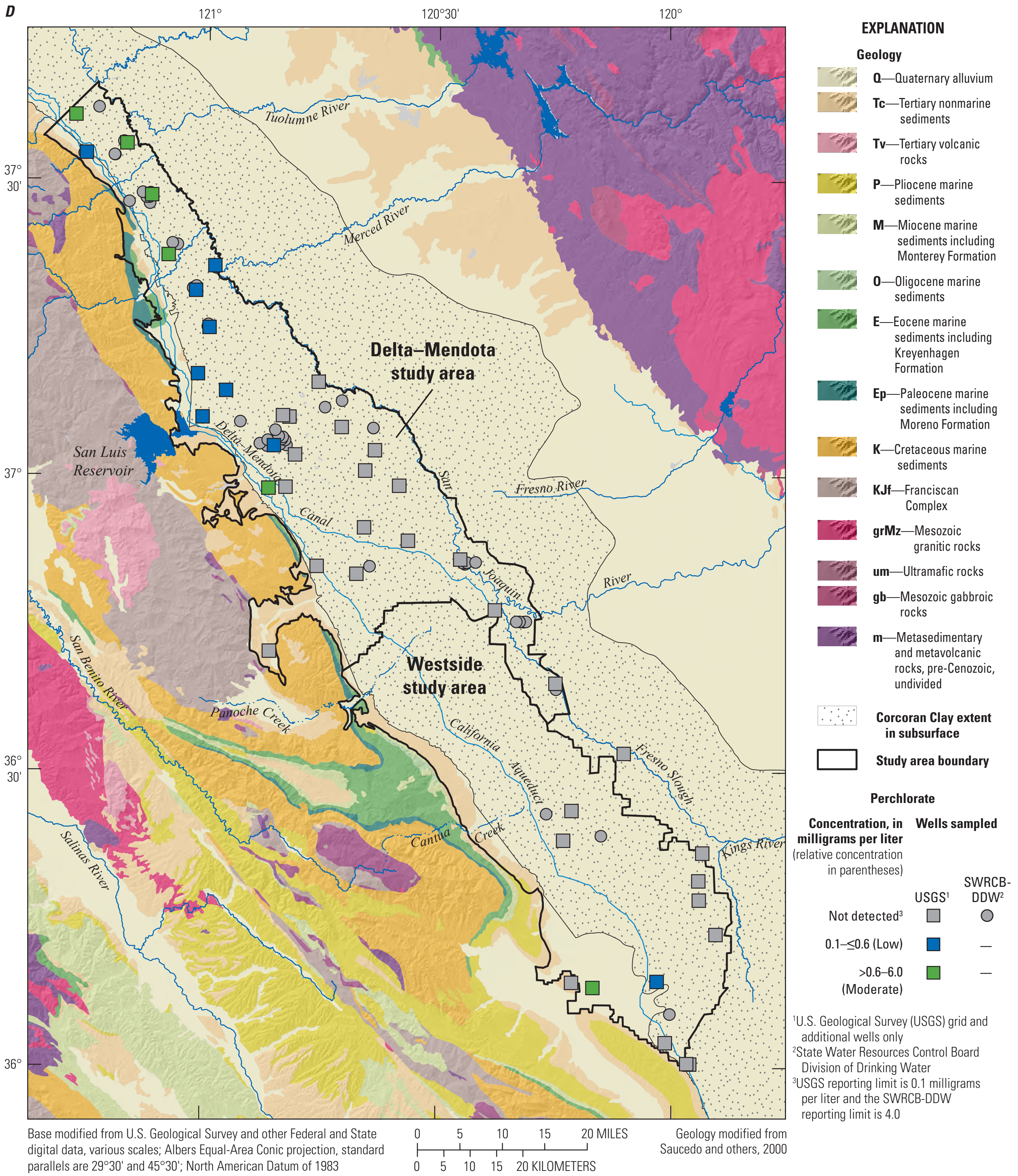
Figure 38. —Continued



[1] U.S. Geological Survey (USGS) grid and additional wells only

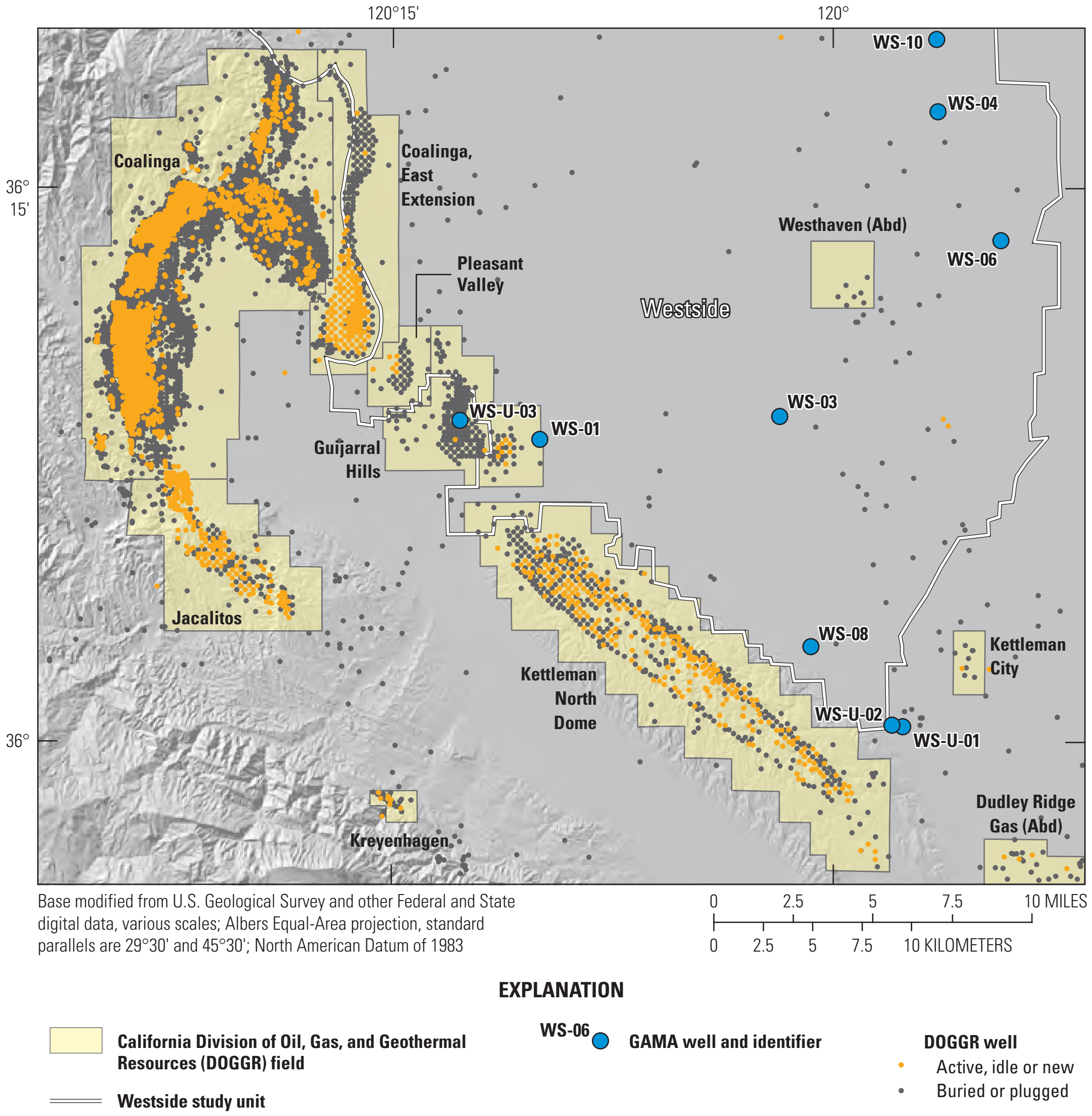
[2] State Water Resources Control Board Division of Drinking Water

[3] USGS reporting limit is 0.1 milligrams per liter and the SWRCB-DDW reporting limit is 4.0

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

Geology modified from Saucedo and others, 2000

Figure 38. —Continued



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

DOGGR fields and wells from California Division of Oil, Gas, and Geothermal Resources (2016b)

Figure 39. Administrative boundaries of oil and gas fields, location of wells from the California Department of Oil, Gas, and Geothermal Resources (DOGGR) database of wells associated with past and present oil and gas operations, and location of wells sampled by the U.S. Geological Survey (USGS) in the southern part of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Herbicides

Herbicides with health-based benchmarks were not present at high RCs or moderate RCs in the WSJV groundwater resources used for public drinking water, but were present at low RCs in 23.1 percent of groundwater resources (table 9*B*). Four herbicides were detected in samples from grid wells, simazine, atrazine, hexazinone, and molinate, and two other herbicides were detected in samples from additional wells, metolachlor and tebuthiuron (tables 4, 5; Mathany and others, 2013). All concentrations of herbicides were very low; the maximum RC for any individual herbicide or for the sum of all herbicides present in a sample was 0.02 (fig. 37). The most frequently detected herbicide in the WSJV study unit, simazine, was the most frequently detected herbicide resulting from agricultural, non-point source contamination in California (Troiano and others, 2001). Atrazine and simazine were among the most commonly detected herbicides in groundwater from wells in major aquifers across the United States (Gilliom and others, 2006). Historically, simazine was most commonly used in vineyards and orchards in the study unit, but also was used in rights-of-way for weed control (Domagalski and Dubrovsky, 1991).

The median concentrations of herbicides in groundwater in the two study areas were not significantly different (table 10*A*), although all of the grid wells with detections of herbicides were in the Delta–Mendota study area (fig. 38*B*). Concentrations of herbicides were greater in modern or mixed-age groundwater compared to premodern groundwater (table 10*A*). Of the 11 samples with detections of herbicides, 10 had modern or mixed-age groundwater. The well classified as having premodern groundwater (WS-U-01) in which herbicides were detected is a production well with a long screened interval that likely mixes groundwater with a wide range of ages; the fraction of modern groundwater containing herbicides could be too low to result in high enough values of tritium or ^{14}C to identify the presence of modern groundwater (Landon and others, 2010). The positive correlation between herbicides concentrations and DO concentration and negative correlation with pH (table 10*B*) likely reflect the association of higher DO concentrations and lower pH values in modern or mixed-age groundwater compared to premodern groundwater (table 7*A*; figs. 11–13).

Herbicide concentrations were not correlated with the percentage of agricultural land use (table 10*B*), nor were they correlated with nitrate concentrations (Spearman's rho = 0.24, $p = 0.125$,). Even among the 18 wells with modern or mixed-age groundwater, the concentration of herbicides was not correlated with percentage of agricultural land use (Spearman's rho = 0.28, $p = 0.261$) or with nitrate (Spearman's rho = 0.30, $p = 0.219$). Half of the wells with modern or mixed-age groundwater and detections of herbicides had anoxic groundwater conditions, indicating that the lack of correlation between nitrate and herbicide concentrations could be the result of degradation of nitrate from some samples under reducing conditions.

Trihalomethanes

Water used for drinking water and other household uses in domestic and public-supply systems commonly is disinfected with chlorine solutions (for example, sodium hypochlorite, or bleach; chlorine gas; chloramines; and chlorine dioxide). In addition to disinfecting the water, the chlorine compounds react with organic matter to produce trihalomethanes (THMs) and other chlorinated or brominated disinfection byproducts (for example, Ivahnenko and Barbash, 2004). The EPA MCL for total trihalomethanes, 80 µg/L, applies to the sum of the concentrations of the four THMs: chloroform, bromodichloromethane, dibromochloromethane, and bromoform. Chloroform was the most frequently detected VOC in groundwater across the USA (Zogorski and others, 2006).

Trihalomethanes were only detected at low RCs in the WSJV study unit (table 9*B*). The detection frequency for chloroform was 10.3 percent, and the detection frequency for any THM was 12.8 percent. Chloroform was detected in both study areas, and dibromochloromethane and bromoform were detected only in the Delta–Mendota study area (Mathany and others, 2013). Concentrations of THMs were negatively correlated with the percentage of agricultural land use and positively correlated with the septic tank density (table 10*B*). The THM concentrations were not correlated with groundwater age or with depths to the top or bottom of the screened interval, but were greater in samples from wells screened below the Corcoran Clay than in samples from wells screened above it (tables 10*A*, *B*).

These relations between THM concentrations and potential explanatory factors indicated that the distribution of THMs in WSJV wells could be more related to well operations than to the introduction of THMs to the aquifer system by recharge from irrigation with chlorinated water. Shock chlorination (often carried out by pouring bleach down a well) is a recommended procedure for treating bacterial contamination and odor problems in domestic drinking-water supply wells (Centers for Disease Control and Prevention, 2006), which could cause a reservoir of chlorinated water to form in the well bore and surrounding aquifer material. The chlorine would decay rapidly, but any THMs formed by reaction between the chlorine and organic matter could remain in the aquifer and then be pumped by the well.

Concentrations of THMs were greater in oxic groundwater and were positively correlated with dissolved oxygen concentrations (tables 10*A*, *B*); THMs can biodegrade under anoxic conditions (Zogorski and others, 2006).

Perchlorate

Perchlorate is an inorganic anion that is highly soluble in water. It was classified as a special-interest constituent because at the inception of the GAMA Priority Basin Project in 2003, perchlorate had recently been detected in public-supply wells in several areas of the State, and state agencies were evaluating whether or not an SWRCB-DDW MCL should be established. The SWRCB-DDW MCL of 6 μg/L was established in 2007. Perchlorate has natural and anthropogenic sources to groundwater. It forms naturally in the atmosphere and is present at very low concentrations in precipitation (Dasgupta and others, 2005; Parker and others, 2008; Rajagopalan and others, 2009). Naturally deposited perchlorate salts in the soils and unsaturated zones of aquifers in areas with arid to semi-arid climates can be re-solubilized and carried into deeper groundwater by recharge of applied irrigation water (Rao and others, 2007; Fram and Belitz, 2011). Perchlorate is a component of solid rocket fuel and is used in explosives, fireworks, safety flares, and other products (Dasgupta and others, 2005; U.S. Environmental Protection Agency, 2005). It also can be present in some fertilizers (Dasgupta and others, 2006; Böhlke and others, 2009) and can form in the chlorine solutions used for drinking-water disinfection (Greiner and others, 2008).

Perchlorate was not present at high RCs in the groundwater resources used for public drinking water of the WSJV study unit, but was present at moderate RCs in 15 percent (table 8). Perchlorate concentrations were greater in oxic groundwater than in anoxic groundwater (table 10*A*). Perchlorate was not detected in any of the 20 samples with manganese-reducing or manganese- and iron-reducing conditions, which likely reflects degradation of perchlorate: perchlorate and nitrate are reduced at similar oxidation-reduction potentials (Nozawa-Inoue and others, 2005).

The detection frequencies of perchlorate at concentrations greater than the thresholds of 0.1, 0.5, 1.0, and 4.0 μg/L were compared to the predicted probability of perchlorate being present at concentrations greater than the thresholds under natural conditions (Fram and Belitz, 2011) to evaluate if the distribution of perchlorate in the WSJV study unit was consistent with natural conditions or if anthropogenic sources of perchlorate were likely contributors to the concentrations detected in groundwater samples. Samples with oxic, suboxic, or nitrate-reducing conditions were divided into two groups by study area, and for each group, the average aridity index and the detection frequencies of perchlorate at concentrations greater than 0.1, 0.5, 1, and 4 μg/L were calculated (fig. 40). Detection frequencies in the samples from Westside study area wells, all of which were premodern age groundwater, were consistent with the predicted probability of detection expected under natural conditions. In contrast, detection frequencies in the samples from Delta–Mendota study area wells were greater than those likely under natural conditions for all four concentration thresholds, indicating that anthropogenic sources likely contributed notable amounts of perchlorate to the groundwater samples.

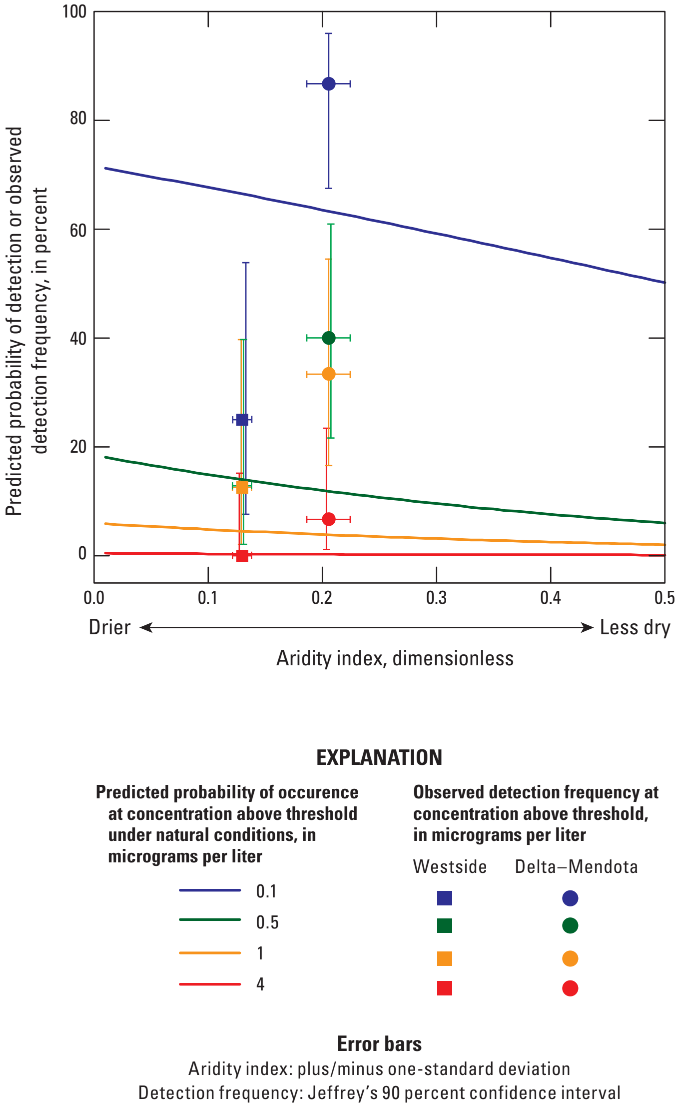


Figure 40. Predicted probability of detecting perchlorate in groundwater as a function of aridity index and the threshold concentration compared to the observed detection frequency of perchlorate in groundwater samples that had oxic, suboxic, or nitrate-reducing oxidation-reduction conditions, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Relations between perchlorate concentrations and concentrations of other constituents and potential explanatory factors also suggested that anthropogenic sources or processes contributed perchlorate to WSJV study unit groundwater. In groundwater from the 23 USGS grid and additional wells with oxic, suboxic, or nitrate-reducing conditions, perchlorate concentrations were positively correlated with nitrate (Spearman's rho = 0.85, $p < 0.001$; fig. 41*A*), selenium (rho = 0.69, $p < 0.001$), and strontium (rho = 0.56, $p = 0.006$) concentrations, with number of herbicide or fumigant compounds detected (rho = 0.47, $p = 0.024$), with noble-gas inferred groundwater recharge temperature (rho = 0.52, $p = 0.012$; fig. 41*A*) and with tritium activity (rho = 0.66, $p = 0.001$). As discussed in the section "Total Dissolved Solids, Sulfate, and Chloride", groundwater with noble gas recharge temperature greater than 22°C was inferred to represent recharge of pumped groundwater that was applied at the land surface for agricultural irrigation (fig. 20). Nitrate fertilizers, herbicides, and fumigants can be added to agricultural fields and then carried into groundwater by recharge of water used for irrigation. As discussed in the sections "Selenium" and "Strontium", both selenium and strontium can be incorporated into sulfate minerals that precipitate in WSJV soils and sediments, and δ^{34}S values of sulfate and geochemical modeling indicate that concentrations of selenium and strontium in groundwater are linked to dissolution of sulfate minerals (figs. 30–32). Perchlorate salts can also accumulate in soils and sediments in arid environments and then those salts can be dissolved when recharge increases due to application of water for irrigation (Erickson, 1981; Rajagopalan and others, 2006; Rao and others, 2007; Jackson and others, 2010; Fram and Belitz, 2011). These results are consistent with the hypothesis that mobilization of naturally deposited perchlorate salts from sediments and soils by recharge of water used for agricultural irrigation was responsible for increasing the detection frequency of perchlorate at concentrations greater than 1 µg/L in Delta–Mendota groundwater to frequencies higher than expected for natural hydrologic conditions. However, contribution of perchlorate from fertilizers (for example, Böhlke and others, 2009) cannot be ruled out.

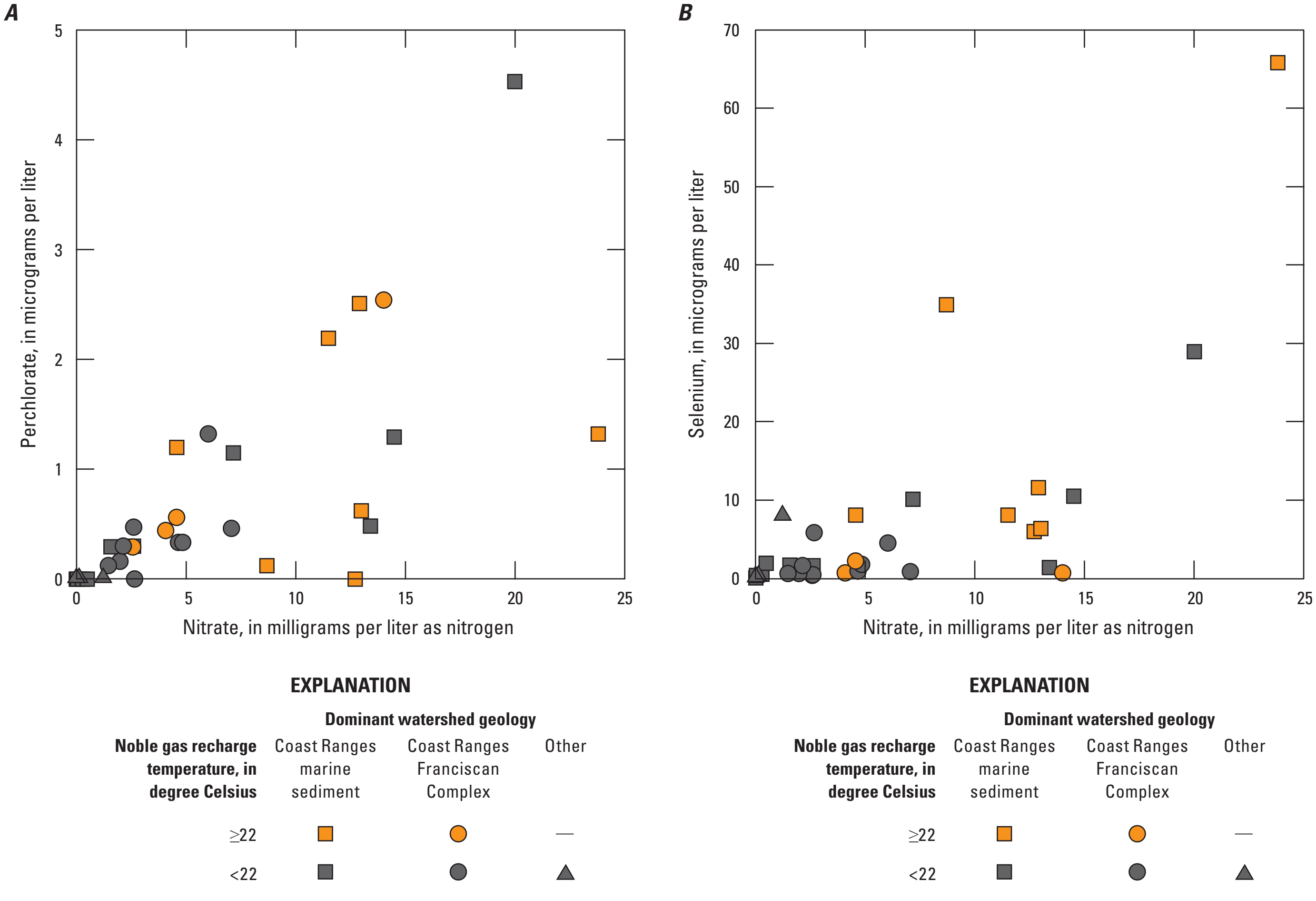


Figure 41. Concentrations of selected constituents as a function of dominant watershed geology and noble-gas inferred recharge temperature of groundwater in samples that had oxic, suboxic, or nitrate-reducing oxidation-reduction conditions, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, nitrate and perchlorate and *B*, nitrate and selenium.

Like perchlorate concentrations, selenium concentrations were positively correlated to nitrate (fig. 41*B*), and strontium concentrations, δ^{34}S of sulfate (fig. 30), noble-gas inferred groundwater-recharge temperature (fig. 41*B*), and tritium activities, suggesting that some of the elevated selenium concentrations in WSJV groundwater were the result of mobilization of naturally deposited selenium-bearing minerals in soils and sediments by recharge of water applied for irrigation.

Dubrovsky and others (1993) reached the same conclusion to account for patterns in selenium and TDS concentrations in samples from transects of multi-level monitoring wells in the Panoche Creek fan near the southern end of the Delta–Mendota study area (main transect began near the site of WSJV study unit well DM-02, and ended near Interstate-5, see fig. 5). In that study, selenium concentrations greater than 50 µg/L were found in groundwater from wells with screened intervals at depths of 6–46 m below the water table, and selenium concentrations were lower in groundwater above and below these depths. On the basis of tritium activities and stable isotope ratios in groundwater samples, Dubrovsky and others (1993) concluded that the groundwater with these elevated selenium concentrations represented recharge of water used for irrigation during the early period of extensive development of irrigated agriculture in the region. Large-scale irrigated agriculture and extensive groundwater pumping began in the 1940's and 1950's (Belitz and Heimes, 1990; Davis and Poland, 1957). This first water leached natural salts—including selenium-bearing sulfate salts—from the soils, resulting in a transient pulse of groundwater with elevated selenium concentrations (Dubrovsky and others, 1993).

Because this study focused on groundwater resources used for public drinking water, most of the wells were deeper than the monitoring wells sampled by Dubrovsky and others (1993). The four wells sampled for this study in the Delta–Mendota study area that had selenium concentrations greater than 10 µg/L (DM-11, -20, -28, -U-16), had well depths ranging from 51 to 78 m blsd (appendix table 1–2), which corresponded to depths below water level of 23 to 56 m [The depth to water table at each well location was estimated from the Spring 2000 water level map of Faunt (2009).] Only three of the wells had data for depth of top of screened interval; those depths ranged from 36 to 50 m below water level. Groundwater with noble-gas inferred recharge temperatures greater than 22 °C was found in Delta–Mendota study area wells as deep as 163 m below water table and with top of screened interval as deep as 88 m below water table. These results suggest that the front of groundwater affected by this transient pulse of high concentrations of selenium, perchlorate, and perhaps other constituents derived from dissolution of salts in the soils by irrigation water has moved deeper into the Delta–Mendota study area groundwater system during the 26 years between collection of the water samples by Dubrovsky and others (1993) and collection of the samples for this study. In some areas, the front of this pulse now appears to be reaching depth zones in the aquifer system that are used by public-supply wells.

Summary and Conclusions

Water quality in groundwater resources used for public drinking-water supply in the Western San Joaquin Valley (WSJV) was investigated by the USGS in cooperation with the California State Water Resources Control Board (SWRCB) as part of its Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. The WSJV study unit included two study areas, corresponding to the Delta–Mendota and Westside groundwater subbasins of the San Joaquin Valley groundwater basin. The two primary objectives of this study were addressed at the study-area scale and for the overall WSJV study unit: (1) a status assessment yielding quantitative estimates of the quality of groundwater resources used for public drinking water in 2010, and (2) an evaluation of natural and anthropogenic factors that could be affecting the groundwater quality. The assessments characterized the quality of untreated groundwater, not the quality of treated drinking water delivered to consumers by water distributors.

The status assessment was based on data collected by the U.S. Geological Survey (USGS) for the GAMA Priority Basin Project (USGS-GAMA) and data compiled in the SWRCB Division of Drinking Water (SWRCB DDW) database. The study unit was divided into forty 100-km^2 grid cells. Water-quality and ancillary data were collected for the USGS-GAMA wells in 39 of the 40 grid cells during 2010 (39 grid wells) and from 4 additional wells (public-supply wells screened or open at similar depths as the grid wells). These 43 wells were either public-supply wells or were wells screened at depths similar to those of public-supply wells in the vicinity. Samples were analyzed for organic constituents (volatile organic compounds and pesticides), inorganic constituents (major ions, trace elements), special interest constituents (perchlorate, NDMA, 1,2,3-TCP), and geochemical and age-dating tracers. Additional water-quality data were obtained from the SWRCB-DDW database for samples collected from 74 other public-supply wells within the study unit, sampled for regulatory compliance purposes between March 2007 and August 2010.

To provide context, concentrations of constituents measured in groundwater were compared to U.S. Environmental Protection Agency (EPA) and SWRCB-DDW regulatory and non-regulatory benchmarks for drinking-water quality. Relative concentration (RC) is the sample concentration divided by the benchmark concentration for the constituent. An RC value greater than 1.0 was defined as high for all constituents. For inorganic constituents and nutrients, RC values between 1.0 and 0.5 were defined as moderate; for organic and special interest constituents, RC values between 1.0 and 0.1 were defined as moderate. Lesser RCs were defined as low. The status assessment used a spatially weighted, grid-based method to estimate the proportion of the groundwater resources used for public drinking water containing high or moderate RCs for a particular constituent or class of constituents (aquifer-scale proportion). This method provides statistically unbiased results at the scale of the Delta–Mendota and Westside study areas within the WSJV study unit and permits comparison of the two study areas to other areas assessed by the GAMA Priority Basin Project statewide.

Groundwater resources used for public drinking water in the WSJV study unit are among the most saline and most affected by high concentrations of inorganic constituents of all groundwater resources used for public drinking water that have been assessed by the GAMA Priority Basin Project statewide. Among the 82 GAMA Priority Basin Project study areas statewide, the Delta–Mendota study area ranks above the 90th percentile for aquifer-scale proportions of groundwater resources having concentrations of total dissolved solids (TDS), sulfate, chloride, manganese, boron, chromium(VI), selenium, and strontium above benchmarks (RC greater than 1.0), and the Westside study area ranked above the 90th percentile for TDS, sulfate, manganese, and boron.

In the WSJV study unit as a whole, one or more inorganic constituents with regulatory or non-regulatory, health-based benchmarks [EPA and SWRCB-DDW maximum contaminant levels (MCL) and action levels (AL), SWRCB-DDW notification levels (NL), or EPA lifetime health advisory levels (HAL)] were detected at high RCs in 53 percent of the groundwater resources used for public drinking water and at moderate RCs in 30 percent. In contrast, organic constituents with health-based benchmarks were present at high RCs only in 3.1 percent of the groundwater resources used for public drinking water, and at moderate RCs in another 3.1 percent. Individual constituents present at high RCs in greater than 2 percent of groundwater resources used for public drinking water included: boron (51 percent, SWRCB-DDW NL), chromium(VI) (estimated 25 percent, SWRCB-DDW MCL), arsenic (10 percent, EPA MCL), strontium (5.1 percent, EPA HAL), nitrate (3.9 percent, EPA MCL), molybdenum (3.8 percent, EPA HAL), selenium (2.6 percent, EPA MCL), and benzene (2.6 percent, SWRCB-DDW MCL). High RCs of nitrate, chromium(VI), molybdenum, selenium, and strontium were found only in the Delta–Mendota study area and high RCs of benzene were found only in the Westside study area.

In addition, in the study unit as whole, 50 percent of the groundwater resources used for public drinking water had TDS concentrations greater than the non-regulatory, aesthetic-based SWRCB-DDW upper secondary maximum contaminant level (SMCL), and 44 percent had manganese concentrations greater than the SWRCB-DDW SMCL.

Natural and anthropogenic factors that could affect the groundwater quality were evaluated by using statistical tests of associations between constituent concentrations and values of potential explanatory factors, inferences from geochemical and age-dating tracer results, and by considering the water-quality results in the context of the hydrogeologic setting of the WSJV study unit. The evaluation of factors used data from the 43 wells sampled by USGS-GAMA for the status assessment and data from 16 monitoring wells sampled by USGS-GAMA during the same period. Factors evaluated included land-use characteristics (percentages of natural, urban, and agricultural land use and densities of septic tanks and underground fuel tanks around the well site), location characteristics (study area, lateral position between western and eastern edges of the study unit, depths to top and bottom of screened interval in well, and climate index), geologic features (aquifer lithology in the screened interval, well-screen position relative to the Corcoran Clay, and dominant lithology of sources of recharge in the upgradient watershed), and groundwater age and geochemical conditions (age classification, redox classification, dissolved oxygen concentration, and pH). The geochemical and age-dating tracers used included tritium and carbon-14; stable isotope ratios in water, nitrate, and sulfate; strontium isotopic composition; arsenate and arsenite species concentrations; and noble-gas inferred groundwater recharge temperatures.

Natural factors, particularly the lithologies of the source areas for groundwater recharge and of the aquifers, were the dominant factors affecting groundwater quality in most of the WSJV study unit. However, where groundwater resources used for public supply included groundwater recharged in the modern era, mobilization of constituents by recharge of water used for irrigation also affected groundwater quality. Public-supply wells in the Westside study area had a median depth of 305 m and primarily tapped groundwater recharged hundreds to thousands of years ago, whereas public-supply wells in the Delta–Mendota study area had a median depth of 85 m and primarily tapped either groundwater recharged within the last 60 years or groundwater consisting of mixtures of this modern recharge and older recharge.

Public-supply wells in the WSJV study unit are screened in the Tulare Formation of Plio-Pleistocene age, and zones above and below the Corcoran Clay horizon are used. The Tulare Formation primarily consists of alluvial sediments derived from the Coast Ranges to the west, except along the valley trough at the eastern margin of the WSJV study unit where the Tulare Formation consists of fluvial sands derived from the Sierra Nevada to the east. Groundwater from wells screened in the Sierra Nevada sands had manganese-reducing or manganese- and iron-reducing oxidation-reduction (redox) conditions. These redox conditions commonly were associated with elevated arsenic or molybdenum concentrations, and the dominance of arsenic(III) in the dissolved arsenic supports reductive dissolution of iron and manganese oxyhydroxides as the mechanism. In addition, groundwater from many wells screened in Sierra Nevada sands contained low concentrations of nitrite or ammonium, indicating reduction of nitrate by denitrification or dissimilatory processes, respectively.

The Coast Ranges adjacent to the WSJV study unit include two unusual geologic units that strongly affect groundwater quality in the study unit. Elevated concentrations of TDS, sulfate, boron, selenium and strontium in groundwater were primarily associated with aquifer sediments and recharge derived from areas of the Coast Ranges dominated by Cretaceous-to-Miocene age, organic-rich, reduced marine shales. Previous studies have demonstrated that these shales are the source of selenium in WSJV soils, surface water, and groundwater. Low sulfur-isotopic values ($\delta^{34}S$) of dissolved sulfate indicate that the sulfate was largely derived from oxidation of biogenic pyrite from the shales, and correlations between $\delta^{34}S$ and trace element concentrations, geologic setting, and groundwater geochemical modeling indicated that distributions of sulfate, strontium, and selenium in groundwater were controlled by dissolution of secondary sulfate minerals in soils and sediments.

Elevated concentrations of chromium(VI) were primarily associated with aquifer sediments and recharge derived from areas of the Coast Ranges dominated by the Franciscan Complex and ultramafic rocks. The Franciscan Complex also has boron-rich, sodium-chloride dominated hydrothermal fluids. These fluids mix with groundwater to a limited extent, contributing to elevated concentrations of boron, chloride, and TDS.

Groundwater from wells screened in Coast Ranges alluvium was primarily oxic and relatively alkaline (median pH value of 7.55) in the Delta–Mendota study area, and primarily nitrate-reducing or suboxic and alkaline (median pH value of 8.4) in the Westside study area. Many groundwater samples from those wells have elevated concentrations of arsenic(V), molybdenum, selenium, or chromium(VI), consistent with desorption of metal oxyanions from mineral surfaces under those geochemical conditions.

High concentrations of benzene were associated with deep wells located in the vicinity of petroleum deposits at the southern end of the Westside study area. Groundwater from these wells had premodern age and anoxic geochemical conditions, and the ratios among concentrations of hydrocarbon constituents were different from ratios found in fuels and combustion products, which is consistent with a geogenic source for the benzene rather than contamination from anthropogenic sources.

Water stable-isotope compositions, groundwater recharge temperatures, and groundwater ages were used to infer four types of groundwater: (1) groundwater derived from natural recharge of water from major rivers draining the Sierra Nevada; (2) groundwater primarily derived from natural recharge of water from Coast Ranges runoff; (3) groundwater derived from recharge of pumped groundwater applied to the land surface for irrigation; and (4) groundwater derived from recharge during a period of much cooler paleoclimate. Water previously used for irrigation was found both above and below the Corcoran Clay, supporting earlier inferences that this clay member is no longer a robust confining unit.

Recharge of water used for irrigation has direct and indirect effects on groundwater quality. Elevated nitrate concentrations and detections of herbicides and fumigants in the Delta–Mendota study area generally were associated with greater agricultural land use near the well and with water recharged during the last 60 years. However, the extent of the groundwater resource affected by agricultural sources of nitrate was limited by groundwater redox conditions sufficient to reduce nitrate. The detection frequency of perchlorate in Delta–Mendota groundwater was greater than expected for natural conditions. Perchlorate, nitrate, selenium, and strontium concentrations were correlated with one another and were greater in groundwater inferred to be recharge of previously pumped groundwater used for irrigation. The source of the perchlorate, selenium, and strontium appears to be salts deposited in the soils and sediments of the arid WSJV that are dissolved and flushed into groundwater by the increased amount of recharge caused by irrigation. In the Delta–Mendota study area, the groundwater with elevated concentrations of selenium was found deeper in the aquifer system than it was reported by a previous study 25 years earlier, suggesting that this transient front of groundwater with elevated concentrations of constituents derived from dissolution of soil salts by irrigation recharge is moving down through the aquifer system and may now be reaching the depth zone used for public drinking water supply.

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Table 1. Study area and grid-cell sizes, and numbers of public-supply wells and wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[km^2, square kilometers; SWRCB-DDW, California State Water Resources Control Board Division of Drinking Water]

Study area (abbreviations)	Area (km^2)	Gridded area (km^2)	Grid-cell area (km^2)	Number of SWRCB-DDW public-supply wells (number also sampled by USGS)[1]		Number of wells sampled by USGS		
				Well with data for any constituent	Wells with no data	Grid wells	Additional wells	Monitoring wells
Delta–Mendota (DM)	3,030	3,021	100	81 (13)	38 (2)	29	1	16
Westside (WS)	2,590	1,001	100	8 (2)	7 (4)	10	3	0
Study unit total	5,620	4,022	100	89 (15)	45 (6)	39	4	16

[1] For wells with USGS and SWRCB-DDW data, the USGS data were used.

Table 2. Summary of constituent groups and number of constituents sampled for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[“Intermediate” and “slow” sampling schedules refer to the amount of time required for a field crew to complete all work at a well.
Constituent names: 1,2,3-TCP, 1,2,3-trichloropropane; na, not applicable; NDMA, *N*-nitrosodimethylamine; TDS, total dissolved solids]

	Sampling schedule	
	Intermediate	Slow
Number of grid wells sampled	24	15
Number of additional wells sampled	1	3
Constituent class	**Number of constituents**	
Inorganic constituents		
Specific conductance	1	1
Major and minor ions, trace elements (including alkalinity, TDS, and uranium[1])	36	36
Chromium(VI)	na	1
Nutrients[2]	5	6
Organic constituents		
Pesticides and pesticide degradates	83	83
Volatile organic compounds (VOCs)[3]	85	85
Constituent of special interest		
Perchlorate and 1,2,3-TCP	2	2
NDMA	na	1
Geochemical and age-dating tracers		
Dissolved oxygen, pH, and temperature	3	3
Arsenic and iron redox species	2	2
Isotope ratios[4]	4	9
Carbon-14	1	1
Tritium	1	1
Noble gases (helium, neon, argon, krypton, xenon)	5	5
Sum:	228	236

[1] Uranium was analyzed with the trace elements, but was assigned to the inorganic constituent class “uranium and other radioactive constituents” for this study.

[2] Nitrate, nitrite, ammonia, total nitrogen, and phosphate were analyzed in samples from all grid wells; dissolved organic carbon only was analyzed in samples on the slow schedule.

[3] Includes 15 constituents classified as fumigants or fumigant synthesis byproducts (table 3*A* in Mathany and others, 2013).

[4] Ratios of stable isotopes of oxygen and hydrogen in water, stable isotopes of carbon in dissolved inorganic carbon, and stable isotopes of helium in dissolved helium were analyzed in all samples; ratios of stable isotopes of oxygen and nitrogen in dissolved nitrate, sulfur in dissolved sulfate, boron in dissolved boron, and strontium in dissolved strontium were measured only in samples on the slow schedule.

Table 3. Classification of relative concentrations of organic, special-interest, and inorganic constituents used for assessing groundwater quality in the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Relative concentration (RC) is defined as the measured value divided by a benchmark concentration. **Abbreviations**: >, greater than; ≤, less than or equal to]

RC category	RCs for organic and special-interest constituents	RCs for inorganic constituents
High	> 1	> 1
Moderate	> 0.1 and ≤ 1	> 0.5 and ≤ 1
Low	≤ 0.1	≤ 0.5

Table 4. Benchmark type and value and reporting limits for constituents present at high or moderate relative concentrations in samples used for the status assessment, and for organic constituents present at any concentration in more than 10 percent of grid-well samples, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Relative concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, RC greater than (>) 1.0 is defined as high, and 1.0 greater than or equal to (≥) RC > 0.5 is defined as moderate. For organic constitutents, RC > 1.0 is defined as high, and 1.0 ≥ RC > 0.1 is defined as moderate. **Benchmark types**: Regulatory, health-based benchmarks: MCL-CA, California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) maximum contaminant level; MCL-US, U.S. Environmental Protection Agency (EPA) maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, EPA lifetime health advisory level; NL-CA, SWRCB-DDW notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units**: mg/L, milligrams per liter; pCi/L, picocuries per liter; µg/L, micrograms per liter. **Other abbreviations**: na, not available; USGS, U.S. Geological Survey]

Constituent	Benchmarks			Reporting limits[2]		Understanding assessment presented?
	Type[1]	Value	Units	USGS	SWRCB-DDW	
Inorganic constituents with health-based benchmarks						
Nutrients						
Nitrate, as nitrogen[3]	MCL-US	10	mg/L	0.02	0.1	yes
Trace elements						
Aluminum	MCL-CA	1,000	µg/L	[6]1.6	50	no
Arsenic	MCL-US	10	µg/L	0.044	2	yes
Boron	NL-CA	1,000	µg/L	2.8	100	yes
Chromium(VI)	MCL-CA	10	µg/L	0.1	na	yes
Chromium	MCL-CA	50	µg/L	[6]0.42	5	no
Molybdenum	HAL-US	40	µg/L	0.028	na	yes
Selenium	MCL-US	50	µg/L	0.040	5	yes
Strontium	HAL-US	4,000	µg/L	0.40	na	yes
Vanadium	NL-CA	50	µg/L	0.16	2	no
Radioactive						
Gross alpha-particle activity[4,7]	MCL-US	15	pCi/L	na[7]	3	no
Radium activity[4,7]	MCL-US	5	pCi/L	na[7]	na	no
Uranium[4]	MCL-US	30	µg/L	0.008	1	no

Table 4. Benchmark type and value and reporting limits for constituents present at high or moderate relative concentrations in samples used for the status assessment, and for organic constituents present at any concentration in more than 10 percent of grid-well samples, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Relative concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, RC greater than (>) 1.0 is defined as high, and 1.0 greater than or equal to (≥) RC > 0.5 is defined as moderate. For organic constitutents, RC > 1.0 is defined as high, and 1.0 ≥ RC > 0.1 is defined as moderate. **Benchmark types**: Regulatory, health-based benchmarks: MCL-CA, California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) maximum contaminant level; MCL-US, U.S. Environmental Protection Agency (EPA) maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, EPA lifetime health advisory level; NL-CA, SWRCB-DDW notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units**: mg/L, milligrams per liter; pCi/L, picocuries per liter; µg/L, micrograms per liter. **Other abbreviations**: na, not available; USGS, U.S. Geological Survey]

Constituent	Benchmarks			Reporting limits[2]		Understanding assessment presented?
	Type[1]	Value	Units	USGS	SWRCB-DDW	
Inorganic constituents with aesthetic-based benchmarks						
Iron	SMCL-CA	300	µg/L	6	50	yes
Manganese	SMCL-CA	50	µg/L	0.7	10	yes
Chloride	SMCL-CA	[5]500	mg/L	0.06	1	yes
Sulfate	SMCL-CA	[5]500	mg/L	0.18	na	yes
Specific conductance[8]	SMCL-CA	[5]1,600	µS/cm	na	na	no
Total dissolved solids (TDS)	SMCL-CA	[5]1,000	mg/L	12	na	yes
Organic constituents with health-based benchmarks						
Volatile organic compounds (VOCs)						
Benzene	MCL-CA	1	µg/L	0.06	0.5	yes
Chloroform	MCL-US	80	µg/L	0.02	0.5	yes[9]
Tetrachloroethene	MCL-US	5	µg/L	0.026	0.5	no
Pesticides (including fumigants)						
1,2-Dibromo-3-chloropropane (DBCP)[4]	MCL-US	0.2	µg/L	0.03	0.01	no
Simazine	MCL-US	4	µg/L	0.006	1	yes[9]
Constituent of special interest						
Perchlorate	MCL-CA	6	µg/L	0.1	4	yes

[1] Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks: MCL-CA, SMCL-CA, and NL-CA are from the California State Water Resources Control Board (2015); MCL-US, and HAL-US are from the U.S. Environmental Protection Agency (2012).

[2] Non-detections are reported in the SWRCB-DDW database as a concentration of zero or as less than the reporting limit. The most prevalent reporting limit inferred from data for non-detections is listed for each constituent.

[3] Concentrations of nitrate, as nitrate reported in the SWRCB-DDW data are converted to concentrations of nitrate, as nitrogen, for comparison with USGS-GAMA data.

[4] Lead, gross alpha-particle activity, radium activity, uranium, and 1,2-dibromo-3-chloropropane were reported at high or moderate RCs in the SWRCB-DDW database during the period of March 1, 2007, through August 30, 2010, but not in USGS-grid or USGS-understanding wells.

[5] The SMCL-CA benchmarks for chloride, sulfate, TDS, and specific conductance have recommended and upper benchmark levels. The upper benchmark level is used as the comparison benchmark in this study.

[6] The reporting limit is a study reporting limit (SRL) as defined by Olsen, L.D, Fram, M.S., and Belitz, Kenneth, 2010, Review of trace-element field-blank data collected for the California Groundwater Ambient Monitoring and Assessment (GAMA) Program, May 2004–January 2008: U.S. Geological Survey Scientific Investigations Report 2009–5220, 47 p., https://pubs.usgs.gov/sir/2009/5220/.

[7] Radium and gross alpha-particle activities were not measured in samples collect by USGS-GAMA, and only a limited number of wells in the SWRCB-DDW database had data for these constituents.

[8] Specific conductance was converted to TDS and not assessed as a separate constituent.

[9] Simazine is evaluated as part of the class of herbicides, and chloroform is evaluated as part of the class of trihalomethanes.

Table 5. Benchmark type and value and reporting limits for constituents present only at low relative concentrations or lacking benchmarks and detected in samples collected for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Relative concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, RC greater than (>) 1.0 is defined as high, and 1.0 greater than or equal to (≥) RC > 0.5 is defined as moderate. For organic constitutents, RC > 1.0 is defined as high, and 1.0 ≥ RC > 0.1 is defined as moderate. **Benchmark types**: Regulatory, health-based benchmarks: AL-US, U.S. Environmental Protection Agency (EPA) action level; MCL-CA, California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) maximum contaminant level; MCL-US, EPA maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, EPA lifetime health advisory level; NL-CA, SWRCB-DDW notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units**: mg/L, milligrams per liter; µg/L, micrograms per liter. **Other abbreviations**: $CaCO_3$, calcium carbonate; na, not available; USGS, U.S. Geological Survey]

Constituent	Benchmarks			Reporting limits[2]	
	Type[1]	Value	Units	USGS	SWRCB-DDW
Inorganic constituents with benchmarks					
Antimony	MCL-US	6	µg/L	0.027	6
Barium	MCL-CA	1,000	µg/L	0.4	100
Beryllium	MCL-US	4	µg/L	0.012	1
Cadmium	MCL-US	5	µg/L	0.016	1
Copper	AL-US	1,300	µg/L	1.7	10
Fluoride	MCL-CA	2	mg/L	0.02	0.1
Lead	AL-US	15	µg/L	0.08	5
Ammonia, as nitrogen	HAL-US	30	mg/L	0.02	na
Nickel	MCL-CA	100	µg/L	0.36	10
Nitrite, as nitrogen	MCL-US	1	mg/L	0.001	0.1
Silver	SMCL-CA	100	µg/L	0.005	1
Thallium	MCL-US	2	µg/L	0.01	0.2
Zinc	SMCL-CA	5,000	µg/L	4.8	20
Inorganic constituents with no benchmarks					
Alkalinity	None	None	mg/L as $CaCO_3$	4	na
Bromide	None	None	mg/L	0.01	na
Calcium	None	None	mg/L	0.022	2
Cobalt	None	None	µg/L	0.38	na
Dissolved organic carbon	None	None	mg/L	0.66	na
Iodide	None	None	mg/L	0.001	na
Lithium	None	None	µg/L	0.22	na
Magnesium	None	None	mg/L	0.008	2
Nitrogen, total	None	None	mg/L	0.05	na
Orthophosphate	None	None	mg/L	0.004	0.04
Potassium	None	None	mg/L	0.032	1
Silica	None	None	mg/L	0.029	na
Sodium	None	None	mg/L	0.06	na
Tungsten	None	None	µg/L	0.11	na

Table 5. Benchmark type and value and reporting limits for constituents present only at low relative concentrations or lacking benchmarks and detected in samples collected for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Relative concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, RC greater than (>) 1.0 is defined as high, and 1.0 greater than or equal to (≥) RC > 0.5 is defined as moderate. For organic constitutents, RC > 1.0 is defined as high, and 1.0 ≥ RC > 0.1 is defined as moderate. **Benchmark types**: Regulatory, health-based benchmarks: AL-US, U.S. Environmental Protection Agency (EPA) action level; MCL-CA, California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) maximum contaminant level; MCL-US, EPA maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, EPA lifetime health advisory level; NL-CA, SWRCB-DDW notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units**: mg/L, milligrams per liter; µg/L, micrograms per liter. **Other abbreviations**: $CaCO_3$, calcium carbonate; na, not available; USGS, U.S. Geological Survey]

Constituent	Benchmarks			Reporting limits[2]	
	Type[1]	Value	Units	USGS	SWRCB-DDW
Organic constituents with health-based benchmarks					
Dibromochloromethane	MCL-US	[3]80	µg/L	0.12	1
Carbon disulfide	NL-CA	160	µg/L	0.06	na
Bromoform	MCL-US	[3]80	µg/L	0.1	0.5
Methyl *tert*-butyl ether (MTBE)	MCL-CA	13	µg/L	0.1	3
1,1-Dichloroethane	MCL-CA	5	µg/L	0.044	0.5
Trichloroethene	MCL-US	5	µg/L	0.022	na
Isopropylbenzene	NL-CA	770	µg/L	0.042	0.5
n-Propylbenzene	NL-CA	260	µg/L	0.036	na
Ethylbenzene	MCL-CA	300	µg/L	0.036	0.5
1,2-Dichloropropane	MCL-US	5	µg/L	0.026	0.5
o-Xylene	MCL-US	1,750	µg/L	0.08	0.5
m-Xylene and *p*-Xylene	MCL-US	1,750	µg/L	0.032	0.5
Atrazine	MCL-CA	1	µg/L	0.007	0.5
Hexazinone	HAL-US	400	µg/L	0.008	na
Molinate	MCL-CA	20	µg/L	0.0026	2
Metolachlor	HAL-US	700	µg/L	0.014	0.5
Tebuthiuron	HAL-US	1,000	µg/L	0.028	na
Organic constituents with no benchmarks					
1,2,3-Trimethylbenzene	None	None	µg/L	0.06	na
o-Ethyltoluene	None	None	µg/L	0.032	na
S-Ethyldipropylthioncarbamate (EPTC)	None	None	µg/L	0.002	na
Prometryn	None	None	µg/L	0.006	2
Deethylatrazine	None	None	µg/L	0.014	na
3,4-Dichloroaniline	None	None	µg/L	0.0042	na
2,6-Diethylaniline	None	None	µg/L	0.006	na
2-Ethyl-6-methylaniline	None	None	µg/L	0.01	na
3,5,-Dichloroaniline	None	None	µg/L	0.003	na

[1] Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks: MCL-CA, SMCL-CA, and NL-CA are from the California State Water Resources Control Board (2015); MCL-US, AL-US, and HAL-US are from the U.S. Environmental Protection Agency (2012).

[2] Non-detections are reported in the California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database as a concentration of zero or as less than the reporting limit. The most prevalent reporting limit inferred from data for non-detections is listed.

[3] The MCL-US threshold for trihalomethanes is for the sum of chloroform, bromoform, bromodichloromethane, and dibromochloromethane.

Table 6. Constituents reported in the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database at concentrations greater than benchmarks in samples collected during the historical period (March 1980 through February 2007), but not during the study period used for the status assessment (March 2007 through August 2010), Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Benchmark types**: Regulatory, health-based benchmarks: MCL-CA, California Department of Public Health (CDPH) maximum contaminant level; MCL-US, U.S. Environmental Protection Agency (EPA) maximum contaminant level; NL-CA, SWRCB-DDW notification level. Non-regulatory, aesthetic/technical-based benchmarks. **Benchmark units**: mg/L, milligrams per liter; µg/L, micrograms per liter. **Other abbreviations**: mm/dd/yyyy, month/day/year]

Constituent	Benchmark			Date of most recent high value (mm/dd/yyyy)	Number of wells with historical data	Number of wells that have had a high relative concentration
	Type[1]	Value	Units			
Inorganic constituents						
Aluminum[2]	MCL-CA	1,000	µg/L	03/31/2005	100	2
Cadmium	MCL-US	5	µg/L	12/11/2006	109	6
Chromium[2]	MCL-CA	50	µg/L	03/31/2005	110	3
Fluoride	MCL-CA	2	mg/L	01/30/2003	113	2
Lead	MCL-US	15	µg/L	11/03/2005	103	6
Organic constituents						
1,2-Dichloroethane	MCL-CA	0.5	µg/L	10/25/1986	117	1
1,4-Dichlorobenzene	MCL-CA	5	µg/L	06/11/2004	117	1
Bromodichloromethane	MCL-US	80	µg/L	07/01/1991	118	1
Tert-butyl alcohol	NL-CA	12	µg/L	07/08/2003	58	1
Carbon tetrachloride	MCL-CA	0.5	µg/L	02/28/1990	117	1
Dibromochloromethane	MCL-US	80	µg/L	07/01/1991	118	2
Ethylene dibromide (EDB)	MCL-US	0.05	µg/L	06/27/1990	109	1
Special-interest constituents						
Perchlorate[2]	MCL-CA	6	µg/L	05/09/2001	68	2

[1] Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks: MCL-CA, and NL-CA are from the California State Water Resources Control Board (2015); MCL-US are from the U.S. Environmental Protection Agency (2012).

[2] Constituent detected at moderate relative-concentrations during the study period, therefore, aquifer-scale proportion results are presented.

Table 7*A*. Results of Wilcoxon rank-sum tests on potential explanatory factors, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[*p*-values less than 0.05 were considered significant and *p*-values greater than or equal to 0.05 were considered not signifcant. **Study area**: DM, Delta–Mendota; WS, Westside. **Redox class**: anoxic, dissolved oxygen (DO) less than (<) 1 milligrams per liter (mg/L); oxic, DO greater than (>) 1 mg/L. **Groundwater age**: modmix, modern or mixed age groundwater with tritium greater than or equal to 0.5 tritium units (TU); pre, pre-modern age groundwater with tritium <0.5 TU. **Corcoran Clay**: above, above Corcoran Clay; below, below Corcoran Clay. **Aquifer geology**: CR, Coast Range alluvium; SN, Sierra Nevada sands. **Other abbreviations**: LUFT, leaking or formerly leaking underground fuel tank; ns, not significant]

	***p*-value and relative value of medians in the two categories for significant results**				
Factor group	**Location**	**Geologic conditions**		**Groundwater age and geochemistry**	
Categorical factor	**Study area**	**Corcoran Clay**	**Aquifer lithology**	**Redox class**	**Age class**
Categories	**DM, WS**	**above, below**	**CR, SN**	**oxic, anoxic**	**modmix, pre**
Number of wells in tests	**43**	**38**	**41**	**43**	**43**
Continuous factors representing land use characteristics					
Percentage of agricultural land use	0.926 ns	0.908 ns	0.099 ns	0.315 ns	0.453 ns
Percentage of natural land use	0.802 ns	0.411 ns	0.516 ns	0.458 ns	0.971 ns
Percentage of urban land use	0.550 ns	0.373 ns	0.477 ns	0.314 ns	0.441 ns
Density of LUFTs	0.139 ns	0.348 ns	0.597 ns	0.187 ns	0.047 modmix > pre
Density of septic tanks	0.001 DM > WS	0.411 ns	0.968 ns	0.004 oxic > anoxic	0.001 modmix > pre
Continuous factors representing location characteristics					
Aridity index	<0.001 DM > WS	0.707 ns	0.829 ns	0.003 oxic > anoxic	<0.001 modmix > pre
Lateral position	0.050 ns	0.194 ns	<0.001 CR > SN	0.015 oxic > anoxic	0.538 ns
Depth to top of screened interval[1]	0.002 WS > DM	0.002 below > above	0.338 ns	0.775 ns	0.002 pre > modmix
Depth to bottom of screened interval[1]	<0.001 WS > DM	0.001 below > above	0.267 ns	0.297 ns	0.001 pre > modmix
Continuous factors representing geochemical conditions					
Dissolved oxygen concentration	0.067 ns	0.621 ns	<0.001 CR > SN	<0.001 oxic > anoxic	0.001 modmix > pre
pH	<0.001 WS > DM	0.233 ns	0.276 ns	0.056 ns	0.001 pre > modmix

[1] Of the 43 wells, 41 had data for depth to bottom of screened interval or bottom of well and 30 had data for depth to top of screened interval.

Table 7*B*. Results of Spearman's rho tests on potential explanatory factors, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[All tests were done on a dataset consisting of the 43 grid and additional wells sampled by the U.S. Geological Survey (USGS) for the study unit, except for tests involving depth to top and bottom of screened intervals. ρ (rho), Spearman's rank-correlation statistic. The *p*-values (significance level of the Spearman's rho test) less than threshold value (α) of 0.05 are considered significant: bold text, significant correlation; blue shading, positive correlation; orange shading, negative correlation. **Abbreviations**: USTs, leaking (or formerly leaking) underground storage tanks; <, less than]

		Land-use characteristics				Location characteristics				Geochemistry	
	p-value *rho*	Percentage of natural land use	Percentage of urban land use	Density of USTs	Density of septic tanks	Aridity index	Normalized lateral position	Depth to top of screened interval	Depth to bottom of screened interval[1]	Dissolved oxygen concentration	pH
Land-use characteristics	Percentage of agricultural land use	<0.001 –0.78	<0.001 –0.70	0.151 –0.22	0.227 –0.19	0.831 –0.03	0.997 –0.00	0.440 –0.14	0.421 –0.13	0.546 –0.09	0.130 –0.23
	Percentage of natural land use		0.072 0.28	0.547 –0.09	0.650 –0.07	0.452 –0.12	0.905 0.02	0.551 0.11	0.900 0.02	0.569 –0.09	0.171 0.21
	Percentage of urban land use			0.002 0.46	0.121 0.24	0.930 –0.01	0.214 –0.19	0.440 0.14	0.133 0.24	0.628 0.08	0.269 0.17
	Density of LUFTs				<0.001 0.59	0.040 0.31	0.009 –0.40	0.006 –0.49	0.070 –0.29	0.559 0.09	0.295 –0.16
	Density of septic tanks					<0.001 0.80	0.635 –0.07	0.024 –0.41	0.008 –0.41	0.180 0.36	0.003 –0.44
Location measures	Aridity index						0.544 0.09	0.001 –0.56	< 0.001 –0.66	0.004 0.43	<0.001 –0.59
	Normalized lateral position							0.869 –0.03	0.885 –0.02	0.003 0.44	0.306 –0.16
	Depth to top of screened interval								<0.001 0.91	0.663 –0.08	<0.001 0.70
	Depth to bottom of screened interval[1]									0.277 –0.17	<0.001 0.67
Geo-chemistry	Dissolved oxygen concentration										0.039 –0.32

[1] For wells missing data for depth to bottom of screened interval, well depth was used. Of the 43 wells, 41 had data for depth to bottom of screened interval or bottom of well, and 30 had data for depth to top of screened interval.

Table 7*C*. Results of contingency table tests on potential explanatory factors, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Results in table body are given as *p*-values (significance level of the test statistic). For contingency table tests yielding a significant relation, the potential explanatory factors contributing most to the result of significance are described. Contribution determined by comparison of the magnitude of the test statistic for each element of the 2 x 2 matrix. **Study area**: DM, Delta–Mendota; WS, Westside. **Redox class**: anoxic, dissolved oxygen (DO) less than (<) 1 milligrams per liter (mg/L); oxic, DO greater than (>) 1 mg/L. **Groundwater age class**: modmix, modern or mixed (tritum > 0.5 tritium units, TU; and any ^{14}C percent modern carbon, pmc); Pre, pre-modern (tritium < 0.5 TU and ^{14}C < 90 pmc). **Corcoran Clay class**: above, above Corcoran Clay; below, below Corcoran Clay. **Aquifer geology**: CR, Coast Range alluvium; SN, Sierra Nevada sands. **Other abbreviations**: ns, no significant differences]

	Potential explanatory factor	**Geochemistry and age**		**Geology**	
		Redox class (oxic, anoxic)	**Groundwater age (modmix, pre)**	**Corcoran Clay (above, below)**	**Aquifer lithology (CR, SN)**
Location	Study area (DM, WS)	0.051 ns	<0.001 WS samples are pre and not modmix	0.908 ns	0.781 ns
Geochemistry and age	Redox class (oxic, anoxic)		<0.001 oxic samples are modmix and not pre	0.405 ns	<0.001 SN is anoxic and not oxic
	Groundwater age (modmix, pre)			0.721 ns	0.422 ns
Geology	Corcoran Clay (above, below)				0.204 ns

Table 8. Aquifer-scale proportions for constituents present at high or moderate relative concentrations in groundwater resources used for public drinking water and organic constituents detected at any concentration with detection frequencies greater than 10 percent in samples collected from grid wells, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) categories for inorganic constituents**: high, RC greater than (>) 1.0, moderate; 1.0 greater than or equal to (≥) RC > 0.5; low, RC less than or equal to (≤) 0.5. **RC categories for organic and special-interest constituents**: high, RC > 1.0; moderate, 1.0 ≥ RC > 0.1; low, RC ≤ 0.1. RC defined as measured value divided by benchmark value. Constituents not listed in this table either do not have benchmarks or were detected only at low RCs. Benchmark types and values listed in table 4. **Abbreviations**: na, not available]

WSJV study unit	Number		Raw detection frequency (percentage)		Aquifer-scale proportions (percentage)	
Constituent	**Wells**	**Cells**	**Moderate RC**	**High RC**	**Moderate RC**	**High RC**
Inorganic constituents with health-based benchmarks						
Nutrients						
Nitrate	115	39	24.3	3.6	15.0	3.9
Trace elements						
Aluminum	96	39	1.0	0	1.3	0
Arsenic	96	39	24.0	13.5	16.3	10.1
Boron	48	39	35.4	43.8	31.8	51.3
Chromium(VI)[1]	96	39	1.0	37.5	0.5	24.8
Chromium	96	39	13.5	0	7.3	0
Molybdenum	43	39	16.3	4.7	16.7	3.8
Selenium	95	39	2.1	1.1	1.7	2.6
Strontium	43	39	11.6	4.7	12.8	5.1
Vanadium	48	39	2.1	0	0.9	0
Uranium and other radioactive constituents						
Uranium	63	39	3.2	1.6	2.1	0.6
Gross alpha-particle activity[2]	45	22	15.6	8.9	na	na
Radium[2]	37	18	0	2.7	na	na
Inorganic constituents with aesthestic-based benchmarks						
Chloride	94	39	20.2	6.4	22.0	14.1
Sulfate	94	39	23.4	17.0	23.6	28.6
Total dissolved solids	94	39	47.9	38.5	44.0	49.7
Iron	96	39	4.2	13.5	4.4	14.4
Manganese	97	39	6.2	37.1	8.3	44.3
Organic constituents with health-based benchmarks						
Pesticides and fumigants						
Simazine	78	39	0	0	0	0
1,2-Dibromo-3-chloropropane	95	39	5.3	0	3.1	0
Volatile organic compounds						
Benzene	95	39	0	3.2	0	2.6
Chloroform	95	39	0	0	0	0
Tetrachloroethene	95	39	2.1	1.1	0.7	0.5
Special-interest constituents						
Perchlorate[3]	94	39	>6.2	0	15.4	0

[1] Measured chromium(VI) concentrations were available for 30 wells in 15 cells. For the other 66 wells, chromium(VI) concentrations were estimated to be 0.9 times the measured chromium concentration.

[2] Data for gross alpha-particle activity, and radium were available for wells in less than two-thirds of the 39 cells; therefore, aquifer-scale proportions were not calculated.

[3] The moderate-RC aquifer-scale proportion for perchlorate was calculated using U.S. Geological Survey (USGS)-GAMA data only. The reporting limit for perchlorate in the SWRCB-DDW database, 4 micrograms per liter (μg/L), corresponds to an RC of 0.67. The raw occurrence frequency of moderate-RC is only a minimum estimate of the actual raw occurrence frequency.

Table 9*A*. Aquifer-scale proportions for inorganic constituents in groundwater resources used for public drinking water in the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) categories**: high, RC greater than (>) 1.0 for at least one constituent in the class; moderate, RC > 0.5 for at least one constituent in the class and no constituents with RC > 1; low, RC less than or equal to 0.5 for all constituents in the class. RC defined as measured value divided by benchmark value. **Abbreviations**: SMCL, secondary maximum contaminant level]

Constituent class	Aquifer-scale proportion (percentage)		
	Low RC[1]	Moderate RC	High RC
Inorganic constituents with health-based benchmarks (HBB)			
Nutrients	81.1	15.0	3.9
Trace elements	20.7	27.1	52.2
Uranium or other radioactive constituents	91.6	5.1	3.3
Any HBB inorganic constituent	17.3	29.9	52.8
Inorganic constituents with aesthetic-based (SMCL) benchmarks			
Total dissolved solids, chloride, or sulfate	6.3	41.1	52.3
Manganese and iron	46.2	8.2	45.6
Any SMCL inorganic constituent	3.2	26.9	69.9

[1] Non-detections of inorganic constituents are included in the low-RC aquifer-scale proportion.

Table 9*B*. Aquifer-scale proportions for organic and special-interest constituents in groundwater resources used for public drinking water in the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) categories**: high, RC greater than (>) 1.0 for at least one constituent in the class; moderate, RC > 0.1 for at least one constituent in the class and no constituents with RC > 1.0; low, RC less than or equal to 0.1 for all constituents in the class; not detected, no constituents in the class detected. RC defined as measured value divided by benchmark value.]

Constituent class	Aquifer-scale proportions (percentage)			
	Not detected	Low RC	Moderate RC	High RC
Any organic constituent	64.1	29.8	3.1	3.1
Any pesticide	74.4	22.5	3.1	0
Herbicides	76.9	23.1	0	0
Fumigants	92.3	4.6	3.1	0
Any volatile organic compound (VOC)	82.1	14.1	0.7	3.1
Trihalomethanes	87.2	12.8	0	0
Solvents	94.9	3.9	0.7	0.5
Gasoline hydrocarbons	97.4	0	0	2.6

Table 10*A*. Results of Wilcoxon rank-sum tests for significance of relations between values of selected potential explanatory factors and concentrations of selected water-quality constituents in samples collected by the U.S. Geological Survey (USGS) for the status assessment of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[The *p*-values less than 0.05 were considered significant. **Study area**: DM, Delta–Mendota; WS, Westside. **Redox status**: anoxic, dissolved oxygen (DO) less than (<) 1 milligram per liter (mg/L); oxic, DO greater than (>) 1 mg/L. **Groundwater age**: modmix, modern or mixed-age groundwater with tritium > 0.5 tritium unit (TU); pre, pre-modern age groundwater with tritium < 0.5 TU. **Corcoran Clay**: above, above Corcoran Clay; below, below Corcoran Clay. **Aquifer geology**: CR, Coast Range alluvium; SN, Sierra Nevada sands. **Other abbreviations**: ns, no significant differences]

	***p*-value and relative value of medians in the two categories**				
Factor group	**Location**	**Geologic conditions**		**Groundwater age and geochemistry**	
Categorical factor	**Study area**	**Corcoran Clay**	**Aquifer lithology**	**Redox class**	**Age class**
Categories	**DM, WS**	**above, below**	**CR, SN**	**oxic, anoxic**	**modmix, pre**
Number of wells in tests	**43**	**38**	**41**	**43**	**43**
Inorganic constituents with health-based benchmarks					
Nitrate	0.224	0.756	< 0.001	< 0.001	0.008
	ns	ns	CR > SN	oxic > anoxic	Modmix > pre
Arsenic	0.543	0.161	0.074	0.018	0.179
	ns	ns	ns	anoxic > oxic	ns
Boron	0.239	0.119	0.276	0.831	0.369
	ns	ns	ns	ns	ns
Chromium(VI)	0.012	0.613	0.025	< 0.001	0.045
	DM > WS	ns	CR > SN	oxic > anoxic	Modmix > pre
Chromium	0.004	0.687	< 0.001	< 0.001	0.075
	DM > WS	ns	CR > SN	oxic > anoxic	ns
Molybdenum	< 0.001	0.686	0.016	< 0.001	< 0.001
	WS > DM	ns	SN > CR	anoxic > oxic	Pre > modmix
Selenium	0.895	0.685	< 0.001	< 0.001	0.129
	ns	ns	CR > SN	oxic > anoxic	ns
Strontium	0.015	0.931	0.213	0.191	0.161
	DM > WS	ns	ns	ns	ns
Inorganic constituents with aesthetic-based benchmarks					
Sulfate	0.245	0.840	0.801	0.474	0.124
	ns	ns	ns	ns	ns
Chloride	0.002	0.862	0.866	0.841	0.200
	DM > WS	ns	ns	ns	ns
Total dissolved solids	0.606	0.470	0.860	0.309	0.369
	ns	ns	ns	ns	ns
Iron	0.832	0.965	0.001	0.002	0.721
	ns	ns	SN > CR	anoxic > oxic	ns
Manganese	0.832	0.292	< 0.001	< 0.001	0.061
	ns	ns	SN > CR	anoxic > oxic	ns
Organic and special-interest constituents with health-based benchmarks					
Benzene	0.036	0.100	0.150	0.111	0.079
	WS > DM	ns	ns	ns	ns
Total trihalomethanes	0.537	0.042	0.366	0.030	0.338
	ns	Below > above	ns	oxic > anoxic	ns
Total herbicides	0.113	0.498	0.389	0.095	< 0.001
	ns	ns	ns	ns	Modmix > pre
Perchlorate	0.064	0.277	< 0.001	< 0.001	< 0.001
	ns	ns	CR > SN	oxic > anoxic	Modmix > pre

Table 10*B*. Results of Spearman's rho tests for significance of relations between values of selected potential explanatory factors and concentrations of selected water-quality constituents in samples collected by the U.S. Geological Survey (USGS) for the status assessment of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[All tests were done on a dataset consisting of the 43 grid and additional wells sampled by USGS for the study unit, except for tests involving depth to top and bottom of screened interval. ρ (rho), Spearman's rank-correlation statistic. The *p*-values (significance level of the Spearman's rho test) less than threshold value (α) of 0.05 are considered significant: bold text, significant correlation; blue shading, positive correlation; orange shading, negative correlation. **Abbreviations**: LUFTs, leaking (or formerly leaking) underground storage tanks; THMs, trihalomethanes; <, less than]

	Land-use characteristics					**Location characteristics**				**Geochemistry**	
p*-value** ***rho	**Percentage of agricultural land use**	**Percentage of natural land use**	**Percentage of urban land use**	**Density of LUFTs**	**Density of septic tanks**	**Aridity index**	**Normalized lateral position**	**Depth to top of screened or open interval**	**Depth to bottom of screened or open interval[1]**	**Dissolved oxygen (DO) concentration**	**pH**
Inorganic constituents with health-based benchmarks											
Nitrate	0.941	0.172	0.608	0.213	0.142	0.059	**0.020**	0.294	0.457	**<0.001**	0.180
	–0.01	–0.21	0.08	0.19	0.23	0.29	**0.35**	–0.20	–0.12	**0.82**	–0.21
Arsenic	0.853	0.926	0.210	0.446	0.748	0.281	0.067	0.961	0.994	**0.005**	0.634
	–0.03	0.01	0.19	0.12	0.05	–0.17	–0.28	0.01	0.00	**–0.42**	0.07
Boron	0.316	**0.008**	0.158	**0.007**	0.122	0.605	**0.002**	**0.025**	0.633	0.912	0.195
	–0.16	**0.40**	–0.22	**–0.40**	–0.24	–0.08	**0.46**	**0.41**	0.08	–0.02	0.20
Chromium(VI)	0.603	**0.008**	0.552	0.552	0.125	**0.004**	**0.004**	0.715	0.114	**<0.001**	**0.014**
	0.13	**–0.60**	0.15	0.14	0.37	**0.64**	**0.64**	–0.10	–0.38	**0.86**	**–0.57**
Chromium	0.553	0.728	0.885	0.727	0.058	**0.002**	**0.001**	0.559	**0.048**	**<0.001**	**0.032**
	–0.10	–0.05	0.02	0.05	0.29	**0.47**	**0.50**	–0.11	**–0.31**	**0.70**	**–0.33**
Molybdenum	0.551	0.763	0.881	0.237	**0.001**	**<0.001**	**0.028**	**0.003**	**<0.001**	**<0.001**	**<0.001**
	0.09	0.05	–0.02	–0.18	**–0.48**	**–0.63**	**–0.34**	**0.52**	**0.52**	**–0.65**	**0.55**
Selenium	0.947	0.197	0.986	0.530	0.731	0.315	0.123	0.849	0.963	**<0.001**	0.372
	0.01	–0.20	0.00	0.10	0.05	0.16	0.24	0.01	0.01	**0.72**	–0.14
Strontium	0.142	0.106	0.258	0.947	0.741	**0.036**	**0.046**	0.123	0.041	0.162	**0.001**
	0.23	–0.25	–0.18	–0.01	0.05	**0.32**	**0.31**	–0.29	–0.32	0.22	**–0.47**
Inorganic constituents with aesthetic-based benchmarks											
Sulfate	0.416	0.901	0.507	0.133	**0.009**	0.142	0.994	**0.043**	0.211	0.586	0.514
	0.13	–0.02	–0.10	–0.23	**–0.40**	–0.23	0.00	**0.37**	0.20	–0.08	0.10
Chloride	0.361	0.143	0.507	0.850	0.159	**0.014**	**0.049**	0.250	**0.010**	0.837	0.061
	–0.14	0.23	–0.10	–0.03	0.22	**0.38**	**0.30**	–0.22	**–0.40**	0.03	–0.29
Total dissolved solids	0.973	0.427	0.229	0.148	0.057	0.856	0.263	0.587	0.516	0.412	0.891
	–0.01	0.12	–0.19	–0.22	–0.29	–0.03	0.17	0.10	–0.10	–0.13	0.02
Iron	0.180	0.856	0.480	0.479	0.644	0.378	0.079	0.675	0.839	**0.007**	0.244
	0.21	0.03	–0.11	–0.11	–0.07	–0.14	–0.27	–0.08	–0.03	**–0.40**	0.244

Table 10*B*. Results of Spearman’s rho tests for significance of relations between values of selected potential explanatory factors and concentrations of selected water-quality constituents in samples collected by the U.S. Geological Survey (USGS) for the status assessment of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[All tests were done on a dataset consisting of the 43 grid and additional wells sampled by USGS for the study unit, except for tests involving depth to top and bottom of screened interval. ρ (rho), Spearman’s rank-correlation statistic. The *p*-values (significance level of the Spearman’s rho test) less than threshold value (α) of 0.05 are considered significant: bold text, significant correlation; blue shading, positive correlation; orange shading, negative correlation. **Abbreviations**: LUFTs, leaking (or formerly leaking) underground storage tanks; THMs, trihalomethanes; <, less than]

	Land-use characteristics					Location characteristics				Geochemistry	
p*-value** ***rho	**Percentage of agricultural land use**	**Percentage of natural land use**	**Percentage of urban land use**	**Density of LUFTs**	**Density of septic tanks**	**Aridity index**	**Normalized lateral position**	**Depth to top of screened or open interval**	**Depth to bottom of screened or open interval[1]**	**Dissolved oxygen (DO) concentration**	**pH**
Inorganic constituents with aesthetic-based benchmarks—Continued											
Manganese	0.174	0.993	0.395	0.945	0.363	0.206	**0.009**	0.319	0.765	**< 0.001**	0.829
	0.21	0.00	–0.13	–0.01	–0.14	–0.20	**–0.40**	–0.19	–0.05	**–0.78**	–0.03
Organic and special-interest constituents with health-based benchmarks											
Benzene	**0.002**	**0.003**	0.190	0.370	0.114	**0.018**	0.529	0.585	0.284	0.124	**0.007**
	–0.46	**0.45**	0.20	–0.14	–0.24	**–0.36**	0.10	0.10	0.17	–0.24	**0.41**
Total THMs	**0.045**	0.314	0.092	0.107	**0.016**	0.251	0.215	0.842	0.768	**0.027**	0.142
	–0.31	0.16	0.26	0.25	**0.36**	0.18	0.19	0.04	0.05	**0.34**	–0.23
Total herbicides	0.812	0.665	0.733	0.742	0.723	0.371	0.203	0.155	0.116	**0.030**	**0.017**
	–0.04	0.07	0.05	0.05	0.06	0.14	0.20	–0.26	–0.25	**0.33**	**–0.36**
Perchlorate	0.449	0.638	0.565	0.695	**0.013**	**<0.001**	**0.012**	0.658	0.380	**<0.001**	**0.021**
	–0.12	–0.07	0.09	0.06	**0.38**	**0.49**	**0.38**	–0.08	–0.14	**0.91**	**–0.35**

[1] For wells missing data for depth to bottom of perforations, well depth was used. Of the 43 wells, 41 had data for depth to bottom of perforation or bottom of well, and 30 had data for depth to top of perforations.

[2] Total THMs include chloroform, dibromochloromethane, and bromoform.

Table 11. Results of Spearman's rho tests for correlations between concentrations of selected water-quality constituents in samples collected by the U.S. Geological Survey (USGS) for the status assessment of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[All tests were done on a dataset consisting of the 43 grid and additional wells sampled by USGS for the study unit. ρ (rho), Spearman's rank-correlation statistic. The *p*-values (significance level of the Spearman's rho test) less than threshold value (α) of 0.05 are considered significant; bold text, significant correlation; blue shading, positive correlation; orange shading, negative correlation. **Abbreviations**: TDS, total dissolved solids; <, less than]

p-value *rho*	Arsenic	Boron	Chromium (VI)	Chromium	Molybdenum	Selenium	Strontium	Sulfate	Chloride	TDS	Iron	Manganese	Perchlorate
Nitrate	**0.010**	0.390	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.020**	0.836	0.697	0.971	**<0.001**	**<0.001**	**<0.001**
	–0.39	–0.13	**0.72**	**0.66**	**–0.56**	**0.78**	**0.35**	0.03	0.06	0.01	**–0.50**	**–0.79**	**0.84**
Arsenic		**0.031**	0.120	**0.003**	**0.032**	**0.004**	0.058	0.417	0.567	0.197	0.118	**<0.001**	**<0.001**
		–0.33	–0.38	**–0.44**	**0.33**	**–0.43**	–0.29	–0.13	–0.09	–0.20	0.24	**0.50**	**–0.53**
Boron			0.492	0.074	0.285	0.648	0.291	0.058	**0.035**	**0.004**	0.244	0.468	0.800
			0.17	0.27	0.17	–0.07	0.16	0.29	**0.32**	**0.43**	–0.18	–0.11	–0.04
Chromium(VI)				**<0.001**	**0.004**	**0.001**	**0.012**	0.876	0.767	0.876	**0.010**	**<0.001**	**<0.001**
				0.88	**–0.64**	**0.70**	**0.58**	–0.04	0.07	–0.04	**–0.59**	**–0.83**	**0.81**
Chromium					**<0.001**	**<0.001**	**0.003**	0.897	**0.025**	0.261	**<0.001**	**<0.001**	**<0.001**
					–0.61	**0.55**	**0.44**	–0.02	**0.34**	0.18	**–0.65**	**–0.61**	**0.70**
Molybdenum						0.099	0.090	**0.008**	**0.042**	0.401	0.262	**<0.001**	**<0.001**
						–0.26	–0.26	**0.40**	**–0.31**	0.13	0.17	**0.50**	**–0.66**
Selenium							**0.039**	**0.048**	0.600	0.445	**<0.001**	**<0.001**	**<0.001**
							0.32	**0.30**	–0.08	0.12	**–0.53**	**–0.70**	**0.73**
Strontium								**<0.001**	**0.006**	**<0.001**	0.380	0.446	**0.023**
								0.57	**0.42**	**0.66**	–0.14	–0.12	**0.35**
Sulfate									0.596	**<0.001**	0.957	0.713	0.907
									0.08	**0.74**	0.01	0.06	0.02
Chloride										**<0.001**	0.805	0.682	0.377
										0.59	0.04	0.06	0.14
TDS											0.548	0.673	0.920
											–0.09	0.07	0.02
Iron												**<0.001**	**0.004**
												0.74	**–0.43**
Manganese													**<0.001**
													–0.78

Appendix 1. Data Tables

Table 1–1. Well construction, lateral position, and aridity index data for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[LSD, land-surface datum; m; meter; NAVD 88, North American Vertical Datum 1988; —, no data available]

Well identification	Well depth (m below LSD)	Top of screened interval (m below LSD)	Bottom of screened interval (m below LSD)	Altitude of LSD (m above NAVD 88)[2]	Normalized lateral position (dimensionless)	Aridity index[3]
Delta–Mendota study-area grid wells						
DM-01	278.3	202.1	275.2	50.3	0.00	0.16
DM-02	76.2	42.7	76.2	49.4	0.11	0.16
DM-03	94.5	50.0	93.9	37.5	0.65	0.19
DM-04	54.9	35.1	52.4	33.5	0.19	0.21
DM-05	70.1	35.1	67.1	44.8	0.13	0.16
DM-06	182.0	104.2	178.9	26.5	0.42	0.23
DM-07	91.4	—	—	30.8	0.68	0.20
DM-08	79.2	56.4	—	44.5	0.96	0.19
DM-09	192.0	—	—	27.4	0.38	0.22
DM-10	137.2	112.8	135.3	29.6	0.46	0.22
DM-11	51.2	44.5	51.2	15.8	0.17	0.23
DM-12	106.7	—	—	39.9	0.50	0.21
DM-13	152.4	121.9	152.4	46.9	0.78	0.18
DM-14	31.7	—	—	19.2	0.03	0.23
DM-15	66.4	60.4	66.4	44.2	0.55	0.18
DM-16	45.7	39.6	45.7	34.7	0.33	0.20
DM-17	85.3	—	—	351.7	1.00	0.17
DM-18 (1)	169.2	—	—	106.1	0.93	0.16
DM-19	106.7	76.2	106.7	69.5	0.71	0.17
DM-20	64.0	57.9	64.0	42.7	0.57	0.22
DM-21	152.4	—	—	68.6	0.83	0.20
DM-22	108.2	85.3	105.2	45.7	0.34	0.18
DM-23	61.0	42.7	61.0	33.8	0.56	0.19
DM-24	45.7	39.6	45.7	37.2	0.20	0.20
DM-25	45.7	39.6	45.7	30.8	0.23	0.21
DM-26	85.3	48.8	85.3	43.6	0.83	0.20
DM-27	175.3	106.7	175.3	29.6	0.40	0.19
DM-28	54.3	—	—	59.7	0.90	0.17
DM-29	70.1	—	—	28.7	0.02	0.21

Table 1–1. Well construction, lateral position, and aridity index data for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[LSD, land-surface datum; m; meter; NAVD 88, North American Vertical Datum 1988; —, no data available]

Well identification	Well depth (m below LSD)	Top of screened interval (m below LSD)	Bottom of screened interval (m below LSD)	Altitude of LSD (m above NAVD 88)[2]	Normalized lateral position (dimensionless)	Aridity index[3]
Westside study-area grid wells						
WS-01	304.8	121.9	304.8	146.9	0.74	0.13
WS-02	206.7	106.1	206.7	66.4	0.01	0.14
WS-03	642.8	—	—	94.5	0.38	0.13
WS-04	189.0	91.4	189.0	72.2	0.10	0.14
WS-05	472.4	198.1	—	83.5	0.56	0.14
WS-06	—	—	—	70.4	0.05	0.14
WS-07	310.9	198.1	—	72.8	0.33	0.14
WS-08(1)	457.2	180.4	—	110.0	0.28	0.12
WS-09	185.9	176.8	182.9	56.4	0.04	0.14
WS-10	182.9	97.5	182.9	70.7	0.01	0.14
Additional wells						
DM-U-01	—	—	—	29.6	0.44	0.19
WS-U-01	192.0	121.9	192.0	75.3	0.16	0.13
WS-U-02	173.7	64.0	166.1	84.7	0.18	0.13
WS-U-03	259.1	—	—	186.2	0.88	0.14
Monitoring wells						
DM-U-02	34.4	32.0	33.5	21.0	0.00	0.23
DM-U-03	6.1	3.7	5.2	21.0	0.00	0.23
DM-U-04	33.5	27.4	33.5	53.3	0.91	0.18
DM-U-05	108.2	102.1	108.2	53.3	0.91	0.18
DM-U-06	48.8	45.7	48.8	53.3	0.91	0.18
DM-U-07	167.6	161.5	167.6	51.2	0.62	0.18
DM-U-08	120.4	114.3	120.4	51.2	0.62	0.18
DM-U-09	65.5	59.4	65.5	51.2	0.62	0.18
DM-U-10	167.6	161.5	167.6	50.6	0.09	0.16
DM-U-11	23.8	17.7	23.8	50.6	0.09	0.16
DM-U-12	106.7	100.6	106.7	50.6	0.09	0.16
DM-U-13	115.8	73.2	79.2	59.4	0.84	0.22
DM-U-14	131.1	118.9	125.0	35.1	0.43	0.23
DM-U-15	35.1	29.0	35.1	35.1	0.43	0.23
DM-U-16	77.7	71.6	77.7	35.1	0.43	0.23
DM-U-17	41.1	35.1	41.1	57.9	0.84	0.22

[1] Two wells were unused; all others were production wells.

[2] Land-surface datum (LSD) is a datum plane that is approximately at land surface at each well. The elevation of the LSD is described in feet above North American Vertical Datum 1988.

[3] Aridity index (dimensionless) is average annual precipitation divided by average annual evapotranspiration.

Table 1–2. Land-use characteristics for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Well identification**: DM, Delta–Mendota study area; WS, Westsides study area. **Other abbreviations**: LUFT, leaking (or formerly leaking) underground fuel tank; tanks/km^2, number of tanks per square kilometer]

Well identification	Land use[1]			Septic density[2] (tanks/km^2)	LUFT density[3] (tanks/km^2)
	Agricultural (percent)	Natural (percent)	Urban (percent)		
Delta–Mendota study-area grid wells					
DM-01	72	7	21	0.6	0.02
DM-02	83	14	3	0.5	0.07
DM-03	18	4	78	3.4	3.38
DM-04	84	2	14	5.0	0.09
DM-05	57	20	23	0.4	0.23
DM-06	30	2	68	13.2	0.15
DM-07	34	65	1	1.4	0.01
DM-08	52	38	10	2.2	0.03
DM-09	0	2	98	13.0	0.38
DM-10	33	3	64	6.8	0.23
DM-11	33	33	35	2.2	0.06
DM-12	100	0	0	1.8	0.01
DM-13	95	5	0	0.8	0.02
DM-14	2	94	4	3.1	0.03
DM-15	82	18	0	0.3	0.01
DM-16	98	2	0	3.1	0.05
DM-17	0	100	0	0.3	0.00
DM-18	91	7	1	0.3	0.00
DM-19	98	1	1	0.3	0.02
DM-20	100	0	0	1.0	0.02
DM-21	41	59	0	1.8	0.01
DM-22	99	1	0	1.0	0.02
DM-23	100	0	0	0.8	0.04
DM-24	100	0	0	1.9	0.26
DM-25	97	3	0	1.0	0.01
DM-26	98	0	2	1.5	0.01
DM-27	56	33	11	0.8	0.01
DM-28	94	6	0	0.2	0.01
DM-29	98	2	0	1.0	0.01
Westside study-area grid wells					
WS-01	89	2	9	0.2	0.01
WS-02	96	4	0	0.6	0.01
WS-03	99	1	0	0.2	0.01
WS-04	85	15	0	0.6	0.02
WS-05	94	6	0	0.4	0.00
WS-06	93	1	6	0.1	0.01
WS-07	99	0	1	0.3	0.00
WS-08	92	1	8	0.4	0.03
WS-09	76	7	18	0.7	0.02
WS-10	54	24	22	0.6	0.03
Additional wells					
DM-U-01	79	5	16	1.0	0.01
WS-U-01	4	37	58	0.5	0.03
WS-U-02	4	48	48	0.7	0.03
WS-U-03	0	85	15	0.4	0.01
Monitoring wells					
DM-U-02	4	75	21	3.3	0.03
DM-U-03	4	75	21	3.3	0.03
DM-U-04	28	17	55	0.2	0.01
DM-U-05	28	17	55	0.2	0.01
DM-U-06	28	17	55	0.2	0.01
DM-U-07	96	4	0	0.3	0.01
DM-U-08	96	4	0	0.3	0.01
DM-U-09	96	4	0	0.3	0.01
DM-U-10	58	41	1	0.7	0.63
DM-U-11	58	41	1	0.7	0.63
DM-U-12	58	41	1	0.7	0.63
DM-U-13	50	49	0	1.0	0.01
DM-U-14	97	0	3	2.7	0.02
DM-U-15	97	0	3	2.7	0.02
DM-U-16	97	0	3	2.7	0.02
DM-U-17	50	49	0	1.0	0.01

[1] Land-use percentages within 500 meters of the well site (Johnson and Belitz, 2009).

[2] Septic-tank density within 500 meters of the well site, calculated from census data (U.S. Census Bureau, 1992).

[3] Leaking (or formerly leaking) underground fuel-tank density within a 500-meter radius of the well site, calculated from tank sites (California State Water Resources Control Board, 2007).

Table 1–3. Geologic factor data, and U.S. Geological Survey (USGS) station identification numbers for wells sampled by the USGS for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Lithology**: CR, Coast Ranges alluvium; SN, Sierra Nevada sands. **Watershed geology**: CR-FC, Coast Ranges Franciscan Complex; CR-MS, Coast Ranges marine sediments]

Well identification	USGS station identification number	Well screen relative to Corcoran Clay Member of the Tulare Formation[1]	Lithology at depth of well screen[2]	Dominant geologic unit in watershed[4]
Delta–Mendota study-area grid wells				
DM-01	363907120144401	Below	SN	—
DM-02	364632120223403	Above	SN	—
DM-03	370310120510801	Above	CR	CR-FC
DM-04	370200120380001	Above	SN	—
DM-05	365100120270001	Above	SN	—
DM-06	372800121070001	Below	CR	CR-MS
DM-07	370800120570001	Above	CR	CR-FC
DM-08	370602121002301	Below	CR	CR-FC
DM-09	371800121010001	Below[3]	CR	CR-FC
DM-10	371500120590001	Below	CR	CR-FC
DM-11	373345121103201	Above	CR	CR-MS
DM-12	373600121170001	Below[3]	CR	CR-FC
DM-13	365800120490001	Below	CR	CR-MS
DM-14	372100120590001	Above	CR	CR-MS
DM-15	365400120390001	Above	SN	CR-MS
DM-16	370000120390001	Above	SN	—
DM-17	364200120510001	Outside of area	CR	CR-FC
DM-18	365000120450001	Below[3]	CR	CR-MS
DM-19	365000120400001	Above	CR	CR-MS
DM-20	372200121050001	Above	CR	CR-MS
DM-21	373200121150001	Below[3]	CR	CR-FC
DM-22	365300120330001	Above	SN	CR-MS
DM-23	370200120480001	Above	CR	CR-FC
DM-24	365900120340001	Above	SN	—
DM-25	370500120420001	Above	SN	—
DM-26	371000121010001	Below	CR	CR-FC
DM-27	370600120490001	Below	SN	CR-FC
DM-28	365800120510001	Above	CR	CR-MS
DM-29	370900120450001	Above	SN	—
Westside study-area grid wells				
WS-01	360800120090001	Outside of area	CR	CR-MS
WS-02	362100119550001	Across	SN	—
WS-03	360851120014602	Below[3]	CR	CR-MS
WS-04	361706119562201	Above	CR	CR-MS
WS-05	362300120130001	Below	CR	CR-MS
WS-06	361300119540001	Unknown	Unknown	CR-MS
WS-07	362600120120001	Below	SN	CR-MS
WS-08	360237120004201	Across	CR	CR-MS
WS-09	363100120050001	Below	SN	—
WS-10	361900119560001	Above	SN	CR-MS

Table 1–3. Geologic factor data, and U.S. Geological Survey (USGS) station identification numbers for wells sampled by the USGS for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[**Lithology**: CR, Coast Ranges alluvium; SN, Sierra Nevada sands. **Watershed geology**: CR-FC, Coast Ranges Franciscan Complex; CR-MS, Coast Ranges marine sediments]

Well identification	USGS station identification number	Well screen relative to Corcoran Clay Member of the Tulare Formation[1]	Lithology at depth of well screen[2]	Dominant geologic unit in watershed[4]
Additional wells				
DM-U-01	370613120500001	Unknown	Unknown	CR-FC
WS-U-01	360000119570001	Above	CR	CR-MS
WS-U-02	360029119580001	Above	CR	CR-MS
WS-U-03	360800120120001	Outside of area	CR	CR-MS
Monitoring wells				
DM-U-02	372101120583501	Above	CR	CR-MS
DM-U-03	372101120583503	Above	CR	CR-MS
DM-U-04	370102120535903	Above	CR	CR-FC
DM-U-05	370102120535901	Below	CR	CR-FC
DM-U-06	370102120535902	Above	CR	CR-FC
DM-U-07	365322120401201	Below	CR	CR-MS
DM-U-08	365322120401202	Above	CR	CR-MS
DM-U-09	365322120401203	Above	CR	CR-MS
DM-U-10	364650120221901	Below	SN	CR-MS
DM-U-11	364650120221903	Above	SN	CR-MS
DM-U-12	364650120221902	Above	SN	CR-MS
DM-U-13	371726121051501	Above	CR	CR-FC
DM-U-14	372553121102501	Below	CR	CR-MS
DM-U-15	372553121102503	Above	CR	CR-MS
DM-U-16	372553121102502	Above	CR	CR-MS
DM-U-17	371726121051502	Above	CR	CR-FC

[1] Estimated by comparing altitude of screened interval to altitude of Corcoran Clay horizon (Faunt, 2009).

[2] Estimated by comparing altitude of screened interval to altitude of Sierra Nevada sands (Miller and others, 1971; Belitz and Heimes, 1990).

[3] Depth to top of screened intervals estimated from relation between depth of top and bottom of screened interval for wells for which data exists for both parameters.

[4] Wells were assigned to the subbasin Hydrologic Unit Code (HUC_10; U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service, 2013) in which well site was located or from which well site was directly downgradient. The HUC_10 in the Coast Ranges were matched to named watersheds with geologic classifications from Davis (1961).

Table 1–4. Groundwater-age parameters for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Well identification**: DM, Delta–Mendota study-area grid well; DM-U, Delta–Mendota study-area understanding well; WS, Westside study-area grid well; WS-U, Westside study-area understanding well. **Groundwater age class**: Mixed, groundwater containing components recharged before and after 1952; modern, groundwater recharged since 1952; premodern, groundwater recharged before 1952. **Other abbreviations**: na, no data; pmC, percent modern carbon; TU, tritium units]

Well identification	Tritium (TU)	Carbon-14 (pmC)[1]	Groundwater age classification
Delta–Mendota study-area grid wells			
DM-01	–0.09	2	Premodern
DM-02	4.95	90	Modern
DM-03	2.25	91	Modern
DM-04	3.51	109	Modern
DM-05	3.10	104	Modern
DM-06	0.94	61	Mixed
DM-07	1.19	73	Mixed
DM-08	2.38	96	Modern
DM-09	3.32	79	Mixed
DM-10	1.12	43	Mixed
DM-11	2.63	86	Mixed
DM-12	1.03	36	Mixed
DM-13	0.06	18	Premodern
DM-14	3.35	91	Modern
DM-15	0.09	6	Premodern
DM-16	0.00	33	Premodern
DM-17	0.28	8	Premodern
DM-18	0.03	6	Premodern
DM-19	0.03	1	Premodern
DM-20	2.13	65	Mixed
DM-21	2.31	93	Modern
DM-22	0.00	14	Premodern
DM-23	0.06	51	Premodern
DM-24	5.32	117	Modern
DM-25	0.56	83	Mixed
DM-26	2.63	102	Modern
DM-27	–0.03	1	Premodern
DM-28	3.32	na	Modern or Mixed
DM-29	2.88	110	Modern
Westside study-area grid wells			
WS-01	0.12	66	Premodern
WS-02	0.47	0	Premodern
WS-03	0.00	13	Premodern
WS-04	0.09	9	Premodern
WS-05	0.09	1	Premodern
WS-06	0.00	12	Premodern
WS-07	0.03	5	Premodern
WS-08	–0.03	3	Premodern
WS-09	0.03	1	Premodern
WS-10	–0.03	5	Premodern
Additional wells			
DM-U-01	1.00	75	Mixed
WS-U-01	0.00	1	Premodern
WS-U-02	–0.09	2	Premodern
WS-U-03	0.00	2	Premodern
Monitoring wells			
DM-U-02	3.44	101	Modern
DM-U-03	2.47	105	Modern
DM-U-04	1.97	109	Modern
DM-U-05	1.69	93	Modern
DM-U-06	1.56	99	Modern
DM-U-07	–0.03	1	Premodern
DM-U-08	0.06	5	Premodern
DM-U-09	0.03	13	Premodern
DM-U-10	–0.15	1	Premodern
DM-U-11	2.5	87	Mixed
DM-U-12	0	4	Premodern
DM-U-13	0.12	56	Premodern
DM-U-14	4.57	63	Mixed
DM-U-15	3.47	95	Modern
DM-U-16	3.04	72	Mixed
DM-U-17	0.12	44	Premodern

[1] The ^{14}C data were reported in Mathany and others (2013) in units of percent modern (pM), as reported by the analyzing laboratory. The ^{14}C data are reported here in units of percent modern carbon (pmC). Data were converted from pM to pmC by using $pmC = \frac{pM\left(1+\frac{\delta^{13}C}{1000}\right)^{2}}{0.975^{2}}$, derived from Plummer and others (2004): where $\delta^{13}C$ is the measured ^{13}C composition in units of per mil.

Table 1–5. Geochemical condition parameters for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Well identification**: DM, Delta–Mendota study-area grid well; DM-U, Delta–Mendota study-area understanding well; WS, Westside study-area grid well; WS-U, Westside study-area understanding well. **Oxidation-reduction classes**: anoxic sub-classes: Mn-Fe-red, manganese and iron reducing; Mn-red, manganese-reducing; NO_3-red, nitrate-reducing. **Reduced nitrogen species**: NH_3, ammonia; NO_2, nitrite. **Ratios of oxidized to reduced species of metals**: As(V)/As(III), ratio of arsenic(V) to arsenic(III); Fe(III)/Fe(II), ratio of iron(III) to iron(II). **Other abbreviations**: mg/L, milligrams per liter; —, not detected; <, less than; >, greater than]

Well identification	pH, field (standard units)	Dissolved oxygen, field (mg/L)	Oxidation-reduction class[1]		Reduced nitrogen species[2]	Ratios of oxidized and reduced species of metals	
			Redox class	Subclass of anoxic		Fe(III)/Fe(II)	As(V)/As(III)
Delta–Mendota study-area grid wells							
DM-01	8.0	<0.2	Anoxic	Mn-red	NH_3	0.64	0.20
DM-02	7.8	<0.2	Anoxic	Mn-Fe-red	NH_3	0.03	—
DM-03	7.4	3.1	Oxic	—	—	—	>10
DM-04	7.6	<0.2	Anoxic	Mn-red	NH_3	0.64	0.05
DM-05	7.2	<0.2	Anoxic	Mn-Fe-red	NH_3	<0.01	<0.01
DM-06	7.5	1.7	Oxic	—	—	1.3	—
DM-07	7.5	5.6	Oxic	—	—	>10	—
DM-08	7.5	5.0	Oxic	—	—	—	—
DM-09	7.6	0.9	Oxic	—	—	—	—
DM-10	7.9	1.0	Oxic	—	NH_3	—	—
DM-11	7.7	6.0	Oxic	—	—	—	—
DM-12	7.6	5.0	Oxic	—	—	>10	—
DM-13	7.9	<0.2	Anoxic	Mn-red	NH_3	0.18	<0.01
DM-14	7.5	0.5	Anoxic	NO_3-red	—	—	—
DM-15	7.5	<0.2	Anoxic	Mn-red	NH_3	—	—
DM-16	7.5	<0.2	Anoxic	Mn-red	NH_3	0.10	<0.01
DM-17	8.7	<0.2	Anoxic	Suboxic	NH_3	—	—
DM-18	7.5	<0.2	Anoxic	Mn-Fe-red	NH_3	0.13	<0.01
DM-19	7.7	0.2	Anoxic	NO_3-red	—	—	—
DM-20	7.5	7.1	Oxic	—	—	—	—
DM-21	7.6	6.7	Oxic	—	—	1.6	—
DM-22	7.1	<0.2	Anoxic	Mn-Fe-red	NH_3	0.18	<0.01
DM-23	7.6	1.3	Oxic	—	—	—	>10
DM-24	7.0	<0.2	Anoxic	Mn-Fe-red	NH_3	0.06	0.07
DM-25	7.3	<0.2	Anoxic	Mn-Fe-red	NH_3	0.03	<0.01
DM-26	7.1	4.6	Oxic	—	—	>10	—
DM-27	7.9	<0.2	Anoxic	Mn-red	NH_3	3.0	0.30
DM-28	7.1	6.3	Oxic	—	—	>10	—
DM-29	6.8	<0.2	Anoxic	Mn-Fe-red	NH_3	0.03	0.01

Table 1–5. Geochemical condition parameters for wells sampled by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[**Well identification**: DM, Delta–Mendota study-area grid well; DM-U, Delta–Mendota study-area understanding well; WS, Westside study-area grid well; WS-U, Westside study-area understanding well. **Oxidation-reduction classes**: anoxic sub-classes: Mn-Fe-red, manganese and iron reducing; Mn-red, manganese-reducing; NO_3-red, nitrate-reducing. **Reduced nitrogen species**: NH_3, ammonia; NO_2, nitrite. **Ratios of oxidized to reduced species of metals**: As(V)/As(III), ratio of arsenic(V) to arsenic(III); Fe(III)/Fe(II), ratio of iron(III) to iron(II). **Other abbreviations**: mg/L, milligrams per liter; —, not detected; <, less than; >, greater than]

Well identification	pH, field (standard units)	Dissolved oxygen, field (mg/L)	Oxidation-reduction class[1]		Reduced nitrogen species[2]	Ratios of oxidized and reduced species of metals	
			Redox class	Subclass of anoxic		Fe(III)/Fe(II)	As(V)/As(III)
Westside study-area grid wells							
WS-01	7.7	10.1	Oxic	—	—	4.2	—
WS-02	8.3	<0.2	Anoxic	Suboxic	NH_3	—	—
WS-03	7.8	<0.2	Anoxic	NO_3-red	NO_2	—	—
WS-04	8.1	<0.2	Anoxic	Suboxic	NO_2	3.1	—
WS-05	8.6	<0.2	Anoxic	Suboxic	NH_3	<0.01	>10
WS-06	8.5	<0.2	Anoxic	Suboxic	NH_3	>10	—
WS-07	8.3	0.2	Anoxic	Mn-red	NH_3	0.23	<0.01
WS-08	8.5	0.9	Anoxic	Suboxic	NO_2	1.2	>10
WS-09	7.6	<0.2	Anoxic	Mn-red	NH_3	0.02	—
WS-10	7.9	<0.2	Anoxic	Mn-red	NH_3	<0.01	0.60
Additional wells							
DM-U-01	7.7	<0.2	Anoxic	Mn-Fe-red	—	0.14	0.58
WS-U-01	8.3	<0.2	Anoxic	Mn-red	NH_3	<0.01	0.04
WS-U-02	8.3	<0.2	Anoxic	Suboxic	NH_3, NO_2	0.50	>10
WS-U-03	8.0	<0.2	Anoxic	Mn-red	—	1.8	0.60
Monitoring wells							
DM-U-02	7.3	0.5	Anoxic	NO_3-red	—	—	—
DM-U-03	7	6.6	Oxic	—	—	—	>10
DM-U-04	7.4	3.1	Oxic	—	—	—	>10
DM-U-05	7.7	5.6	Oxic	—	—	—	>10
DM-U-06	7.7	2	Oxic	—	—	—	>10
DM-U-07	8.3	0.4	Anoxic	Mn-red	NH_3	—	<0.01
DM-U-08	7.8	0.3	Anoxic	Mn-red	NH_3	>10	0.07
DM-U-09	7.4	0.2	Anoxic	NO_3-red	—	—	—
DM-U-10	7.9	0.3	Anoxic	Mn-red	NH_3	—	0.60
DM-U-11	7.3	0.3	Anoxic	Mn-red	NH_3	0.19	0.14
DM-U-12	7.9	0.6	Anoxic	Mn-red	NH_3	0.50	4.3
DM-U-13	7.2	7.9	Oxic	—	—	—	>10
DM-U-14	7.6	3.6	Oxic	—	—	—	—
DM-U-15	7.4	4.8	Oxic	—	—	—	—
DM-U-16	7.5	9.3	Oxic	—	—	—	—
DM-U-17	7.5	5.8	Oxic	Mn-Fe-red	—	0.94	>10

[1] Oxidation-reduction classification based on McMahon and Chapelle (2008) and Jurgens and others (2009), except that the boundary between oxic and anoxic was changed to 1.0 mg/L.

[2] Ammonia detected relative to reporting level of 0.02 mg/L as nitrogen, and nitrite detected relative to reporting level of 0.002 mg/L as nitrogen.

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Appendix 2. Aquifer-Scale Proportions in Study Areas

Aquifer-scale proportions in the two study areas of the Western San Joaquin Valley (WSJV) study unit for constituents detected at high or moderate relative concentrations (RCs) in the grid or U.S. Geological Survey (USGS)-understanding wells, for constituents reported at high or moderate RCs in the California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database in samples collected between March 2007 and September 2010, and for organic constituents detected in more than 10 percent of grid wells are listed in appendix tables 2–1*A*, *B*. Aquifer-scale proportions for constituent classes in the two study areas of the WSJV study unit are listed in appendix tables 2–2*A*, *B*.

Table 2–1*A*. Aquifer-scale proportions for all constituents detected at high or moderate relative concentrations and for organic constituents detected in greater than 10 percent of grid wells, Delta–Mendota (DM) study area, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) categories for inorganic constituents**: high, RC greater than (>) 1.0; moderate, 1.0 greater than or equal to (≥) RC > 0.5; low, RC less than or equal to (≤) 0.5. **RC categories for organic and special-interest constituents**: high, RC > 1.0; moderate, 1.0 ≥ RC > 0.1; low, RC ≤ 0.1. RC defined as measured value divided by benchmark value. Constituents not listed in this table either do not have benchmarks or were detected only at low RCs. Benchmark types and values listed in table 4. **Abbreviations**: na, not available]

Delta–Mendota study-area constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)				90-percent confidence interval for grid-based high-RC proportion[3]	
					Spatially weighted		Grid-based			
	Wells	Cells	Moderate RC	High RC	Moderate RC	High RC	Moderate RC	High RC	Lower limit	Upper limit
Inorganic constituents with health-based benchmarks										
Nutrients										
Nitrate	97	29	27.8	4.1	17.4	5.3	10.3	7.6	3.8	22.4
Trace elements										
Aluminum	80	29	1.3	0.0	1.7	0.0	0	0	0	6.4
Arsenic	79	29	26.6	13.9	19.3	11.8	20.7	6.9	2.0	17.8
Boron	35	29	28.6	45.7	25.0	53.4	24.1	55.2	40.1	69.5
Chromium(VI)[1]	80	29	1.2	45.0	0.7	33.4	0	31.0	18.6	46.1
Chromium	80	29	16.3	0	9.8	0	10.3	0	0	6.4
Molybdenum	30	29	6.7	6.7	6.9	5.2	6.9	6.9	2.0	17.8
Selenium	78	29	1.3	1.3	0.6	3.4	3.4	3.4	0.6	12.7
Strontium	30	29	13.3	6.7	13.8	6.9	13.8	6.9	2.0	17.8
Vanadium	35	29	0	0	0	0	0	0	0.0	6.4
Uranium and other radioactive constituents										
Uranium	47	29	4.3	2.1	2.9	0.9	0	0	0	6.4
Gross alpha-particle activity[2]	40	17	15.0	10.0	na	na	na	na	na	na
Radium[2]	34	15	0	2.9	na	na	na	na	na	na
Inorganic constituents with aesthetic-based benchmarks										
Chloride	79	29	22.8	7.6	28.4	19.0	31.0	17.2	8.2	30.9
Sulfate	79	29	22.8	12.7	22.0	23.0	13.8	31.0	18.6	46.1
Total dissolved solids	79	29	39.2	46.8	42.9	52.1	41.0	51.2	40.1	69.5
Iron	81	29	4.9	13.6	5.9	15.9	6.9	17.2	8.2	30.9
Manganese	82	29	2.4	36.6	1.4	44.6	3.4	44.8	30.5	59.9

Table 2–1*A*. Aquifer-scale proportions for all constituents detected at high or moderate relative concentrations and for organic constituents detected in greater than 10 percent of grid wells, Delta–Mendota (DM) study area, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[**Relative-concentration (RC) categories for inorganic constituents**: high, RC greater than (>) 1.0; moderate, 1.0 greater than or equal to (≥) RC > 0.5; low, RC less than or equal to (≤) 0.5. **RC categories for organic and special-interest constituents**: high, RC > 1.0; moderate, 1.0 ≥ RC > 0.1; low, RC ≤ 0.1. RC defined as measured value divided by benchmark value. Constituents not listed in this table either do not have benchmarks or were detected only at low RCs. Benchmark types and values listed in table 4. **Abbreviations**: na, not available]

Delta–Mendota study-area constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)				90-percent confidence interval for grid-based high-RC proportion[3]	
					Spatially weighted		Grid-based			
	Wells	Cells	Moderate RC	High RC	Moderate RC	High RC	Moderate RC	High RC	Lower limit	Upper limit
Organic constituents with health-based benchmarks										
Pesticides and fumigants										
Simazine	61	29	0	0	0	0	0	0	0	6.4
1,2-Dibromo-3-chloropropane	78	29	6.4	0	4.1	0	0	0	0	6.4
Volatile organic compounds										
Benzene	78	29	0	0	0	0	0	0	0	6.4
Chloroform	78	29	0	0	0	0	0	0	0	6.4
Tetrachloroethene	78	29	2.6	1.3	1.0	0.7	0	0	0	6.4
Special-interest constituents										
Perchlorate	78	29	> 6.2	0	> 6.8	0	17.2	0	0	6.4

[1] Measured chromium(VI) concentrations were available for 23 wells in 11 cells. For the other 57 wells, chromium(VI) concentrations were estimated to be 0.9 times the measured chromium concentration.

[2] Data for gross alpha-particle activity and radium were available for wells in less than two-thirds of the 29 cells; therefore, aquifer-scale proportions were not calculated.

[3] The reporting limit for perchlorate in the SWRCB-DDW database, 4 micrograms per liter (µg/L), corresponds to an RC of 0.67; therefore, the moderate RC spatially weighted aquifer-scale proportion and the raw occurrence frequency of moderate RC are only minimum estimates.

Table 2–1*B*. Aquifer-scale proportions for all constituents detected at high or moderate relative concentrations and for organic constituents detected in greater than 10 percent of grid wells, Westside (WS) study area, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) categories for inorganic constituents**: high, RC greater than (>) 1.0; moderate, 1.0 greater than or equal to (≥) RC > 0.5; low, RC less than or equal to (≤) 0.5. **RC categories for organic and special-interest constituents**: high, RC > 1.0; moderate, 1.0 ≥ RC > 0.1; low, RC ≤ 0.1. RC defined as measured value divided by benchmark value. Constituents not listed in this table either do not have benchmarks or were detected only at low RCs. Benchmark types and values listed in table 4.]

Westside study-area constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)				90-percent confidence interval for grid-based high-RC proportion[3]	
					Spatially weighted		Grid-based			
	Wells	Cells	Moderate RC	High RC	Moderate RC	High RC	Moderate RC	High RC	Lower limit	Upper limit
Inorganic constituents with health-based benchmarks										
Nutrients										
Nitrate	18	10	11.1	0	13.3	0	20.0	0	0	17.1
Trace elements										
Aluminum	16	10	0	0	0	0	0	0	0	17.1
Arsenic	17	10	11.8	11.8	7.5	6.3	20.0	0	0	17.1
Boron	13	10	53.8	38.5	51.7	45.0	50.0	40.0	18.5	65.3
Chromium(VI)[1]	16	10	0	0	0	0	0	0	0	17.1
Chromium	16	10	0	0	0	0	0	0	0	17.1
Molybdenum	13	10	38.5	0	45.0	0	40.0	0	0	17.1
Selenium	17	10	5.9	0	5.0	0	10.0	0	0	17.1
Strontium	13	10	7.7	0	10.0	0	10.0	0	0	17.1
Vanadium	13	10	7.7	0	3.3	0	10.0	0	0	17.1
Uranium and other radioactive constituents										
Uranium	16	10	0	0	0	0	0	0	0	17.1
Gross alpha-particle activity[2]	5	5	20.0	0	na	na	na	na	na	na
Radium	3	3	0	0	na	na	na	na	na	na
Inorganic constituents with aesthetic-based benchmarks										
Chloride	15	10	6.7	0	3.3	0	0	0	0	17.1
Sulfate	15	10	26.7	40.0	26.3	45.0	40.0	40.0	18.5	65.3
Total dissolved solids	15	10	46.7	40.0	48.3	41.7	41.0	51.3	18.5	65.3
Iron	15	10	0	13.3	0	10	0	0	0	17.1
Manganese	15	10	26.7	40.0	27.1	45.7	30.0	30.0	11.7	55.8

Table 2–1*B*. Aquifer-scale proportions for all constituents detected at high or moderate relative concentrations and for organic constituents detected in greater than 10 percent of grid wells, Westside (WS) study area, Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project..—Continued

[**Relative-concentration (RC) categories for inorganic constituents**: high, RC greater than (>) 1.0; moderate, 1.0 greater than or equal to (≥) RC > 0.5; low, RC less than or equal to (≤) 0.5. **RC categories for organic and special-interest constituents**: high, RC > 1.0; moderate, 1.0 ≥ RC > 0.1; low, RC ≤ 0.1. RC defined as measured value divided by benchmark value. Constituents not listed in this table either do not have benchmarks or were detected only at low RCs. Benchmark types and values listed in table 4.]

Westside study-area constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)				90-percent confidence interval for grid-based high-RC proportion[3]	
					Spatially weighted		Grid-based			
	Wells	Cells	Moderate RC	High RC	Moderate RC	High RC	Moderate RC	High RC	Lower limit	Upper limit
Organic constituents with health-based benchmarks										
Pesticides and fumigants										
Simazine	17	10	0	0	0	0	0	0	0	6.4
1,2-Dibromo-3-chloropropane	17	10	0	0	0	0	0	0	0	6.4
Volatile organic compounds										
Benzene	17	10	0	17.6	0	10.0	0	0	0	6.4
Chloroform	17	10	0	0	0	0	0	0	0	6.4
Tetrachloroethene	17	10	0	0	0	0	0	0	0	6.4
Special-interest constituents										
Perchlorate[3]	16	10	>6.2	0	>10.0	0	10.0	0	0	6.4

[1] Measured chromium(VI) concentrations were available for 7 wells in 4 cells. For the other 9 wells, chromium(VI) concentrations were estimated to be 0.9 times the measured chromium concentration.

[2] Data for gross alpha-particle activity and radium were available for wells in less than two-thirds of the 29 cells; therefore, aquifer-scale proportions were not calculated.

[3] The reporting limit for perchlorate in the SWRCB-DDW database, 4 micrograms per liter, corresponds to an RC of 0.67; therefore, the moderate RC spatially weighted aquifer-scale proportion and the raw occurrence frequency of moderate RC are only minimum estimates.

Table 2–2*A*. Summary of aquifer-scale proportions for inorganic constituents in the Delta–Mendota (DM) and Westside (WS) study areas of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[**Relative-concentration (RC) categories**: high, RC greater than (>) 1.0 for at least one constituent in the class; moderate, RC > 0.5 for at least one constituent in the class and no constituents with RC > 1; low, RC less than or equal to 0.5 for all constituents in the class. RC defined as measured value divided by benchmark value.]

Constituent class	Aquifer-scale proportion (percent)		
	Low RC	Moderate RC	High RC
Inorganic constituents with health-based benchmarks			
Nutrients			
Delta–Mendota study area	79.7	15.0	5.3
Westside study area	85.0	15.0	0
Trace elements			
Delta–Mendota study area	21.8	21.8	56.4
Westside study area	17.5	42.5	40.0
Uranium and other radioactive constituents			
Delta–Mendota study area	90.5	5.1	4.4
Westside study area	95.0	5.0	0
Any inorganic constituent with health-based benchmark			
Delta–Mendota study area	18.2	24.0	57.8
Westside study area	14.2	47.5	38.3
Inorganic constituents with aesthetic-based benchmarks			
Total dissolved solids, chloride, and sulfate			
Delta–Mendota study area	4.9	43.7	51.4
Westside study area	10.0	35.0	55.0
Manganese and iron			
Delta–Mendota study area	54.0	1.4	44.6
Westside study area	23.4	28.3	48.3
Any inorganic constituent with aesthetic-based benchmark			
Delta–Mendota study area	3	32.2	65.3
Westside study area	5.0	11.7	83.3

Table 2–2*B*. Summary of aquifer-scale proportions for organic constituents in the Delta–Mendota (DM) and Westside (WS) study areas of the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[**Relative-concentration (RC) categories**: high, RC greater than (>) 1.0 for at least one constituent in the class; moderate, RC > 0.1 for at least one constituent in the class and no constituents with RC > 1.0; low, RC less than or equal to 0.1 for all constituents in the class; not detected, no constituents in the class detected. RC defined as measured value divided by benchmark value.]

Constituent class	Aquifer-scale proportions (percent)			
	Not detected	Low RC	Moderate RC	High RC
Any organic constituent				
Delta–Mendota study area	55.2	39.2	4.9	0.7
Westside study area	90	0	0	10
Any volatile organic compound (VOC)				
Delta–Mendota study area	79.3	19.0	1.0	0.7
Westside study area	90	0	0	10
Trihalomethanes				
Delta–Mendota study area	86.2	13.8	0	0
Westside study area	0	0	0	0
Solvents				
Delta–Mendota study area	93.1	5.2	1.0	0.7
Westside study area	0	0	0	0
Gasoline hydrocarbons				
Delta–Mendota study area	96.6	3.4	0	0
Westside study area	90	0	0	10
Any pesticide				
Delta–Mendota study area	65.5	30.3	4.1	0
Westside study area	0	0	0	0
Herbicides				
Delta–Mendota study area	69.0	31.0	0	0
Westside study area	0	0	0	0
Fumigants				
Delta–Mendota study area	89.7	6.2	4.1	0
Westside study area	0	0	0	0

Appendix 3. Radioactive Constituents

The class of radioactive constituents includes constituents for which abundances commonly are measured as activities rather than concentrations. Activity is measured in units of picocuries per liter (pCi/L), and 1 picocurie equals approximately two atoms decaying per minute. When atoms decay, alpha or beta particles and gamma radiation can be released. Gross alpha-particle activity is a measure of the total activity of non-volatile isotopes decaying by alpha emission. The U.S. Environmental Protection Agency maximum contaminant level (EPA MCL; 15 pCi/L) for gross alpha-particle activity applies to adjusted gross alpha-particle activity, which is equal to the measured gross alpha-particle activity minus uranium activity (U.S. Environmental Protection Agency, 2000). Data collected by the U.S. Geological Survey-Groundwater Ambient Monitoring and Assessment (USGS-GAMA) program and data compiled in the California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database are reported as gross alpha-particle activity without correction for uranium activity (“unadjusted”). Gross alpha-particle activity is used as a screening tool to determine whether other radioactive constituents must be analyzed. For regulatory purposes, analysis of uranium is only required if gross alpha-particle activity is greater than 15 pCi/L (California State Water Resources Control Board, 2015); therefore, the SWRCB-DDW database contains substantially more data for gross alpha-particle activity than for uranium. As a result, it is not always possible to calculate the adjusted gross alpha-particle activity. For this reason, results for unadjusted gross alpha-particle activity (that is, without correction for uranium) are the primary data used in the status assessments made by USGS-GAMA for Priority Basin Project study units.

Most uranium results in the SWRCB-DDW databases are reported as activities because the SWRCB-DDW MCL for uranium is 20 pCi/L. A conversion factor of 1.35 µg/pCi/L was used to convert the data to uranium concentrations for comparison with the USGS-GAMA data. This conversion factor was obtained from the relation between uranium concentrations and activities reported for 36 samples from wells in the WSJV study unit in the SWRCB-DDW database between March 2007 and August 2010.

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Appendix 4. Results from the Lawrence Livermore National Laboratory—Noble Gases and Helium Isotope Ratios

Noble-gas data for the Western San Joaquin Valley (WSJV) study unit provided by Lawrence Livermore National Laboratory (LLNL) not available at the time of publication of the Data-Series Report (Mathany and others, 2013) are tabulated in this appendix (appendix table 4–1). Recharge temperatures of groundwater were calculated from dissolved neon, argon, krypton, and xenon concentrations using methods described in Aeschbach-Hertig and others (1999). The accuracy of calculated recharge temperatures depends on the fit between modeled and measured noble-gas concentrations. Noble gas concentrations were modeled using closed system equilibration and partial re-equilibration models, and models with chi-squared probabilities of less than 1 percent were rejected (Aeschbach-Hertig and others, 2000). Chi-squared probability is the probability that the number of degrees of freedom in the model exceeds sum of the squared deviations between the measured and modeled noble gas concentrations.

Table 4–1. Concentrations of dissolved noble gases, helium isotopic ratios, and calculated recharge temperatures for groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[The five-digit number in parentheses below the constituent name is the USGS parameter code used to uniquely identify a specific constituent or property. No results were reported for USGS-GAMA grid-well DM-17. **Measurement errors**: Helium-3/Helium-4 ratios and helium-4 and argon concentrations: 2-percent error; krypton, neon, and xenon concentrations: 3-percent error. **Well identification**: DM, Delta–Mendota study-area grid well; DM-U, Delta–Mendota study-area understanding well; WS, Westside study-area grid well; WS-U, Westside study-area understanding well. **Other abbreviations**: cm^{3}STP/gH$_2$O, cubic centimeter of gas at standard temperature and pressure per gram of water; ° C, degrees Celsius; —, not analyzed; ±, plus or minus]

USGS-GAMA site identification number	Helium-4 (85561)	Neon (61046)	Argon (85563)	Krypton (85565)	Xenon (85567)	Helium-3/ Helium-4 (61040) atom ratio x 10^{-7}	Recharge temperature °C
	cm^{3}STP/gH$_2$0						
	x 10^{-7}	x 10^{-7}	x 10^{-4}	x 10^{-8}	x 10^{-8}		
Delta–Mendota study-area grid wells							
DM-01	3.19	2.71	4.06	9.06	1.23	2.43	14.9 ± 0.1
DM-02	3.09	2.71	3.89	8.72	1.10	7.01	17.5 ± 0.3
DM-03	0.76	3.10	4.14	8.88	1.16	18.00	15.7 ± 0.1
DM-04	0.73	2.45	3.65	8.10	1.10	22.40	15.8 ± 0.1
DM-05	0.45	1.92	3.06	6.74	0.92	15.40	21.2 ± 0.1
DM-06	1.31	2.11	3.17	6.75	0.88	6.21	24.0 ± 0.1
DM-07	2.50	2.22	3.27	6.90	0.89	5.15	23.9 ± 0.1
DM-08	1.88	1.95	2.92	6.19	0.80	4.84	27.4 ± 0.1
DM-09	7.34	2.45	3.51	7.48	1.00	4.27	19.2 ± 0.1
DM-10	14.67	2.35	4.02	7.32	1.08	3.09	18.7 ± 0.5
DM-11	0.81	3.98	4.86	5.71	0.88	15.40	19.6 ± 3.0
DM-12	0.92	2.86	3.77	7.93	1.04	12.05	19.1 ± 0.1
DM-13	2.49	2.65	3.73	7.96	1.06	4.52	17.5 ± 0.1
DM-14	0.86	2.42	3.57	7.82	1.04	18.40	20.3 ± 0.1
DM-15	1.57	2.75	4.02	8.80	1.26	6.24	15.3 ± 0.2
DM-16	6.53	2.25	3.56	8.16	1.10	3.55	18.4 ± 0.1
DM-17	—	—	—	—	—	—	—
DM-18	8.56	8.54	7.62	13.24	1.46	4.44	20.8 ± 0.1
DM-19	1.36	2.25	3.53	7.83	1.15	5.62	15.0 ± 0.3
DM-20	1.16	4.61	4.88	9.29	1.15	15.40	21.5 ± 0.1
DM-21	0.94	3.60	3.88	7.81	1.06	16.11	23.1 ± 0.4
DM-22	5.22	2.67	3.88	8.68	1.22	2.05	15.7 ± 0.2
DM-23	0.79	2.88	3.96	8.50	1.16	12.24	17.8 ± 0.1
DM-24	1.20	1.83	3.17	7.20	0.95	12.86	19.6 ± 3.0
DM-25	2.69	2.28	3.68	8.29	1.15	6.97	17.3 ± 0.1
DM-26	2.06	2.46	3.66	7.94	1.13	5.78	21.3 ± 0.1
DM-27	8.07	2.43	3.89	8.09	1.09	1.53	18.3 ± 0.2
DM-28	0.70	2.78	3.32	6.83	0.90	16.10	23.6 ± 0.1
DM-29	0.42	1.61	2.73	6.18	0.84	22.30	19.6 ± 3.0

Table 4–1. Concentrations of dissolved noble gases, helium isotopic ratios, and calculated recharge temperatures for groundwater samples collected by the U.S. Geological Survey (USGS) for the Western San Joaquin Valley (WSJV) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[The five-digit number in parentheses below the constituent name is the USGS parameter code used to uniquely identify a specific constituent or property. No results were reported for USGS-GAMA grid-well DM-17. **Measurement errors**: Helium-3/Helium-4 ratios and helium-4 and argon concentrations: 2-percent error; krypton, neon, and xenon concentrations: 3-percent error. **Well identification**: DM, Delta–Mendota study-area grid well; DM-U, Delta–Mendota study-area understanding well; WS, Westside study-area grid well; WS-U, Westside study-area understanding well. **Other abbreviations**: cm^{3}STP/gH$_2$O, cubic centimeter of gas at standard temperature and pressure per gram of water; ° C, degrees Celsius; —, not analyzed; ±, plus or minus]

USGS-GAMA site identification number	Helium-4 (85561)	Neon (61046)	Argon (85563)	Krypton (85565)	Xenon (85567)	Helium-3/Helium-4 (61040) atom ratio x 10^{-7}	Recharge temperature °C
	cm^{3}STP/gH$_2$0						
	x 10^{-7}	x 10^{-7}	x 10^{-4}	x 10^{-8}	x 10^{-8}		
Westside study-area grid wells							
WS-01	2.08	7.07	7.30	12.54	1.47	13.20	17.1 ± 0.2
WS-02	7.63	2.40	3.78	8.63	1.14	6.37	16.8 ± 0.2
WS-03	0.66	2.24	3.26	7.07	0.94	11.56	23.8 ± 0.1
WS-04	0.96	2.78	3.93	8.87	1.13	9.66	17.3 ± 0.3
WS-05	3.49	2.65	3.84	8.58	1.19	2.23	16.7 ± 0.2
WS-06	0.86	2.71	3.88	8.66	1.14	10.00	17.2 ± 0.1
WS-07	1.43	2.92	4.01	8.78	1.26	6.53	15.9 ± 0.5
WS-08	0.83	2.57	3.96	7.41	0.94	8.86	20.2 ± 0.1
WS-09	3.93	2.76	4.01	8.42	1.10	2.86	17.7 ± 0.2
WS-10	1.18	2.17	3.31	7.31	1.02	6.83	18.3 ± 0.1
Additional wells							
DM-U-01	0.64	2.61	3.72	8.07	1.06	16.40	18.1 ± 0.1
WS-U-01	2.66	3.46	4.52	9.58	1.35	5.08	13.6 ± 0.2
WS-U-02	1.40	3.85	4.67	9.82	1.28	8.89	14.9 ± 0.1
WS-U-03	0.66	1.83	3.09	6.94	0.98	9.31	23.5 ± 4.2
Monitoring wells							
DM-U-02	1.09	2.33	3.57	7.84	1.01	14.80	20.3 ± 0.2
DM-U-03	0.49	2.04	3.24	7.18	0.94	13.80	22.9 ± 0.1
DM-U-04	0.79	3.46	4.51	9.51	1.25	13.20	16.8 ± 0.1
DM-U-05	0.89	2.70	3.95	8.17	1.13	12.70	18.2 ± 0.2
DM-U-06	0.73	3.23	4.17	8.60	1.16	16.50	18.2 ± 0.1
DM-U-07	3.72	2.55	3.80	8.36	1.19	2.36	13.8 ± 0.1
DM-U-08	1.30	2.47	3.74	8.38	1.09	4.86	18.3 ± 0.2
DM-U-09	0.81	2.15	3.28	7.28	0.97	8.46	22.5 ± 0.1
DM-U-10	6.84	2.78	4.01	8.85	1.21	1.63	13.2 ± 0.1
DM-U-11	0.69	2.27	6.71	6.89	1.00	10.62	19.6 ± 3.0
DM-U-12	9.45	2.49	3.83	8.28	1.21	3.17	16.7 ± 0.3
DM-U-13	0.77	2.06	3.13	6.75	0.83	8.97	26.1 ± 0.2
DM-U-14	0.77	3.22	3.97	8.44	1.00	25.59	24.9 ± 0.7
DM-U-15	0.56	2.37	3.73	8.35	1.11	17.38	17.6 ± 0.1
DM-U-16	0.55	2.34	3.38	7.49	0.94	14.61	23.2 ± 0.3
DM-U-17	—	—	—	—	—	—	—

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Director, California Water Science Center
U.S. Geological Survey
6000 J Street, Placer Hall
Sacramento, California 95819
http://ca.water.usgs.gov

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