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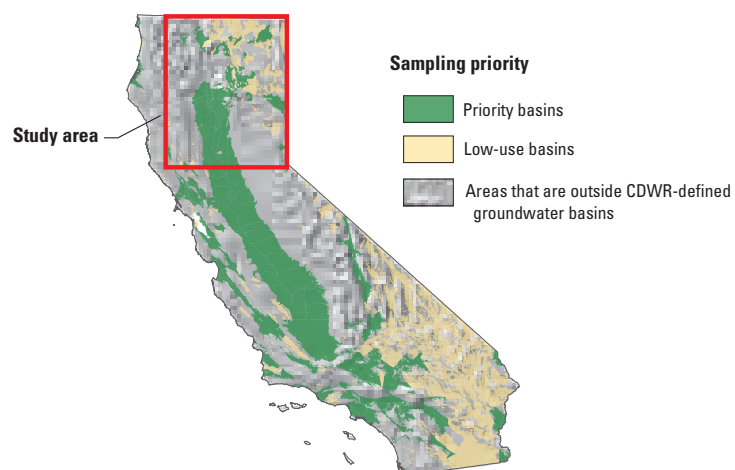
*A product of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program*

## Status and Understanding of Groundwater Quality in the Cascade Range and Modoc Plateau Study Unit, 2010: California GAMA Priority Basin Project



Scientific Investigations Report 2014–5238

**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:** Well in Lassen County, California. (Photograph taken by Stephen Schmitt, U.S. Geological Survey.)

**Back cover:** View looking west toward Mount Shasta. (Photograph taken by George Bennett, U.S. Geological Survey.)

# **Status and Understanding of Groundwater Quality in the Cascade Range and Modoc Plateau Study Unit, 2010: California GAMA Priority Basin Project**

By Miranda S. Fram and Jennifer L. Shelton

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Scientific Investigations Report 2014–5238

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

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## Conversion Factors, Datums, Abbreviations, and Acronyms

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft <sup>2</sup> )	0.09290	square meter (m <sup>2</sup> )
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
Flow rate		
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:  
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:  
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$

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

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

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

\*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft<sup>3</sup>/d)/ft<sup>2</sup>]ft. In this report, the mathematically reduced form, foot squared per day (ft<sup>2</sup>/d), is used for convenience.

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 either in milligrams per liter (mg/L) or micrograms per liter (μg/L). One milligram per liter is equivalent to 1 part per million (ppm); 1 microgram per liter is equivalent to 1 part per billion (ppb). Activities for radioactive constituents are given in picocuries per liter (pCi/L) or tritium units (TU).



## Abbreviations and Acronyms

AL-US	U.S. Environmental Protection Agency action level
BQ	benchmark quotient
CAMP	Cascade Range and Modoc Plateau
CDPH	California Department of Public Health (California Department of Health Services prior to July 1, 2007)
CDPR	California Department of Pesticide Regulation
CDWR	California Department of Water Resources
DO	dissolved oxygen
ES	Eastside Sacramento Valley Eastside
GAMA	Groundwater Ambient Monitoring and Assessment Program
HAL-US	U.S. Environmental Protection Agency lifetime health advisory level
HBSL	health-based screening level
HL	Honey Lake Valley
ka	kilo annum (thousand years ago)
LLNL	Lawrence Livermore National Laboratory
LU	Cascade Range and Modoc Plateau Low Use Basins
Ma	mega annum (million years ago)
MCL-CA	California Department of Public Health maximum contaminant level
MCL-US	U.S. Environmental Protection Agency maximum contaminant level
MTBE	methyl <i>tert</i> -butyl ether
NAWQA	National Water-Quality Assessment Program (USGS)
NL-CA	California Department of Public Health notification level
per mil	parts per thousand
pmc	percent modern carbon
QV	Quaternary volcanic areas
RC	relative-concentration
RSD5-US	U.S. Environmental Protection Agency risk-specific dose at a risk factor of 10-5
SH	Shasta Valley and Mount Shasta volcanic area
SMCL	secondary maximum contaminant level
SMCL-CA	California Department of Public Health secondary maximum contaminant level
SMCL-US	U.S. Environmental Protection Agency secondary maximum contaminant level
TEAP	terminal electron-acceptor processes
SWRCB	State Water Resources Control Board (California)
TDS	total dissolved solids
THM	trihalomethane
TV	Tertiary volcanic areas
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UST	underground storage tank
VOC	volatile organic compound

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# Status and Understanding of Groundwater Quality in the Cascade Range and Modoc Plateau Study Unit, 2010: California GAMA Priority Basin Project

By Miranda S. Fram and Jennifer L. Shelton

## Abstract

Groundwater quality in the Cascade Range and Modoc Plateau study unit was investigated as part of the California State Water Resources Control Board's Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. The study was designed to provide a statistically unbiased assessment of untreated groundwater quality in the primary aquifer system. The depth of the primary aquifer system for the Cascade Range and Modoc Plateau study unit was delineated by the depths of the screened or open intervals of wells in the State of California's database of public-supply wells. Two types of assessments were made: a *status assessment* that described the current quality of the groundwater resource, and an *understanding assessment* that made evaluations of relations between groundwater quality and potential explanatory factors representing characteristics of the primary aquifer system. The assessments characterize the quality of untreated groundwater, not the quality of treated drinking water delivered to consumers by water distributors.

The *status assessment* was based on water-quality data collected in 2010 by the U.S. Geological Survey from 90 wells and springs (USGS-grid wells) and on water-quality data compiled from the State of California's regulatory compliance database for samples collected from 240 public-supply wells between September 2007 and September 2010. To provide context, the water-quality data discussed in this report were compared to California and Federal drinking-water regulatory and non-regulatory benchmarks for treated drinking water. Groundwater quality is defined in terms of relative concentrations (RCs), which are calculated by dividing the concentration of a constituent in groundwater by the concentration of the benchmark for that constituent. The RCs for inorganic constituents (major ions, trace elements, nutrients, and radioactive constituents) were classified as "high" (the RC is greater than 1.0, indicating that the concentration is above the benchmark), "moderate" (the RC is from 1.0 to greater than 0.5), or "low" (the RC is less than or equal to 0.5). For organic constituents (volatile organic compounds and pesticides) and special-interest constituents

(perchlorate), the boundary between moderate and low RCs was set at 0.1. All benchmarks used for organic constituents were health-based. For inorganic constituents, health-based and aesthetic-based benchmarks were used. Constituents without benchmarks were not considered in the *status assessment*.

The primary metric used for quantifying regional-scale groundwater quality was the aquifer-scale proportion—the areal percentages of the primary aquifer system with high, moderate, and low RCs for a given constituent or class of constituents. The study unit was divided into six study areas on the basis of geologic differences (Eastside Sacramento Valley, Honey Lake Valley groundwater basin, Cascade Range and Modoc Plateau Low Use Basins, Quaternary Volcanic Areas, Shasta Valley and Mount Shasta Volcanic Area, and Tertiary Volcanic Areas), and each study area was divided into equal-area grid cells. Aquifer-scale proportions were calculated for individual constituents and constituent classes for each of the six study areas and for the study unit as a whole by using grid-based (one well per cell) and spatially weighted (many wells per cell) statistical methods.

The *status assessment* showed that inorganic constituents were present at high and moderate RCs in greater proportions of the Cascade Range and Modoc Plateau study unit than were organic constituents. One or more inorganic constituents with health-based benchmarks were present at high RCs in 9.4 percent, and at moderate RCs in 14.7 percent of the primary aquifer system. Arsenic was present at high RCs in approximately 3 percent of the primary aquifer system; boron, molybdenum, uranium, and vanadium each were present at high RCs in approximately 2 percent of the primary aquifer system. One or more inorganic constituents with aesthetic-based benchmarks were present at high RCs in 15.1 percent of the primary aquifer system and at moderate RCs in 4.9 percent. Manganese, iron, and total dissolved solids were present at high RCs in approximately 12 percent, 5 percent, and 2 percent, respectively, of the primary aquifer system.

Organic constituents were not detected at high or moderate RCs in the primary aquifer system, and one or more organic constituents were detected at low RCs in approximately 40 percent of the primary aquifer system.

Two classes of organic constituents were detected in more than 10 percent of the primary aquifer system: trihalomethanes (chloroform only) and herbicides. The special interest constituent perchlorate was not detected at high RCs, but was detected at moderate RCs in approximately 2 percent of the primary aquifer system.

The *understanding assessment* relied on statistical tests to evaluate relations between concentrations of constituents and values of potential explanatory factors representing geology, land use, well construction, hydrologic conditions, groundwater age, and geochemical conditions.

The majority of the high and moderate RCs of arsenic, boron, molybdenum, uranium, and total dissolved solids were in samples from the Honey Lake Valley groundwater basin study area. Groundwater mixing with hydrothermal fluids present in the study area, evaporative concentration of groundwater in the Honey Lake playa, presence of uranium-bearing sediment derived from the adjacent Sierra Nevada, and release of arsenic and other trace elements from sediments under high pH and low dissolved oxygen conditions all appeared to contribute to these elevated concentrations. Thermal springs are in many parts of the Cascade Range and Modoc Plateau study unit and could account for locally elevated concentrations of arsenic, boron, molybdenum, and total dissolved solids in samples from the other study areas. Vanadium concentrations were greater in oxic samples than in anoxic samples, but were not correlated with pH, contrary to expectations from previous studies.

Organic constituents were not detected at high or moderate RCs, and the occurrence of low organic constituents at low RCs ranged from 27 percent to 73 percent of the primary aquifers system in the six study areas. The Shasta Valley and Mount Shasta Volcanic study area had significantly greater occurrence of low RCs of herbicides compared to all of the other study areas, which could reflect the greater prevalence of modern groundwater in the Shasta Valley and Mount Shasta Volcanic study area and the presence of potential sources of herbicides, including applications to timberlands and roadside rights-of-way. The Eastside Sacramento Valley study area had the greatest occurrence of low concentrations of chloroform, and chloroform occurrence was most strongly associated with the combination of septic-tank density greater than two tanks per square kilometer and urban land use greater than 10 percent within a radius of 500 meters of the well. These conditions were most prevalent in the Eastside Sacramento Valley study area. The detection frequency of low concentrations of perchlorate was consistent with the probability of occurrence expected under natural conditions, except in the Eastside Sacramento Valley study area, where detection frequencies were much higher than expected and could not be explained by known anthropogenic sources of perchlorate.

## Introduction

Groundwater composes approximately half of the water used for public and domestic drinking-water supply in California (Kenny and others, 2009). To assess the quality of ambient groundwater in aquifers used for drinking-water supply and to establish a baseline groundwater-quality monitoring program, the California State Water Resources Control Board (SWRCB), in cooperation with the U.S. Geological Survey (USGS) and Lawrence Livermore National Laboratory (LLNL), implemented the Groundwater Ambient Monitoring and Assessment (GAMA) Program (website at <http://www.waterboards.ca.gov/gama/>). The SWRCB initiated the GAMA Program in 2000 in response to a Legislative mandate (State of California, 1999, 2001a). The statewide GAMA Program currently consists of four projects: (1) the GAMA Priority Basin Project, carried out by the USGS (website at <http://ca.water.usgs.gov/gama/>); (2) the GAMA Domestic Well Project, carried out by the SWRCB; (3) the GAMA Special Studies, carried out by LLNL, and (4) the GeoTracker GAMA on-line groundwater information system, managed by the SWRCB. The SWRCB's GAMA Domestic Well Project sampled private domestic wells on a voluntary, first-come-first-serve basis in six counties between 2002 and 2011. From 2004 through 2012, the GAMA Priority Basin Project did water-quality assessments for groundwater resources used for public drinking-water supplies. The groundwater resources used for public-drinking water supplies typically are deeper than the groundwater resources used for domestic drinking-water supplies. In 2012, the GAMA Priority Basin Project began water-quality assessments of shallow aquifers, the groundwater resources typically used for private domestic and small system drinking-water supplies.

The GAMA Priority Basin Project was initiated in response to the Groundwater Quality Monitoring Act of 2001 to assess and monitor the quality of groundwater in California (State of California, 2001b). It is a comprehensive assessment of statewide groundwater quality designed to help understand and identify risks to groundwater resources better and to increase the availability of information about groundwater quality to the public. For the GAMA Priority Basin Project, the USGS, in cooperation with the SWRCB, developed a monitoring plan to assess groundwater basins through direct sampling of groundwater and other statistically reliable sampling approaches (Belitz and others, 2003; California State Water Resources Control Board, 2003). Additional partners in the GAMA Priority Basin Project include the California Department of Public Health (CDPH), California Department of Pesticide Regulation (CDPR), California Department of Water Resources (CDWR), and local water agencies and well owners (Kulongoski and Belitz, 2004).

The ranges of hydrologic, geologic, and climatic conditions in California were considered in the design of the statewide assessment of groundwater quality. Belitz and others (2003) partitioned the state into 10 hydrogeologic provinces, each with distinctive hydrologic, geologic, and

climatic characteristics (*fig. 1*). All these hydrogeologic provinces include groundwater basins designated by the CDWR (California Department of Water Resources, 1980; 2003). Groundwater basins generally consist of relatively permeable, unconsolidated deposits of alluvial origin. Eighty percent of the approximately 16,000 active and standby public-supply wells listed in the statewide database maintained by the CDPH (hereinafter referred to as CDPH wells) are in CDWR-designated groundwater basins. [The CDPH Drinking Water Program which regulated water quality in public-supply wells was transferred to the SWRCB Division of Drinking Water on July 1, 2014, however the label “CDPH” is retained in this report for consistency with other GAMA Priority Basin Project publications and because the CDPH had jurisdiction over public-supply wells at the time that samples were collected for this study.] Twenty percent of the CDPH wells are in areas composed of igneous, metamorphic, or volcanic rocks, rather than in alluvial basins. Groundwater basins were prioritized for sampling on the basis of the number of CDPH wells in the basin, with secondary consideration given to municipal groundwater use, agricultural pumping, the number of historically leaking underground fuel tanks, and the number of square-mile (mi<sup>2</sup>) sections having registered pesticide applications (Belitz and others, 2003). Of the 472 basins designated by the CDWR, 116 contained approximately 95 percent of the CDPH 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 35 GAMA Priority Basin Project study units that together represent approximately 95 percent of all CDPH wells. The entire Cascade Range and Modoc Plateau hydrogeologic province was defined as the Cascade Range and Modoc Plateau (CAMP) study unit (*fig. 1*). The CAMP study unit includes 3 priority basins, 47 low-use basins, and areas outside of groundwater basins.

The GAMA Priority Basin Project was designed to produce three types of water-quality assessments for each study unit: (1) Status, the assessment of the current quality of the groundwater resource; (2) Understanding, the identification of the natural and human factors affecting groundwater quality and an explanation of the relations between water quality and selected explanatory factors; and (3) Trends, the detection of changes in groundwater quality over time (Kulongoski and Belitz, 2004). These three objectives were modeled after those of the USGS National Water Quality Assessment (NAWQA) Program (Hirsch and others, 1988). The assessments are intended to characterize the quality of groundwater in the primary aquifer system of the study unit, not the treated drinking water delivered to consumers by water purveyors. The primary aquifer system for a study unit is defined by the depths of the screened or open intervals of the wells listed in the CDPH database for the study unit. The CDPH database lists wells used for public drinking-water supplies and includes wells from systems classified as community (such as

cities, towns, and mobile-home parks); non-transient, non-community (such as schools, workplaces, and restaurants); and transient, non-community (such as campgrounds, parks, and highway rest areas) (California Department of Public Health, 2013a). The purpose of the CDPH database is to house water-quality data for samples collected from public-supply wells for regulatory compliance. Groundwater quality in shallower or deeper parts of the aquifer system can differ from that in the primary aquifer system. In particular, shallower groundwater may be more vulnerable to surface contamination.

The purposes of this report are to provide (1) a *study unit description* of the hydrogeologic setting of the CAMP study unit, (2) a *status assessment* of the current status of groundwater quality in the primary aquifer system of the CAMP study unit, and (3) an *understanding assessment* that identifies the natural and human factors that could be affecting groundwater quality in the CAMP study unit and a discussion of statistical tests of relations between groundwater quality and potential explanatory factors. Temporal trends in groundwater quality are not discussed in this report. Noble gas data provided by the Lawrence Livermore National Laboratory that were not available at the time of publication of the Data-Series Report (Shelton and others, 2013) are presented in *appendix E* of this report.

Features of the hydrogeologic setting are described for the six study areas. Geology, land-use patterns, and hydrology in the study areas are summarized. Characteristics of the primary aquifer system, including geology, land use, hydrologic conditions, depth, groundwater age, and geochemical conditions are described by using ancillary data compiled for the 90 wells and springs sampled by the USGS for the GAMA Priority Basin Project (USGS-GAMA) in the CAMP study unit.

The *status assessment* is designed to provide a statistically representative characterization of groundwater quality in the primary aquifer system at the study-unit scale (Belitz and others, 2003; 2010). This report describes methods used in designing the sampling networks for the *status assessment* and estimating aquifer-scale proportions for constituents (Belitz and others, 2010). Aquifer-scale proportion is defined as the areal proportion of the primary aquifer system with groundwater of defined quality (Belitz and others, 2010). Water-quality data from 262 wells were used in the *status assessment*: 90 wells sampled by USGS-GAMA for the CAMP study unit (Shelton and others, 2013) and 172 other wells in the CDPH database within the study unit that had water-quality data for samples collected between September 16, 2007, through September 16, 2010. Two methods were used to calculate aquifer-scale proportions from these data, both of which were based on a 90-cell grid covering the CAMP study unit; the methods either used data from one well per cell (grid-based method) or from many wells per cell (spatially weighted method) (Belitz and others, 2010). Aquifer-scale proportions for constituents and classes of constituents were computed for the CAMP study unit as a whole and for the six study areas within the study unit.





**Figure 1.** Location of the Cascade Range and Modoc Plateau (CAMP) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, and the California hydrogeologic provinces.

To provide context, the water-quality data discussed in this report were compared to California and Federal drinking-water regulatory and non-regulatory benchmarks for treated drinking water. Groundwater quality is defined in terms of relative-concentrations (RCs), 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 untreated groundwater resources in the primary aquifer system in the study unit, not the treated drinking water delivered to consumers by water purveyors. After withdrawal from the ground, water may be treated, disinfected, and (or) blended with other waters to maintain acceptable water quality. Regulatory benchmarks apply to treated water that is served to the consumer, not to untreated groundwater.

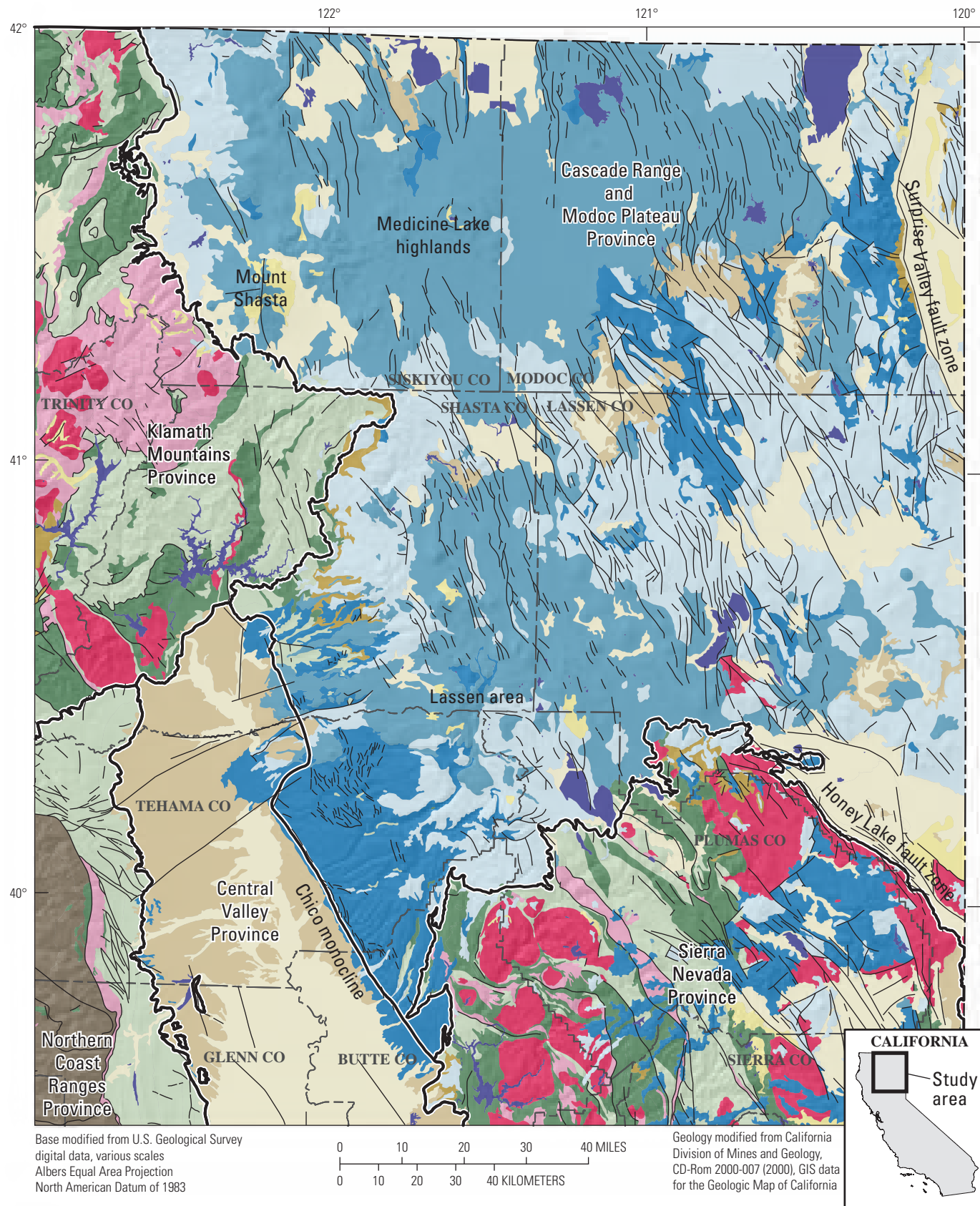
The *understanding assessment* evaluates relations between groundwater quality and potential explanatory factors by using statistical tests. Potential explanatory factors examined include aquifer lithology, study area, land use near the well, septic and underground storage-tank densities near the well, depths to the top and bottom of the open or screened interval in the well, aridity index, groundwater age, oxidation-reduction conditions, and pH.

## Study-Unit Description

The CAMP study unit covers an area of approximately 15,000 mi<sup>2</sup> (39,000 square kilometers [km<sup>2</sup>]) in Siskiyou, Modoc, Shasta, Lassen, Tehama, Plumas, and Butte Counties

(*fig. 2*). The study unit corresponds to the Cascade Range and Modoc Plateau hydrogeologic province in the northeastern corner of the State (*fig. 1*; Belitz and others, 2003). The province is defined on the basis of geologic and State boundaries; it is bounded to the west by the Mesozoic and Paleozoic rocks of the Klamath Mountains province, to the south by Mesozoic and Paleozoic rocks of the Sierra Nevada province, to the southwest by the Cenozoic sediment deposits of the Central Valley province, to the north by the Oregon State line, and to the east by the Nevada State line (*fig. 2*).

Hydrologic features of the CAMP study unit belong to three major watersheds: the Sacramento River watershed (CDWR basin numbers beginning with 5-), the Klamath River watershed (CDWR basin numbers beginning with 1-), and closed basins of the North Lahontan region (CDWR basin numbers beginning with 6-) (*fig. 3*) (California Department of Water Resources, 2003). The largest river in the study unit, the Pit River, flows across the study unit from south of Goose Lake in the northeast to Lake Shasta on the Sacramento River in the southwest. The headwaters of the Sacramento River are on the southwestern slopes of Mount Shasta. Creeks in the southwestern part of the study unit flow into the main stem of the Sacramento River. Along the Oregon border, the Lost River drainage, including Clear Lake and Tule Lake, is connected to the Klamath River by a set of canals and tunnels (not shown). The Shasta River flows through Shasta Valley and enters the Klamath River below Iron Gate Dam. In the North Lahontan region along the Nevada border, the basins are closed basins; rivers drain into perennial or intermittent lakes within the basins.



**Figure 2.** Geologic features of the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



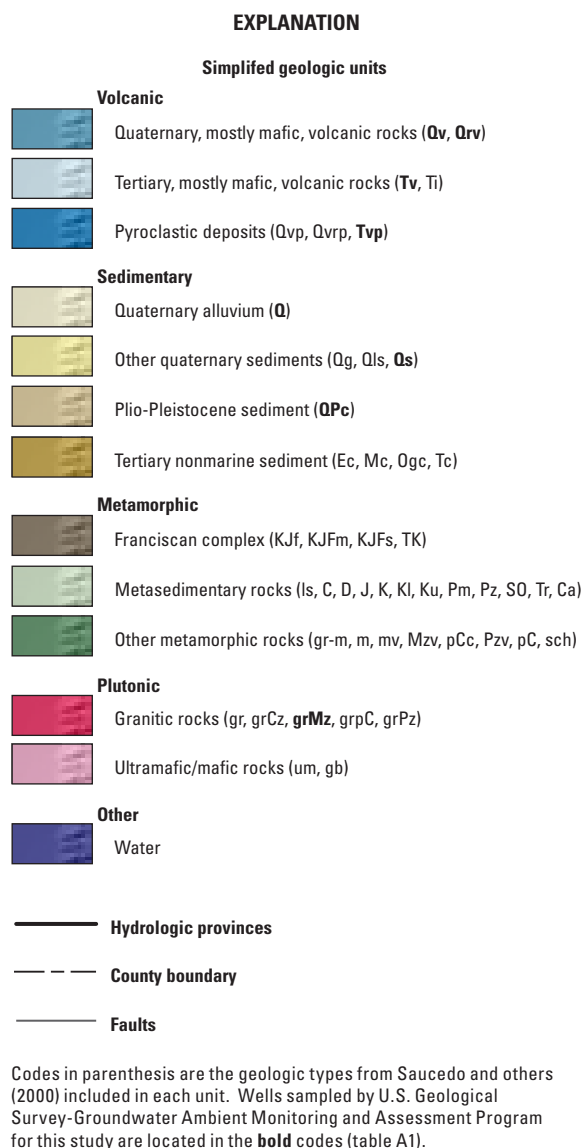


Figure 2. —Continued

Climate in the Cascade Range and Modoc Plateau hydrogeologic province primarily varies with elevation and location relative to mountain ranges. Land-surface elevations in the study unit range from approximately 1,500 feet (ft) along the margin of the Sacramento Valley to 14,179 ft on Mount Shasta. Precipitation is greatest on the western side of the study unit, reaching up to 80 inches per year (in/yr) on Mount Shasta and up to 120 in/yr in high elevations in Lassen Volcanic National Park (PRISM Climate Group, Oregon State University, 2010). Elevation ranges from 4,000 to 5,500 ft throughout most of the central and eastern parts of the study unit, and climate is classified as the Great Basin desert (defined as high, cold desert). The central and eastern parts of the study unit are in the rain shadow of the Cascade Range and the Shasta Valley is in the rain shadow of the Klamath Mountains. Average annual precipitation is 10–20 in/yr in most of the central and eastern area and 20–40 in/yr at higher elevations (Western Regional Climate Center, 2010). Much of the precipitation in the entire study unit falls as snow, particularly at elevations above 4,500 ft, and nearly all of the precipitation falls in the winter (between November and May). Summers are hot and dry.

The CAMP study unit consists entirely of Cenozoic-age volcanic and sedimentary rocks and deposits (fig. 2). It was divided into six study areas on the basis of geologic features (fig. 4). The objective of dividing the study unit into these study areas was to investigate potential differences in groundwater quality among these geologically distinct aquifer systems. Four of the study areas correspond to CDWR-defined groundwater basins (California Department of Water Resources, 1980; 2003), and two correspond to mapped geologic units (Jennings, 1977; Saucedo and others, 2000) (appendix A).

CAMP-ES study area: Eastside Sacramento Valley,

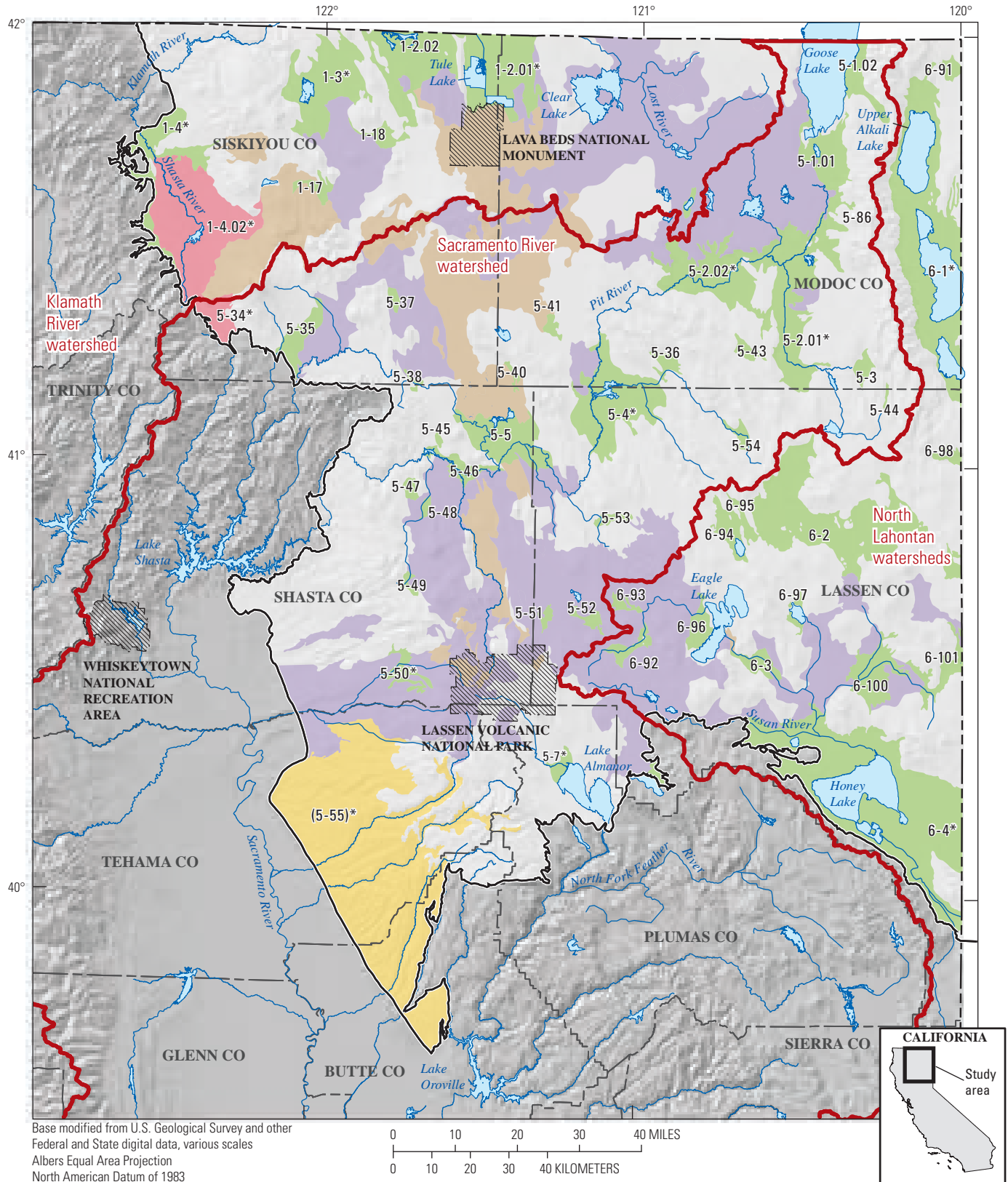
CAMP-HL study area: Honey Lake Valley groundwater basin,

CAMP-LU study area: Cascade Range and Modoc Plateau Low Use Basins,

CAMP-QV study area: Quaternary Volcanic Areas mapped as Qv on the State geologic map,

CAMP-SH study area: Shasta Valley and Mount Shasta Volcanic Area,

CAMP-TV study area: Tertiary Volcanic Areas mapped as Tv on the State geologic map.



**Figure 3.** California Department of Water Resources (CDWR) defined groundwater basins and major hydrologic features in the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

## EXPLANATION

Volcanic areas that contain California Department of Public Health (CDPH) public-supply wells, and were defined as groundwater basins by California Department of Water Resources [(CDWR) (1980)] but discontinued by CDWR (2003)

Basin number	Basin name	Study area
5-34 1-4.02	Mount Shasta Volcanic Area Shasta Valley Volcanics	SH SH
5-55	Sacramento Valley Eastside Tuscan Formation Highlands	ES
1-23 and 5-32	Modoc Plateau Recent Volcanic Areas	none
1-24, 5-33, and 6-103	Modoc Plateau Pleistocene Volcanic Areas	QV

Volcanic areas that contain CDPH public-supply wells and were never defined as groundwater basins by CDWR (mostly Tertiary Volcanic study area)

CDWR defined groundwater basins that contain CDPH public-supply wells (basin number marked with asterisk on map)

Basin number	Basin name	Study area	Reference
6-4	Honey Lake Valley	HL	CDWR, 2004a
1-4	Shasta Valley	SH	CDWR, 2004b
1-2.01	Upper Klamath basin, Tule Lake subbasin	LU	CDWR, 2004c
1-3	Butte Valley	LU	CDWR, 2004d
5-2.01	Alturas basin, South Fork Pit River subbasin	LU	CDWR, 2004e
5-2.02	Alturas basin, Warm Springs Valley subbasin	LU	CDWR, 2004f
5-4	Big Valley	LU	CDWR, 2004g
5-5	Fall River Valley	LU	CDWR, 2004h
5-7	Lake Almanor Valley	LU	CDWR, 2004i
5-35	McCloud Area	LU	CDWR, 2004j
5-46	Lake Britton Area	LU	CDWR, 2004k
5-50	North Battle Creek	LU	CDWR, 2004l
6-1	Surprise Valley	LU	CDWR, 2004m

CDWR defined groundwater basins that do not contain CDPH public-supply wells

Basin number	Basin name	Basin number	Basin name
1-2.02	Upper Klamath basin, Lower Klamath Lake subbasin	5-49	Dry Burney Creek Valley
1-17	Bray Town Area	5-51	Butte Creek Valley
1-18	Red Rock Valley	5-52	Grays Valley
1-22	Fairchild Swamp Area	5-53	Dixie Valley
5-1	Goose Lake	5-54	Ash Valley
5-3	Jess Valley	5-86	Joseph Creek
5-8	Mountain Meadows Valley	6-2	Madeline Plains
5-36	Round Valley	6-3	Willow Creek Valley
5-37	Toad Well Area	6-91	Cow Head Lake Valley
5-38	Pondosa Town Area	6-92	Pine Creek Valley
5-40	Hot Springs Valley	6-93	Harvey Valley
5-41	Egg Lake Valley	6-94	Grasshopper Valley
5-43	Rock Prairie Valley	6-95	Dry Valley
5-44	Long Valley	6-96	Eagle Lake Area
5-45	Clayton Valley	6-97	Horse Lake Valley
5-47	Goose Valley	6-98	Tuledad Canyon Valley
5-48	Burney Creek Valley	6-99	Painters Flat
5-49	Dry Burney Creek Valley	6-100	Secret Valley
		6-101	Bull Flat

National parks, recreation areas, or monuments

Cascade Range and Modoc Plateau Province

County boundary

Major watershed boundaries

## Eastside Sacramento Valley Study Area (ES)

The ES study area (fig. 4) corresponds to the former CDWR-defined volcanic groundwater basin 5-55, the Eastside Sacramento Valley Tuscan Formation Highlands (fig. 3); California Department of Water Resources, 1980). It is no longer designated as a CDWR basin because volcanic areas statewide were reclassified as groundwater source areas rather than basins to restrict the definition of basins to alluvial basins (California Department of Water Resources, 2003). Groundwater source areas are non-basin areas that may serve as sources of recharge to adjacent basins by subsurface flow. The boundary between the ES study area and the Sacramento Valley is defined by the Chico monocline, a normal fault active within the last 1 mega-annum (Ma) moving the Sierra Nevada upward relative to the Central Valley (figs. 2; A1F). East of the Chico monocline, the Tuscan Formation dips less than 5 degrees; west of the monocline, the Tuscan Formation dips at least 20 degrees, disappearing beneath the younger valley sediments (Harwood and Helley, 1987). The other boundaries of the ES study area are defined by the extent of surface outcrops of the Tuscan Formation.

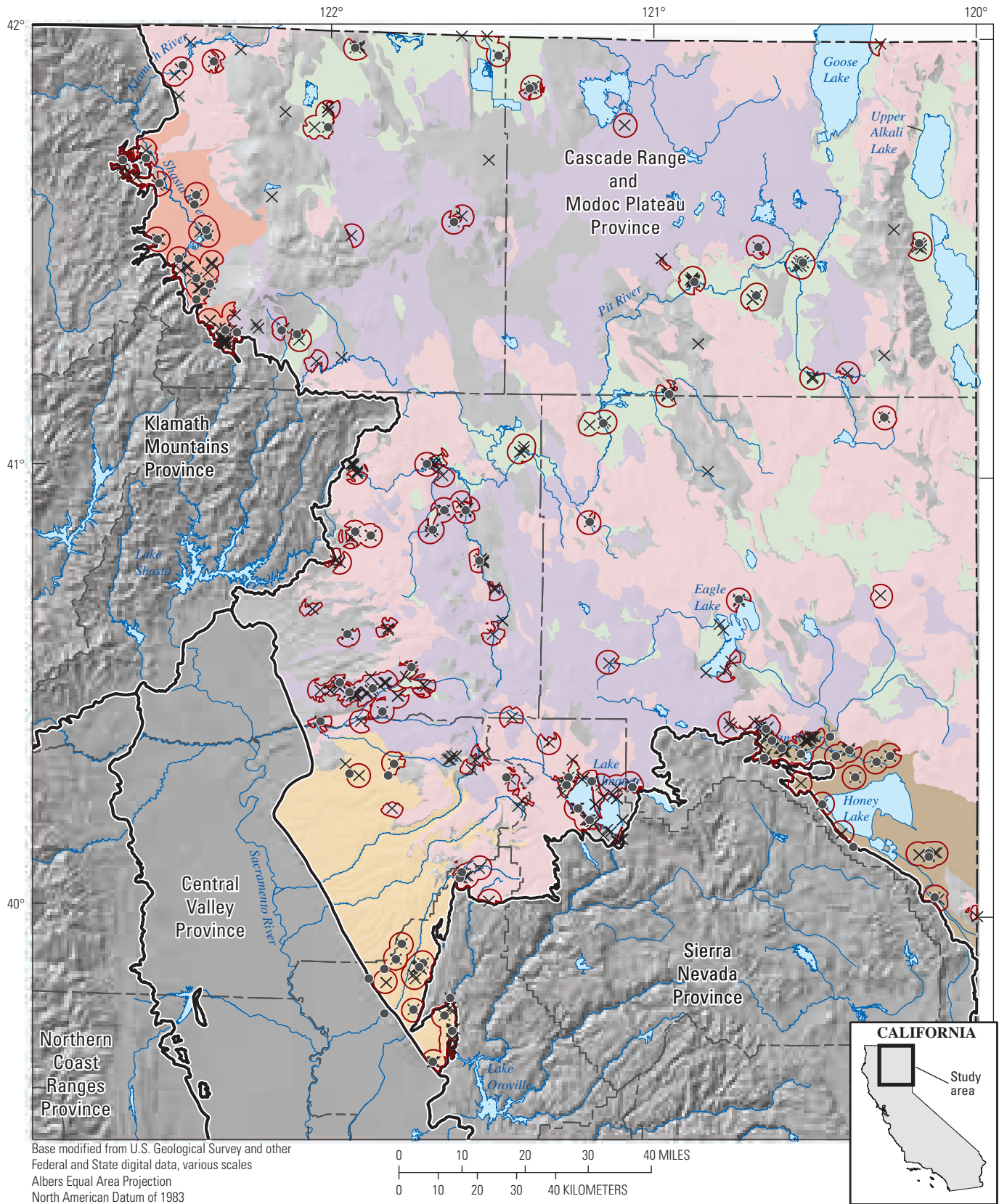
The Tuscan Formation in the ES study area consists of many volcanic mudflows, or lahars. The lahars erupted approximately 3 Ma from vents on the flanks of now-extinct volcanoes west and south of Lassen Volcanic National Park, and form a unit up to 1,700 ft thick (Lydon, 1968). About three quarters of the exposed area is tuff breccia, a massive chaotic assemblage of boulder to pebble size fragments of andesitic lava in a clastic matrix of volcanic ash and fine volcanic debris (Lydon, 1968). The Formation grades westward from lahar deposits to volcanic sediments, and in the Central Valley, the Tuscan Formation sediments are an important aquifer. The tuff breccia is less permeable than the volcanic sediments, resulting in variable well yields. Several communities in the southern part of the ES study area have had to rely on drinking water brought in by tanker trucks because of low well yields (California Department of Water Resources, 2003). The Tuscan Formation may be described in CDWR well completion reports as volcanic or sedimentary materials depending on the facies and on the interpretation of the person preparing the report.

## Honey Lake Valley Study Area (HL)

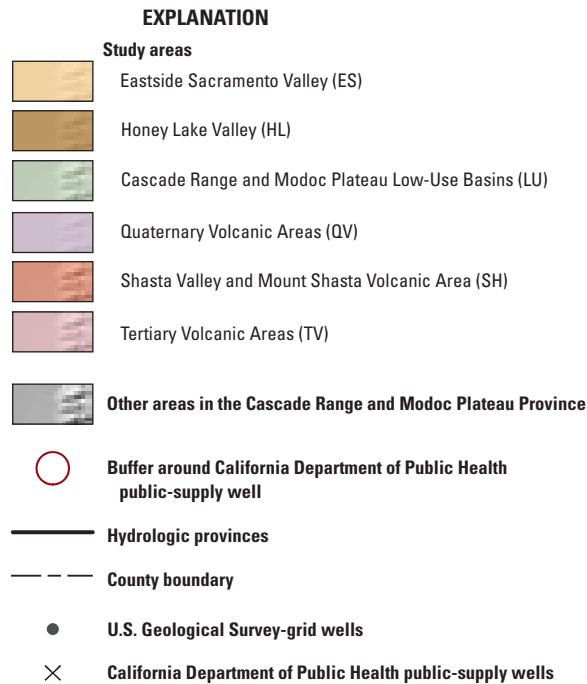
The HL study area (fig. 4) corresponds to the CDWR-defined Honey Lake Valley groundwater basin (fig. 3; CDWR basin number 6-4; California Department of Water Resources, 2004a). The Honey Lake Valley is a topographically closed basin that is geologically part of the Basin and Range geologic province (California Department of Conservation, California Geological Survey, 2002). The basin is bounded on the south by the Honey Lake fault, which separates it from the Mesozoic granitic rocks of the Sierra Nevada, and on the other sides by Quaternary and Tertiary lava flows (figs. 2; A1G).

Figure 3. —Continued





**Figure 4.** Study areas and well locations in the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



**Figure 4.** —Continued

The Honey Lake Valley is a down-faulted basin containing up to 6,000 ft of Pliocene to Recent (5 Ma to present) sediments with interbedded lava flows and pyroclastic deposits (California Department of Water Resources, 1963; Handman and others, 1990). The primary water-bearing units are the Pleistocene to Recent lacustrine and alluvial sediments (California Department of Water Resources, 2004a). Honey Lake was on the western edge of Pleistocene Lake Lahontan, a large lake that covered most of northwestern Nevada from about 45,000 to about 10,000 years ago (Benson and Thompson, 1987). Near-shore deposits from this large lake are relatively coarse-grained and highly permeable and are an important source of groundwater to wells. Pleistocene volcanic rocks interbedded with the lake sediments on the north side of the basin act as conduits for groundwater recharge to the basin.

More than 40 intermittent and perennial streams flow into the valley and terminate at Honey Lake. The amount of groundwater recharge is low, however, because about 90 percent of the total precipitation and stream inflow to the basin is lost by evapotranspiration (Handman and others, 1990). The sources of groundwater recharge are direct infiltration of precipitation at higher elevations in the watershed, infiltration of streamflow on alluvial fans on the valley margins, and infiltration of irrigation return water. In addition, upwelling of thermal waters along the faults bounding the basin could contribute up to 40 percent of recharge locally (Mayo and others, 2010). Faults within

the basin limit lateral groundwater flow (Rose and others, 1997). Groundwater discharges by evapotranspiration and by pumping. Most of the groundwater extraction in the basin is for irrigation. In addition, geothermal waters associated with the faults bounding the basin are extracted for power generation (Brown and Caldwell, 2007).

## Cascade Range and Modoc Plateau Low-Use Basins Study Area (LU)

The LU study area includes 47 CDWR-defined groundwater basins (figs. 3, 4). Of these 47 basins, 11 contain wells listed in the CDPH database of wells used for public drinking-water supply. Hydrologic features of those 11 basins are discussed briefly here.

The Tule Lake subbasin of the Upper Klamath River groundwater basin is bounded on the east and west by north-south trending normal faults, on the south by Pleistocene and Holocene lava flows of the Medicine Lake volcano, and on the north by the Oregon state line (figs. 2, 3; CDWR basin number 1-2.01; California Department of Water Resources, 2004c). The subbasin is composed of Pliocene to Holocene age lacustrine deposits that have relatively low permeability and interbedded Miocene, Pliocene and Pleistocene basalt lava flows. The principal aquifer is the highly permeable Miocene/Pliocene basalt lava flows beneath the lake sediments. In 2001, 10 deep irrigation wells were drilled into this aquifer, and they have yields ranging from 4,000 to 12,000 gallons per minute (gpm) (Gannett and others, 2007). The subbasin primarily is recharged by subsurface flow through permeable basalt lava flows that are exposed in the highlands north and east of the subbasin and by subsurface flow from the adjacent Lower Klamath Lake subbasin (Gannett and others, 2007).

The surface-water hydrology of the Tule Lake subbasin has been extensively modified as part of the U.S. Bureau of Reclamation Klamath Project (Gannett and others, 2007). Prior to the project, Tule Lake was much larger, surrounded by vast wetlands, and fed by the Lost River. Hydraulic head gradients indicate the lake drains in the subsurface southward through the Medicine Lake Highlands toward the Pit River (fig. 3; Gannett and others, 2007). The Lost River is now connected to the Klamath River by a man-made canal, and much of the subbasin has been drained for agricultural use. The existing Tule Lake Sump collects irrigation return water that is then pumped out of the basin into Lower Klamath Lake. The subbasin is extensively irrigated with surface water from Upper Klamath Lake (in Oregon). Pumpage of groundwater has increased dramatically since 2001, largely because groundwater is used to augment surface-water supplies so that more surface water can be left in streams to help maintain fish populations (National Research Council, 2008).

Butte Valley is a closed basin in the Klamath River watershed. The basin was formed by faulting and is defined by the surface extent of alluvial fill (*figs. 2, 3*; CDWR basin number 1-3; California Department of Water Resources, 2004d). The main aquifer units are coarse-grained lake deposits and interbedded volcanic units, particularly the Butte Valley Basalt in the southeast part of the basin (Planert and Williams, 1995). Major sources of groundwater recharge include subsurface flow through volcanic units, infiltration of precipitation and stream flow, and irrigation return water. Major sources of groundwater discharge include subsurface flow through volcanic units; evapotranspiration; pumping, primarily for agricultural use (Planert and Williams, 1995).

The South Fork Pit River and Warm Springs Valley subbasins of the Alturas area are defined by surface exposure of Holocene alluvial deposits and the Plio-Pleistocene Alturas Formation (*figs. 2, 3*; CDWR basin numbers 5-2.01 and 5-2.02; California Department of Water Resources, 2004e, f). The basins are surrounded by Quaternary and Tertiary lava flows and separated by surface exposure of the Plio-Pleistocene Warm Springs Tuff member of the Alturas Formation. The basins are dissected by many northwest-southwest trending faults, and the Alturas Formation is folded into three synclines with northwest-southwest trending axes (California Department of Water Resources, 1963). These structures affect groundwater flow in the basin. The Warm Springs subbasin has hot springs on faults that permit deep circulation of groundwater. The main water-bearing units in the basins are permeable beds of tuff, ashy sandstone, and diatomite in the lacustrine Alturas Formation. Basalt lava flows, which are exposed around the basins and also are interbedded with the Alturas Formation, serve as primary recharge areas.

The boundaries of the Big Valley groundwater basin are defined by surface extent of Holocene alluvial deposits and the Pleistocene Bieber Formation, and the basin is surrounded by Pliocene (TV study area) and Pleistocene (QV study area) lava flows (*figs. 2, 3*; CDWR basin number 5-4; California Department of Water Resources, 2004g). The Pit River flows through the western side of the valley. The principal water-bearing units are pumiceous sand and volcanic sand layers in the lacustrine Bieber Formation.

The Fall River Valley is defined by surface exposure of Pleistocene and Holocene alluvial and lacustrine deposits, and is surrounded by Pliocene, Pleistocene, and Holocene volcanic rocks (*figs. 2, 3*; CDWR basin number 5-5; California Department of Water Resources, 2004h). The Fall River Springs, which historically have been among the largest springs in the United States at 1,400–2,000 cubic feet per second (ft<sup>3</sup>/s) of discharge (Meinzer, 1927), discharge into the valley from the north and provide most of the base flow for the surface-water features in the valley. The source of the water

for the Fall River Springs appears to be precipitation on the vast Medicine Lake Highlands 60 kilometers (km) to the north (Rose and others, 1996).

The Lake Almanor Valley groundwater basin is along the northwest shore of Lake Almanor (*figs. 2, 3*; CDWR basin number 5-7; California Department of Water Resources, 2004i). The basin consists of Quaternary alluvial and lacustrine deposits and is bounded by Pliocene volcanic rocks. Lake Almanor is a reservoir operated by the Pacific Gas and Electric Company for power generation, recreation, and irrigation. The primary sources of inflow to the lake are submerged springs in the Pliocene volcanic rocks; the Upper North Fork Feather River, which drains the southern slope of the highlands in the Lassen Volcanic National Park area; and the Hamilton Branch, which drains Mountain Meadows reservoir (*fig. 3*; Plumas County Flood Control and Conservation District, 2007).

The McCloud Area groundwater basin is on the southeast slope of Mount Shasta between approximately 3,000 and 6,000 ft elevation (*figs. 2, 3*; CDWR basin number 5-35; California Department of Water Resources, 2004j). The basin is defined by the surface extent of a thin veneer of mostly Holocene alluvial and glacial deposits. The basin is underlain and bounded on the north and east by Pliocene and Pleistocene volcanic rocks and on the south by Paleozoic metasedimentary deposits of the Klamath Mountains (*figs. 2, 3*). The area has many freshwater springs (for example, Poeschel and others, 1986).

The Lake Britton groundwater basin is where Hat Creek joins the Pit River (*fig. 3*; CDWR basin number 5-46; California Department of Water Resources, 2004k). The basin is defined by the surface extent of Recent alluvial deposits and is surrounded and underlain by Pliocene (TV study area) and Pleistocene (QV study area) lava flows.

The North Fork Battle Creek Valley groundwater basin is just west of Lassen Volcanic National park (*fig. 3*; CDWR basin number 5-50; California Department of Water Resources, 2004l). The basin is defined by the surface extent of Recent alluvial deposits and is surrounded and underlain by Pliocene (TV study area) and Pleistocene (QV study area) lava flows. These alluvial deposits are approximately 32 ft thick and overlie a succession of lava flows. The main water-bearing unit is the interbedded layer of sand, gravel, ash, and cinder between the lava flows.

The Surprise Valley groundwater basin is on the northeastern edge of the study unit (*fig. 3*; CDWR basin number 6-1; California Department of Water Resources, 2004m). The long, narrow basin is a graben bounded on all sides by normal faults (*fig. 2*). The Surprise Valley fault is the westernmost large-offset normal fault in the northwestern Basin and Range, and there has been more than 15,000 ft (4.5 km) of vertical offset between the Warner Mountains



and the Surprise Valley in the last 14 Ma (Egger and Miller, 2011). The valley is filled with over 5,000 ft of alluvial and lacustrine deposits, most of which are lacustrine sediments from Pleistocene Lake Surprise.

The Surprise Valley is a closed basin. Streams entering the valley, primarily from the Warner Mountains to the west, terminate in the three seasonal, shallow, saline lakes along the central axis of the valley (*fig. 3*). The primary source of groundwater recharge is infiltration of surface water through alluvial fans along the base of the Warner Mountains and through coarse stream deposits at the northern end of the valley (California Department of Water Resources, 1963). The principal aquifers are the Holocene alluvial fans and near-shore deposits from Pleistocene Lake Surprise. Groundwater discharges by evapotranspiration and pumping, primarily for agricultural uses. The Surprise Valley has numerous hot springs associated with the Surprise Valley fault and sub-surface faults within the basin, and heated groundwater is extracted for use in geothermal power generation (Glen and others, 2013).

## Shasta Valley and Mount Shasta Volcanic Area Study Area (SH)

The SH study area corresponds to the CDWR-defined Shasta Valley groundwater basin (CDWR basin number 1-4; California Department of Water Resources, 2004b) and the former CDWR-defined volcanic groundwater basin 5-34, Mount Shasta Volcanic Area (California Department of Water Resources, 1980) (*figs. 3, 4*). The CDWR Shasta Valley groundwater basin is defined by Quaternary alluvial deposits up to 140 ft thick along the western and northern sides of Shasta Valley. The groundwater basin appears to be hydrologically connected with the volcanic rocks of the Mount Shasta Volcanic Area (Mack, 1960). Mesozoic marine sedimentary and metasedimentary rocks, and Paleozoic metamorphic rocks likely underlie the SH study area (Chesterman and Saucedo, 1984), and are exposed in the Klamath Mountains on the western margin of the study area (*fig. 2*).

Mount Shasta is part of the Cascade Range, which extends from northern California to southern British Columbia. The Cascade Range has been an active volcanic arc for the last approximately 36 Ma as a result of subduction of the Juan de Fuca plate under the North American plate (Bally and Palmer, 1989). The Mount Shasta magmatic system has been active for approximately 600,000 years, and the current mountain is a composite of four major cones that erupted over the last 250,000 years (Wood and Kienle, 1990). The most recent eruption in the youngest cone was in 1786, and there are still active fumaroles and hot springs on the summit.

The mountain is formed primarily of andesitic lava flows and pyroclastic deposits. Mount Shasta also hosts seven glaciers (Howat and others, 2007).

Most of the SH study area consists of the Mount Shasta Volcanic Area (5-34; *fig. 3*). Approximately two-thirds of the Mount Shasta Volcanic Area is covered by a debris avalanche that fell from Mount Shasta between 300,000 and 380,000 years ago (Crandell, 1989). The avalanche deposits are up to 300 ft thick and consist of two facies: a block facies containing blocks of andesite lava flows and volcanoclastic deposits up to several hundred feet across and a matrix facies consisting of an unsorted, unstratified mix of boulders through clay size material, primarily from andesite lava flows and material scoured from the valley floor. The principal aquifer in the valley is the Holocene Pluto's Cave basalt lava flow from Mount Shasta (Mack, 1960; Blodgett and others, 1988; California Department of Water Resources, 2004b). It is exposed on the surface in the southeastern part of the study unit. Many of the groundwater sources used for public drinking-water supplies in the SH study area are springs (Blodgett and others, 1988).

The Shasta River is listed as impaired under the Clean Water Act, because of elevated stream temperatures and low dissolved oxygen (DO) levels that have a detrimental effect on fish populations, and has a Total Maximum Daily Load (TMDL) Action Plan (North Coast Regional Water Quality Control Board, 2006). The Action Plan lists several anthropogenic factors that could be causing the increased temperatures and decreased DO levels, including irrigation return flows, impoundments, flow modifications and diversions, agricultural practices that decrease shade and increase inputs of organic matter, and wastewater discharge. Groundwater and spring discharges are the primary sources of cold water to the river. Groundwater pumping, primarily for agricultural uses, has become a contentious issue in the valley because pumping may decrease spring discharge and increase the depth to the water table, thereby decreasing inflow of cold water to the river (National Research Council, 2008).

Groundwater is recharged in the SH study area by infiltration of stream flow and snow melt into permeable lava flows, mostly in the southern part of the valley on the slopes of Mount Shasta. Much of the valley floor receives less than 15 in/yr of precipitation; thus, direct infiltration from precipitation is minimal. Percolation of irrigation water, water from behind small impoundments, and water from Lake Shastina (*fig. A1B*) also contribute to groundwater recharge. Groundwater is discharged by seepage to streams; evapotranspiration; and pumping for agricultural, municipal, and domestic supplies. Most of the groundwater is pumped from Pluto's Cave basalt lava flow or from the alluvial fans on the west side of the valley (California Department of Water Resources, 2004b).

## Quaternary Volcanic Areas (QV) and Tertiary Volcanic Areas (TV) Study Areas

The QV and TV study areas consist of areas mapped as Quaternary volcanic rocks (Qv) and Tertiary volcanic rocks (Tv), respectively, on the State geologic map (Saucedo and others, 2000) (*fig. 2*). The QV study area includes the former CDWR-defined volcanic groundwater basins 5-33, 1-24, and 6-103, which are collectively called the Modoc Plateau Pleistocene Volcanic Areas (*fig. 3*; California Department of Water Resources, 1980). The former CDWR-defined volcanic groundwater basins 5-32, 1-23, and 6-102, which are collectively called the Modoc Plateau Recent Volcanic Areas (not shown on *fig. 3*), are mapped as Holocene volcanic rocks (Qrv) on the State geologic map and are not included in the QV study area.

The QV and TV study areas both include Cascade Range and Modoc Plateau volcanic rocks. The oldest Cascade Range rocks are mid-Tertiary (35 Ma to 26 Ma) volcanic rocks of the Western Cascade series, an old, deeply eroded ancestor of the modern Cascade Range volcanoes, and are exposed north of the Shasta Valley (du Bray and John, 2011). The modern Cascade Range includes the Mount Shasta, Lassen, and Medicine Lake volcanic systems. The Lassen volcanic area, much of which is in Lassen Volcanic National Park, has a complex eruptive history, with 537 volcanic vents younger than 7 Ma (Guffanti and others, 1990). On a regional scale, it consists of hundreds of coalescing small volcanoes primarily formed of basalt and basaltic andesite lavas and, superimposed on this regional volcanism, is a series of five large volcanic centers composed of more silicic lavas (Clynne, 1990; Guffanti and others, 1990). Lassen is the most recent volcanic center and has been active for approximately 600,000 years. The youngest feature is a dacite dome field on the flank of the now-eroded main andesitic cone. One of these domes, Lassen Peak, last erupted in 1915–21. Medicine Lake Volcano is east of the main line of Cascade Range volcanic arc volcanoes. It is a large shield volcano covering approximately 770 mi<sup>2</sup> (2,000 km<sup>2</sup>) and formed primarily of basalt and basaltic andesite lavas erupted during the late Pleistocene (less than 1 Ma) (Donnelly-Nolan, 1988). The most recent eruptions were small rhyolite flows about 900 years ago (Donnelly-Nolan and others, 1990). Mount Shasta and Medicine Lake Volcano are composed of Quaternary and Holocene volcanic rocks and, thus, are partially included in the QV study area. Most of Lassen Volcanic National Park is in the QV study area, some is in the TV study area, and a small sliver is Holocene volcanic rocks.

The Modoc Plateau is the northern extension of the Walker Lane belt, a 60–190 miles (mi) (100–300 km) wide zone of distributed late Cenozoic dextral strike-slip and normal faulting between the Sierra Nevada and the Basin and Range provinces (Page, 1995; Oldow and Cashman, 2009). The Modoc Plateau is covered with volcanic rocks, primarily basalt and basaltic andesite lava flows, ranging in age from late Miocene to Recent (approximately 15 Ma to present).

Locally, there are also pyroclastic deposits and more silicic volcanic features.

The QV and TV study areas were defined as separate areas in order to examine potential relations between groundwater water quality and age of the aquifer materials. The basalt and basaltic andesite lava flows that compose most of the QV and TV study areas may undergo changes in mineralogy with time. Primary igneous minerals and volcanic glass can become oxidized and hydrated, and new minerals can be deposited in voids. These differences in aquifer mineralogy could result in differences in groundwater composition and water quality.

Groundwater in volcanic rocks primarily is contained in rubble zones at the tops and bottoms of lava flows, cavities between lava flows, cracks and fissures resulting from thermal and tectonic stresses, volcanic pipes and lava tubes, and open gas vesicles (Planert and Williams, 1995; Todd and Mays, 2012). The distribution of permeable zones is unpredictable, although the probability of large groundwater yields generally is greater in areas near fault zones (Planert and Williams, 1995). Hydraulic conductivity values from wells in Tertiary volcanic rocks in the Klamath Basin in Oregon and California range from less than 1 meter per day (m/d) to over 600 m/d (estimated from data in Gannett and others, 2007). For comparison, the hydraulic conductivity of sand generally ranges from 2 to 45 m/d (Todd and Mays, 2012). Within the TV study area, the Western Cascades series rocks have much lower permeability than Modoc Plateau lavas because secondary mineralization from hydrothermal alteration has filled many of the void spaces in the Western Cascades series rocks (Newcomb and Hart, 1958; Gannett and others, 2007).

The volcanic units are highly permeable and generally have little soil or sediment on top of them, thus groundwater is readily recharged by infiltration of precipitation and snow melt and by capture of stream flow. The QV, TV, and SH study areas contain many springs, located where high permeability zones intersect the land surface, and these springs can be a large component of inflow to streams. These springs include several first magnitude springs, defined as springs with discharge greater than 100 cubic feet per second (ft<sup>3</sup>/s; Meinzer, 1927). For example, five springs discharging in the QV study area near where Hat Creek joins the Pit River have a combined discharge of over 315,000 gpm (700 cubic feet per second), and isotopic data indicate the recharge area was approximately 30 mi (50 km) to the south in the high elevations in Lassen Volcanic National Park (Rose and others, 1996).

## Methods

This section describes the methods used for the *status* and *understanding assessments*. Methods used to collect and analyze groundwater samples and results for the evaluation of quality-control data are described by Shelton and others



(2013). Methods used for compiling data for potential explanatory factors are described in [appendix A](#).

## Status Assessment

The *status assessment* was designed to quantify groundwater quality in areal proportions of the primary aquifer system. The primary aquifer system is defined by the depth intervals over which wells listed in the CDPH database are screened or open. The use of the term “primary aquifer system” does not imply a discrete aquifer unit exists. 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). Thus, the primary aquifer system generally corresponds to the deeper portion of the aquifer system that is tapped by public drinking-water supply wells. However, this segregation between the depths of public-supply and domestic wells may not apply in areas outside of groundwater basins. Wells in fractured-rock aquifers are most productive at depths where fractures in the local rock are saturated with water, and the density of fractures typically decreases with depth (Freeze and Cherry, 1979; Ingebritsen and Sanford, 1998). Nearly all of the wells used in *status assessments* for the CAMP study unit are listed in the CDPH database and are, therefore, classified as public drinking-water supply wells. To the extent that domestic wells in the study unit are screened or open over the same depth intervals as the CDPH wells, the assessments presented in this report also are applicable to the parts of the aquifer system used for domestic drinking-water supplies.

This section describes the methods used for (1) defining groundwater quality, (2) assembling the data used for the assessment, (3) selecting constituents for evaluation, and (4) calculating aquifer-scale proportions. Two statistical approaches were used for calculating aquifer-scale proportions: a “grid-based” approach that used one well to represent each grid cell, and a “spatially weighted” approach that used many wells to represent each grid cell (Belitz and others, 2010).

The CDPH database contains historical records from more than 25,000 wells, requiring the use of targeted retrievals to effectively access relevant water-quality data. For example, for the area representing the CAMP study unit, the CDPH database contains about 75,000 records for samples collected between 1982 and 2010 from 388 wells. The CDPH data were used in the spatially weighted calculations of aquifer-scale proportions.

## Groundwater Quality Defined as Relative-Concentrations

In this study, groundwater-quality data are presented as *relative concentrations* (RCs), which is the ratio of a constituent’s concentration measured in a groundwater sample to the concentration of a constituent’s regulatory or

non-regulatory benchmark used to evaluate drinking-water quality. The use of RC is similar to the approaches employed by other studies to place the concentrations of constituents in groundwater in a toxicological context (for example, U.S. Environmental Protection Agency, 1986; Toccalino and others, 2004; Toccalino and Norman, 2006; Rowe and others, 2007). The RC is defined as follows:

$$\text{Relative concentration (RC)} = \frac{\text{Sample concentration}}{\text{Benchmark concentration}}$$

An RC value less than 1 indicates that the sample concentration was less than the benchmark concentration, and an RC value greater than 1 indicates that the sample concentration was greater than the benchmark concentration. The use of RCs permits comparison on a single scale for constituents that can be present at a wide range of concentrations. RCs can only be computed for constituents with water-quality benchmarks; therefore, constituents without water-quality benchmarks were not included in the *status assessment*.

Regulatory and non-regulatory benchmarks apply to treated water that is served to the consumer, not to untreated groundwater. To place the results in context, however, concentrations of constituents measured in the untreated groundwater were compared to benchmarks established by the U.S. Environment Protection Agency (USEPA) and the California Department of Public Health (CDPH; U.S. Environmental Protection Agency, 1999a, 2009a; 2012; California Department of Public Health, 2010, 2013b). The benchmarks used for each constituent were selected in the following order of priority:

1. Regulatory, health-based levels established by the CDPH and the USEPA: maximum contaminant levels (MCL-CA and MCL-US) and USEPA action levels (AL-US), respectively.
2. Non-regulatory, non-health based, aesthetic-based levels established by the CDPH: secondary maximum contaminant levels (SMCL-CA). The salinity indicators chloride, sulfate, and TDS have recommended and upper SMCL-CA levels, and the values for the upper levels were used.
3. Non-regulatory, health-based levels established by the CDPH and the USEPA: CDPH notification levels (NL-CA), USEPA lifetime health advisory levels (HAL-US), and USEPA risk-specific doses for 1:100,000 ( $10^{-5}$ ; RSD5-US).

For constituents with multiple types of benchmarks, this hierarchy sometimes did not result in selection of the benchmark with the lowest concentration. Additional information on the types of benchmarks used and lists of the benchmark values for all constituents analyzed are provided by Shelton and others (2013).

The two microbial indicators analyzed in samples from the CAMP study unit, total coliforms and *E.coli*, have drinking-water quality benchmarks, but are not included in the *status assessments* for the individual study units because the results are to be presented in one report for all 35 GAMA Priority Basin Project public-supply aquifer study units (Carmen Burton, USGS, written commun., 2014).

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 MCL-US or Health-Based Screening Level (HBSL), and defined this ratio as the benchmark quotient (BQ). HBSLs are not used in this report because HBSLs are not currently used as benchmarks by California drinking-water regulatory agencies. 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 1*). 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, 1999b) 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 VOCs) were present at BQ greater than 0.1 in approximately 10 percent of the samples and that inorganic constituents (nutrients, trace elements and radioactive constituents) were present at BQ 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 occur naturally in groundwater, and their concentrations usually are stable or change slowly compared to those of organic constituents. Having 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 prevalent at concentrations close to benchmarks and may therefore warrant more immediate attention from water-resource managers.

The boundary between low and moderate RC is not intended as a demarcation of the presence of contamination from anthropogenic sources. Unlike the other classes of inorganic constituents, concentrations of nutrients in groundwater commonly 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 with contamination from anthropogenic sources to be categorized as a low RC for nitrate. 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. Similarly, groundwater containing anthropogenic organic constituents with RCs less than 0.1 was classified as a low RC for organic constituents, even though contamination from anthropogenic sources was present.

**Table 1.** Relative-concentration categories used for assessing groundwater quality.

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark.  
**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

Data Used for Status Assessment

Groundwater-quality data collected by the USGS for the GAMA Priority Basin Project (USGS-GAMA) and data compiled from the CDPH database were used in the *status assessment*. The grid-based calculations of aquifer-scale

proportions used data collected by USGS-GAMA for the CAMP study unit ([appendix A](#)), and the spatially weighted calculations of aquifer-scale proportions used the data from the grid-based calculations, plus data compiled for many wells in the CDPH database. Comparisons of USGS-GAMA and CDPH data are presented in [appendix B](#).

### Data for Grid-Based Calculations of Aquifer-Scale Proportions

The data used for the grid-based calculations of aquifer-scale proportions were from the 90 wells and springs (USGS-grid wells) sampled by USGS-GAMA. Only a subset of the entire area of the CAMP study unit was included in the gridded area. The CAMP study unit had relatively few CDPH wells, and these wells were not evenly distributed; thus, if the entire study unit had been included in the gridded area, there would have been many grid cells that did not contain any CDPH wells ([fig. 4](#)). To minimize the number of cells without any wells, only the areas of the study unit near CDPH wells were included in the gridded area. For each study area, a 1.86-mi (3-kilometers; km) radius circle was drawn around each CDPH well in the study area. If the area within 3-km of the well included more than one study area, the circle was truncated at the boundaries of the study area containing the well ([figs. A1A–G](#)). For example, the area within 3-km of well LU-11 includes parts of the LU and TV study areas and areas not in any study area ([fig. A1D](#)). The 3-km buffer around LU-11 only includes the parts in the LU study area. The aggregate areas encompassed by these circles in each of the six study areas were divided into 15 equal-area grid cells (Scott, 1990). The sizes of the grid cells ranged from 19 square

kilometers (km<sup>2</sup>) in the ES study area to 47 km<sup>2</sup> in the QV study area ([table 2](#)).

All CDPH 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 selected as the USGS-grid well and sampled. For cells without accessible CDPH wells, a CDPH well located close to the the cell boundary in an adjacent grid cell could be selected if the well was closer to the cell it was being selected to represent than it was to the USGS-grid well in the cell in which it was located, and the CDWR well completion report for the well indicated that the screened or open intervals were in the appropriate aquifer lithology. For cells not represented by a CDPH well, appropriate USGS-grid wells were selected by door-to-door canvassing.

Of the 90 USGS-grid wells selected, 82 were listed in the CDPH database (74 wells and 8 springs), and the other 8 (6 domestic wells, 1 irrigation well, and 1 spring used for irrigation) had screened or open intervals at depths similar to those of wells listed in the CDPH database. Seven USGS-grid wells were located in cells adjacent to the cells they were selected to represent. In two of these seven cases, a well in the Central Valley was selected to represent an Eastside Sacramento Valley study area cell ([fig. A1F](#)). The screened intervals in these two wells were deep enough to intersect the Tuscan Formation. The 90 USGS-grid wells were named with an alphanumeric GAMA\_ID consisting of an initial prefix identifying the study unit (CAMP), a second prefix indicating the study area (ES, HL, LU, QV, SH, or TV), and followed by a number indicating the order of sample collection in each study area ([appendix A](#)). For ease of use, the prefix “CAMP” is dropped from the GAMA\_ID in this report.

**Table 2.** Study-area names, study-area and grid-cell sizes, and numbers of California Department of Public Health (CDPH) wells and U.S. Geological Survey (USGS)-grid wells in each study area, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[**Abbreviations:** km<sup>2</sup>, square kilometers; na, not applicable; TDS, total dissolved solids]

Study area	Study-area code	Area (km <sup>2</sup> )	Gridded area (km <sup>2</sup> )	Fraction of total gridded area	Grid-cell area (km <sup>2</sup> )	Number of CDPH wells with any data <sup>1</sup>	Number of CDPH wells with data for nitrate, arsenic, and TDS <sup>2</sup>	Number of USGS-grid wells
Sacramento Valley Eastside	ES	2,004	287	0.104	19	26	15	15
Honey Lake Valley	HL	1,261	371	0.134	25	34	15	15
Cascade Range and Modoc Plateau Low-Use Basins	LU	4,826	510	0.184	34	42	12	15
Quaternary Volcanic Areas	QV	10,399	711	0.257	47	63	14	15
Shasta Valley and Mount Shasta Volcanic Area	SH	878	369	0.133	25	39	16	15
Tertiary Volcanic Areas	TV	10,985	517	0.187	34	36	3	15
Other areas	na	8,647	na	na	na	na	na	na
Total		39,000	2,763	1	31	240	75	90

<sup>1</sup>Of these, 63 also were USGS-grid wells.

<sup>2</sup>Of these, 21 also were USGS-grid wells.

Approximately 8 percent of the wells listed in the CDPH database for the CAMP study unit were springs; however, this could be a minimum estimate of the percentage of springs. Springs are sites where groundwater naturally flows from below ground to above land surface. In some cases, the connection between the spring and the distribution system had been improved with a horizontal well bore. In the CDPH database, a spring with a horizontal well bore may be given a name that identifies it as a well. Of the 90 USGS-grid wells sampled, 9 were springs and 81 were wells. For ease of discussion, all sites are referred to as wells, unless the difference between a well and a spring is important to the discussion.

Samples collected from USGS-grid wells were analyzed for 214 constituents (*table 3*). Water-quality data collected by USGS-GAMA are tabulated in Shelton and others (2013) and also are available from the SWRCB's publically accessible internet database GeoTracker GAMA (website at [http://www.waterboards.ca.gov/gama/geotracker\\_gama.shtml](http://www.waterboards.ca.gov/gama/geotracker_gama.shtml)) and the USGS's publically accessible internet database NWISWeb (website at <http://waterdata.usgs.gov/ca/nwis/>).

### Additional Data Used for Spatially Weighted Calculations of Aquifer-Scale Proportions

The spatially weighted calculations of aquifer-scale proportions used data from the 90 USGS-grid wells and from the 240 wells in the CDPH database with water-quality data for samples collected between September 16, 2007, and September 16, 2010. Of these 240 wells, 63 also were USGS-grid wells, and only the USGS-GAMA data were used. Many of the 177 wells having only CDPH data had data for a limited number of constituents, commonly only nitrate. For example, only 75 of the 177 wells had CDPH data for all three of the constituents nitrate, arsenic, and total dissolved solids (TDS) (*table 2*). Water-quality data collected by the CDPH are available from the SWRCB's GeoTracker GAMA (website at [http://www.waterboards.ca.gov/gama/geotracker\\_gama.shtml](http://www.waterboards.ca.gov/gama/geotracker_gama.shtml)).

### Selection of Constituents for Evaluation

Aquifer-scale proportions are presented for a subset of 214 constituents analyzed in samples collected by USGS-GAMA for the CAMP study unit. This subset was selected by using the following criteria:

- Constituents present at high or moderate RCs (*table 1*) in the USGS-grid well dataset or in the CDPH database for any sample collected between September 16, 2007, and September 16, 2010.
- Organic constituent classes having at least one constituent with an area-weighted detection frequency of greater than 10 percent in the USGS-grid well dataset.

**Table 3.** Summary of constituent groups analyzed in the 90 samples collected by the U.S. Geological Survey (USGS) for the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Constituent names: *E. coli*, *Escherichia coli*. Other abbreviations and symbols: B, Boron; C, carbon; H, hydrogen; He, helium; O, oxygen; pCi/L, picocuries per liter; Sr, strontium; TDS, total dissolved solids;  $\delta$ , delta;  $\mu\text{g/L}$ , microgram per liter]

Constituents	Number of constituents analyzed
Inorganic constituents	
Specific conductance	1
Gross alpha and gross beta particle activity <sup>1</sup>	2
Major ions and trace elements (including alkalinity and TDS)	35
Nutrients	5
Radon-222	1
Uranium and uranium isotopes <sup>2</sup>	1
Organic constituents	
Pesticides and pesticide degradates	63
Volatile organic compounds (VOCs) <sup>3</sup>	85
Constituent of special interest	
Perchlorate	1
Geochemical and age-dating tracers	
Arsenic and iron redox species ratios	2
$\delta^{11}\text{B}$ of dissolved boron	1
Carbon-14 and $\delta^{13}\text{C}$ of dissolved carbonates	2
Dissolved oxygen, pH, and temperature	3
$\delta^2\text{H}$ and $\delta^{18}\text{O}$ stable isotopes of water	2
Noble gases (helium, neon, argon, krypton, xenon), and $^3\text{He}/^4\text{He}$ of dissolved helium	6
$^{87}\text{Sr}/^{86}\text{Sr}$ of dissolved strontium	1
Tritium	1
Microbial constituents	
Total coliform and <i>E. coli</i>	2
Sum	214

<sup>1</sup>Both gross alpha and gross beta particle activities were measured after 72-hour and 30-day holding times; data from the 30-day measurement are used in this report.

<sup>2</sup>Uranium concentration was measured in all samples; the activities of the uranium isotopes uranium-234, uranium-235, and uranium-238 were measured in a subset of samples. The two samples having total uranium activity greater than the California Department of Public Health maximum contaminant level (MCL-CA) of 20 pCi/L also had uranium concentration greater than the U.S. Environmental Protection Agency maximum contaminant level (MCL-US) of 30  $\mu\text{g/L}$ .

<sup>3</sup>Includes 10 constituents classified as fumigants or fumigant synthesis byproducts.



These criteria identified 17 inorganic constituents (table 4A), and 2 organic constituent classes (herbicides and trihalomethanes) and perchlorate (table 5). An additional 28 inorganic constituents were detected by USGS-GAMA in samples from the CAMP study unit that either have no drinking-water quality benchmarks or were only detected at low RCs (table 4B). Aquifer-scale proportions are not presented for constituents only detected at low RCs because the proportion of the primary aquifer system having low RCs for those constituents is 100 percent. All of the 18 geochemical and age-dating tracers examined were detected in samples (table 4B). A total of 19 organic constituents with drinking-water quality benchmarks were detected at low RCs, and 8 organic constituents with no benchmarks also were detected (table 5). Because no organic constituents were detected at high or moderate RCs, the organic constituents were evaluated as classes rather than as individual constituents. The remaining 121 constituents were not detected by USGS-GAMA in the CAMP study unit. A complete list of the constituents analyzed by USGS-GAMA in the CAMP study unit can be found in the CAMP Data Series Report (Shelton and others, 2013).

The CDPH database also was used to identify constituents that have been reported at high RCs historically but not currently (table 6). The historical period was defined as the period starting with the earliest record maintained in the CDPH electronic database and ending just prior to the interval used for the *status assessment*: November 16, 1982, through September 15, 2007. Constituent concentrations could have been historically high but not currently high because of improvement of groundwater quality with time or abandonment of wells with high concentrations of constituents. Historically high concentrations of constituents that do not otherwise meet the criteria listed previously were not considered representative of potential groundwater-quality concerns in the study unit during the period of study.

The CAMP study unit had 12 historically high constituents (table 6). Of the nine inorganic constituents, one was also found at moderate RCs in the 3-year period used in the *status assessment* and was detected in moderate RCs in the USGS-grid wells (fluoride) (table 4A). Of the eight other inorganic constituents, two were not analyzed by USGS-GAMA (mercury and radium-228) and the remaining five were either not detected or were detected only at low RCs in USGS-grid wells. Of the three volatile organic constituents, none were detected at moderate or high RCs in the 3-year period used in the *status assessment*; however, two were detected at low RCs (methyl *tert*-butyl ether [MTBE] and tetrachloroethene [PCE]) in USGS-grid wells in the study unit (table 5). Of the 12 historically high constituents, 9 were detected at high concentrations in only 1 CDPH well each (table 6).

## Calculation of Aquifer-Scale Proportions

Seven primary aquifer systems were defined for the CAMP study unit: six to represent each of the six study areas and an aggregated system to represent the study unit as a whole. The proportions of these primary aquifer systems in the six study areas with high, moderate, and low RCs of constituents were calculated by using the grid-based and spatially weighted approaches 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. Aquifer-scale proportions for the primary aquifer system in the study unit as a whole were calculated as an area-weighted combination of the proportions for the six study areas. Calculations of aquifer-scale proportions were made for individual constituents and for classes of constituents. Aquifer-scale proportions for constituent classes were calculated by using the maximum RC for any constituent in the class to represent the class. For example, a well having a high RC for arsenic, moderate RC for fluoride, and low RCs for 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.

The grid-based calculations used the USGS-grid well dataset. Aquifer-scale proportions were calculated for each of the study areas separately because cell sizes differed among the study areas (table 2). High-RC aquifer-scale proportion was calculated as the fraction of the USGS-grid wells in the study area having high RCs for a constituent (equation 1). The moderate-RC aquifer-scale proportion was calculated similarly. Confidence intervals for grid-based high-RC aquifer-scale proportions were computed by using the Jeffrey’s interval for the binomial distribution (Brown and others, 2001; Belitz and others, 2010).

$$P_{SA,g}^{high} = \frac{N_{SA}^{high}}{N_{SA}} \quad (1)$$

where

$P_{SA,g}^{high}$	is the grid-based high-RC aquifer-scale proportion for the study area SA,
$N_{SA}^{high}$	is the number of cells in the study area represented by a well having high RC for the constituent; and
$N_{SA}$	is the number of cells in the study area having a well with data for the constituent (the value of this parameter is 15 for all 6 of the study areas, because the USGS-grid wells had data for all constituents evaluated).

**Table 4A.** Benchmark type and value and reporting limits for inorganic constituents detected at moderate or high relative-concentrations in samples collected for the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. For inorganic constituents, RC greater than 1.0 is defined as high and RC less than or equal to 1 and greater than 0.5 is defined as moderate. **Benchmark type:** AL-US, USEPA action level. Regulatory, health-based benchmarks: MCL-CA, CDPH maximum contaminant level; MCL-US, USEPA maximum contaminant level; Prop MCL-US, proposed USEPA maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark units:** mg/L, milligrams per liter; pCi/L, picocuries per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter. **Other abbreviations:** CDPH, California Department of Public Health; na, not available; ssLc, sample-specific critical level; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey]

Constituent	Benchmarks		Units	Reporting limits		Understanding assessment presented?
	Type <sup>1</sup>	Value		USGS	CDPH <sup>2</sup>	
Inorganic constituents with health-based benchmarks						
Nutrients						
Ammonia, as nitrogen	HAL-US <sup>3</sup>	24.7	mg/L	0.01	na	No
Nitrate, as nitrogen <sup>4</sup>	MCL-US	10	mg/L	0.02	0.1	No
Trace elements						
Arsenic	MCL-US	10	µg/L	0.02	2	Yes
Boron	NL-CA	1,000	µg/L	3	100	Yes
Fluoride	MCL-CA	2	mg/L	0.04	0.1	No
Lead <sup>5</sup>	AL-US	15	µg/L	1	0.2	No
Molybdenum	HAL-US	40	µg/L	0.01	na	Yes
Strontium	HAL-US	4,000	µg/L	0.2	na	No
Vanadium	NL-CA	50	µg/L	0.08	2	Yes
Radioactive constituents						
Gross alpha particle activity	MCL-US	15	pCi/L	ssLc	3	No
Radon-222 activity	Prop MCL-US	4,000	pCi/L	ssLc	na	No
Uranium	MCL-US	30	µg/L	0.004	1	Yes
Inorganic constituents with secondary maximum contaminant level benchmarks						
Chloride	SMCL-CA	500	mg/L	0.06	1	No
Iron	SMCL-CA	300	µg/L	6	50	Yes
Manganese	SMCL-CA	50	µg/L	0.7	10	Yes
Specific conductance	SMCL-CA	1,600	µS/cm	5	na	No
Total dissolved solids (TDS)	SMCL-CA	1,000	mg/L	12	na	Yes

<sup>1</sup>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 SMCL-CA, California Department of Public Health (2013b); MCL-US and AL-US, U.S. Environmental Protection Agency (2009a); NL-CA, California Department of Public Health (2010); HAL-US, U.S. Environmental Protection Agency (2012); Prop MCL-US, U.S. Environmental Protection Agency (1999a).

<sup>2</sup>Nondetections are reported in the CDPH database as a concentration of zero or as less than the reporting limit. The most prevalent reporting limit, as inferred from data for nondetections, is listed.

<sup>3</sup>HAL-US benchmark is 30 mg/L for ammonia as ammonia. To facilitate comparison to the analytical results, this HAL-US has been converted and reported as 24.7 mg/L as nitrogen. The benchmark applies to total dissolved ammoniacal nitrogen (ammonia gas plus ammonium ion).

<sup>4</sup>Concentrations of nitrate, as nitrate, reported in the CDPH data are converted to concentrations of nitrate, as nitrogen, for comparison with USGS-GAMA data.

<sup>5</sup>Although lead was not detected at high or moderate RCs in USGS-GAMA samples, it was reported at high and moderate RCs in the CDPH database during September 16, 2007, through September 16, 2010, and, therefore, is included on this table.

**Table 4B.** Benchmark type and value and reporting limits for detected inorganic constituents having no benchmarks or present only at low relative-concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. For inorganic constituents, RC less than or equal to 0.5 is defined as low. **Benchmark type:** Regulatory, health-based benchmarks: AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level; MCL-US, USEPA maximum contaminant level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark units:** cm<sup>3</sup>STP/gH<sub>2</sub>O, cubic centimeters of gas at standard pressure and temperature per gram of water; mg/L, milligrams per liter; pCi/L, picocuries per liter; per mil, parts per thousand; pmC, percent modern Carbon; std units, standard pH units; °C, degrees Celsius; µg/L, micrograms per liter. **Other abbreviations:** CDPH, California Department of Public Health; na, not available; ssLc, sample-specific critical level; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; >, greater than; <, less than]

Constituent	Benchmarks		Units	Reporting limits <sup>2</sup>	
	Type <sup>1</sup>	Value		USGS	CDPH
Inorganic constituents with benchmarks					
Aluminum	MCL-CA	1,000	µg/L	1.7	50
Antimony	MCL-US	6	µg/L	0.027	6
Barium	MCL-CA	1,000	µg/L	0.4	na
Beryllium	MCL-US	4	µg/L	0.006	1
Cadmium	MCL-US	5	µg/L	0.016	1
Chromium	MCL-CA	50	µg/L	0.42	1
Copper	AL-US	1,300	µg/L	1.7	10
Gross beta particle activity	MCL-US	50	pCi/L	ssLc	na
Nickel	MCL-CA	100	µg/L	0.36	10
Nitrite, as nitrogen	MCL-US	1	mg/L	0.001	0.1
Selenium	MCL-US	50	µg/L	0.03	2
Silver	SMCL-CA	100	µg/L	0.005	1
Sulfate	SMCL-CA	500	mg/L	0.09	2
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, as CaCO <sub>3</sub>	none	none	mg/L	4	na
Bromide	none	none	mg/L	0.01	na
Calcium	none	none	mg/L	0.022	na
Cobalt	none	none	µg/L	0.38	na
Iodide	none	none	mg/L	0.001	na
Lithium	none	none	µg/L	0.22	na
Magnesium	none	none	mg/L	0.008	na
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 4B.** Benchmark type and value and reporting limits for detected inorganic constituents having no benchmarks or present only at low relative-concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.—Continued

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. For inorganic constituents, RC less than or equal to 0.5 is defined as low. **Benchmark type:** Regulatory, health-based benchmarks: AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level; MCL-US, USEPA maximum contaminant level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark units:** cm<sup>3</sup>STP/gH<sub>2</sub>O, cubic centimeters of gas at standard pressure and temperature per gram of water; mg/L, milligrams per liter; pCi/L, picocuries per liter; per mil, parts per thousand; pmC, percent modern Carbon; std units, standard pH units; °C, degrees Celsius; µg/L, micrograms per liter. **Other abbreviations:** CDPH, California Department of Public Health; na, not available; ssLc, sample-specific critical level; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; >, greater than; <, less than]

Constituent	Benchmarks		Units	Reporting limits <sup>2</sup>	
	Type <sup>1</sup>	Value		USGS	CDPH
Geochemical and age-dating tracers					
<sup>3</sup> He/ <sup>4</sup> He of helium	none	none	dimensionless	na	na
<sup>87</sup> Sr/ <sup>86</sup> Sr of dissolved strontium	none	none	dimensionless	na	na
Arsenic and iron redox species ratios	none	none	dimensionless	na	na
Carbon-14	none	none	pmC	na	na
Dissolved oxygen	none	none	mg/L	na	na
Noble gases (helium, neon, argon, krypton, xenon)	none	none	cm <sup>3</sup> STP/gH <sub>2</sub> O	na	na
pH	SMCL-US	<6.5 or >8.5	std units	na	na
Temperature	none	none	°C	na	na
Tritium	MCL-CA	20,000	pCi/L	na	na
δ <sup>11</sup> B of dissolved boron	none	none	per mil	na	na
δ <sup>13</sup> C of dissolved carbonates	none	none	per mil	na	na
δ <sup>2</sup> H and δ <sup>18</sup> O stable isotopes of water	none	none	per mil	na	na

<sup>1</sup>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 SMCL-CA, California Department of Public Health (2013b); MCL-US and AL-US, U.S. Environmental Protection Agency (2009a); NL-CA, California Department of Public Health (2010); HAL-US, U.S. Environmental Protection Agency (2012); Prop MCL-US, U.S. Environmental Protection Agency (1999a).

<sup>2</sup>Nondetections are reported in the CDPH database as a concentration of zero or as less than the reporting limit. The most prevalent reporting limit as inferred from data for nondetections is listed.

**Table 5.** Benchmark type and value and reporting limits for organic and special-interest constituents detected in samples collected for the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[**Benchmark type:** Regulatory, health-based benchmarks: AL-US, U.S. Environmental Protection Agency (USEPA) action level; HAL-US, USEPA lifetime health advisory level; MCL-CA, California Department of Public Health (CDPH) maximum contaminant level; MCL-US, USEPA maximum contaminant level; Prop MCL-US, proposed USEPA maximum contaminant level; RSD5-US, U.S. Environmental Protection Agency risk specific dose at a risk factor of 10E–5. Non-regulatory, health-based benchmarks: NL-CA, CDPH notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark unit:** µg/L, micrograms per liter. **Other abbreviations:** USGS, U.S. Geological Survey]

Constituent	Benchmarks			Reporting limits		In constituent class that has assessment results tabulated?
	Type¹	Value	Units	USGS	CDPH²	
Pesticides						
Insecticides and fungicides						
Carbaryl	RSD5-US	400	µg/L	0.06	na	No
Metalaxyl	none	none	none	0.014	na	No



**Table 5.** Benchmark type and value and reporting limits for organic and special-interest constituents detected in samples collected for the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.—Continued

[**Benchmark type:** Regulatory, health-based benchmarks: AL-US, U.S. Environmental Protection Agency (USEPA) action level; HAL-US, USEPA lifetime health advisory level; MCL-CA, California Department of Public Health (CDPH) maximum contaminant level; MCL-US, USEPA maximum contaminant level; Prop MCL-US, proposed USEPA maximum contaminant level; RSD5-US, U.S. Environmental Protection Agency risk specific dose at a risk factor of 10E-5 µg/L.; Non-regulatory, health-based benchmarks: NL-CA, CDPH notification level. Non-regulatory, aesthetic/technical-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark unit:** µg/L, micrograms per liter. **Other abbreviations:** USGS, U.S. Geological Survey]

Constituent	Benchmarks			Reporting limits		In constituent class that has assessment results tabulated?
	Type¹	Value	Units	USGS	CDPH²	
Pesticides—Continued						
Herbicides and herbicide degradates						
Deethylatrazine	none	none	µg/L	0.014	na	No
3,4-Dichloroaniline	none	none	µg/L	0.0042	na	No
Atrazine	MCL-CA	1	µg/L	0.008	na	Yes³
Hexazinone	HAL-US	400	µg/L	0.008	na	Yes³
Prometon	HAL-US	100	µg/L	0.012	na	Yes³
Simazine	MCL-US	4	µg/L	0.006	na	Yes³
Tebuthiuron	HAL-US	500	µg/L	0.028	na	Yes³
Volatile organic compounds (VOCs)						
Trihalomethanes						
Chloroform	MCL-US⁴	80	µg/L	0.03	0.5	Yes
Solvents						
1,1-Dichloroethene (1,1-DCE)	MCL-CA	6	µg/L	0.02	0.5	No
Dichloromethane	MCL-US	5	µg/L	0.04	0.5	No
Tetrachloroethene (PCE)	MCL-US	5	µg/L	0.03	0.5	No
1,1,1-Trichloroethane (1,1,1-TCA)	MCL-US	200	µg/L	0.03	0.5	No
Gasoline hydrocarbons and oxygenates						
Benzene	MCL-CA	1	µg/L	0.03	0.5	No
2-Ethyltoluene	none	none	µg/L	0.03	na	No
Isopropylbenzene	NL-CA	770	µg/L	0.04	0.5	No
4-Isopropyltoluene	none	none	µg/L	0.06	na	No
Methyl <i>tert</i> -butyl ether (MTBE)	MCL-CA	13	µg/L	0.1	1	No
<i>n</i> -Propylbenzene	NL-CA	260	µg/L	0.04	0.5	No
1,2,3,4-Tetramethylbenzene	none	none	µg/L	0.1	na	No
1,2,3,5-Tetramethylbenzene	none	none	µg/L	0.1	na	No
1,2,3-Trimethylbenzene	none	none	µg/L	0.1	na	No
1,3,5-Trimethylbenzene	NL-CA	330	µg/L	0.03	0.5	No
Other VOCs						
Carbon disulfide	NL-CA	160	µg/L	0.04	0.5	No
1,4-Dichlorobenzene	MCL-CA	5	µg/L	0.03	0.5	No
Trichlorotrifluoroethane (CFC-113)	MCL-CA	1,200	µg/L	0.03	0.5	No
Special-interest constituents						
Perchlorate	MCL-CA	6	µg/L	0.1	2	Yes

<sup>1</sup>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 SMCL-CA, California Department of Public Health (2013b); MCL-US and AL-US, U.S. Environmental Protection Agency (2009a); NL-CA, California Department of Public Health (2010); HAL-US and RSD5-US, U.S. Environmental Protection Agency (2012); Prop MCL-US, U.S. Environmental Protection Agency (1999a).

<sup>2</sup>Nondetections are reported in the CDPH database as a concentration of zero or as less than the reporting limit. The most prevalent reporting limit as inferred from data for nondetections is listed.

<sup>3</sup>These five herbicides were evaluated as a class by using the sum of the relative concentrations of the individual constituents.

<sup>4</sup>The MCL-US for chloroform applies to the sum of the four trihalomethanes chloroform, bromodichloromethane, dibromochloromethane, and bromoform. Only chloroform was detected in the CAMP study unit.

**Table 6.** Constituents reported at concentrations greater than benchmarks in the California Department of Public Health (CDPH) database historically (November 16, 1982, to September 15, 2007), but not during the 3-year time period used in status assessment (September 16, 2007, to September 16, 2010), Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[**Benchmark type:** Regulatory, health-based benchmarks: AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level; MCL-US, USEPA maximum contaminant level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark units:** mg/L, milligrams per liter; pCi/L, picocuries per liter; µg/L, micrograms per liter. **Other abbreviations:** mm/dd/yyyy, month/day/year; USEPA, U.S. Environmental Protection Agency]

Constituent	Benchmark			Date of most recent high value (mm/dd/yyyy)	Number of wells with historical data	Number of wells with a high value
	Type <sup>1</sup>	Value	Units			
Inorganic constituents						
Antimony	MCL-US	6	µg/L	02/20/1997	226	1
Copper	AL-US	1,300	µg/L	08/05/1992	214	1
Fluoride <sup>2</sup>	MCL-CA	2	mg/L	12/11/1996	270	1
Mercury <sup>3</sup>	MCL-US	2	µg/L	12/18/2003	231	1
Nickel	MCL-CA	100	µg/L	05/21/2007	225	1
Nitrite, as nitrogen	MCL-US	1	mg/L	02/07/2006	323	3
Radium-228 activity <sup>3</sup>	MCL-US	5	pCi/L	03/05/2007	133	1
Sulfate	SMCL-CA	500	mg/L	11/17/1989	231	1
Thallium	MCL-US	2	µg/L	12/14/1994	220	3
Organic constituents						
Methy <i>tert</i> -butyl ether (MTBE)	MCL-CA	13	µg/L	11/05/2002	210	1
Tetrachloroethene (perchloroethene, PCE)	MCL-US	5	µg/L	02/22/2005	252	3
Trichloroethylene (TCE)	MCL-US	5	µg/L	03/09/2005	252	1

<sup>1</sup>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 SMCL-CA, California Department of Public Health (2013b); MCL-US and AL-US, U.S. Environmental Protection Agency (2009a); NL-CA, California Department of Public Health (2010); HAL-US, U.S. Environmental Protection Agency (2012); Prop MCL-US, U.S. Environmental Protection Agency (1999a).

<sup>2</sup>Constituent detected at moderate relative concentrations within 3-year period in the CDPH database and in the grid-well dataset; therefore, it was selected for additional evaluation in the status assessment for the study unit.

<sup>3</sup>Constituent not analyzed by U.S. Geological Survey-GAMA for the CAMP study unit.

The spatially weighted calculations used the USGS-grid well dataset and data from the CDPH database. High-RC aquifer-scale proportion was calculated for each constituent by computing the proportion of high-RC wells in each cell and then calculating the average proportion for the cells in each study area (*equation 2*; Isaaks and Srivastava, 1989; Belitz and others, 2010). The moderate-RC aquifer-scale proportion was calculated similarly.

$$P_{SA,s}^{high} = \frac{\sum_c \frac{W_{SA,c}^{high}}{W_{SA,c}}}{N_{SA}} \quad (2)$$

where

$P_{SA,s}^{high}$  is the spatially weighted high-RC aquifer-scale proportion for the study area SA,  
 $W_{SA,c}^{high}$  is the number of wells in a particular cell in the study area having high RC for the constituent,  
 $W_{SA,c}$  is the number of wells in a particular cell in the study area having data for the constituent, and  
 $\sum_c$  is summation over the number of cells in the study area (the number of cells is 15 for all 6 study areas).

The grid-based and spatially weighted approaches both are designed to be spatially unbiased; however, the grid-based approach sometimes does not detect constituents that are present at high RCs (or moderate RCs) in small proportions of the primary aquifer system. The spatially weighted approach uses a greater number of wells and, therefore, has a greater chance of detecting small targets. This situation rarely occurred in the CAMP study unit because the 90 USGS-grid wells provided the majority of the data for all constituents except for nitrate.

High-RC aquifer-scale proportions for the study unit as a whole were calculated as an area-weighted combination of the grid-based or spatially weighted aquifer-scale proportions for the six study areas (equation 3). Moderate-RC aquifer-scale proportions were calculated similarly.

$$P_{SU}^{high} = \sum_{SA} F_{SA} P_{SA}^{high} \quad (3)$$

where

$P_{SU}^{high}$	is the area-weighted high-RC aquifer-scale proportion for the CAMP study unit,
$P_{SA}^{high}$	is the high-RC aquifer-scale proportion for study area SA,
$F_{SA}$	is the fraction of the study unit gridded area occupied by study area SA (table 2), and
$\sum_{SA}$	is summation over the six study areas.

Study unit detection frequencies for organic constituents also were calculated as area-weighted detection frequencies. The grid-based detection frequency in each study area was calculated by using equation 1 with  $N_{SA}^{high}$  replaced by the number of samples with detections, and then the detection frequency for the study unit as a whole was calculated by using equation 3. Because of the area weighting, the study unit detection frequencies for organic constituents in this report can differ from the unweighted detection frequencies reported by Shelton and others (2013).

In addition, for each constituent, the raw frequencies of occurrence of high and moderate RCs for individual constituents were calculated by using the same dataset as was used for the spatially weighted calculations. However, these raw occurrence frequencies are not spatially unbiased because the wells in the CDPH database are not uniformly distributed (fig. 4). 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 occurrence frequency of high RCs would be greater than the high aquifer-scale proportion. Raw occurrence frequencies are provided for reference, but were not used to assess aquifer-scale proportions.

## Understanding Assessment

The purposes of the *understanding assessment* were to place groundwater quality in a physical and chemical context and to better understand the natural and human factors affecting groundwater quality. The assessment was based on the statistical strength of relations between concentrations or occurrences of selected water-quality constituents and values of selected potential explanatory factors. The potential explanatory factors evaluated were land use near the well, septic and underground-storage tank densities near the well, study area, aquifer lithology, depths to the top and bottom of the open or screened interval in the well, aridity index, groundwater age, oxidation-reduction conditions, and pH. Correlations among these factors that could affect apparent relations between aquifer lithology and water quality are also described. Data were compiled for the 90 USGS-grid wells sampled by USGS-GAMA. Other CDPH wells were not used for the *understanding assessment* because ancillary data for most of the CDPH wells were not available. This section describes the methods used for (1) selecting constituents for evaluation and (2) testing the statistical significance of correlations.

## Selection of Constituents for Understanding Assessment

Constituents present at high RCs in greater than approximately 2 percent of the primary aquifer system were selected for evaluating relations between potential explanatory factors and groundwater quality. Nine inorganic constituents met this criterion and, therefore, have an *understanding assessment* section in this report (table 4A). No organic or special-interest constituents were present at high RCs in greater than approximately 2 percent of the primary aquifer system.

Organic constituent classes containing at least one individual constituent with an area-weighted detection frequency in the study unit as a whole of greater than 10 percent and special-interest constituents with an area-weighted detection frequency greater than 10 percent also were selected for evaluating relations between potential explanatory factors and groundwater quality. Two organic constituent classes, trihalomethanes and herbicides, and the special-interest constituent perchlorate met this criterion and, therefore, have an understanding assessment section in this report (table 5).

## Statistical Analysis

Nonparametric statistical methods were used to test the significance of correlations among the factors and between the factors and water-quality constituents. Nonparametric statistics are robust techniques that generally are not affected by outliers and do not require that the data follow any particular distribution (Helsel and Hirsch, 2002). The significance level ( $p$ ) used for hypothesis testing for this report was compared to a threshold value ( $\alpha$ ) of 5 percent ( $\alpha=0.05$ ) to evaluate whether the relation was statistically significant ( $p$  less than  $\alpha$ ).

Three different statistical tests were used because the set of potential explanatory factors included categorical and continuous variables. Groundwater age, aquifer lithology, study area, oxidation-reduction class, and depth class were treated as categorical variables; for example, groundwater ages were classified as modern, pre-modern, or mixed. Land use, septic-tank density, leaking or formerly leaking underground-storage tank (UST) density, aridity index, elevation, depths to top and bottom of screened or open interval, pH, and dissolved oxygen were treated as continuous variables; for example, land use was represented by percentages of land-use types. Depth and oxidation-reduction status were treated both as continuous (depth to top and bottom of screened or open interval and DO concentration, respectively) and as categorical (depth class as spring, shallow well, overlapping well, or deep well, and oxidation-reduction class as oxic or anoxic) variables ([appendix A](#)).

Correlations between continuous variables were evaluated by using the Spearman's rho ( $\rho$ ) test to calculate the rank-order correlation coefficient ( $\rho$ ) and the significance level of the correlation ( $p$ ).

Relations between categorical variables and continuous variables were evaluated by using a multi-stage Kruskal-Wallis test to determine whether one or more of the groups had a significantly different median. The Kruskal-Wallis test is equivalent to the Wilcoxon rank-sum test for a categorical variable with two values. Pairwise Wilcoxon rank-sum tests were not used because the overall significance level for six pairwise tests with  $\alpha=0.05$  for a categorical variable with 4 groups is  $\alpha=0.26$  (Helsel and Hirsch, 2002). If the Kruskal-Wallis test detected a significant difference among the medians, then Tukey's multiple comparison test was applied to the ranks of the data to determine which pairs had significantly different mean ranks. (Helsel and Hirsch, 2002).

Relations between categorical variables were evaluated by using contingency tables. For the 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  $i^{\text{th}}$  row and  $j^{\text{th}}$  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  $(1-\alpha)$  quantile of a chi-squared distribution (Helsel and Hirsch, 2002). If the contingency table test yielded a result of significance, then the location of the most important pairs was determined by comparing magnitudes of the components of the test statistic to each other.

Contingency table tests also were used to evaluate whether aquifer-scale proportions for a constituent were significantly different among the six study areas. For these six-by-two contingency tables, the entries in the cells of the matrix are determined from the number of wells in a study area for which there were data for the constituent and the aquifer-scale proportions. Contingency tables were constructed to evaluate whether the high-RC aquifer-scale proportion was significantly different among the study areas and to evaluate whether the proportion having high-RC or moderate-RC significantly differed among the study areas. For example, if a study area had 24 wells with data for a constituent, and the high-RC and moderate-RC aquifer-scale proportions were 1.2 percent and 8.7 percent, respectively, the entries for that study area would be [0.29 23.7] in the contingency table testing whether the high-RC aquifer-scale proportion was significantly different among the study areas and [2.38 21.62] in the contingency table testing whether the proportion having high-RC or moderate-RC significantly differed among the study areas.

## Characteristics of the Primary Aquifer System

The CAMP study unit covers a broad range of geologic, hydrologic, and land-use settings. Data for a finite set of potential explanatory factors were compiled: geology, land use and densities of leaking (or formerly leaking) underground storage tanks and septic systems, hydrologic conditions, well depth and groundwater age, and geochemical conditions. Methods used for assigning values of potential explanatory factors to the CAMP study-unit wells are described in [appendix A](#).

Correlations among explanatory factors are important to identify because apparent correlations between an explanatory factor and a water-quality constituent could reflect correlations between that explanatory factor and other explanatory factors rather than a causative relation between that explanatory factor and the water-quality constituent. Results of statistical tests of correlations among potential explanatory factors are summarized in [tables 7A–C](#).

**Table 7A.** Results of multi-stage Kruskal-Wallis tests for differences in values of selected potential explanatory factors between samples classified into groups by study area, aquifer lithology, age class, oxidation-reduction (redox) class, and depth class, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Kruskal-Wallis test p-values are listed in table. If Kruskal-Wallis test indicated significant differences (p-value less than a threshold value,  $\alpha$ , of 0.05) among the groups, the groups that were significantly different were determined using Tukey's test on the ranks of the data. Groups with significant differences are listed in table. **Study area:** ES, Sacramento Valley Eastside; HL, Honey Lake Valley; LU, Cascade Range and Modoc Plateau Low-Use Basins; QV, Quaternary Volcanic Areas; SH, Shasta Valley and Mount Shasta Volcanic Area; TV, Tertiary Volcanic Areas. **Geology class:** G, granitic and sedimentary; M, metamorphic or metamorphic and sedimentary or metamorphic and volcanic; S, sedimentary; V, volcanic; VS, sedimentary and volcanic (see appendix A for explanation). **Depth class:** Deep, top and bottom of perforations >200 ft; Overlapping, top of perforations <200 ft and bottom of perforations >200 ft; Shallow, top and bottom of perforations <200 ft; Spring, groundwater emerges at land surface without pumping. **Age class:** Mixed, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; Modern, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; pre-modern, tritium<0.5 TU (see appendix A for explanation). **Redox class:** oxic, DO>1.0 mg/L and Mn<50  $\mu\text{g/L}$  and Fe<100  $\mu\text{g/L}$ ; anoxic, DO<1.0 mg/L; mixed, DO<1.0 mg/L and Mn>50  $\mu\text{g/L}$  and/or Fe>100  $\mu\text{g/L}$ . Samples classified as mixed were grouped into the anoxic class for analysis (*appendix A*). **Other abbreviations:** DO, dissolved oxygen; ft, feet below land surface; mg/L, milligrams per liter; ns, no significant differences; pmc, percent modern carbon; TU, tritium units; USTs, leaking or formerly leaking underground-storage tanks; >, greater than; <, less than;  $\mu\text{g/L}$ , micrograms per liter]

p-value significant relations <sup>1</sup>	Study area (ES, HL, SH, LU, QV, TV)	Aquifer lithology class (G, M, S, V, VS)	Age class (mod, mix, pre)	Redox class (oxic, anoxic)	Depth class (spring, shallow, overlap, deep)
Land-use characteristics					
Percentage of agricultural land use	<0.001 HL and LU>ES, QV, and TV SH>QV	0.022 S>V and VS	0.772 ns	<0.001 Anoxic>Oxic	0.222 ns
Percentage of undeveloped land use	<0.001 ES, QV, and TV>LU	0.007 V>M and S VS>S	0.785 ns	0.006 Oxic>Anoxic	0.156 ns
Percentage of urban land use	0.026 LU>QV and TV	0.250 ns	0.963 ns	0.344 ns	0.110 ns
Density of septic tanks	<0.001 ES and SH>LU and QV	0.314 ns	0.166 ns	0.015 Oxic>Anoxic	0.715 ns
Density of USTs	<0.001 SH>HL, LU, and QV ES>HL	0.094 ns	0.309 ns	0.387 ns	0.179 ns
Climate and hydrology variables					
Aridity index	<0.001 ES, QV, and TV>HL and LU SH>HL	<0.001 V>G and S VS>S	0.001 Mod>Pre	<0.001 Oxic>Anoxic	0.097 ns
Elevation	<0.001 HL, LU, QV, and TV>ES and SH	0.025 G, S, V, and VS>M	0.268 ns	0.087 ns	0.762 ns



**Table 7A.** Results of multi-stage Kruskal-Wallis tests for differences in values of selected potential explanatory factors between samples classified into groups by study area, aquifer lithology, age class, oxidation-reduction (redox) class, and depth class, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.—Continued

[Kruskal-Wallis test p-values are listed in table. If Kruskal-Wallis test indicated significant differences (p-value less than a threshold value,  $\alpha$ , of 0.05) among the groups, the groups that were significantly different were determined using Tukey's test on the ranks of the data. Groups with significant differences are listed in table. **Study area:** ES, Sacramento Valley Eastside; HL, Honey Lake Valley; LU, Cascade Range and Modoc Plateau Low-Use Basins; QV, Quaternary Volcanic Areas; SH, Shasta Valley and Mount Shasta Volcanic Area; TV, Tertiary Volcanic Areas. **Geology class:** G, granitic and sedimentary; M, metamorphic or metamorphic and sedimentary or metamorphic and volcanic; S, sedimentary; V, volcanic; VS, sedimentary and volcanic (see appendix A for explanation). **Depth class:** Deep, top and bottom of perforations >200 ft; Overlapping, top of perforations <200 ft and bottom of perforations >200 ft; Shallow, top and bottom of perforations <200 ft; Spring, groundwater emerges at land surface without pumping. **Age class:** Mixed, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; Modern, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; pre-modern, tritium<0.5 TU (see appendix A for explanation). **Redox class:** oxic, DO>1.0 mg/L and Mn<50  $\mu\text{g/L}$  and Fe<100  $\mu\text{g/L}$ ; anoxic, DO<1.0 mg/L; mixed, DO>1.0 mg/L and Mn>50  $\mu\text{g/L}$  and/or Fe>100  $\mu\text{g/L}$ . Samples classified as mixed were grouped into the anoxic class for analysis (*appendix A*). **Other abbreviations:** DO, dissolved oxygen; ft, feet below land surface; mg/L, milligrams per liter; ns, no significant differences; pmc, percent modern carbon; TU, tritium units; USTs, leaking or formerly leaking underground-storage tanks; >, greater than; <, less than;  $\mu\text{g/L}$ , micrograms per liter]

p-value significant relations <sup>1</sup>	Study area (ES, HL, SH, LU, QV, TV)	Aquifer lithology class (G, M, S, V, VS)	Age class (mod, mix, pre)	Redox class (oxic, anoxic)	Depth class (spring, shallow, overlap, deep)
Characteristics of primary aquifers					
Depth to top of screened or open interval	0.139 ns	0.031 V>M and S VS>M	0.077 ns	0.325 ns	NA
Depth to bottom of screened or open interval <sup>3</sup>	0.038 ES>SH	0.323 ns	<0.001 Pre>Mod and mix	0.101 ns	NA
pH	0.001 HL>ES and SH LU>ES	0.125 ns	<0.001 Pre>Mix>Mod	0.007 Anoxic>Oxic	<0.001 Deep and overlap> Spring and shallow
Dissolved oxygen concentration	0.017 QV and TV>HL	0.017 V>M, S, and VS	<0.001 Mod and mix>Pre	<0.001 Oxic>Anoxic	<0.001 Spring>Shallow, overlap, and deep

<sup>1</sup> Explanation for reporting of significant differences using the results for percentage of agricultural land use by study unit as an example. The Tukey's test results showed that the following seven pairs had significant differences: LU>ES, LU>QV, LU>TV, HL>ES, HL>QV, HL>TV, and SH>QV. Because both LU and HL have significantly greater agricultural land use than ES, QV, and TV, the notation for the first six pairs is condensed to 'HL and LU>ES, QV, and TV.' Because SH had significantly greater agricultural land use than QV, but not significantly greater than ES and TV, the seventh pair cannot be condensed with the first six. Agricultural land use was not significantly different for all the pairs not listed, in other words, agricultural land use in HL and LU were not significantly different from each other, agricultural land use in ES, QV, and TV were not significantly different from each other, and agricultural land use in SH was not significantly different from that in ES, HL, LU, or TV.

<sup>2</sup> Although the Kruskal-Wallis test indicated no significant differences among the six study areas, if the statistical tests were performed using 15 pairwise Wilcoxon rank-sum tests, then HL>ES with a p-value of 0.014.

<sup>3</sup> Eleven wells did not have data for depth to the bottom of the screened or open interval, but did have data for well depth (*table 42*). Well depth data were used to represent data for the depth of the bottom of the screened or open interval for these wells.

**Table 7B.** Results of Spearman's tests for correlations between selected potential explanatory factors, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Abbreviations:  $\rho$  (rho), Spearman's correlation statistic; USTs, leaking (or formerly leaking) underground storage tanks; <, less than p-values (significance level of the Spearman's test) less than threshold value ( $\alpha$ ) of 0.05 are considered significant: bold black text, significant positive correlation; bold red text, significant negative correlation]

p-value ( $\rho$ )	Percentage of natural land use	Percentage of urban land use	Density of septic tanks	Density of USTs	Aridity index	Elevation	Depth to top of screened or open interval	Depth to bottom of screened or open interval <sup>1</sup>	pH	Dissolved oxygen concentration
Percentage of agricultural land use	<b>&lt;0.001</b> <b>-0.64</b>	0.065 0.20	0.380 -0.09	0.535 -0.07	<b>&lt;0.001</b> <b>-0.58</b>	0.562 0.06	0.522 -0.08	0.264 -0.13	<b>&lt;0.001</b> <b>0.38</b>	<b>&lt;0.001</b> <b>-0.55</b>
Percentage of natural land use		<b>&lt;0.001</b> <b>-0.81</b>	0.093 -0.18	0.539 -0.07	<b>&lt;0.001</b> <b>0.40</b>	0.648 -0.05	0.566 -0.07	0.411 -0.10	0.082 -0.18	<b>0.001</b> <b>0.335</b>
Percentage of urban land use			0.055 0.20	0.342 0.10	<b>0.036</b> <b>-0.22</b>	0.206 0.13	0.286 0.13	0.022 0.27	0.789 0.03	0.253 -0.122
Density of septic tanks				<b>&lt;0.001</b> <b>0.44</b>	<b>0.003</b> <b>0.31</b>	<b>&lt;0.001</b> <b>-0.38</b>	0.811 -0.03	0.756 0.04	<b>0.007</b> <b>-0.28</b>	0.103 0.17
Density of USTs					<b>0.001</b> <b>0.33</b>	<b>0.003</b> <b>-0.31</b>	0.061 0.23	<b>0.030</b> <b>0.25</b>	<b>0.024</b> <b>-0.24</b>	0.455 0.08
Aridity index						<b>0.043</b> <b>-0.21</b>	0.523 0.08	0.967 0.00	<b>&lt;0.001</b> <b>-0.67</b>	<b>&lt;0.001</b> <b>0.60</b>
Elevation							0.361 0.12	0.958 -0.01	<b>0.013</b> <b>0.26</b>	0.937 0.01
Depth to top of screened or open interval								<b>&lt;0.001</b> <b>0.63</b>	0.093 0.21	0.900 0.02
Depth to bottom of screened or open interval <sup>1</sup>									0.057 0.22	0.335 -0.11
pH										<b>&lt;0.001</b> <b>-0.54</b>

<sup>1</sup>Eleven wells did not have data for depth to the bottom of the screened or open interval, but did have data for well depth (table A2). Well depth data were used to represent data for the depth of the bottom of the screened or open interval for these wells.

**Table 7C.** Results of contingency table tests for associations between selected potential explanatory factors, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[If contingency table test indicated a significant relation between the factors ( $p < 0.05$ ), then the correlations contributing most to that significant relation were identified from the components of the contingency table test statistic. **Study area:** ES, Sacramento Valley Eastside; HL, Honey Lake Valley; LU, Cascade Range and Modoc Plateau Low-Use Basins; QV, Quaternary Volcanic Areas; SH, Shasta Valley and Mount Shasta Volcanic Area; TV, Tertiary Volcanic Areas. **Geology class:** G, granitic and sedimentary; M, metamorphic or metamorphic and sedimentary or metamorphic and volcanic; S, sedimentary; V, volcanic; VS, sedimentary and volcanic (see appendix A for explanation). **Depth class:** Deep, top and bottom of perforations  $> 200$  ft; Overlapping, top of perforations  $< 200$  ft and bottom of perforations  $> 200$  ft; Shallow, top and bottom of perforations  $< 200$  ft; Spring, groundwater emerges at land surface without pumping. **Age class:** Mixed, tritium  $> 0.5$  TU and  $^{14}\text{C} < 90$  pmc; Modern, tritium  $> 0.5$  TU and  $^{14}\text{C} > 90$  pmc; pre-modern, tritium  $< 0.5$  TU (see appendix A for explanation). **Redox class:** anoxic,  $\text{DO} < 1.0$  mg/L; mixed,  $\text{DO} > 1.0$  mg/L and  $\text{Mn} > 50$   $\mu\text{g/L}$  and/or  $\text{Fe} > 100$   $\mu\text{g/L}$ ; oxic,  $\text{DO} > 1.0$  mg/L and  $\text{Mn} < 50$   $\mu\text{g/L}$  and  $\text{Fe} < 100$   $\mu\text{g/L}$ . Samples classified as mixed were grouped into the anoxic class for analysis (appendix A). **Other abbreviations:** DO, dissolved oxygen; ft, feet below land surface; LUFTs, leaking underground fuel tanks; mg/L, milligrams per liter; ns, no significant differences; pmc, percent modern carbon; TU, tritium units;  $>$ , greater than;  $<$ , less than;  $\mu\text{g/L}$ , micrograms per liter]

p-value significant relations	Geology class	Depth class	Age class	Redox class
Study area	$< 0.001$ G and S lithology wells are in the HL study area; M lithology wells are in the SH study area; VS lithology wells are in the LU study area.	0.174 ns	0.017 HL wells are more likely to have pre-modern groundwater, and SH wells are less likely to have pre-modern groundwater.	0.029 SH wells are more likely to have oxic groundwater.
Geology class		0.387 ns	0.360 ns	0.021 Wells in sedimentary deposits are more often anoxic than wells in volcanic rocks.
Depth class			0.018 Pre-modern groundwater is more likely to be found in deep wells than in springs or shallow wells, and modern groundwater is more likely to be found in shallow wells than in deep wells.	0.339 ns
Age class				0.072 ns

## Geology

Geology was quantified by two potential explanatory factors: study area and aquifer lithology. As discussed in the “Description of Study Unit” section, the six study areas are geologically distinct. Aquifer lithology in the CAMP study unit was defined by classifying the lithologic descriptions in the CDWR well completions reports and the surficial geology on the State geologic map (Jennings, 1977; Saucedo and others, 2000) into four categories: Mesozoic granitic rocks, Mesozoic and Paleozoic metamorphic rocks, Quaternary sedimentary deposits, and Tertiary and Quaternary volcanic rocks (appendix A).

As expected from the definitions of the study areas, aquifer lithology was correlated with study area. Most CAMP study-unit wells had screened or open intervals in volcanic rocks (47 wells) or in both volcanic rocks and sedimentary deposits (17 wells) (table A1). As expected, all of the wells in the QV and TV study areas had open intervals in volcanic

rocks, and for 26 of the 30, volcanic rocks were the only aquifer lithology. The majority of the wells in the LU study area had screened or open intervals in both sediment and volcanic rocks and only two were screened solely in sediment, likely reflecting preferential siting of public-supply wells in zones with greater yields. Wells in volcanic rocks generally had greater yields than those in sediments (Gannett and others, 2007). The majority of the wells in the ES and SH study areas had open intervals in volcanic rocks. The HL study area was the only study area in which no wells had open intervals in volcanic rocks; all were screened in sediments. Three wells in the HL study area also had screened intervals in the underlying granitic rocks, and 4 wells in the SH study area also had screened or open intervals in underlying metamorphic rocks. These seven wells were located near the margins of the HL and SH groundwater basins where the alluvial sediments were relatively thin. One well in the TV study area north of the SH study area had open intervals in both the volcanic rocks of the Western Cascades series and the underlying metasedimentary rocks.

## Land Use

Land use was classified using an enhanced version of the satellite-derived (30-meter pixel resolution), nationwide 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. About two-thirds of the CAMP study-unit wells had groundwater classified as mixed or pre-modern age, indicating presence of groundwater recharged many decades to thousands of years ago, perhaps (see ‘Well Depth and Groundwater Age’ section); therefore, land-use patterns from several decades ago were thought more likely to be relevant to the groundwater samples than current land-use patterns. The imagery is classified into 25 land-cover classifications (Nakagaki and Wolock, 2005). These 25 land-cover classifications were condensed into 3 principal land-use categories: urban, agricultural, and natural (see [appendix A](#)).

Land use in the whole CAMP study unit was 80.1 percent natural (forests, shrub lands, grasslands, rock, bare ground, and ice), 15.8 percent agricultural, and 4.1 percent urban ([figs. 5, 6A](#)). Natural land consists mainly of forests in the western part of the study unit and at higher elevations, and of shrub lands and grasslands in the eastern part and at lower elevations ([fig. 5](#)). Much of the natural land in the study unit is overseen by the U.S. Forest Service (Lassen, Modoc, Shasta-Trinity, and Klamath National Forests) and may be used for open-range livestock grazing. Natural land use accounts for 75 percent to 95 percent of the ES, HL, QV, SH, and TV study areas ([fig. 6A](#)).

Agricultural land use was unevenly divided among the study areas. More than half of the LU study area was used for agriculture; whereas, less than 2 percent of the ES, QV, and TV study areas were used for agriculture ([fig. 6A](#)). Most of the agricultural land was used for pasture or alfalfa hay and other silage; although wheat, barley, potatoes, wild rice, mint, and other crops also were grown (U.S. Department of Agriculture, 2007). Urban land use constituted less than 5 percent of the land use in the CAMP study unit. The population was dispersed, with an average population density of less than 20 people per square mile (people/mi<sup>2</sup>), compared to an average density of 239 people/mi<sup>2</sup> for the state as a whole, and the population density was greater than 100 people/mi<sup>2</sup> in only about 1 percent of the study unit (California Department of Finance, 2010).

Average land use around wells differed from the overall land use in the study unit because wells are preferentially located where there are people living, working, or recreating. Average land use in the area within the 500-m buffers around the USGS-grid wells was 17.7 percent urban and 10.9 percent agricultural. Unlike many other GAMA Priority Basin Project study units, the average land use around the USGS-grid wells was similar to the average land use around the CDPH wells ([fig. 6A](#)). This could reflect the dispersed population in

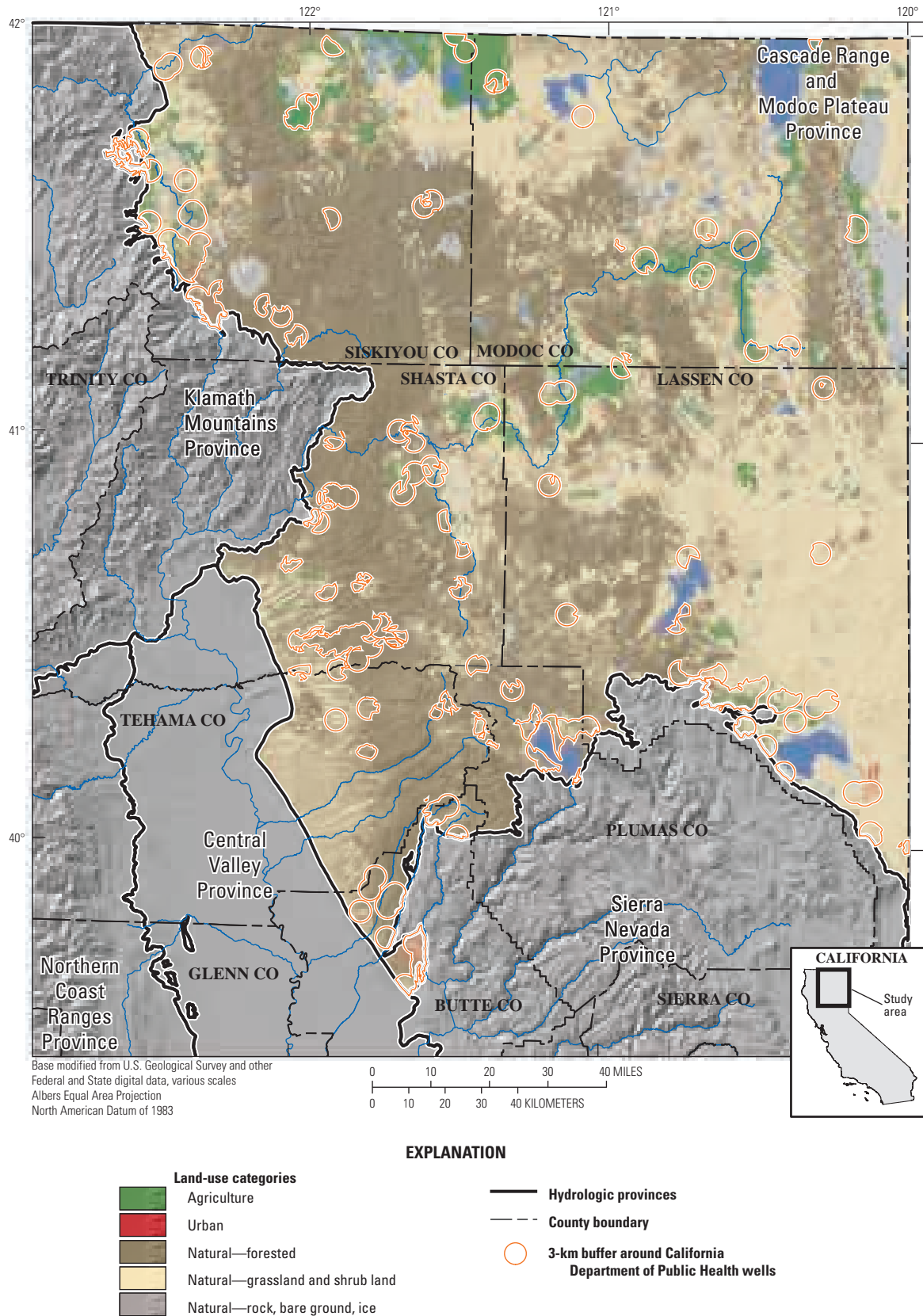
the study unit. Of the 230 public water systems listed in the CDPH database for the study unit, nearly 60 percent served less than 100 people, and only 10 percent served more than 1,000 people. Many of the GAMA Priority Basin Project study units have areas with dense populations that are served by public-water systems that have numerous wells in a small area. In contrast, the CDPH wells in the CAMP study unit are not markedly clumped.

Land use was correlated with study area and aquifer lithology. Wells in the LU and HL study areas were surrounded by significantly greater percentages of agricultural land use than wells in the ES, QV, and TV study areas, and wells in the LU study area were surrounded by more urban land use than wells in the QV and TV study areas ([table 7A](#)). These correlations resulted from the concentration of agricultural activity in areas with thicker soils and sediments, and the greater density of population in agricultural areas compared to natural areas. Wells with sedimentary aquifer lithology were surrounded by significantly greater percentages of agricultural land use than wells with volcanic or volcanic and sedimentary aquifer lithology ([table 7A](#)). The percentage of urban land use was not correlated with aquifer lithology because the majority of wells in the LU study area had open intervals in volcanic rocks beneath the surficial sediments of the groundwater basins.

Septic tanks and leaking (or formerly leaking) underground storage tanks are markers of land-use patterns. Densities of septic tanks and USTs in the 500-m buffers around the USGS-grid wells were calculated from U.S. Census data (U.S. Census, 1990) and locations of environmental cleanup sites (California State Water Resources Control Board, 2007), respectively ([appendix A](#)). Septic tanks generally are associated with dispersed residences or small communities because larger urban areas generally have collective sewer systems. Therefore, septic tanks can be in areas classified as natural or agricultural land use in addition to areas classified as urban land use. The density of septic tanks in the 500-m buffers around the USGS-grid wells in the study unit ranged from 0 to 256 tanks per square kilometer (tanks/km<sup>2</sup>), with a median density of 1.2 tanks/km<sup>2</sup> ([table A1](#)). Dispersed residential development outside of cities is more likely to have individual septic systems than a collective sewer system because of the costs associated with constructing sewage collection and treatment systems. Septic-tank densities were greater in the ES and SH study areas than in the LU and QV study areas ([table 7A](#)).

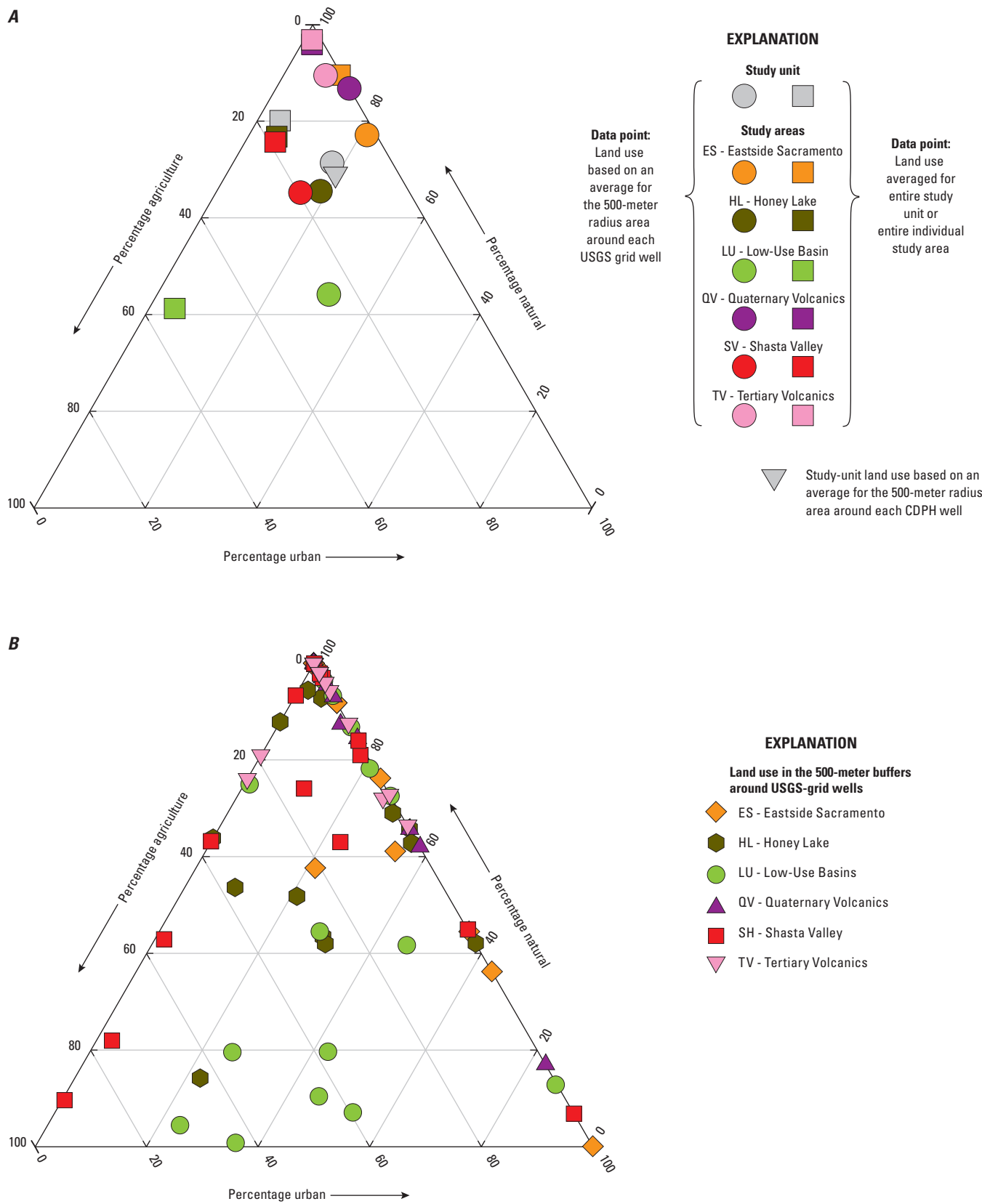
The density of USTs in the 500-m buffers around the USGS-grid wells in the study unit ranged from 0 to 1.82 tanks/km<sup>2</sup>, with a median density of 0.01 tanks/km<sup>2</sup> ([table A1](#)). The UST densities were greater in the SH study area than in the HL, LU, and QV study areas ([table 7A](#)). The UST density showed positive correlation with septic-tank density ([table 7B](#)), consistent with the higher UST and septic-tank densities in the SH study area compared to other study areas ([table 7A](#)).





**Figure 5.** Land use and major hydrologic features for the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.





**Figure 6.** Percentage of urban, agricultural, and natural land use in the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project. *A*, Average land use in the gridded area, average land use within 500-meters of USGS-grid wells, and average land use within 500-meters of California Department of Public Health (CDPH) wells for the study unit as a whole and for each of the six study areas; and *B*, land use within 500-meters of each U.S. Geological Survey (USGS)-grid well by study area.

## Hydrology

Hydrologic conditions were represented by the UNESCO aridity index (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997), and elevation at the well site ([table A2](#)). The aridity index is the average annual precipitation divided by the average annual evapotranspiration; greater values correspond to wetter conditions ([appendix A](#)). Climate in the CAMP study unit ranges from arid to wet, and the aridity index is related to the elevation and position relative to the rain shadows of the Klamath Mountains and the Cascade Range.

Aridity index showed a negative correlation with elevation for the dataset as a whole ([table 7B](#)), but showed positive correlations with elevation for individual study areas (Spearman's test: ES,  $p=0.043$ ,  $\rho=0.53$ ; HL,  $p=0.001$ ,  $\rho=0.78$ ; SH,  $p<0.001$ ,  $\rho=0.86$ ). A positive correlation was expected because of the orographic effect: Air masses moving over rising terrain are forced upwards, and adiabatic cooling results in precipitation; therefore, precipitation generally increases with elevation on the windward side of mountain ranges. The leeward side of the mountain range is a dry area, a rain shadow, because the air mass descending the leeward side has already been stripped of moisture. Precipitation on the leeward side generally is still positively correlated with elevation, but the amount of precipitation at a given elevation is much less than on the windward side. Storm systems in northern California generally move from west to east, and a large part of the study unit is in the rain shadow east of the Klamath Mountains or the Cascade Range. The negative correlation for the dataset as a whole was driven by the fact that the HL study area and most of the LU study area receive the least precipitation because they are in the rain shadows of multiple mountain ranges, but the USGS-grid wells in those areas are at higher elevations than most of the USGS-grid wells in the other study areas.

## Well Depth and Groundwater Age

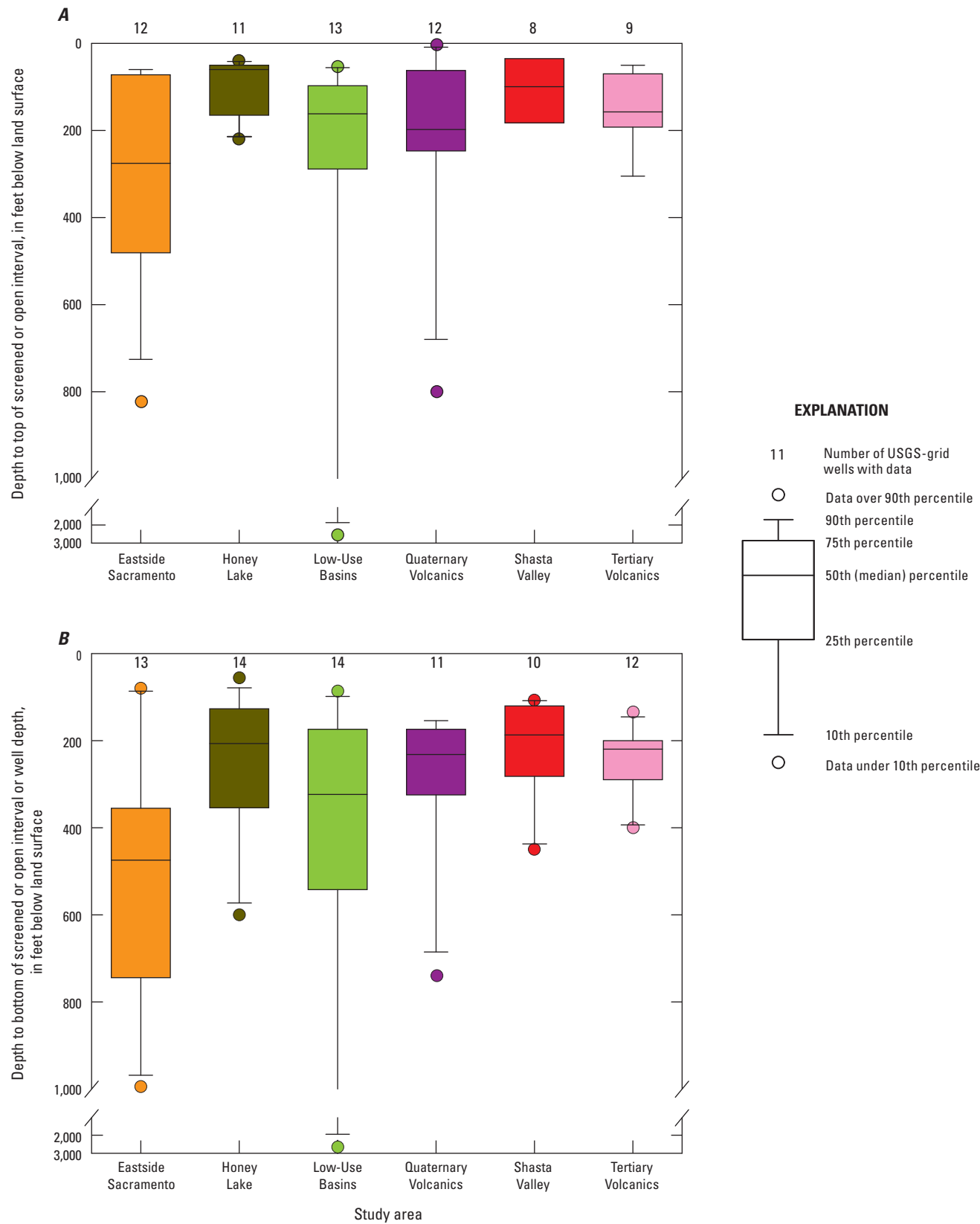
The primary aquifer system in the CAMP study unit was defined as the depth interval over which wells in the CDPH database are screened or open. The 90 USGS-grid wells sampled by USGS-GAMA for the CAMP study unit were considered representative of the primary aquifer system, thus, depth characteristics of these sites can be used to define the primary aquifer system. Of the 63 wells having data for well depth and depth to the bottom of the screened or open intervals, the two depths were equal for 48 of the wells (76 percent). Therefore, depth to the bottom of the screened or open interval was assumed to be equal to well depth for the 11 wells lacking data for depth to the bottom of the screened or open interval ([table A2](#)).

Nine of the sites sampled by USGS-GAMA were springs ([table A2](#)). At least one spring site was sampled in each of

the study areas with the exception of the HL study area, and two-thirds of the springs were in either the QV or the SH study area. For the sites that were wells, median depths to the tops of the screened or open intervals ranged from 60 feet below land surface (ft bls) in the HL study area to 276 ft bls in the ES study area ([fig. 7A](#)), and there were no significant differences among the study areas ([table 7A](#)). Median depths to the bottoms of the screened or open interval (or bottom of well if data for the depth to the bottom of the screened or open interval were not available) ranged from 188 ft bls in the SH study area to 475 ft bls in the ES study area ([fig. 7B](#)), and wells in the ES study area were significantly deeper than those in the SH study area ([table 7A](#)). Springs were not included in the statistical tests involving relations with depths to tops or bottoms of the screened or open intervals.

Brown and Caldwell (2007) catalogued the depths of 3,193 domestic and 407 irrigation wells in Lassen County from a CDWR database of well completion reports. Lassen County covers approximately one-quarter of the CAMP study area and includes all of the HL study area and parts of the LU, QV, and TV study areas. The median depths of wells in the primary aquifer system in those four study areas (216 to 344 ft bls; [fig. 7B](#)) was greater than the median depth of domestic wells in Lassen County (150 ft bls), and less than the median depth of irrigation wells in Lassen County (425 ft bls). This suggests that public-supply wells in the four study areas generally are deeper than domestic wells. However, the division between domestic and municipal wells for the CDWR well completion reports is not the same as the division between private and public wells for the CDPH. At the time of this study, the CDPH database for Lassen County listed 76 public-supply wells, whereas Brown and Caldwell (2007) reported 17 municipal wells in the CDWR well completion report database. Johnson and Belitz (2015) found that approximately 20 percent of wells reported as domestic on CDWR well completion reports statewide were listed as owned by an entity other than a private individual, and thus may be considered small-system or public-supply wells by CDPH.

Groundwater "age" refers to the amount of time elapsed since the water was last in contact with the atmosphere and is related to its residence time in the aquifer system. Data for the age-dating tracers tritium and carbon-14 were used to classify groundwater ages into three categories: modern, mixed, and pre-modern ([appendix A](#)). Tritium values greater than 0.5 tritium units (TU) were defined as indicating presence of some groundwater recharged since 1952. The  $^{14}\text{C}$  values greater than 90 percent modern carbon (pmc) were defined as indicating presence of some groundwater recharged since 1952. Samples with tritium activities less than 0.5 TU were classified as "pre-modern" groundwater; samples with tritium activities greater than 0.5 TU and  $^{14}\text{C}$  values greater than 90 pmc were classified as "modern" groundwater. Samples with tritium activities greater than 0.5 TU and  $^{14}\text{C}$  values less than 90 pmc were classified as "mixed" groundwater.



**Figure 7.** Depths to screened or open interval for U.S. Geological Survey (USGS)-grid wells by study area, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. *A*, to top of screened or open interval; and *B*, to bottom of screened or open interval.

Of the 90 USGS-grid well samples collected by USGS-GAMA, 34 were classified as having modern groundwater, 20 as having mixed groundwater, and 33 as having pre-modern groundwater ([table A4](#)). In addition, three wells with tritium activities greater than 0.5 TU could not be categorized as modern or mixed because of a lack of  $^{14}\text{C}$  data; these wells were excluded from statistical tests and plots for which the three age classes were handled separately.

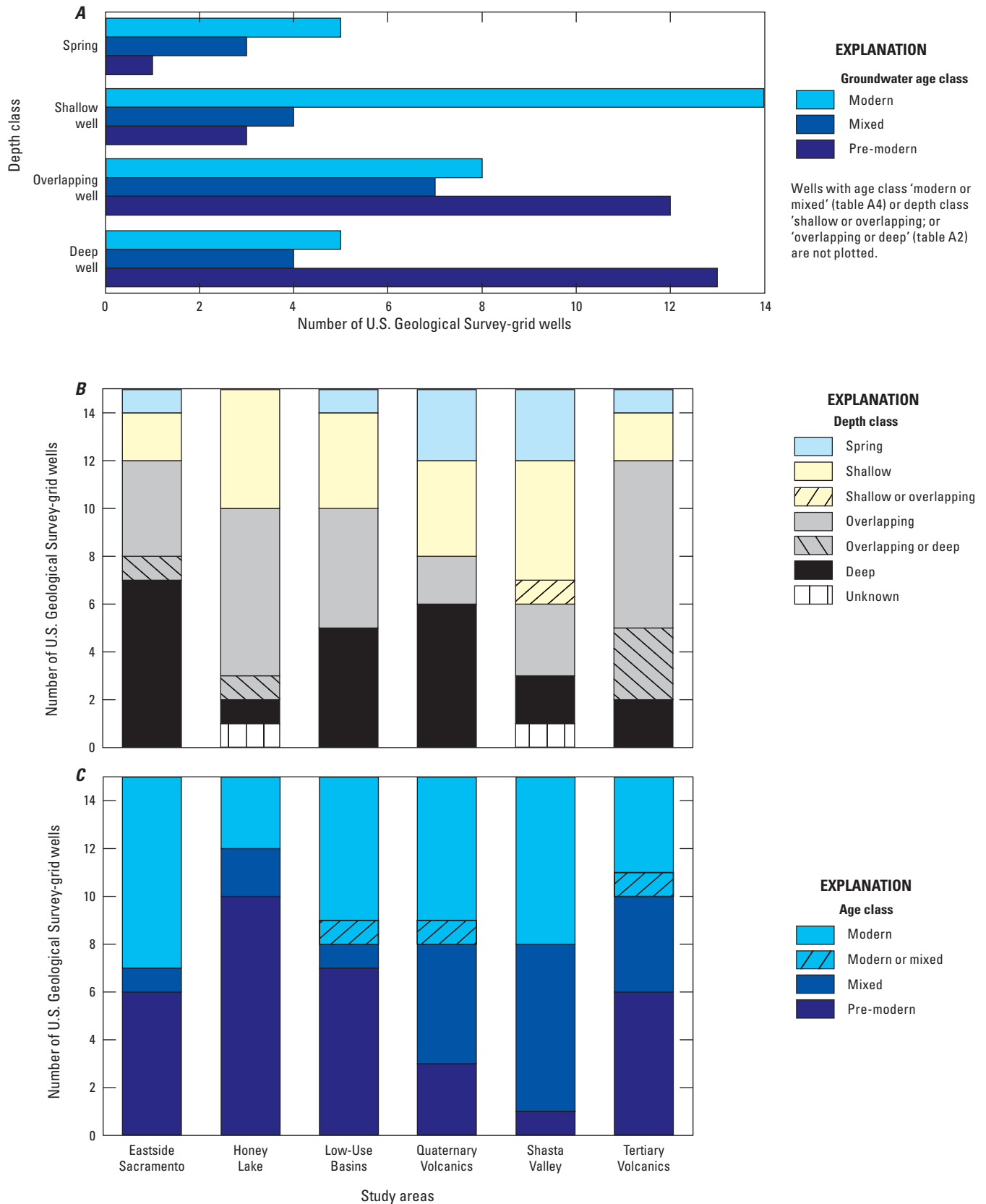
Wells with pre-modern groundwater had significantly greater depths to the bottoms of the screened or open intervals than did wells with modern or mixed groundwater ([table 7A](#)). Classified groundwater ages were used to create a classification system for depth class. The boundary between shallow and deep—the critical depth—was determined by optimizing the segregation of modern and pre-modern age samples into shallow and deep wells, respectively. Wells with screened or open intervals entirely above the critical depth were defined as shallow (22 wells); wells with screened or open intervals beginning above the critical depth and ending below the critical depth were defined as overlapping (28 wells); and wells with screened or open intervals entirely below the critical depth were defined as deep (23 wells) ([table A2](#)). For the CAMP study unit, the critical depth was 200 ft bls ([fig. 8A](#)). Wells deeper than 200 ft bls and lacking data for depth to the top of the screened or open interval were defined as overlapping or deep (five wells); wells with the depth to the top of the screened or open interval less than 200 ft bls and lacking data for well depth were defined as overlapping or shallow (one well); these wells were excluded from statistical tests and plots for which the four depth classes were handled separately. Two wells had insufficient data for classification. The nine springs were considered a separate class.

This classification system was based on the assumption that depth class and age class were related. Pre-modern groundwater was more common in deep wells and less common in springs and shallow wells, and modern groundwater was more common in shallow wells and less common in deep wells ([table 7C](#)); however, all three groundwater age classes were found in all four depth classes, and about 20–35 percent of the samples from all four depth classes yielded mixed-age groundwater ([fig. 8A](#)). Age class also was significantly related to study area. The HL study area had a greater proportion of pre-modern groundwater, and the SH study area had a greater proportion of mixed groundwater and a lower proportion of pre-modern groundwater compared to the other study areas ([table 7C](#); [fig. 8C](#)). Age class and depth class were not correlated with measures of land use ([table 7A](#)). Sites with modern groundwater had significantly greater aridity indices (indicating wetter conditions) than sites with pre-modern groundwater, reflecting the greater abundance of pre-modern groundwater in the HL study area, the most arid (lowest aridity index value) study area.

## Geochemical Conditions

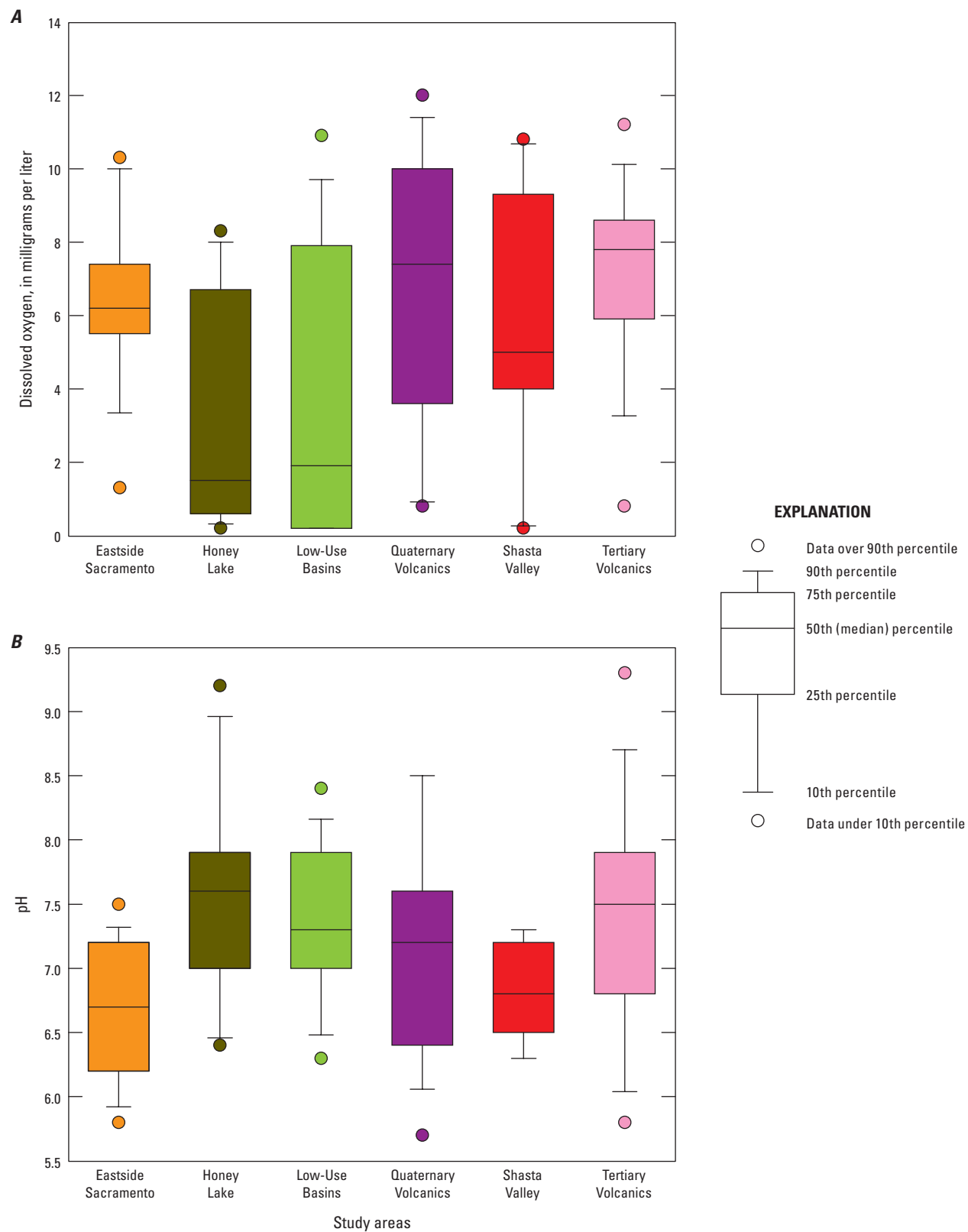
Groundwater geochemical conditions were represented by oxidation-reduction conditions and pH. Oxidation-reduction conditions were classified on the basis of dissolved oxygen (DO), nitrate, manganese, and iron concentrations by using a modified version of the classification scheme of McMahon and Chapelle (2008) and Jurgens and others (2009). The primary modification was that the DO threshold for separating oxic from anoxic groundwater was increased from 0.5 mg/L to 1 mg/L (Fram and Belitz, 2012). For a majority of the sites in the CAMP study unit (72 of the 90 USGS-grid wells [80 percent]), the groundwater was classified as oxic (DO greater than or equal to 1 mg/L) ([tables A5, A6](#)). At least some portion of the water was anoxic in the remaining 20 percent of the wells; 5 wells (6 percent) were classified as mixed, and 13 wells (14 percent) were classified as anoxic. Mixed and anoxic conditions were further subdivided into suboxic, nitrate-reducing, manganese-reducing, and iron-reducing conditions, or a combination of two reducing conditions ([tables A5, A6](#)). Correlations between oxidation-reduction conditions and other potential explanatory factors were tested with oxidation-reduction conditions represented by a continuous variable (DO concentration) and by a categorical variable (redox class). For statistical tests involving redox class, anoxic and mixed categories were combined.

Oxidation-reduction conditions and pH were significantly related to study area, aquifer lithology, groundwater age, and depth class ([table 7A](#)). DO concentrations were significantly greater in springs than in shallow, overlapping, or deep wells, greater in modern and mixed groundwater than in pre-modern groundwater, and greater in samples from volcanic aquifer lithology than in samples from sedimentary aquifer lithology ([table 7A](#)). These observations imply that the CAMP study unit springs discharge water that has had extensive, recent interaction with the atmosphere. Groundwater newly entering the aquifer system likely has not interacted extensively with organic matter or reduced inorganic aquifer materials, and thus DO would not have been consumed. The sedimentary deposits in the CAMP study unit include lacustrine sediments, which commonly contain organic matter. In contrast, volcanic rocks generally have a low abundance of organic matter; thus, DO in groundwater in volcanic rocks can be consumed less rapidly than DO in groundwater in sedimentary deposits of the CAMP study unit. These relations could account for the significantly higher DO concentrations in samples from the QV and TV study areas compared to the HL study area ([table 7A](#); [fig. 9A](#)) and the significantly greater proportion of samples classified as oxic in the SH study area compared to the other study areas ([table 7C](#)).



**Figure 8.** Bar charts showing the relations for wells in the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project between groundwater *A*, age class and depth class; *B*, depth class and study area; and *C*, age class and study area.





**Figure 9.** Values for groundwater samples from the six study areas, Cascade Range and Modoc Plateau study (CAMP) unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. *A*, dissolved oxygen concentration and *B*, pH.

The pH values showed a strong negative correlation with DO concentration (*table 7B*), and, accordingly, pH values were significantly greater in deep and overlapping wells than in springs or shallow wells, and in pre-modern groundwater than in modern or mixed groundwater (*table 7A*). Precipitation in the CAMP study unit is dilute and acidic: median specific conductance values were less than 5 microsiemens per centimeter ( $\mu\text{S}/\text{cm}$ ), and median pH values were approximately 5.4 for annual wet deposition at National Atmospheric Deposition Program sites within the boundaries of the CAMP study unit (National Atmospheric Deposition Program, 2012). These low pH values are primarily controlled by the equilibrium between atmospheric carbon dioxide and carbonic acid ( $\text{H}_2\text{CO}_3$ ) in solution (Stumm and Morgan, 1996). As the length of contact time between groundwater and the aquifer materials increases, pH values generally rise as acid is consumed by weathering reactions of silicate minerals and dissolution of carbonate minerals (if present) (Stumm and Morgan, 1996). The pH values were greater in the HL study area than in the ES and SH study areas (*fig. 9B*), reflecting that samples from the HL study area were more commonly pre-modern age.

## Status and Understanding of Groundwater Quality

The following discussion 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 the number of constituents that were detected at any concentration in the USGS-grid well samples compared to the number analyzed, and a graphical summary of the RCs of constituents detected in the USGS-grid wells. Aquifer-scale proportions are then presented for constituent classes and for the subset of individual constituents that were present at moderate or high RCs (constituents present only at low RCs have aquifer-scale proportions of 100 percent low-RC). Finally, results of statistical tests for relations between water quality and potential explanatory factors are presented for the smaller subset of individual constituents and constituent classes that met further criteria based on RCs or, for organic constituents, detection frequency.

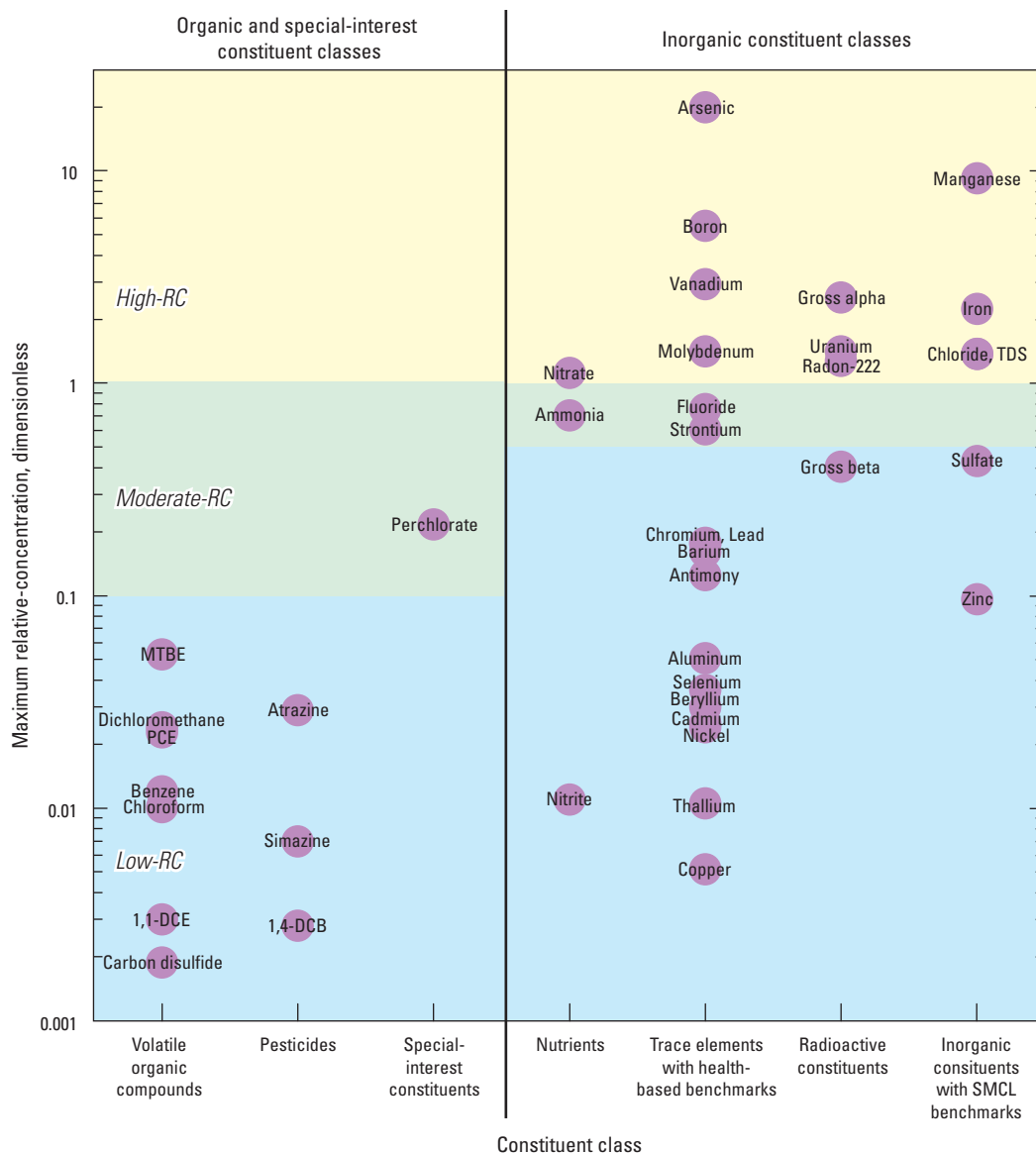
### Inorganic Constituents

Inorganic constituents generally occur naturally in groundwater, although their concentrations can be influenced by human activities as well as by natural factors (Hem, 1985).

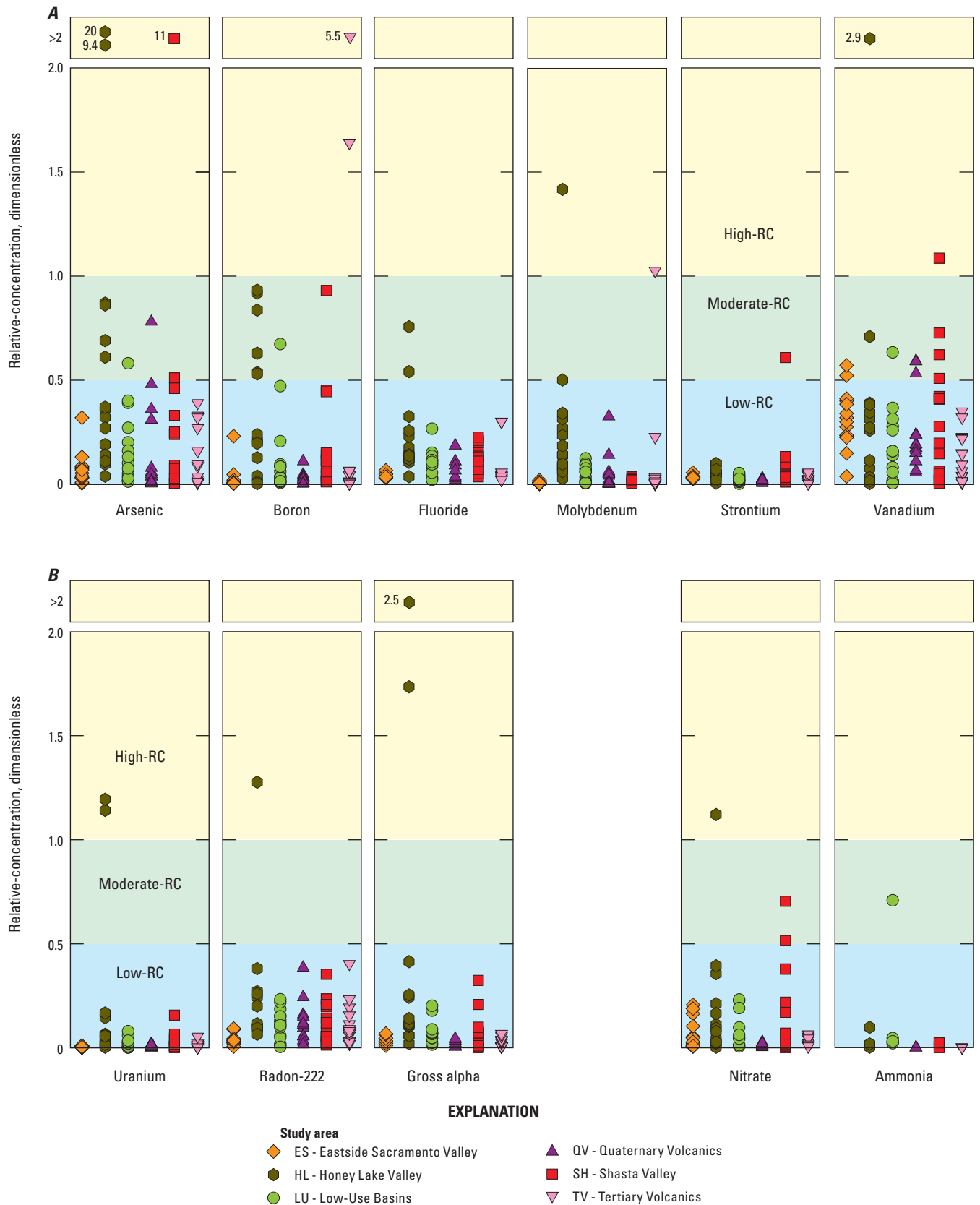
Of the 45 inorganic constituents analyzed by USGS-GAMA, 24 had regulatory or non-regulatory health-based benchmarks, 8 had non-regulatory aesthetic-based secondary maximum contaminant level (SMCL) benchmarks, and 13 had no established benchmarks (*table 4A, 4B*). Of the 32 inorganic constituents with benchmarks, 17 were detected at moderate or high RCs in samples collected by USGS-GAMA for the CAMP study unit or were reported in the CDPH database at moderate or high RCs in samples collected from any well between September 16, 2007, and September 16, 2010 (*table 4A*). The other 28 inorganic constituents either had no established benchmarks or were only detected at low RCs (*table 4B*). Most of the constituents without benchmarks are major or minor ions that are present in nearly all groundwater.

Of the 17 inorganic constituents, 16 were detected at moderate or high RCs in the USGS-grid wells: the nutrients ammonia and nitrate; the trace elements arsenic, boron, fluoride, molybdenum, strontium, and vanadium; the radioactive constituents gross alpha particle activity, radon-222 activity, and uranium; and the constituents with SMCL benchmarks chloride, iron, manganese, specific conductance, and total dissolved solids (TDS) (*table 4A; figs. 10, 11A–C*). The majority of these 16 constituents were detected at moderate or high RCs in 6 percent or less of the grid wells (*figs. 11A–C*). Lead was reported at moderate or high RCs in 4 wells in the CDPH database between September 16, 2007, and September 16, 2010; thus the high-RC and moderate-RC aquifer-scale proportions for lead were not zero when calculated by using the spatially weighted approach (*table 4A*). However, discrepancies between lead concentrations measured by USGS-GAMA and those reported by CDPH for samples from the same wells indicate that the data in the CDPH database for samples from wells in the CAMP study unit could be unreliable (*appendix B*). Lead was not included in the calculation of aquifer-scale proportions for trace elements as a class or for inorganic constituents as a class.

Aquifer-scale proportions for individual inorganic constituents are summarized in *table 8* for the CAMP study unit and in *tables C1A–F* for the six study areas. Aquifer-scale proportions for inorganic constituent classes are summarized in *table 9A* for inorganic constituents with health-based benchmarks and in *table 9B* for inorganic constituents with SMCL benchmarks, and results of statistical tests of differences in aquifer-scale proportions among the study areas are given in *table 10*. The geographic distributions of concentrations of the six inorganic constituents for which *understanding assessment* results are presented are shown in *figures 12A–F*. Results of statistical tests for relations between water quality and potential explanatory factors are presented in *tables 11A–B* and *12* for these six constituents.



**Figure 10.** Maximum relative-concentrations (RC) of constituents detected in U.S. Geological Survey (USGS)-grid wells by constituent class, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. (TDS, total dissolved solids; MTBE, methyl *tert*-butyl ether; PCE, tetrachloroethene; 1,1-DCE, 1,1-dichloroethene; 1,4-DCB, 1,4-dichlorobenzene; SMCL, secondary maximum contaminant level)



**Figure 11.** Relative-concentrations (RC) for water samples from wells in the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project of selected *A*, trace elements with health-based benchmarks; *B*, nutrients and radioactive constituents with health-based benchmarks; and *C*, salinity indicators and trace metals with secondary maximum contaminant level (SMCL) benchmarks.

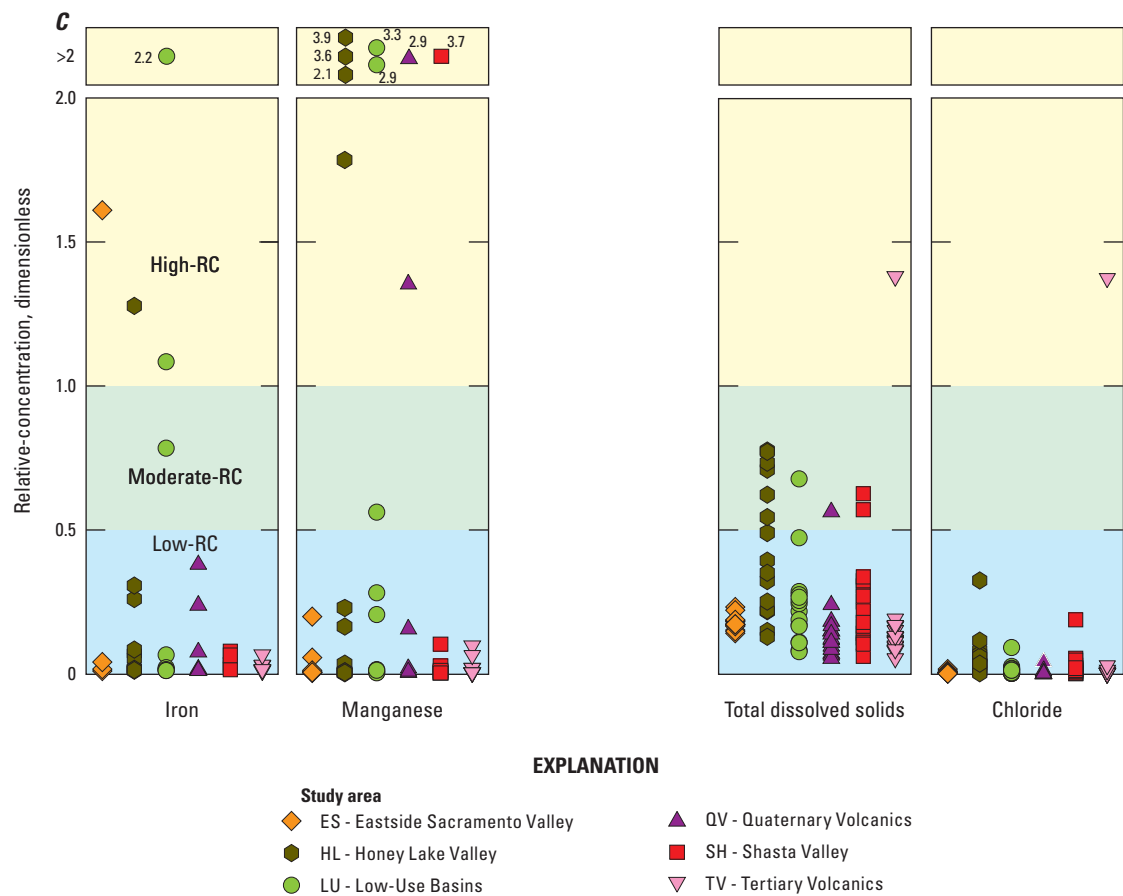
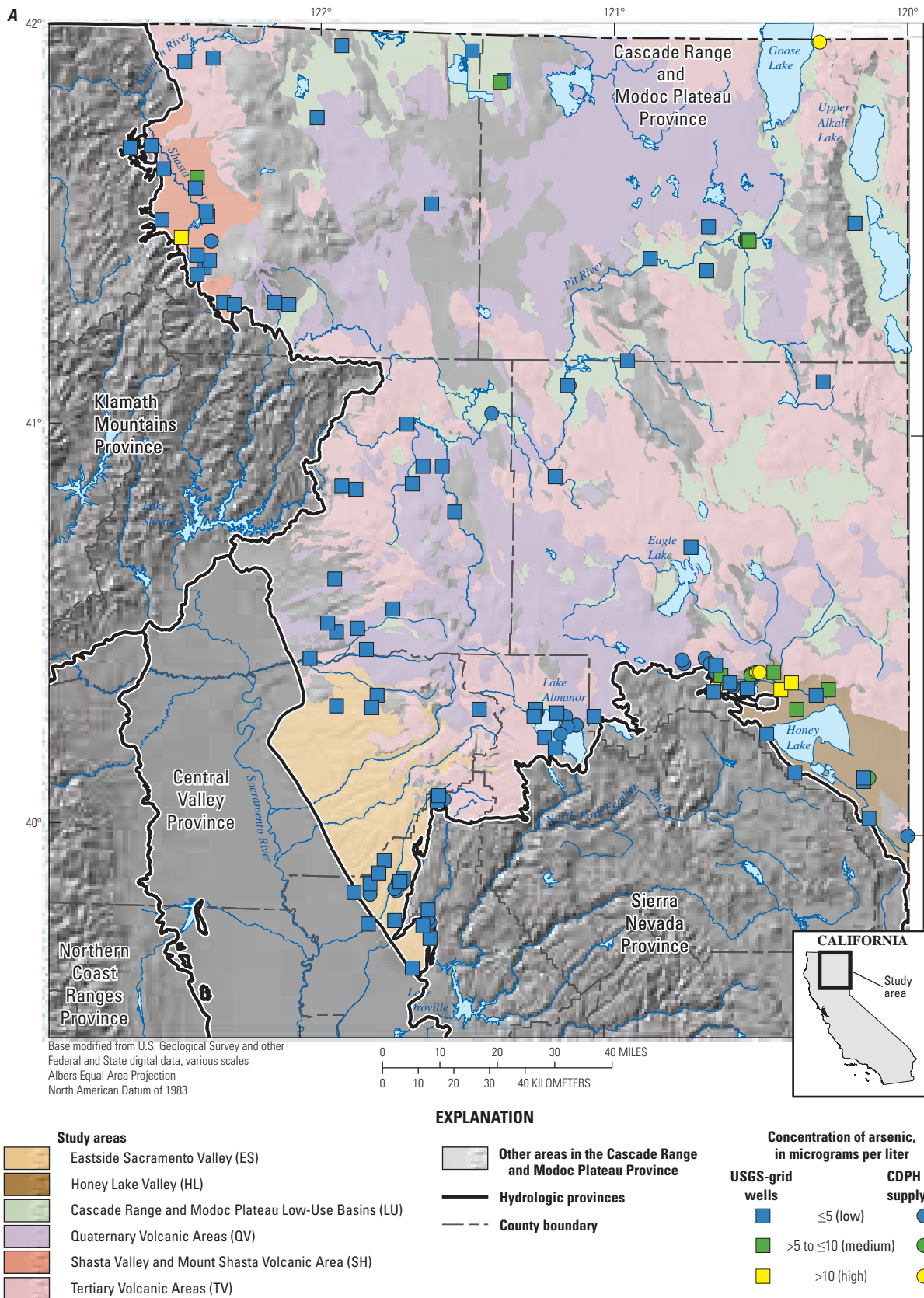


Figure 11. —Continued





**Figure 12.** Concentrations in water samples from U.S. Geological Survey (USGS)-grid wells and all wells in the California Department of Public Health (CDPH) database with data during the 3-year period used in the status assessment from September 16, 2007, through September 16, 2010, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project of A, arsenic; B, boron; C, molybdenum; D, vanadium; E, uranium; F, total dissolved solids; G, manganese; and H, iron.

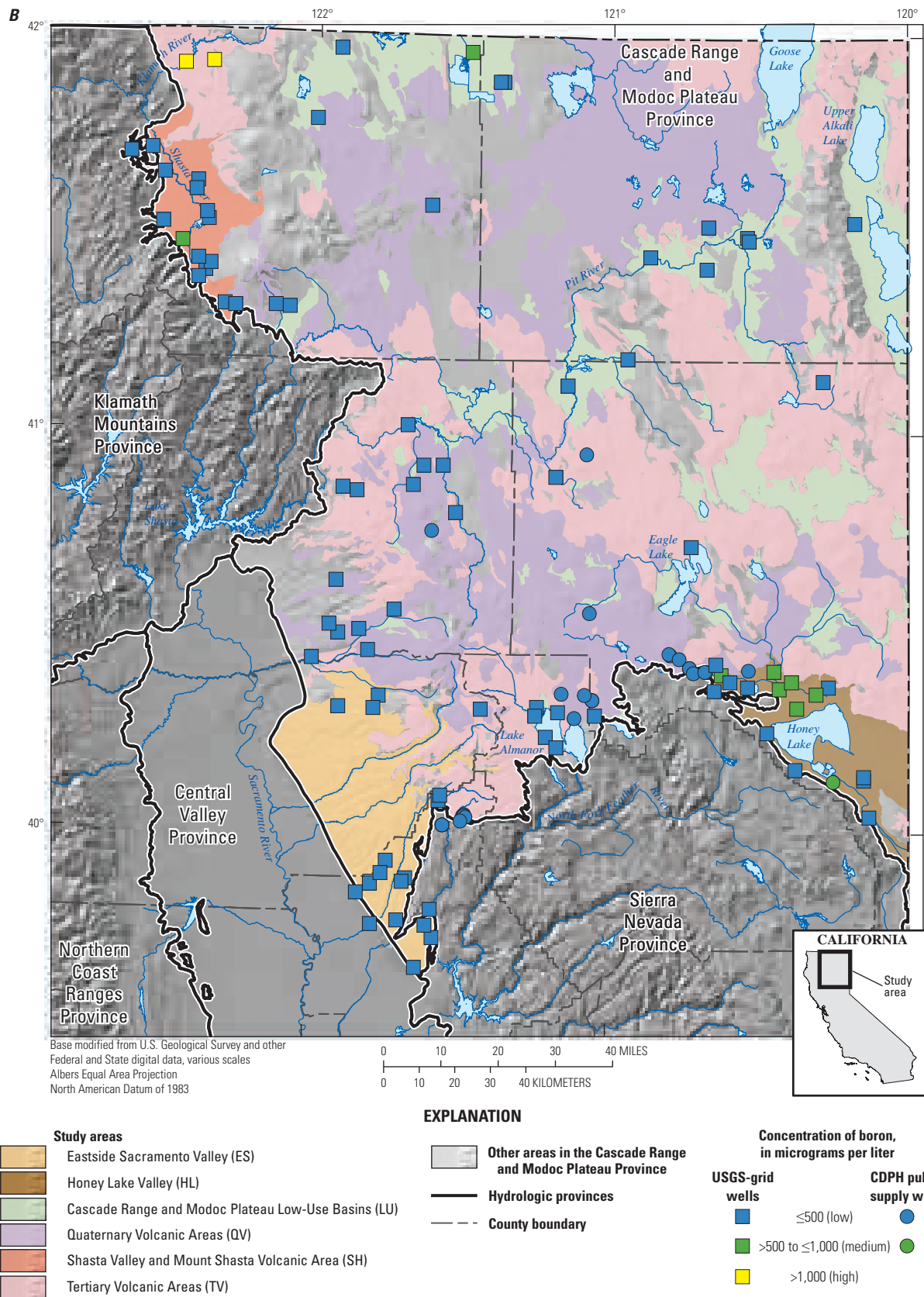


Figure 12. —Continued

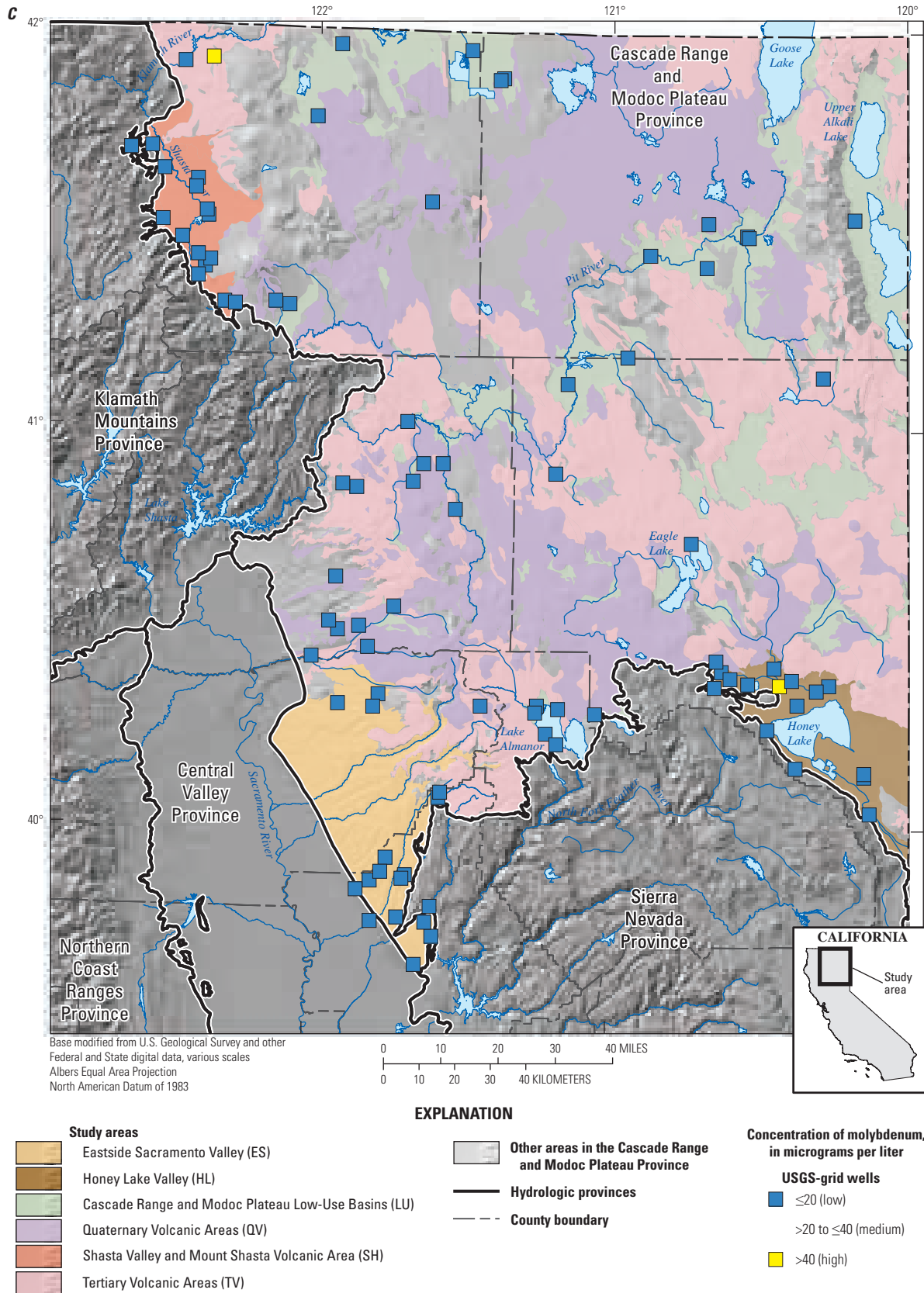


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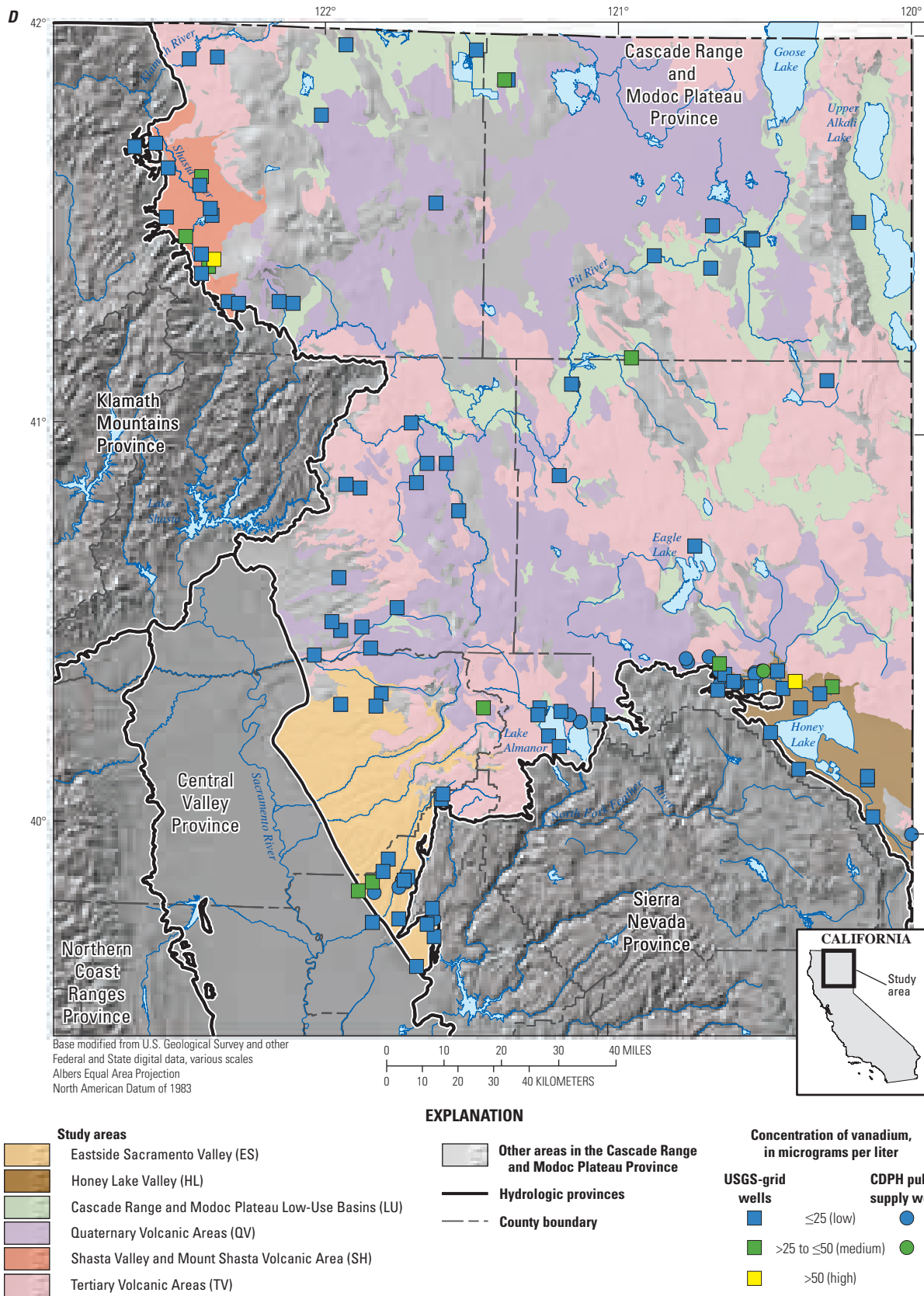


Figure 12. —Continued

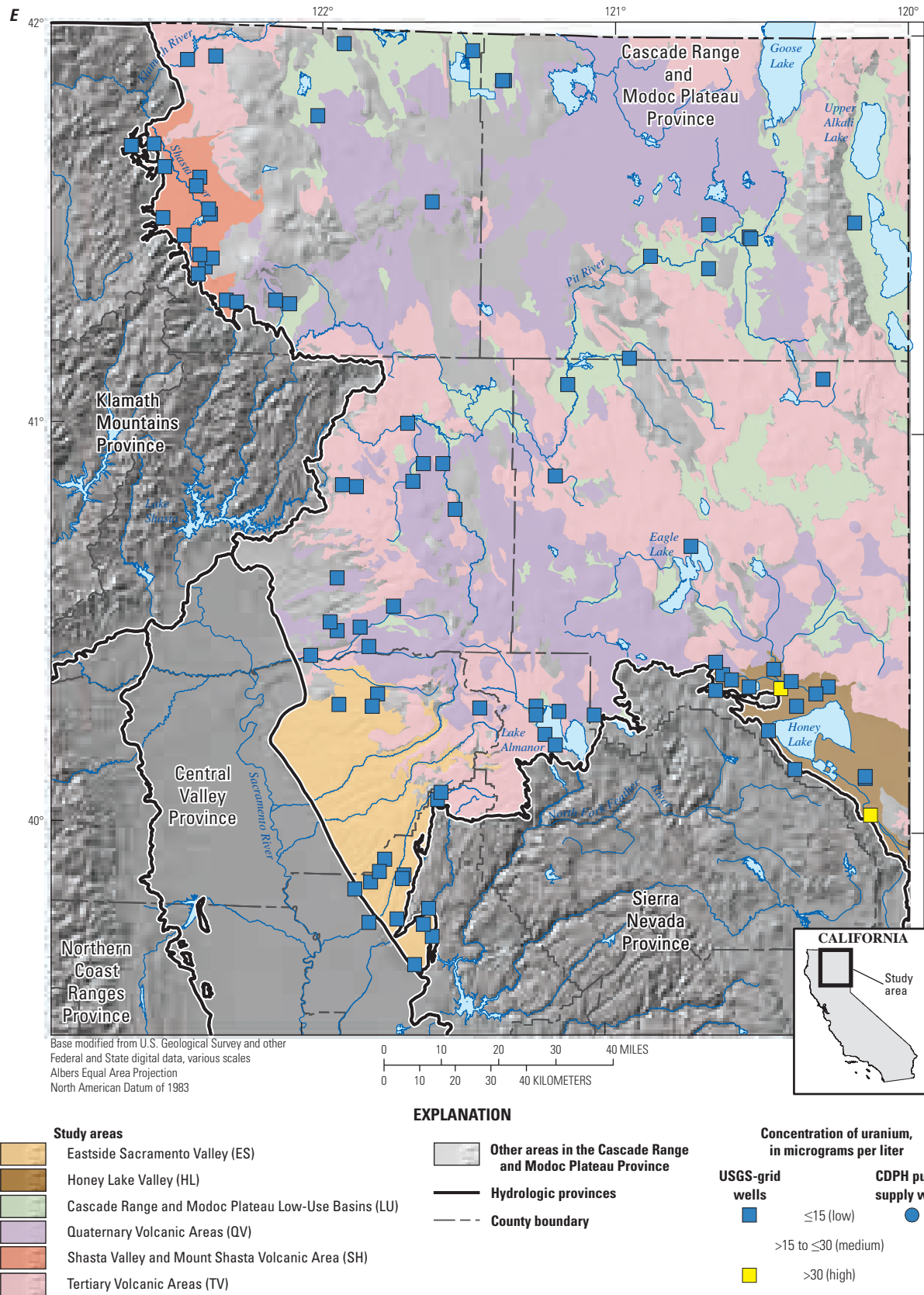


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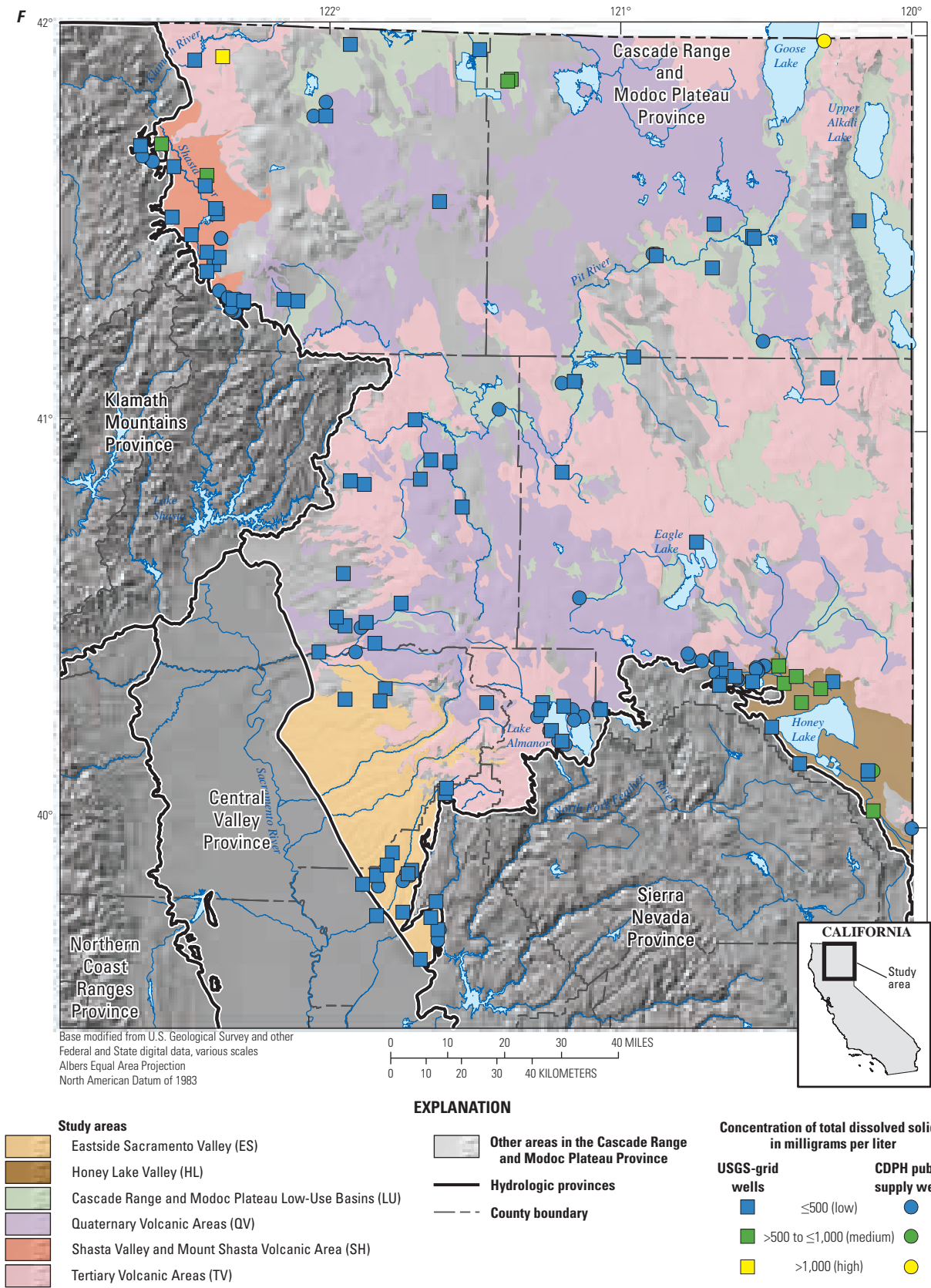


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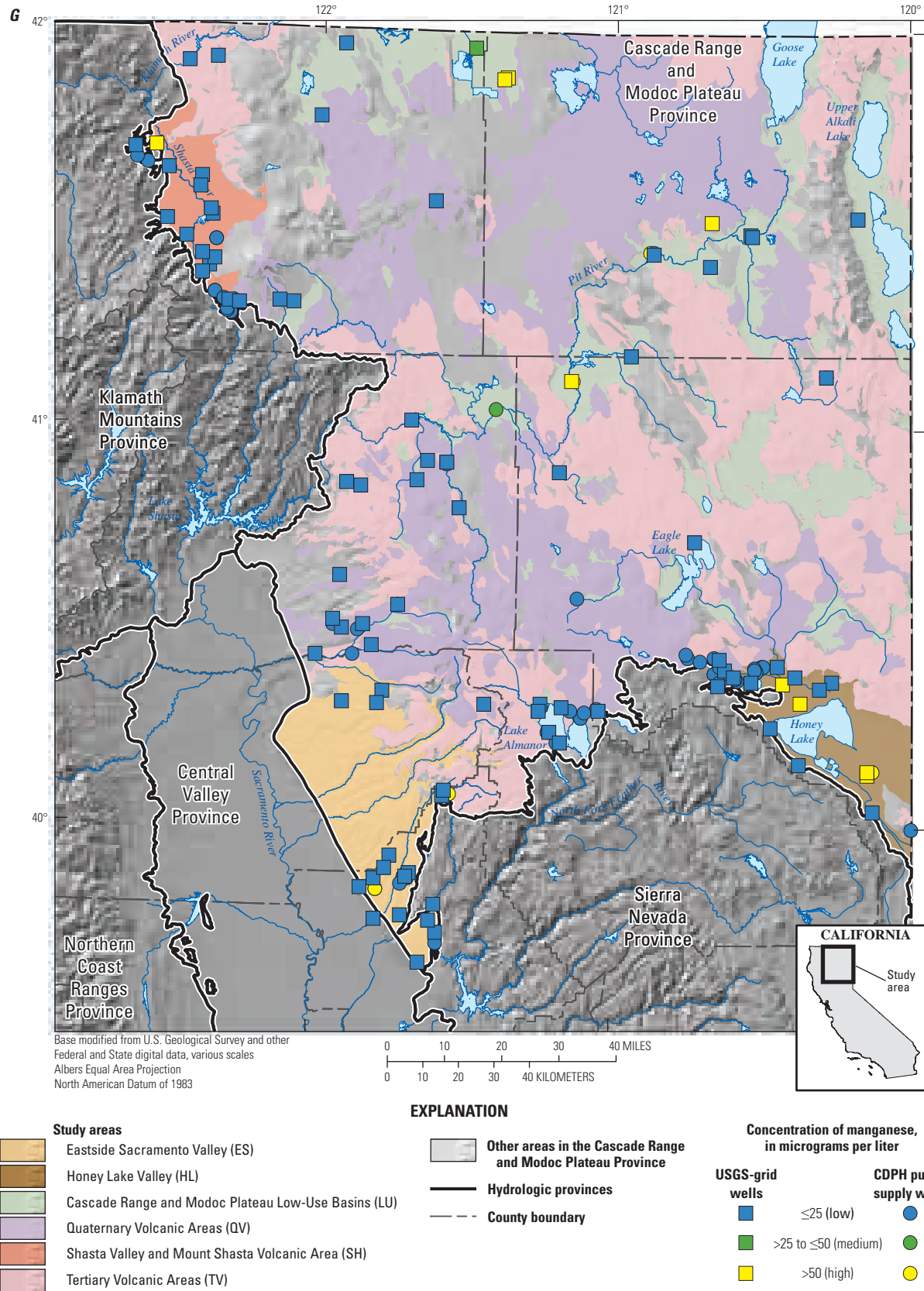


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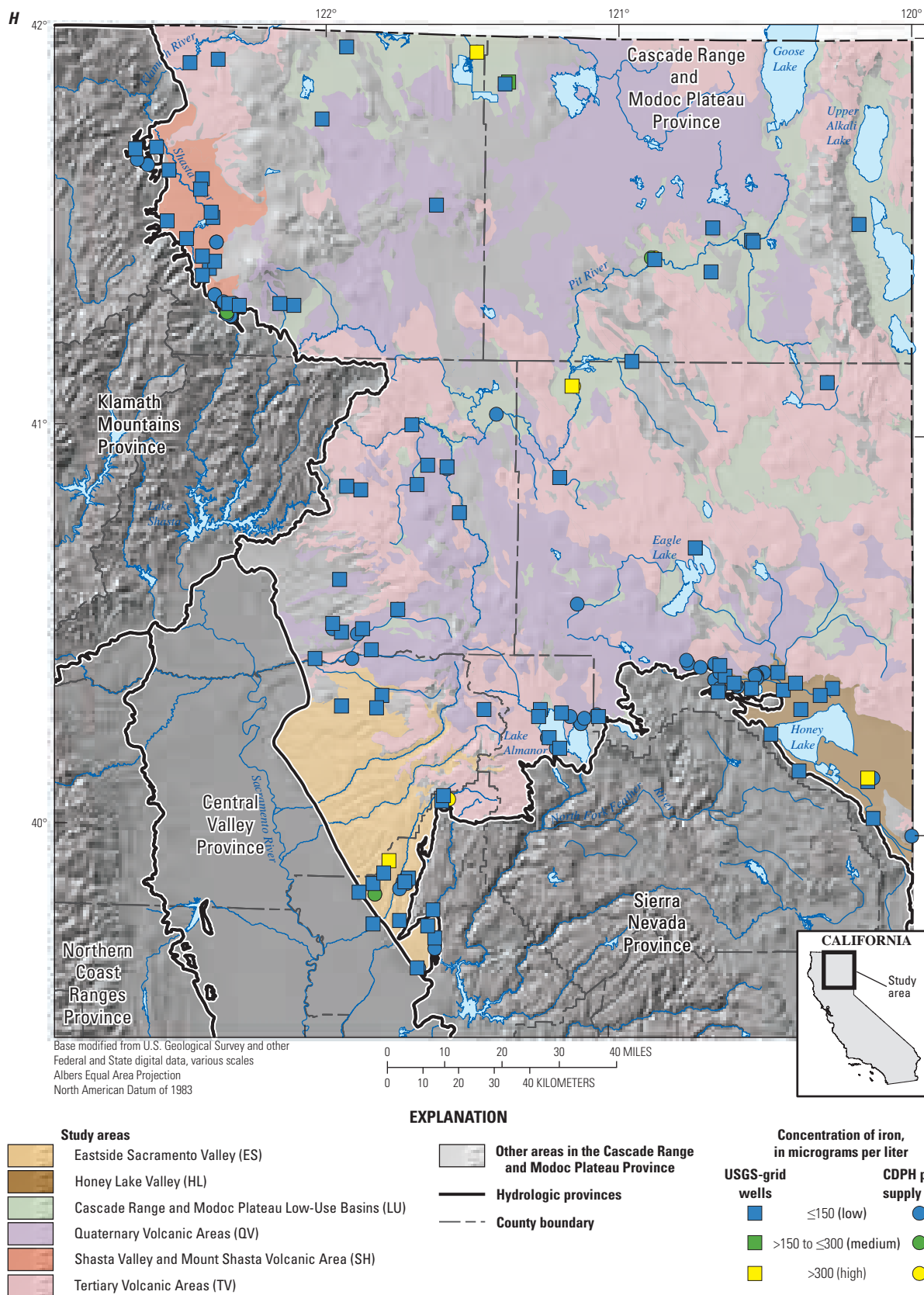


Figure 12. —Continued

**Table 8.** Aquifer-scale proportions for inorganic constituents detected at high or moderate relative concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. RC categories for inorganic constituents: high,  $RC > 1.0$ ; moderate,  $1.0 \geq RC > 0.5$ ; low,  $RC \leq 0.5$ . Inorganic 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.A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency <sup>1</sup> (percent)		Aquifer-scale proportions (percent)				90-percent confidence interval for grid-based high-RC proportion <sup>3</sup>
	Wells	Cells	Moderate-RC	High-RC	Spatially weighted <sup>1</sup>		Grid-based <sup>2</sup>		
					Moderate-RC	High-RC	Moderate-RC	High-RC	
Nutrients									
Ammonia	90	90	1.2	0	1.2	0	1.2	0	0.0–1.5
Nitrate	253	90	1.8	0.4	1.9	0.9	1.8	0.9	0.1–3.9
Trace elements and minor ions with health-based benchmarks									
Arsenic	159	90	6.4	3.8	7.1	3.7	7.4	2.7	0.9–6.7
Boron	115	90	6.8	2.1	7.5	2.5	7.5	2.5	0.8–6.4
Fluoride	151	90	1.2	0	1.3	0	1.8	0	0.0–1.5
Lead	137	90	1.5	2.1	0.9	1.1	0	0	0.0–1.5
Molybdenum	90	90	0	2.2	0	2.1	0	2.1	0.5–5.8
Strontium	90	90	0.9	0	0.9	0.0	0.9	0	0.0–1.5
Vanadium	120	90	9.3	1.4	9.9	1.3	11.3	1.8	0.5–5.4
Radioactive constituents									
Gross-alpha particle activity	150	90	1.8	1.8	0.6	2.1	0	1.8	0.5–5.4
Adjusted gross-alpha particle activity	150	90	0.7	0.7	0.3	0.9	0.9	0	0.0–1.5
Radon-222	90	90	0	0.9	0	0.9	0	0.9	0.1–3.9
Uranium	95	90	0	3.2	0	2.0	0	1.8	0.5–5.4
Inorganic constituents with SMCL benchmarks									
Chloride	146	90	0	0.9	0	1.2	0	1.2	0.2–4.4
Iron	155	90	3.8	7.5	2.8	5.6	1.2	4.0	1.6–8.5
Manganese	154	90	3.2	10.3	2.5	12.1	1.2	10.4	6.0–16.6
Total dissolved solids (TDS)	159	90	6.9	1.3	9.3	1.9	10.1	1.2	0.2–4.4

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 90 grid wells during July 12 through October 14, 2010.

<sup>3</sup>Based on the Jeffrey's interval for the binomial distribution (Brown and others, 2001).

**Table 9A.** Summary of spatially weighted aquifer-scale proportions for inorganic constituent classes with health-based benchmarks, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. **Study area abbreviations:** ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Study unit:** aquifer-scale proportions are area weighted by the percent of the study unit covered by each study area: ES=10.4 percent, HL=13.4 percent, LU=18.4 percent, QV=25.7 percent, SH=13.3 percent, TV=18.7 percent. **Relative-concentration categories:** high, RC greater than 1.0 for at least one constituent in the class; moderate, RC is less than or equal to 1.0 and greater than 0.5 for at least one constituent in the class and no constituents with RC greater than 1; low, RC less than or equal to 0.5 for all constituents in the class]

Constituent classes and study areas	Number of wells	Aquifer-scale proportions (percent)		
		Low-RC or not detected	Moderate-RC	High-RC
Nutrients				
ES	30	100	0	0
HL	35	92.2	1.1	6.7
LU	45	95.3	4.7	0
QV	64	100	0	0
SH	42	88.9	11.1	0
TV	40	100	0	0
CAMP study unit	256	96.6	2.5	0.9
Trace elements <sup>1</sup>				
ES	28	91.1	8.9	0
HL	34	55.3	28.3	16.4
LU	27	77.8	18.9	3.3
QV	31	88.7	11.3	0
SH	29	74.4	16.7	8.9
TV	25	85.3	1.3	13.3
CAMP study unit	174	79.9	13.6	6.5
Radioactive constituents				
ES	24	100	0	0
HL	23	78.3	0	21.7
LU	27	96.7	3.3	0
QV	29	100	0	0
SH	27	100	0	0
TV	22	100	0	0
CAMP study unit	152	96.5	0.6	2.9
Any inorganic constituent with a health-based benchmark <sup>1,2</sup>				
ES	29	91.1	8.9	0
HL	36	35.8	26.1	38.1
LU	30	74.4	22.2	3.3
QV	37	88.7	11.3	0
SH	32	68.9	22.2	8.9
TV	27	85.3	1.3	13.3
CAMP study unit	190	76.0	14.7	9.4

<sup>1</sup>Data for lead are not included because of possible data quality problems for lead in the California Department of Public Health (CDPH) database for samples collected between September 2007 and September 2010 (see *appendix B*).

<sup>2</sup>The 66 CDPH wells that had data for nitrate and no data for trace elements or radioactive constituents were not included. See text for discussion.



**Table 9B.** Summary of spatially weighted aquifer-scale proportions for inorganic constituent classes with secondary maximum contaminant level (SMCL) benchmarks, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. **Study area abbreviations:** ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Study unit:** aquifer-scale proportions are area weighted by the percent of the study unit covered by each study area: ES=10.4 percent, HL=13.4 percent, LU=18.4 percent, QV=25.7 percent, SH=13.3 percent, TV=18.7 percent. **Relative-concentration categories:** high, RC greater than 1.0 for at least one constituent in the class; moderate, RC less than or equal to 1.0 and greater than 0.5 for at least one constituent in the class and no constituents with RC greater than 1; low, RC less than or equal to 0.5 for all constituents in the class]

Constituent classes and study areas	Number of wells	Aquifer-scale proportions (percent)		
		Low-RC or not detected	Moderate-RC	High-RC
SMCL salinity indicators <sup>1</sup>				
ES	24	100.0	0	0
HL	32	65.6	34.4	0
LU	30	90.0	6.7	3.3
QV	29	93.3	6.7	0
SH	26	86.7	13.3	0
TV	23	93.3	0	6.7
CAMP study unit	164	88.8	9.3	1.9
SMCL metals <sup>2</sup>				
ES	27	87.9	1.0	11.1
HL	31	71.1	0	28.9
LU	24	71.1	6.7	22.2
QV	30	86.7	0	13.3
SH	29	89.4	1.7	8.9
TV	24	94.4	0	5.6
CAMP study unit	165	83.7	1.6	14.8
Any inorganic SMCL constituent <sup>3</sup>				
ES	23	87.6	1.3	11.1
HL	31	53.3	17.8	28.9
LU	24	71.1	6.7	22.2
QV	29	86.7	0	13.3
SH	26	85.0	8.3	6.7
TV	21	91.1	0	8.9
CAMP study unit	154	80.0	4.9	15.1

<sup>1</sup>Salinity indicators with SMCL benchmarks: total dissolved solids, specific conductance, chloride, and sulfate.

<sup>2</sup>Metals with SMCL benchmarks: iron, manganese, and zinc.

<sup>3</sup>Aquifer-scale proportions for any inorganic SMCL constituent were calculated using only wells with data for at least one salinity indicator and at least one SMCL metal.

**Table 10.** Results of contingency table tests for differences in aquifer-scale proportions of selected inorganic constituents and constituent classes between study areas, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[If contingency table test indicated a significant difference in aquifer-scale proportions among the study areas ( $p < 0.05$ ), then pairs with the greatest differences were identified from the components of the contingency table test statistic. **Study area:** ES, Sacramento Valley Eastside; HL, Honey Lake Valley; LU, Cascade Range and Modoc Plateau Low-Use Basins; QV, Quaternary Volcanic Areas; SH, Shasta Valley and Mount Shasta Volcanic Area; TV, Tertiary Volcanic Areas. **Other abbreviations:** <, less than; ns, no significant differences; RC, relative concentration; >, greater than]

Constituents	Proportion high-RC or moderate-RC compared to proportion low-RC	Proportion high-RC compared to proportion moderate-RC or low-RC
Individual inorganic constituents		
Arsenic	<0.001 HL>ES, LU, QV, SH, and TV	0.025 HL>ES and QV
Boron	0.001 HL>ES, LU, QV, and SH	0.022 TV>ES and QV
Molybdenum	0.533 ns	0.533 ns
Vanadium	0.275 ns	0.508 ns
Uranium	0.038 HL>TV	0.038 HL>TV
Total dissolved solids	0.003 HL>ES, LU, QV, and TV	0.296 ns
Manganese	<0.001 HL>ES, LU, QV, SH, and TV	0.025 HL>ES and TV
Iron	0.005 LU>HL, QV, and SH	0.187 ns
Classes of inorganic constituents with health-based benchmarks		
Nutrients (nitrate)	0.020 SH>QV and TV HL>QV	0.011 HL>QV
Trace elements	0.007 HL>ES, QV, and TV	0.049 HL>ES and QV
Radioactive constituents	<0.001 HL>ES, QV, SH, and TV	<0.001 HL>ES, LU, QV, SH, and TV
Any inorganic constituent	<0.001 HL>ES, LU, QV, SH, and TV	<0.001 HL>ES, LU, QV, SH, and TV TV>QV

**Table 11A.** Results of multi-stage Kruskal-Wallis tests for differences in concentrations of selected water-quality constituents between U.S. Geological Survey (USGS)-grid wells classified into groups by study area, aquifer lithology class, age class, oxidation-reduction (redox) class, and depth class, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Kruskal-Wallis test p-values are listed in table. If Kruskal-Wallis test indicated significant differences (p-value less than a threshold value,  $\alpha$ , of 0.05) among the groups, the groups that were significantly different were determined using Tukey's test on the ranks of the data. Groups with significant differences are listed in table. **Study area:** ES, Sacramento Valley Eastside; HL, Honey Lake Valley; LU, Cascade Range and Modoc Plateau Low-Use Basins; QV, Quaternary Volcanic Areas; SH, Shasta Valley and Mount Shasta Volcanic Area; TV, Tertiary Volcanic Areas. **Geology class:** G, granitic and sedimentary; M, metamorphic or metamorphic and sedimentary or metamorphic and volcanic; S, sedimentary; V, volcanic; VS, sedimentary and volcanic (see appendix A for explanation). **Depth class:** Deep, top and bottom of perforations >200 ft; Overlapping, top of perforations <200 ft and bottom of perforations >200 ft; Shallow, top and bottom of perforations <200 ft; Spring, groundwater emerges at land surface without pumping. **Age class:** Mixed, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; Modern, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; Pre-modern, tritium<0.5 TU (see appendix A for explanation). **Redox class:** anoxic, DO<1.0 mg/L; mixed, DO>1.0 mg/L and Mn>50  $\mu\text{g/L}$  and/or Fe>100  $\mu\text{g/L}$ ; oxic, DO>1.0 mg/L and Mn<50  $\mu\text{g/L}$  and Fe<100  $\mu\text{g/L}$ . Samples classified as mixed were grouped in to the anoxic class for analysis (appendix A). **Other abbreviations:** DO, dissolved oxygen; ft, feet below land surface; mg/L, milligrams per liter; ns, no significant differences; pmc, percent modern carbon; SMCL, secondary maximum contaminant level; THM, Trihalomethane; TU, tritium units;  $\mu\text{g/L}$ , micrograms per liter; <, less than; >, greater than]

p-value significant relations <sup>1</sup>	Study area (ES, HL, SH, LU, QV, TV)	Aquifer lithology class (G, M, S, V, VS)	Age class (pre-modern, mixed, modern)	Redox class (oxic, anoxic)	Depth class (spring, shallow, overlap, deep)
Inorganic constituents with health-based benchmarks (HBB)					
Arsenic	0.002 HL>ES, QV, and TV	0.001 S>M and V	<0.001 Pre-modern and mixed>Modern	0.712	0.497
Boron	<0.001 HL>ES, QV, and TV SH>ES and QV	0.001 S>V and VS M>V	<0.001 Pre-modern and mixed>Modern	0.077	0.089
Molybdenum	<0.001 HL>ES, LU, QV, SH, and TV LU>ES	<0.001 G and S>V S>VS	<0.001 Pre-modern and mixed>Modern	0.028 Anoxic>Oxic	0.209
Vanadium	0.035 ES>TV	0.048 S, V, and VS>M	0.06	0.006 Oxic>Anoxic	0.472
Uranium	<0.001 HL>ES, LU, QV, and TV	0.001 G, M, and S>V G>VS	0.113	0.458	0.373
Inorganic constituents with SMCL benchmarks					
Total dissolved solids (TDS)	<0.001 HL>ES, QV and TV	<0.001 M, S, and VS>V S>VS	0.007 Pre-modern>Modern	<0.001 Anoxic>Oxic	0.009 Overlap and shallow>Spring
Manganese	0.147	0.087 ns	0.071	0.004 Anoxic>Oxic	0.711
Iron	0.628	0.996 ns	0.738	0.010 Anoxic>Oxic	0.527

**Table 11A.** Results of multi-stage Kruskal-Wallis tests for differences in concentrations of selected water-quality constituents between U.S. Geological Survey (USGS)-grid wells classified into groups by study area, aquifer lithology class, age class, oxidation-reduction (redox) class, and depth class, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project—Continued

[Kruskal-Wallis test p-values are listed in table. If Kruskal-Wallis test indicated significant differences (p-value less than a threshold value,  $\alpha$ , of 0.05) among the groups, the groups that were significantly different were determined using Tukey's test on the ranks of the data. Groups with significant differences are listed in table. **Study area:** ES, Sacramento Valley Eastside; HL, Honey Lake Valley; LU, Cascade Range and Modoc Plateau Low-Use Basins; QV, Quaternary Volcanic Areas; SH, Shasta Valley and Mount Shasta Volcanic Area; TV, Tertiary Volcanic Areas. **Geology class:** G, granitic and sedimentary; M, metamorphic or metamorphic and sedimentary or metamorphic and volcanic; S, sedimentary; V, volcanic; VS, sedimentary and volcanic (see appendix A for explanation). **Depth class:** Deep, top and bottom of perforations >200 ft; Overlapping, top of perforations <200 ft and bottom of perforations >200 ft; Shallow, top and bottom of perforations <200 ft; Spring, groundwater emerges at land surface without pumping. **Age class:** Mixed, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; Modern, tritium>0.5 TU and  $^{14}\text{C}$ <90 pmc; Pre-modern, tritium<0.5 TU (see appendix A for explanation). **Redox class:** anoxic, DO<1.0 mg/L; mixed, DO>1.0 mg/L and Mn>50  $\mu\text{g/L}$  and/or Fe>100  $\mu\text{g/L}$ ; oxic, DO>1.0 mg/L and Mn<50  $\mu\text{g/L}$  and Fe<100  $\mu\text{g/L}$ . Samples classified as mixed were grouped in to the anoxic class for analysis (appendix A). **Other abbreviations:** DO, dissolved oxygen; ft, feet below land surface; mg/L, milligrams per liter; ns, no significant differences; pmc, percent modern carbon; SMCL, secondary maximum contaminant level; THM, Trihalomethane; TU, tritium units;  $\mu\text{g/L}$ , micrograms per liter; <, less than; >, greater than]

p-value significant relations <sup>1</sup>	Study area (ES, HL, SH, LU, QV, TV)	Aquifer lithology class (G, M, S, V, VS)	Age class (pre-modern, mixed, modern)	Redox class (oxic, anoxic)	Depth class (spring, shallow, overlap, deep)
Organic and special interest constituents					
Herbicides	SH>ES, HL, LU, QV, and TV	0.081 ns	0.014 Modern and mixed>Pre-modern	0.007 Oxic>Anoxic	0.094
THMs (chloroform)	0.012 ES>LU and QV	0.282 ns	0.436	0.157	0.086
Perchlorate	0.024 ES>QV and TV HL>QV	0.155 ns	0.296	0.027 Oxic>Anoxic	0.222

<sup>1</sup>Explanation for reporting of significant differences using the results for arsenic by study unit as an example. The Tukey's test results showed that the following three pairs had significant differences: HL>ES, HL>QV, and HL>TV. Because HL has greater arsenic concentrations than ES, QV, and TV, the notation is condensed to 'HL>ES, QV, and TV.' Arsenic concentrations in ES, QV, and TV were not significantly different from one another. Arsenic concentrations were not significantly different for all of the pairs not listed.

**Table 11B.** Results of Spearman's rho tests for correlations between values of selected potential explanatory factors and concentrations of selected water-quality constituents for the U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[p (rho), Spearman's correlation statistic, p values (significance level of the Spearman's test) less than threshold value ( $\alpha$ ) of 0.05 are considered significant: bold black text, significant positive correlation; **bold red text**, significant negative correlation. **Abbreviations:** DO, dissolved oxygen; GAMA, Groundwater Ambient Monitoring and Assessment Program; SMCL, secondary maximum contaminant level; THM, Trihalomethane; USTs, leaking or formerly leaking underground-storage tanks; <, less than]

p-value (p)	Percentage of agricultural land use	Percentage of natural land use	Percentage of urban land use	Density of septic tanks	Density of USTs	Aridity index	Elevation	Depth to top of screened or open interval	Depth to bottom of screened or open interval <sup>1</sup>	pH	DO concentration
Nutrients and trace elements with health-based benchmarks											
Arsenic	<0.001 0.35	0.338 -0.10	0.740 -0.04	0.139 -0.16	0.077 -0.19	<0.001 -0.55	0.972 -0.00	0.972 0.00	0.577 0.07	<0.001 0.49	<0.001 -0.41
Boron	<0.001 0.58	<0.001 -0.36	0.438 0.08	0.086 -0.18	0.324 -0.10	<0.001 -0.66	0.485 -0.07	0.598 -0.07	0.461 0.09	<0.001 0.55	<0.001 -0.62
Molybde- num	<0.001 0.49	0.008 -0.28	0.343 0.10	0.008 -0.28	0.019 -0.25	<0.001 -0.78	0.090 0.18	0.958 0.01	0.498 0.08	<0.001 0.66	<0.001 -0.60
Vanadium	0.549 0.06	0.276 0.12	0.112 -0.17	0.313 0.11	0.388 0.09	0.980 -0.00	0.032 -0.23	0.346 0.12	0.255 0.13	0.527 0.08	0.870 0.02
Uranium	<0.001 0.40	0.020 -0.24	0.510 0.07	0.450 0.08	0.169 -0.15	<0.001 -0.53	0.158 0.15	0.296 -0.13	0.099 -0.19	<0.001 0.38	0.049 -0.21
Inorganic constituents with SMCL benchmarks											
Total dis- solved solids (TDS)	<0.001 0.59	<0.001 -0.37	0.326 0.10	0.428 -0.08	0.448 -0.08	<0.001 -0.68	0.038 -0.22	0.269 -0.14	0.939 0.01	<0.001 0.42	<0.001 -0.73
Manga- nese	0.012 0.26	0.010 -0.27	0.046 0.21	0.028 -0.23	0.385 -0.09	0.002 -0.32	0.187 0.14	0.193 0.16	0.274 0.13	0.010 0.27	<0.001 -0.47
Iron	0.805 -0.03	0.796 -0.03	0.633 0.05	0.099 -0.18	0.738 -0.04	0.516 -0.07	0.126 0.16	0.939 0.01	0.939 -0.01	0.831 -0.02	0.066 -0.20
Organic and special interest constituents											
Herbicides	0.851 -0.02	0.688 -0.04	0.780 0.03	0.058 0.20	0.367 0.10	0.205 0.14	0.294 -0.11	0.090 -0.21	0.066 -0.22	0.047 -0.21	0.051 0.21
THMs (chloro- form)	0.358 -0.10	0.123 -0.16	0.006 0.29	0.037 0.22	0.099 0.18	0.190 0.14	0.005 -0.29	0.132 -0.19	0.228 0.14	0.009 -0.27	0.614 -0.05
Perchlo- rate	0.014 0.27	0.214 -0.14	0.199 0.14	0.861 0.02	0.616 -0.06	0.021 -0.25	0.496 -0.08	0.201 -0.17	0.996 -0.01	<0.001 -0.54	0.276 -0.12

<sup>1</sup>Eleven wells did not have data for depth to the bottom of the screened or open interval, but did have data for well depth (table A2). Well depth data were used to represent data for the depth of the bottom of the screened or open interval for these wells.



**Table 12.** Results of Spearman's tests for correlations between concentrations of selected inorganic constituents in the U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[ $\rho$  (rho), Spearman's correlation statistic. p values (significance level of the Spearman's test) less than threshold value ( $\alpha$ ) of 0.05 are considered significant: **bold black text**, significant positive correlation; **bold red text**, significant negative correlation; non-bold, not significant. **Abbreviations:** TDS, total dissolved solids; <, less than]

p-value ( $\rho$ )	Boron	Molybdenum	Vanadium	Uranium	Manganese	Iron	TDS
Arsenic	<b>&lt;0.001</b> <b>0.72</b>	<b>&lt;0.001</b> <b>0.77</b>	<b>&lt;0.001</b> <b>0.53</b>	<b>&lt;0.001</b> <b>0.55</b>	<b>0.039</b> <b>0.22</b>	<b>0.456</b> <b>-0.08</b>	<b>&lt;0.001</b> <b>0.50</b>
Boron		<b>&lt;0.001</b> <b>0.82</b>	0.217 0.13	<b>&lt;0.001</b> <b>0.40</b>	<b>&lt;0.001</b> <b>0.44</b>	0.804 0.06	<b>&lt;0.001</b> <b>0.73</b>
Molybdenum			0.265 0.12	<b>&lt;0.001</b> <b>0.42</b>	<b>&lt;0.001</b> <b>0.44</b>	0.572 0.06	<b>&lt;0.001</b> <b>0.62</b>
Vanadium				<b>0.001</b> <b>0.34</b>	<b>0.002</b> <b>-0.32</b>	<b>&lt;0.001</b> <b>-0.40</b>	0.344 0.10
Uranium					<b>0.433</b> <b>-0.08</b>	<b>0.151</b> <b>-0.15</b>	<b>&lt;0.001</b> <b>0.39</b>
Manganese						<b>&lt;0.001</b> <b>0.45</b>	<b>0.003</b> <b>0.31</b>
Iron							0.606 0.06

Inorganic constituents with health-based benchmarks, as a group, were present at high RCs in 9.4 percent of the primary aquifer system and at moderate RCs in 14.7 percent ([table 9A](#)). The proportion of the primary aquifer system having high RCs of inorganic constituents with health-based benchmarks was significantly greater for the HL study areas compared to all of the other study areas ([table 10](#)). Inorganic constituents with SMCL benchmarks (metals and salinity indicators), as a group, were present at high RCs in 15.1 percent of the primary aquifer system and at moderate RCs in 4.9 percent ([table 9B](#)).

## 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 with health-based benchmarks, as a class, had a high-RC aquifer-scale proportion of 6.5 percent and a moderate-RC aquifer-scale proportion of 13.6 percent in the CAMP study unit ([table 9A](#)). The proportion of the primary aquifer system having high or moderate RCs of at least one trace element was significantly greater in the HL study area than in the ES, QV, and TV study areas ([table 10](#)).

Arsenic was detected at high RCs in approximately 3 percent of the CAMP study unit primary aquifer; boron, molybdenum, and vanadium each were detected at high RCs in approximately 2 percent of the system ([table 8](#)). These

four trace elements are discussed in more detail in following sections. Three other trace elements (fluoride, lead, and strontium) were detected at high RCs in less than 2 percent of the primary aquifer system or were only detected at moderate RCs ([table 8](#)).

### Arsenic

Arsenic is a semi-metallic trace element. Natural sources of arsenic in groundwater include dissolution of arsenic-bearing minerals, desorption of arsenic from mineral surfaces, and mixing with hydrothermal fluids. 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 copper ore smelting, coal combustion, arsenical pesticides, arsenical veterinary pharmaceuticals, and wood preservatives (Welch and Stollenwerk, 2003). In addition, mining for copper, gold, and other metals can increase the rate of dissolution of natural arsenic-bearing minerals (Smedley and Kinniburgh, 2002). The CAMP study unit has had relatively little mining activity compared to other areas of the State (U.S. Geological Survey, 2005) and little registered use of arsenical pesticides (California Department of Pesticide Regulation, 2013), thus, anthropogenic sources of arsenic are unlikely to be significant.

The MCL-US for arsenic was lowered from 50  $\mu\text{g/L}$  to 10  $\mu\text{g/L}$  in 2002, and chronic exposure to arsenic concentrations between 10 and 50  $\mu\text{g/L}$  in drinking water has

been linked to increased cancer risk and to non-cancerous effects including skin damage and circulatory problems (U.S. Environmental Protection Agency, 2010). 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, 1999; Welch and others, 2000), and high concentrations of arsenic in groundwater resources used for drinking water are a worldwide concern (Smedley and Kinniburgh, 2002; Welch and others, 2006).

Arsenic was present at high RCs in 2.7 percent of the primary aquifer system in the CAMP study unit and at moderate RCs in 7.4 percent (*table 8*). High or moderate RCs of arsenic were only present in the HL, SH, LU and QV study areas (*figs. 11A, 12A, tables C1A–F*). The proportion of the primary aquifer system having high or moderate RCs of arsenic and the median concentration of arsenic were significantly greater in the HL study area than in the ES, QV, and TV study areas (*tables 10, 11A*). Of the 10 USGS-grid wells with high or moderate RCs of arsenic, 6 were in the HL study area (*figs. 11A, 12A*).

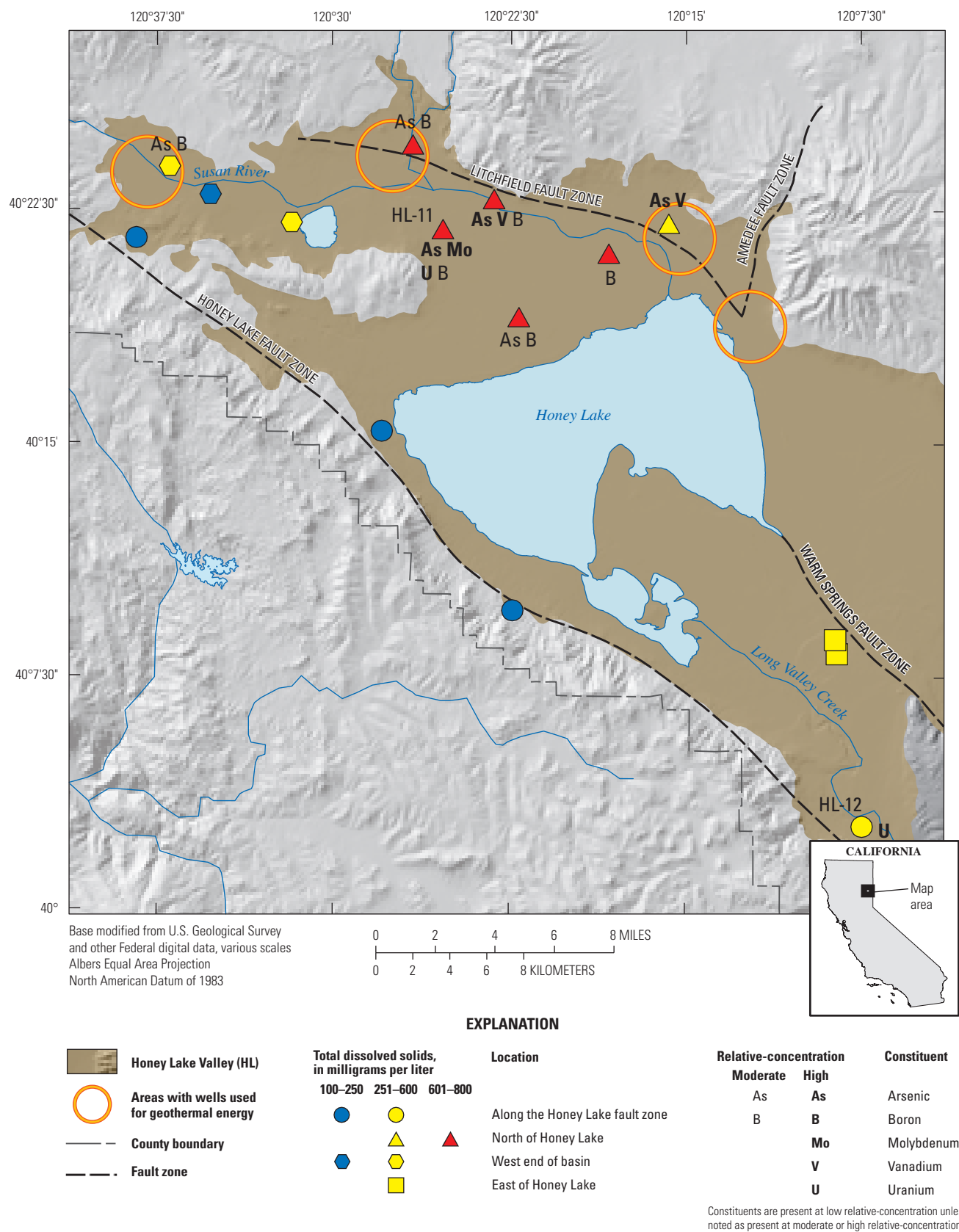
Arsenic concentrations showed significant correlations with groundwater age, aquifer lithology, geochemical conditions, and other water-quality constituents (*tables 11A, 12*). Arsenic concentrations were greater in the HL study area than in the ES, QV, and TV study areas, and were greater in wells in sedimentary deposits than in wells in volcanic rocks (*table 11A*). The positive correlation between arsenic and percentage of agricultural land use and the negative correlation between arsenic and the aridity index (*table 11B*) likely reflect that the HL study area has a greater percentage of agricultural land use and lower aridity index than many of the other study areas (*table 7A*). Mixed and pre-modern age groundwater had higher arsenic concentrations than did modern groundwater (*table 11A*). Arsenic concentrations showed significant positive correlation with pH and negative correlation with DO (*table 11B*). Unlike many of the GAMA Priority Basin Project study units, in the CAMP study unit, arsenic showed no significant relations with measures of well depth (*tables 11A, 11B*). This was expected, given the lack of significant correlations between values of DO and pH and measures of well depth (*tables 7A–C*). Arsenic concentrations showed significant positive correlations with TDS, manganese, boron, molybdenum, vanadium, and uranium (*table 12*), which likely reflects a combination of the effects of geochemical conditions on concentrations of these constituents and the geology of the HL study area. For all of these constituents, except for molybdenum and vanadium, the HL study area had the greatest proportion of the primary aquifer system with high or moderate concentrations (*tables 10, C1A–F*).

All or nearly all of the wells in the HL study area having high or moderate RCs of arsenic, boron, molybdenum, vanadium, and TDS were in the area northwest of Honey Lake (*fig. 13*). A potential source of arsenic and other constituents to groundwater in this area is hydrothermal fluids. Groundwater is used for production of geothermal energy in several areas along the north side of the basin (California Department

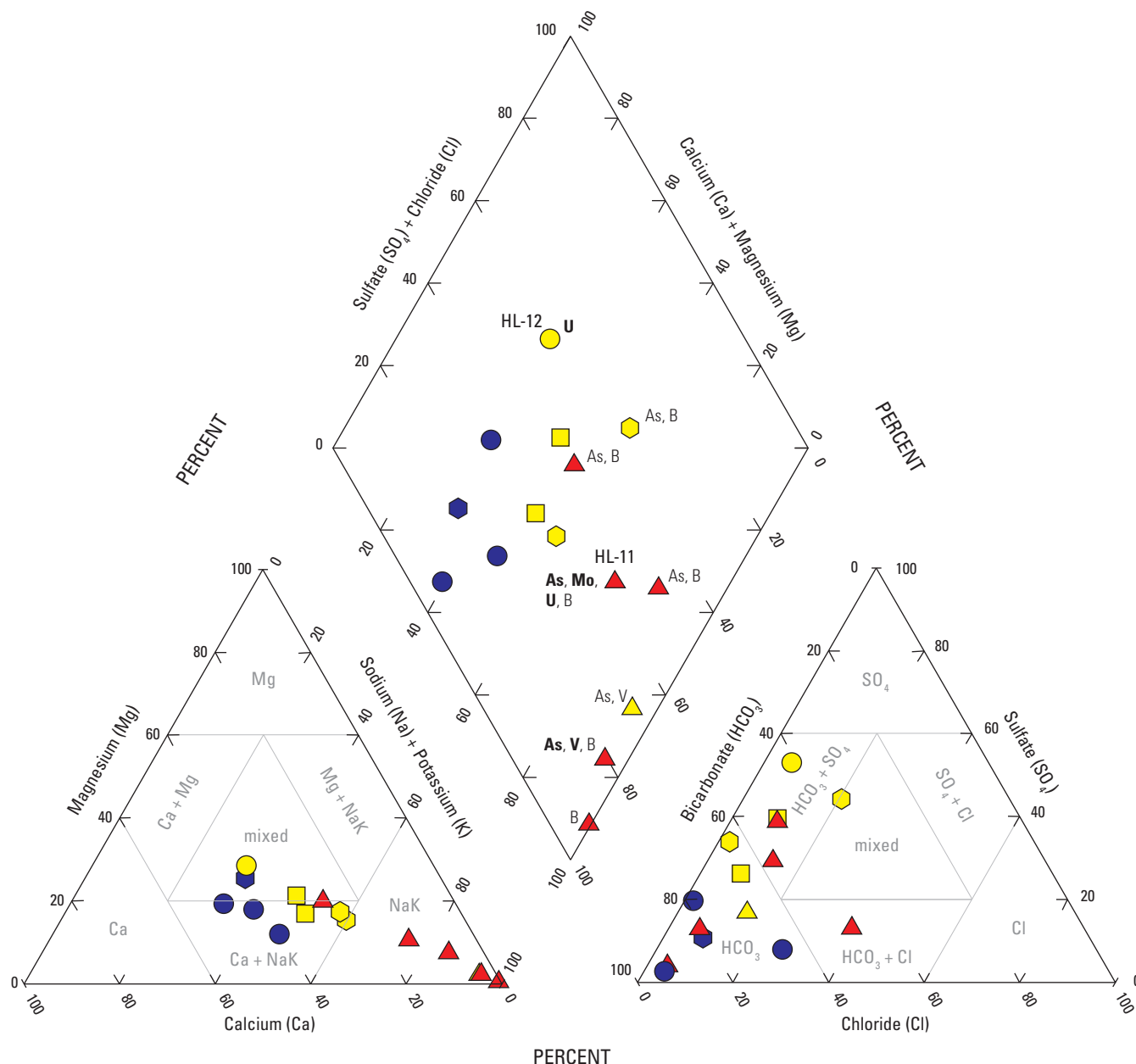
of Conservation, Division of Oil, Gas, and Geothermal Resources, 2009; *fig. 13*). The Wendel and Amedee areas near the northeast edge of Honey Lake have geothermal power plants; whereas, in the Litchfield and Susanville areas in the northwest part of the basin, thermal waters are pumped directly into distribution systems used for conductive heating. Arsenic concentrations of approximately 200 µg/L and boron concentrations of greater than 5,000 µg/L have been measured in water from hot springs in the Wendel and Amedee areas (Wormald, 1968). Geochemical modeling of the major-ion chemistry for groundwater samples from the Honey Lake basin indicated that groundwater on the northwest side of Honey Lake could consist of up to 40 percent geothermal water mixed with water recharged from precipitation (Mayo and others, 2010).

Another source of high arsenic concentrations in groundwater in the HL study area could be interaction with sediments in the Honey Lake playa. The geochemical modelling by Mayo and others (2010) indicated that groundwater on the northwest side of Honey Lake generally evolves from a mixed-cation, bicarbonate-dominated water with low TDS to a sodium-dominated, bicarbonate or bicarbonate-sulfate water with higher TDS. USGS-grid well samples from wells on the west side of the study area generally were mixed-cation-bicarbonate waters or calcium-sodium-bicarbonate waters, and had low RCs of arsenic and relatively low TDS concentrations (hexagons; *figs. 13, 14*). Samples from wells further downgradient along the Susan River towards the northwest side of Honey Lake generally were sodium-bicarbonate or sodium-bicarbonate/-sulfate waters with higher TDS and high or moderate RCs of arsenic (triangles; *figs. 13, 14*).

This evolution in major-ion composition was associated with changes in geochemical conditions that favor increased solubility of arsenic. The evolution in major-ion composition can be represented by the increasing proportion of sodium in the cations (*fig. 14*), and the proportion of sodium in the cations was positively correlated with pH (spearman's test,  $p < 0.001$ ,  $\rho = 0.95$ ) and was negatively correlated with DO concentrations (spearman's test,  $p = 0.013$ ,  $\rho = 0.63$ ). All of the HL study area samples with high or moderate RCs of arsenic had pH values between 7.7 and 8.8, and six of the seven samples also had DO less than or equal to 1.1 mg/L (Shelton and others, 2013). High pH conditions promote desorption of arsenic from aquifer sediments, and anoxic conditions promote release of arsenic from reductive dissolution of iron and manganese oxyhydroxide minerals (Smedley and Kinniburgh, 2002; Stollenwerk, 2003; Welch and others, 2006). On the basis of comparison with studies in the nearby Carson Desert basin in Nevada, sediments in the Honey Lake basin, particularly in the playa area near the lake, appear likely to contain arsenic available for desorption. Like Honey Lake basin, the Carson Desert basin is filled with sediments from volcanic rocks associated with Basin and Range extension and from granitic rocks of the Sierra Nevada as well as lacustrine deposits.



**Figure 13.** Locations of U.S. Geological Survey (USGS)-grid wells, total dissolved solids concentrations, selected trace element concentrations, and selected geologic and hydrologic features of the Honey Lake Valley study area, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



**Figure 14.** Samples from the Honey Lake Valley study area, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



Welch and others (1997) and Welch and Lico (1998) inferred that high arsenic (and uranium and molybdenum) concentrations in Carson Desert groundwater were caused by interaction between high-pH, low-DO groundwater and lacustrine and riverine sediments. Arsenic associated with iron and manganese oxyhydroxide minerals and sedimentary organic matter in these sediments can become soluble under those groundwater geochemical conditions.

Outside of the HL study area, the only other areas with high RCs of arsenic were in the SH study area (USGS-grid well SH-02) and near Goose Lake in the LU study area (CDPH well). Several wells in the LU, QV, and SH study areas had moderate RCs of arsenic (*figs. 11A, 12A*).

The five CAMP study unit study areas in which the primary aquifer system consists primarily of volcanic rocks, the ES, LU, QV, SH, and TV study areas, had high-RC aquifer-scale proportions of arsenic ranging from 0 percent to 6.7 percent (*tables C1A, C–F*). This proportion of high RCs of arsenic is similar to that observed in the volcanic aquifer systems of the Columbia River Plateau, the Snake River Plain, and the island of Oahu (Frans and others, 2012), but lower than the proportion observed in volcanic aquifer systems in the Martis Valley groundwater basin near Lake Tahoe, California, (Fram and Belitz, 2012) and the basalt aquifers of the Carson Valley in western Nevada (Lico and Seiler, 1994). Differences in the pH of groundwater among these aquifer systems in part may account for the differences in the proportion of high RCs of arsenic in groundwater. Approximately half of the samples from the Martis Valley groundwater basin had pH values greater than or equal to 8, and pH values in samples from the Carson Valley basalt aquifers were greater than 9. In contrast, less than 15 percent of samples from volcanic aquifers in the CAMP study unit (*fig. 9B; table A6*), the Columbia River Plateau, the Snake River Plain, and the island of Oahu (Toccalino and others, 2010) had pH values greater than or equal to 8. High pH conditions promote desorption of arsenic from aquifer materials (Smedley and Kinniburgh, 2002; Stollenwerk, 2003; Welch and others, 2006).

## Boron

Boron is a naturally occurring semi-metallic element with high solubility in water. Natural sources of boron to groundwater include dissolution of evaporate minerals, such as borax, ulexite, and colemanite, and boron-bearing silicate minerals, such as tourmaline, that are primarily found in igneous rocks (Hem, 1985; Klein and Hurlbut, 1993). Seawater contains approximately 4,500 µg/L of boron, thus, interactions with marine sediments, connate fluids, or seawater also can be natural sources of boron to groundwater. Boron is associated with thermal springs and volcanic activity (Hem, 1985). Boron can occur in wastewater because borax is a component of many detergents. Other anthropogenic uses of boron compounds include borosilicate glass, boric acid insecticide, chemical reagents, semi-conductors, and fertilizers. Boron is an essential nutrient for plants, but is toxic

to plants at high concentrations. The comparison benchmark used for boron in this study was the CDPH notification level (NL-CA) of 1,000 µg/L (California Department of Public Health, 2010). At concentrations greater than the HAL-US of 6,000 µg/L, boron can adversely affect fetal development (U.S. Environmental Protection Agency, 2008).

Boron was present at high RCs in 2.5 percent and at moderate RCs in 7.5 percent of the primary aquifer system (*table 8*). Boron was only present at high RCs in the TV study area and was present at moderate RCs in the HL, LU, and SH study areas (*figs. 11A, 12B; tables C1A–F*). The proportion of the primary aquifer system having high or moderate RCs of boron was significantly greater in the TV study area than in the ES and QV study areas, and the proportion having high or moderate RCs was significantly greater in the HL study area than in the ES, LU, QV, and SH study areas (*table 10*). Although the only samples with high RCs of boron were from the TV study area, all of the other samples from the TV study area had low RCs of boron; thus, the proportion of the primary aquifer system having high or moderate RCs of boron in the TV study area (15.5 percent; *table C1F*) was less than the proportion in the HL study area (36.7 percent; *table C1B*), where over a third of the samples had moderate RCs of boron.

Boron showed nearly the same pattern of significant correlations with potential explanatory factors as arsenic did; however, some of the processes controlling boron concentrations appeared to be different than those controlling arsenic concentrations. Like arsenic concentrations, boron concentrations were significantly greater in samples from the HL study area than in samples from the ES, QV, and TV study areas; greater in pre-modern and mixed-age groundwater compared to modern groundwater; and greater in sites with sedimentary aquifer lithology compared to sites with volcanic aquifer lithology (*table 11A*). Boron and arsenic concentrations were positively correlated, and as with arsenic concentrations, boron concentrations showed positive correlations with the percentage of agricultural land use, pH, TDS, manganese, molybdenum, and uranium and showed negative correlations with the aridity index and DO (*tables 11B, 12*). As discussed in the section on arsenic, most of these correlations between boron and potential explanatory factors reflect that groundwater in the HL study area commonly has elevated boron concentrations. The source of the boron could be mixing with geothermal fluids (see ‘Arsenic’ section).

The only samples with high RCs of boron in the CAMP study unit were in the TV study area, north of the SH study area (TV-01 and TV-15; *fig. 12B*; Shelton and others, 2013). These two samples did not have high or moderate RCs of arsenic, indicating different mechanisms were responsible for the high boron concentrations in these samples than the mechanisms responsible for elevated boron concentrations in the HL study area. In addition to having a high RC of boron, the sample from the USGS-grid well TV-01 had high RCs for TDS and molybdenum, and it was the only USGS-grid well sample having a major-ion composition dominated by sodium and chloride (*fig. B1*). Saline water with high boron, sodium,



and chloride concentrations emanates from several springs in the Tertiary volcanic rocks north of the Shasta Valley (Mack, 1960), and mixing with these spring waters could account for quality of groundwater from TV-01. Mack (1960) suggested that these saline waters could be derived from connate waters from Mesozoic and Paleozoic marine sedimentary rocks underlying the volcanic rocks. USGS-grid well TV-15 had screened intervals in both the volcanic rocks and the underlying metamorphic rocks ([table A1](#)).

## Molybdenum

Molybdenum is a metallic trace element used in high-strength steel alloys and other industrial products. High concentrations of molybdenum are found in organic-rich sediments and sedimentary rocks deposited in sulfide-reducing environments (Crusius and others, 1996). Most molybdenum ore deposits are associated with porphyry granite or quartz monzonite plutons, and the primary ore mineral is molybdenite ( $\text{MoS}_2$ ) (for example, Misra, 2000). Potential anthropogenic sources include the manufacture and use of molybdenum steel alloys, dry lubricants, and other industrial products, and surface application of biosolids (Evans and Barabash, 2010). Molybdenum has a HAL-US of 40  $\mu\text{g/L}$  in drinking water and is included on the USEPA's Contaminant Candidate List 3 (U.S. Environmental Protection Agency, 2009b). High levels of molybdenum in animals (including humans) can interfere with uptake of copper. Molybdenum is an essential trace nutrient for biological nitrogen fixation and can even be a limiting factor for biological activity in molybdenum-poor environments (Goldman, 1961; Evans and Barabash, 2010).

Molybdenum was present at high RCs in 2.1 percent of the primary aquifer system of the CAMP study unit, and was not present at moderate RCs ([table 8](#)). High RCs of molybdenum were only present in the HL and TV study areas ([figs. 11A, 12C; tables C1A–F](#)). There were no significant differences in aquifer-scale proportions for molybdenum among the study areas ([table 10](#)). Molybdenum concentrations showed a similar pattern of correlations with explanatory factors as did boron concentrations ([tables 11A, B](#)), and, as with boron, these correlations largely reflected the greater molybdenum concentrations in samples from the HL study area ([table 11A](#)).

## Vanadium

Vanadium is a metallic trace element used in high-strength steel alloys. Vanadium concentrations in igneous rocks generally are greater in mafic rocks (basalts and gabbros) than in ultramafic or felsic (granites and dacite/rhyolite) rocks (Fischer and Ohl, 1970; Prytulak and others, 2013) because titanium-rich magnetite, which is most abundant in mafic rocks, has a higher mineral-liquid partition coefficient for vanadium than does other oxide or silicate minerals (for example, Righter and others, 2006). Because of this, sediments derived from mafic igneous rocks (or their metamorphosed equivalents) should have greater

amounts of vanadium than sediments derived from other rock types. Organic-rich sedimentary rocks formed in anoxic environments and phosphorites can also have high vanadium concentrations (Evans and Barabash, 2010). Anthropogenic sources include combustion of fossil fuels and emissions from smelting, foundry, and other iron metallurgy industrial processes (Evans and Barabash, 2010). The USEPA included vanadium as part of the first, second, and third Contaminant Candidate Lists (U.S. Environmental Protection Agency, 1998, 2005a, 2009b), and vanadium has been selected as a potential candidate for regulatory determination from the third list (U.S. Environmental Protection Agency, 2011). The CDPH defined a Notification Level (NL-CA) for vanadium of 50  $\mu\text{g/L}$  based on potential adverse effects on fetal and neonatal development (California Office of Environmental Health Hazard Assessment, 2000).

Vanadium was present at high RCs in 1.8 percent of the primary aquifer system of the CAMP study unit, and at moderate RCs in 11.3 percent ([table 8](#)). These high-RC and moderate-RC proportions were approximately double the percentages reported by Wright and Belitz (2010) for the Cascade Mountains and Modoc Plateau hydrogeologic province in their assessment of the distribution of vanadium in groundwater in California. Wright and Belitz (2010) used statewide data from the CDPH database and the USGS National Water Information System (NWIS) database (<http://waterdata.usgs.gov/nwis>), including data collected by the GAMA Priority Basin Project through 2008, and calculated raw occurrence frequencies of wells with high or moderate RCs of vanadium in the State's 10 hydrogeologic provinces. Their results for the Cascade Range and Modoc Plateau hydrogeologic province were based largely on wells in a few basins in the LU study area. The water-quality data collected for this study in 2010 expanded the availability of data for vanadium concentrations to all six study areas, and the spatial weighting used to calculate high-RC and moderate-RC aquifer-scale proportions eliminated the influence of clustered wells on the resulting proportions. High RCs of vanadium occurred in the HL and SH study areas, and moderate RCs occurred in all study areas, except for the TV study area ([figs. 11A, 12D; tables C1A–F](#)). There were no significant differences in aquifer-scale proportions for vanadium among the study areas ([table 10](#)).

The relations between vanadium and potential explanatory factors were quite different than the relations between arsenic, boron, molybdenum, and uranium and potential explanatory factors. Vanadium was the only trace element or radioactive constituent for which samples from the HL study area did not have significantly greater concentrations than samples from other study areas ([table 11A](#)). Samples from the ES study area had significantly greater concentrations of vanadium than did samples from the TV study area ([table 11A](#)). Vanadium was the only trace element or radioactive constituent that had significantly greater concentrations in oxic conditions ([table 11A](#)); the others all had a negative correlation with DO ([table 11B](#)).

As expected from the association between greater concentrations of vanadium and oxic conditions, vanadium concentrations showed significant negative correlations with iron and manganese concentrations (*table 12*). The negative correlation between site elevation and vanadium concentrations (*table 11B*) reflects the significantly lower elevations in the ES study area compared to the HL, LU, QV, and TV study areas (*table 7A*).

The relations between vanadium and geochemical conditions were weaker than expected. Thermodynamic data indicate that vanadium should be most soluble in alkaline, oxic conditions (Wanty and Goldhaber, 1992), and statistical analysis of data for 1,283 groundwater samples distributed across California showed that vanadium concentrations were indeed higher in oxic groundwater with pH greater than or equal to 8 than in anoxic groundwater with any pH or oxic groundwater with pH less than 8 (Wright and Belitz, 2010). In the CAMP study unit, oxic groundwater with pH greater than or equal to 8 had significantly greater vanadium concentrations than anoxic groundwater (Wilcoxon rank-sum test,  $p=0.008$ ), but did not have significantly different vanadium concentrations than oxic groundwater with pH less than 8 (Wilcoxon rank-sum test,  $p=0.071$ ). Wright and Belitz (2010) also showed that groundwater with high or moderate RCs of vanadium was most frequently detected in areas associated with sediments derived from mafic and intermediate rocks. Nearly all of the groundwater samples from the CAMP study unit were from aquifers largely composed of mafic volcanic rocks or sediments derived from mafic volcanic rocks. The lack of strong correlation between vanadium and geochemical conditions in the CAMP study unit—where the source rocks are expected to have vanadium—indicates the controls on vanadium distribution are complex.

## Nutrients

Nutrients, including nitrate, nitrite, and ammonia, both have natural and anthropogenic sources to groundwater (Dubrovsky and others, 2010). Natural sources include atmospheric deposition, animal waste, and dissolution of organic material in soils. Anthropogenic sources include fertilizer application, livestock and human waste, sewage and septic effluents, and combustion of fossil fuels (emits nitrogen oxides to the atmosphere). Nitrate and nitrite have MCL-US benchmarks (10 and 1 mg/L, as nitrogen, respectively), and high levels of either in drinking water can cause “blue baby” syndrome (U.S. Environmental Protection Agency, 2009a). Ammonia has a HAL-US benchmark of 24.7 mg/L, as nitrogen (*table 4A*). Nitrate is the most oxidized form of nitrogen and, thus, is the most common form in oxic groundwater systems, such as those in most of the CAMP study unit. 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 others, 2002; Dubrovsky and others, 2010).

Nutrients, as a class, were present at high RCs in 0.9 percent of the primary aquifer system in the CAMP study unit and at moderate RCs in 2.5 percent (*table 9A*). Nitrate was found at high RCs in the HL study area and at moderate RCs in the SH study area (*fig. 11B*; *tables C1A–F*). Ammonia was found at moderate RCs in the LU study area (*fig. 11B*; *tables C1A–F*).

## Uranium and Radioactive Constituents

Most of the radioactivity in groundwater comes from decay of naturally occurring uranium and thorium in the rocks or sediments that compose 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 (for example, Hem, 1985). This study included data for the individual constituents uranium and radon-222 and for gross alpha and gross beta particle activities, which are measures of the activities of all radioactive elements in the water sample that decay by alpha or beta particle emission, respectively. Uranium was compared to the MCL-US of 30  $\mu\text{g/L}$  rather than to the MCL-CA of 20 picocuries per liter (pCi/L), and gross alpha particle activities were not adjusted for uranium activity (see *appendix D*).

Radioactive constituents were present at high RCs 2.9 percent of the primary aquifer system, and at moderate RCs in 0.6 percent (*table 9A*). The proportion of the primary aquifer system having high or moderate RCs of at least one radioactive constituent was significantly greater in the HL study area than in the other study areas (*table 10*). Uranium and gross alpha particle activity were present at high RCs in the same 1.8 percent of the primary aquifer system, and radon-222 was present at high RCs in 0.9 percent of the system (*table 8*). All of the detections of high RCs of radioactive constituents occurred in the HL study area (*figs. 11B, 12E*).

Sources of uranium to groundwater include dissolution of uranium-bearing minerals, such as uraninite ( $\text{UO}_2$ ), zircon, and titanite, and desorption of uranium from mineral surfaces in the presence of bicarbonate (Hem, 1985; Jurgens and others, 2010). Chronic exposure to uranium in drinking water at concentrations greater than the MCL-US (30  $\mu\text{g/L}$ ) or activities greater than the MCL-CA (20 pCi/L) can result in toxic effects to the kidneys or increased cancer risks (U.S. Environmental Protection Agency, 2000, 2009a).

The pattern of significant relations between uranium and potential explanatory factors largely reflected that samples from the HL study area had significantly greater concentrations of uranium than did samples from the ES, LU, QV, and TV study areas (*table 11A*). Uranium concentrations showed significant positive correlations with percentage of agricultural land use, pH, and concentrations of arsenic, boron,

molybdenum, vanadium, and TDS and negative correlations with the aridity index and DO concentrations (*tables 11B, 12*).

Despite the significant correlations between uranium and potential explanatory factors, the primary feature that the two USGS-grid wells having samples with high uranium concentrations (HL-11 and HL-12) shared was that both were in the HL study area. The groundwater from HL-12 was oxic (DO=4.4 mg/L), had neutral pH (7.3), did not have high or moderate RCs of other trace elements, and had a mixed cation composition. HL-12 was near the southeastern margin of the study area in the Long Valley Creek drainage (*fig. 13*). The primary rock type in the Long Valley Creek drainage is Mesozoic granite of the northern Sierra Nevada (*fig. 2*), indicating that the aquifer sediment in the vicinity of HL-12 likely contains a high proportion of sediment derived from granite. Granitic rocks elsewhere in the Sierra Nevada are known to yield sediment containing uranium (Wollenberg and Smith, 1968; Thomas and others, 1993; Jurgens and others, 2010).

HL-11 was in the central part of the basin, northwest of Honey Lake (*fig. 13*). The groundwater from HL-11 was anoxic (DO less than 0.2 mg/L), had higher pH (7.8) compared to other samples, had high RCs of arsenic and molybdenum and a moderate RC of boron, and had a cation composition dominated by sodium (*fig. 14*). These chemical characteristics were similar to those of groundwater in the Carson Desert basin in Nevada, where high concentrations of arsenic, uranium, boron, and TDS (and molybdenum) were attributed to a combination of evaporative concentration and oxidation-reduction reactions involving sedimentary organic matter and iron-oxide coatings (Lico and Seiler, 1994; Welch and Lico, 1998). The Honey Lake and Carson Desert basins are both closed basins containing alluvial and lacustrine sediments derived from granitic and mafic volcanic rocks.

## Constituents with Secondary Maximum Contaminant Level (SMCL) Benchmarks

The class of constituents with SMCL benchmarks includes salinity indicators (TDS, specific conductance, chloride, and sulfate) and several trace metals (iron, manganese, and zinc) that are commonly present in groundwater. These constituents affect the aesthetic properties of water, such as taste, color, and odor, or may create technical problems, such as scaling and staining of water delivery systems and fixtures. The SMCL benchmarks are based on these aesthetic and technical concerns and are not health-based benchmarks. Constituents with SMCL benchmarks were present at high RCs in 15.1 percent of the primary aquifer system in the CAMP study unit and at moderate RCs in 4.9 percent (*table 9B*). The constituents with SMCL benchmarks most commonly present at high or moderate RCs were the salinity indicator TDS and the trace metals manganese and iron (*table 8; fig. 11C*).

## Total Dissolved Solids (TDS)

The salinity indicators with SMCL benchmarks found at high or moderate RCs in the CAMP study unit were chloride and TDS. All of the samples with high or moderate RCs of chloride also had high or moderate RCs of TDS. Natural sources of TDS to groundwater include weathering and dissolution of minerals in soils, sediments, and rocks; mixing with saline or brackish waters from the ocean, estuaries (not a factor in the CAMP study unit), or saline lakes; interactions with marine or lacustrine sediments; mixing with hydrothermal solutions; and concentration by evapotranspiration of shallow groundwater (Hem, 1985). Anthropogenic sources of TDS to groundwater include recharge of water used for irrigation, wastewater discharge, and evaporation (Hem, 1985). TDS was present at high RCs in 1.2 percent of the CAMP study unit primary aquifer system and at moderate RCs in 10.1 percent (*table 8*). The proportion of the primary aquifer system having high or moderate RCs of TDS was significantly greater in the HL study area than in the ES, LU, QV, and TV study areas (*tables 10, C1A–F*).

TDS concentrations were significantly greater in the HL study area than in the ES, QV, and TV study areas (*table 11A*), although the only samples from wells having high RCs for TDS were from the TV (TV-01) and LU (a CDPH well east of Goose Lake near the Oregon border) study areas (*fig. 12F*). The other significant correlations between TDS and the potential explanatory factors largely reflected the greater prevalence of moderate-RC concentrations in the HL study area. TDS concentrations were greater in groundwater from sedimentary aquifers than in groundwater from volcanic aquifers, in pre-modern groundwater than in modern groundwater, in anoxic groundwater than in oxic groundwater, and in samples from wells than in samples from springs (*table 11A*). The TDS concentrations showed positive correlations with the percentage of agricultural land use, pH, and arsenic, boron, molybdenum, uranium, and manganese concentrations, and negative correlations with the percentage of natural land use, aridity index, elevation, and dissolved oxygen concentration (*tables 11B, 12*).

Most of the wells with moderate RCs of TDS in the HL study area were clustered just north of Honey Lake (*fig. 13*). As discussed in the “Arsenic” section, this region has areas that are mapped as low-temperature geothermal areas. The wells near the center of the basin also could tap shallow groundwater from the Honey Lake playa, which has elevated TDS due to evaporative concentration. Honey Lake shallow playa groundwater has a maximum TDS concentration of around 1,100 mg/L, much lower than the maximum TDS of over 25,000 mg/L in the Fish Lake playa on the Nevada side of the Honey Lake basin (Mayo and others, 2010). Mayo and others (2010) suggest that the groundwater divide between the Honey Lake and Fish Springs parts of the basin resulted from relatively recent deformation related to isostatic rebound after draining of glacial Lake Lahontan, and that previously, the only terminal sink in the basin was the Fish Springs playa.



As discussed in the “Boron” section, high RCs of TDS in groundwater in the TV study area appeared to be associated with saline thermal spring waters.

## Manganese and Iron

The trace metals with SMCL benchmarks found at high or moderate RCs in the CAMP study unit were iron and manganese. Natural sources of iron and manganese to groundwater include weathering and dissolution of minerals in soils, sediments, and rocks. Iron and manganese oxyhydroxide minerals commonly coat mineral and sediment grains. In addition, iron-bearing silicate, sulfide, and (or) oxide minerals are in most rocks and sediments, and manganese commonly substitutes for iron in silicate minerals. The solubilities of manganese and iron are strongly dependent on oxidation-reduction conditions; the more reduced species are much more soluble (Hem, 1985).

Manganese and iron were present at high RCs in 10.4 percent and 4.0 percent, respectively, of the primary aquifer system in the CAMP study unit and at moderate RCs in 1.2 percent each ([table 8](#)). The proportion of the primary aquifer system with high RCs of manganese was significantly greater in the HL study area than in the ES or QV study areas ([tables 10, C1A–F](#)), and there were no significant differences among the study areas in the proportion with high RCs of iron ([tables 10, C1A–F](#)). High RCs of manganese were present in all study areas ([fig. 12G, tables C1A–F](#)). High RCs of iron were present in all study areas except for the QV study area ([fig. 12H, tables C1A–F](#)).

The spatially weighted proportions of high RCs of manganese in the ES and TV study areas and of iron in the SH and TV study areas were between 2.2 and 5.6 percent, and the grid-based proportions of high RCs were 0 percent because high RCs were only observed in CDPH wells. This difference between the spatially weighted and grid-based results was not unexpected. If a constituent is present at high RCs in less than about 5 percent of the primary aquifer system, then there is less than a 50 probability that 1 well in a 15-well grid network will have a high RC of the constituent (Belitz and others, 2010).

Manganese and iron showed different patterns of correlations with potential explanatory factors and water-quality constituents. Manganese concentrations showed significant positive correlations with percentages of agricultural and urban land use, pH, and concentrations of arsenic, boron, molybdenum, iron, and TDS, and showed significant negative correlations with DO and vanadium concentration ([table 11B, 12](#)). Most of these correlations reflect that of the nine USGS-grid samples that had manganese-reducing conditions, four were from the HL study area ([table A6](#)). In contrast, iron concentrations only showed correlations with vanadium (negative) and manganese (positive) ([table 12](#)). Of the 90 USGS-grid well samples, 6 samples had iron-reducing conditions ([table A6](#)). Neither iron nor manganese showed significant correlations with

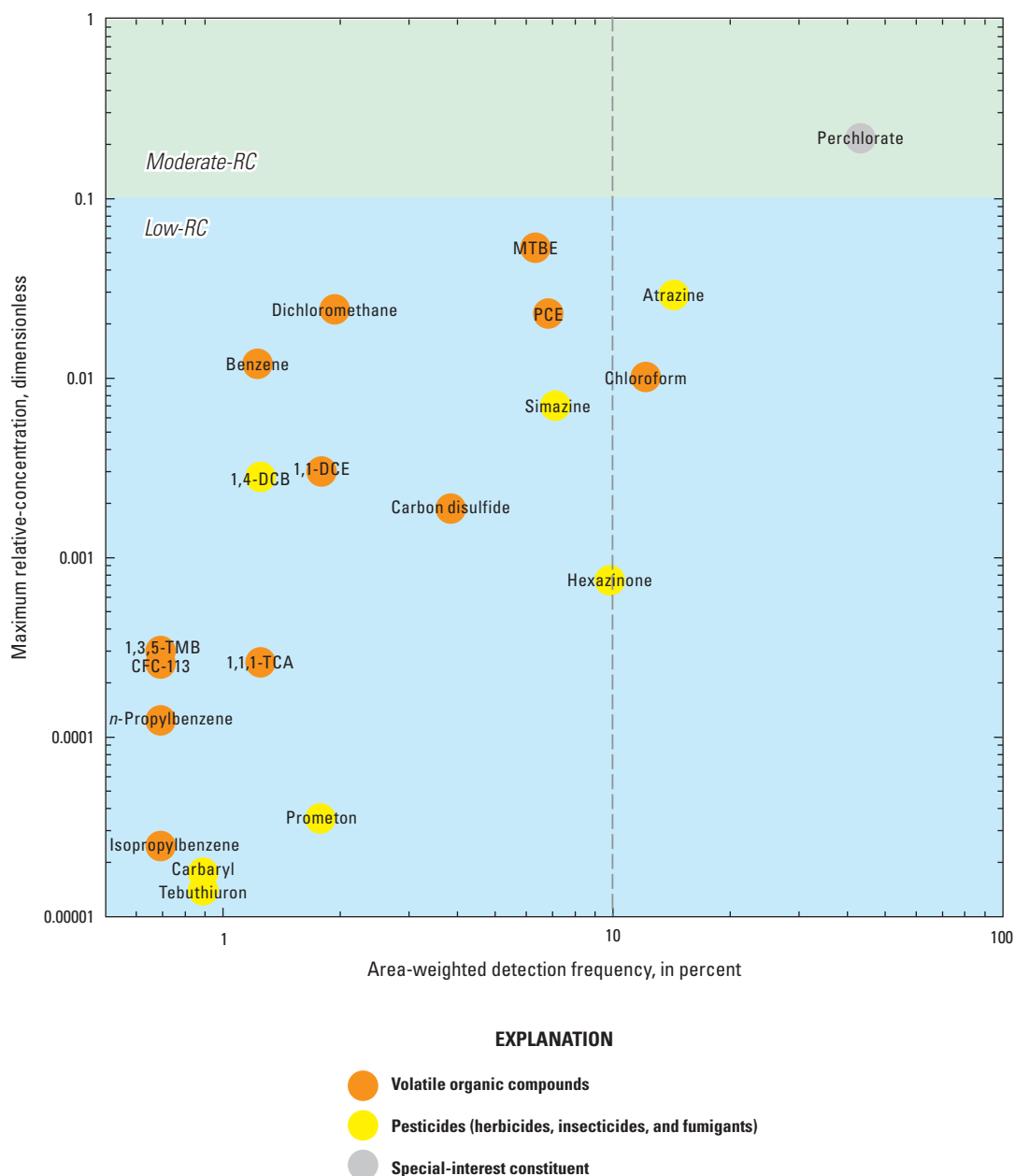
study area, groundwater age, or measures of well depth ([tables 11A, 11B](#)).

## Organic and Special-Interest Constituents

The organic constituents included two constituent classes: volatile organic compounds (VOCs), and pesticides ([table 3](#)). VOCs are present in paints, solvents, fuels, fuel additives, refrigerants, fumigants, and disinfected water and are characterized by their tendency to volatilize (for example, Zogorski and others, 2006). Typically, VOCs persist longer in groundwater than in surface water because groundwater is more isolated from the atmosphere. Pesticides include herbicides, 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). The only special-interest constituent analyzed for the CAMP study unit was perchlorate. At the start of the GAMA Priority Basin Project in 2003, perchlorate was considered a constituent of special interest to the CDPH and SWRCB because it had recently been detected in groundwater at concentrations that may be relevant to human health concerns (Belitz and others, 2003). The CDPH established an MCL-CA for perchlorate in 2007, and although perchlorate is an inorganic constituent, the classification of special-interest constituent is retained in this report for consistency with other GAMA Priority Basin Project reports.

The GAMA Priority Basin Project included analyses of a large number of organic constituents, many of which are not currently (as of 2014) subject to regulation in California drinking water. USGS-GAMA analytical methods for organic constituents had lower reporting limits than required for sampling for compliance with CDPH regulations ([table 5](#)). In the CAMP study unit, the majority of organic constituents detected are subject to regulation in California drinking water. Of the 85 VOCs analyzed, 18 were detected at least once, and of these, 13 have U.S. Environmental Protection Agency maximum contaminant level (MCL-US), California Department of Public Health maximum contaminant level (MCL-CA), or California Department of Public Health notification level (NL-CA) benchmarks ([table 5](#)). Of the 63 pesticides and pesticide degradates analyzed, 9 were detected at least once, and of these, 5 have health-based benchmarks ([table 5](#)). In all, of the 70 organic constituents analyzed that had no health-based regulatory or non-regulatory benchmarks, 8 were detected in groundwater ([table 5](#); Shelton and others, 2013).

[Figure 15](#) summarizes the maximum RCs for individual organic constituents and perchlorate detected in samples from USGS-grid wells and the area-weighted detection frequencies for these constituents in the CAMP study unit as a whole. No organic constituents were detected at high or moderate RCs in the samples from USGS-grid wells, and none were reported at high or moderate RCs in the CDPH database for samples collected between September 18, 2007, and September 16,



**Figure 15.** Detection frequency and maximum relative-concentration (RC) of organic and special-interest constituents detected in U.S. Geological Survey (USGS)-grid wells in the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. (MTBE, methyl *tert*-butyl ether; PCE, tetrachloroethene; 1,1-DCE, 1,1-dichloroethene; 1,4-DCB, 1,4-dichlorobenzene; 1,1,1-TCA, 1,1,1-trichloroethane; 1,3,5-TMB, 1,3,5-trimethylbenzene; CFC-113, 1,1,2-trichloro-1,2,2-trifluoroethane)

2010. The trihalomethane chloroform and the herbicide atrazine were the only individual organic constituents with area-weighted detection frequencies greater than 10 percent (fig. 15). Perchlorate was detected at moderate RCs and had an area-weighted detection frequency of 43 percent (fig. 15). Moran and others (2005) sampled 23 wells in the area of the CAMP study unit and had a 39 percent detection frequency for methyl *tert*-butyl ether (MTBE). However, the reporting

limits used by Moran and others (2005) were lower than those used by USGS-GAMA. If the MTBE results from Moran and others (2005) were screened at the reporting limit used by USGS-GAMA, then the MTBE detection frequency would be 4.3 percent, which is similar to the area-weighted MTBE detection frequency in the CAMP study unit in this study (fig. 15).



Organic constituents with benchmarks were not present at high or moderate RCs in the CAMP study unit primary aquifer system, but were present at low RCs in about 41 percent of the system (*table 13*). The VOCs and pesticides each were detected at low RCs in approximately one-quarter of the primary aquifer system (*table 13*). Relations between water

quality and potential explanatory factors were evaluated for the two organic constituent classes (herbicides and trihalomethanes) having an individual constituent with a detection frequency greater than 10 percent in the study unit as a whole (*tables 11A, 11B*).

**Table 13.** Summary of aquifer-scale proportions calculated using the spatially weighted method for organic constituent classes with health-based benchmarks and perchlorate for study areas, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Study area abbreviations:** ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Study unit:** Aquifer-scale proportions are area weighted by the percent (%) of the study unit covered by each study area: ES=10.4%, HL=13.4%, LU=18.4%, QV=25.7%, SH=13.3%, TV=18.7%. **Relative-concentration categories:** Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. High; concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.1 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.1 of benchmark. **Other abbreviations:** VOC, volatile organic compound]

Constituent classes and study areas	Number of wells	Aquifer-scale proportions (percent)			
		Not detected	Low-RC	Moderate-RC	High-RC
Pesticides (herbicides) <sup>1</sup>					
ES	15	100	0	0	0
HL	15	86.7	13.3	0	0
LU	15	86.7	13.3	0	0
QV	15	80.0	20.0	0	0
SH	15	33.3	66.7	0	0
TV	15	73.3	26.7	0	0
CAMP study unit	90	76.7	23.3	0	0
Trihalomethane (THM) <sup>2</sup>					
ES	23	53.3	46.7	0	0
HL	24	86.7	13.3	0	0
LU	21	93.3	6.7	0	0
QV	26	100	0	0	0
SH	24	86.7	13.3	0	0
TV	20	86.7	13.3	0	0
CAMP study unit	138	87.9	12.1	0	0
Any VOC <sup>3</sup>					
ES	23	46.7	53.3	0	0
HL	24	60.0	40.0	0	0
LU	21	86.7	13.3	0	0
QV	26	86.7	13.3	0	0
SH	24	73.3	26.7	0	0
TV	20	80.0	20.0	0	0
CAMP study unit	138	75.9	24.1	0	0
Any organic constituent with a health-based benchmark <sup>4</sup>					
ES	23	46.7	53.3	0	0
HL	24	60.0	40.0	0	0
LU	21	73.3	26.7	0	0
QV	26	73.3	26.7	0	0
SH	24	26.7	73.3	0	0
TV	20	53.3	46.7	0	0
CAMP study unit	138	58.8	41.2	0	0

**Table 13.** Summary of aquifer-scale proportions calculated using the spatially weighted method for organic constituent classes with health-based benchmarks and perchlorate for study areas, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[**Study area abbreviations:** ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Study unit:** Aquifer-scale proportions are area weighted by the percent (%) of the study unit covered by each study area: ES=10.4%, HL=13.4%, LU=18.4%, QV=25.7%, SH=13.3%, TV=18.7%. **Relative-concentration categories:** Relative-concentration (RC) is defined as the concentration measured in the sample divided by the concentration of the selected benchmark. High; concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.1 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.1 of benchmark. **Other abbreviations:** VOC, volatile organic compound]

Constituent classes and study areas	Number of wells	Aquifer-scale proportions (percent)			
		Not detected	Low-RC	Moderate-RC	High-RC
Perchlorate <sup>5</sup>					
ES	29	9.1	90.9	0	0
HL	35	40.0	53.3	6.7	0
LU	28	53.3	40.0	6.7	0
QV	45	78.6	21.4	0	0
SH	38	53.3	46.7	0	0
TV	24	71.4	28.6	0	0
CAMP study unit	199	56.7	41.0	2.2	0

<sup>1</sup>Herbicides include atrazine, hexazinone, prometon, simazine, and tebuthiuron. The insecticide carbaryl was detected in one sample that also had detections of herbicides; therefore, the aquifer-scale proportions for herbicides are the same as those for pesticides.

<sup>2</sup>Chloroform was the only trihalomethane detected.

<sup>3</sup>Any VOC includes chloroform; the solvents dichloromethane, tetrachloroethene (PCE), 1,1,1-trichloroethane; the organic synthesis compound 1,1-dichloroethene; the fumigant 1,4-dichlorobenzene; the gasoline oxygenate methyl *tert*-butyl ether (MTBE); the gasoline hydrocarbons 1,3,5-trimethylbenzene, benzene, isopropylbenzene, *n*-propylbenzene; and the refrigerant 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113).

<sup>4</sup>Any organic constituent includes pesticides and VOCs.

<sup>5</sup>Perchlorate was analyzed in 84 U.S. Geological Survey-grid samples: 11 in ES; 15 each in HL, LU, and SH; and 14 each in QV and TV.

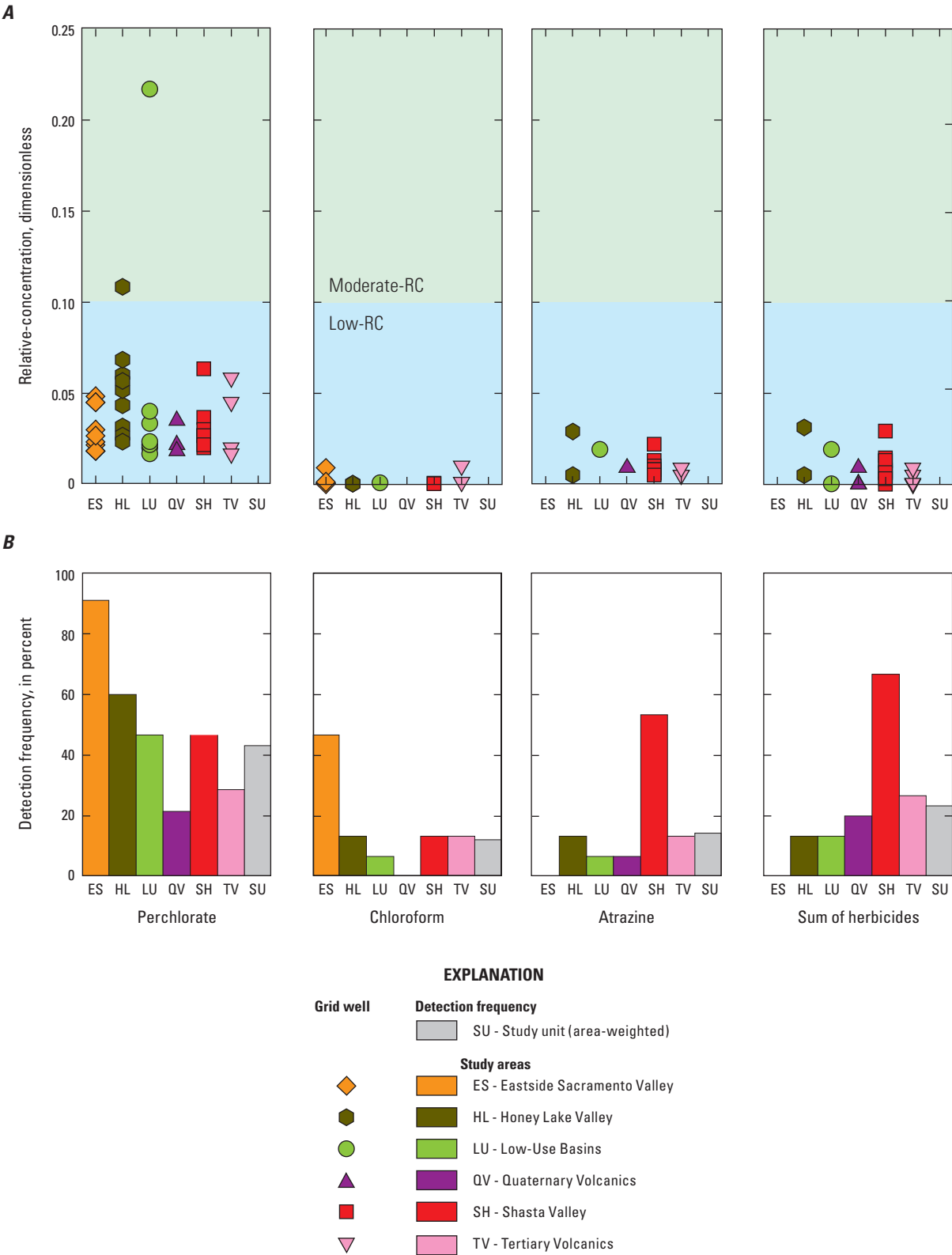
## Herbicides

All but one of the pesticides with human health-based benchmarks detected in the CAMP study unit were herbicides ([table 5](#)). The CDPH database contained no data for pesticides for sites in the CAMP study unit. The detection frequency of herbicides ranged from 0 in the ES study area to 67 percent in the SH study area ([figs. 16, 17A; table 13](#)). All concentrations were very low; the maximum RC for any individual herbicide ([fig. 15](#)) or for the sum of the RCs of all herbicides present in a sample was 0.03 ([fig. 16](#)).

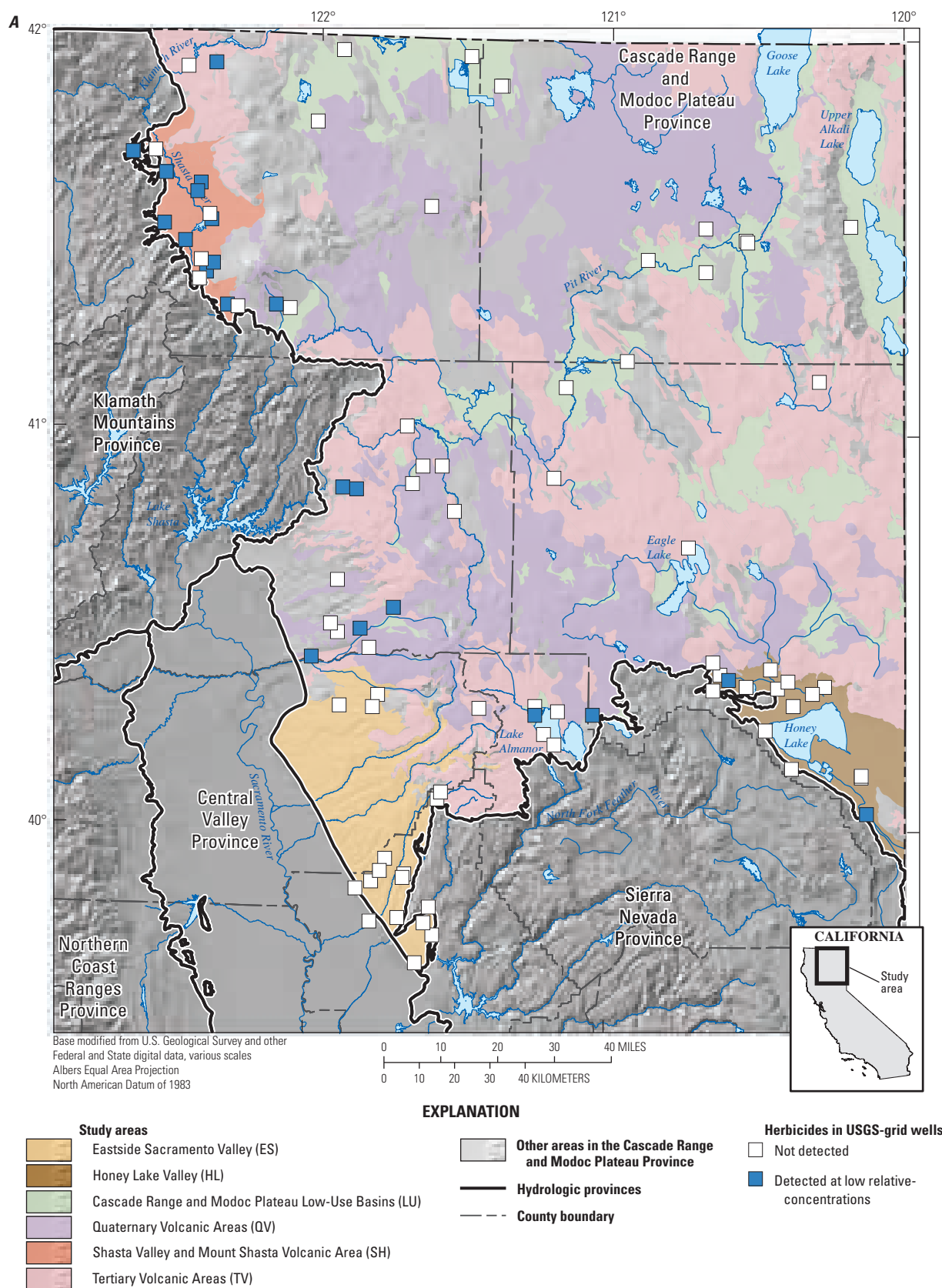
Atrazine was the most frequently detected herbicide, with an area-weighted detection frequency of 14 percent ([fig. 15](#)). It was detected in all of the study areas except the ES study area, and the maximum study area detection frequency was 53 percent in the SH study area ([fig. 16](#)). All of the USGS-grid well samples containing atrazine also contained the degradation product deethylatrazine, and deethylatrazine was detected in about twice the number of USGS-grid well samples than was atrazine (Shelton and others, 2013). The concentrations of deethylatrazine generally were higher than the concentrations of atrazine. Neither the USEPA nor CDPH have established a benchmark for deethylatrazine (as of 2014); thus, a RC cannot be calculated, thereby preventing

it from being included in the *status assessment*. Atrazine and deethylatrazine are the most common pesticides or pesticide degradates detected in the groundwater sampled by the National Water-Quality Assessment (NAWQA) Program (Gilliom and others, 2006), and their co-occurrence could reflect the relatively high degree of persistence of atrazine in groundwater environments (Kolpin and others, 1998). Hexazinone had an area-weighted detection frequency of 9.8 percent ([fig. 15](#)) and was detected in the LU, QV, and SH study areas. Simazine was detected in the HL and SH study areas, and prometon and tebuthiuron were detected only in the SH study area.

Herbicide concentrations were significantly correlated with study area and groundwater age. The total concentration of herbicides was significantly greater in the SH study area than in any of the other study areas, and significantly greater in modern and mixed age groundwater than in pre-modern groundwater ([table 11A](#)). The negative correlation between pH and herbicide concentration ([table 11B](#)) likely reflects the lower pH values in samples from the SH study area ([table A6](#)), and the greater herbicide concentrations in oxic compared to anoxic groundwater ([table 11A](#)) likely reflects the significant association between oxic groundwater and the SH study area ([table 7C](#)).



**Figure 16.** Area-weighted detection frequency and graphs of relative-concentrations (RC) of selected organic and special-interest constituents detected in U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



**Figure 17.** Relative-concentrations (RC) in groundwater samples from U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project for *A*, herbicides; *B*, trihalomethanes; and *C*, perchlorate. (RL, reporting limit)

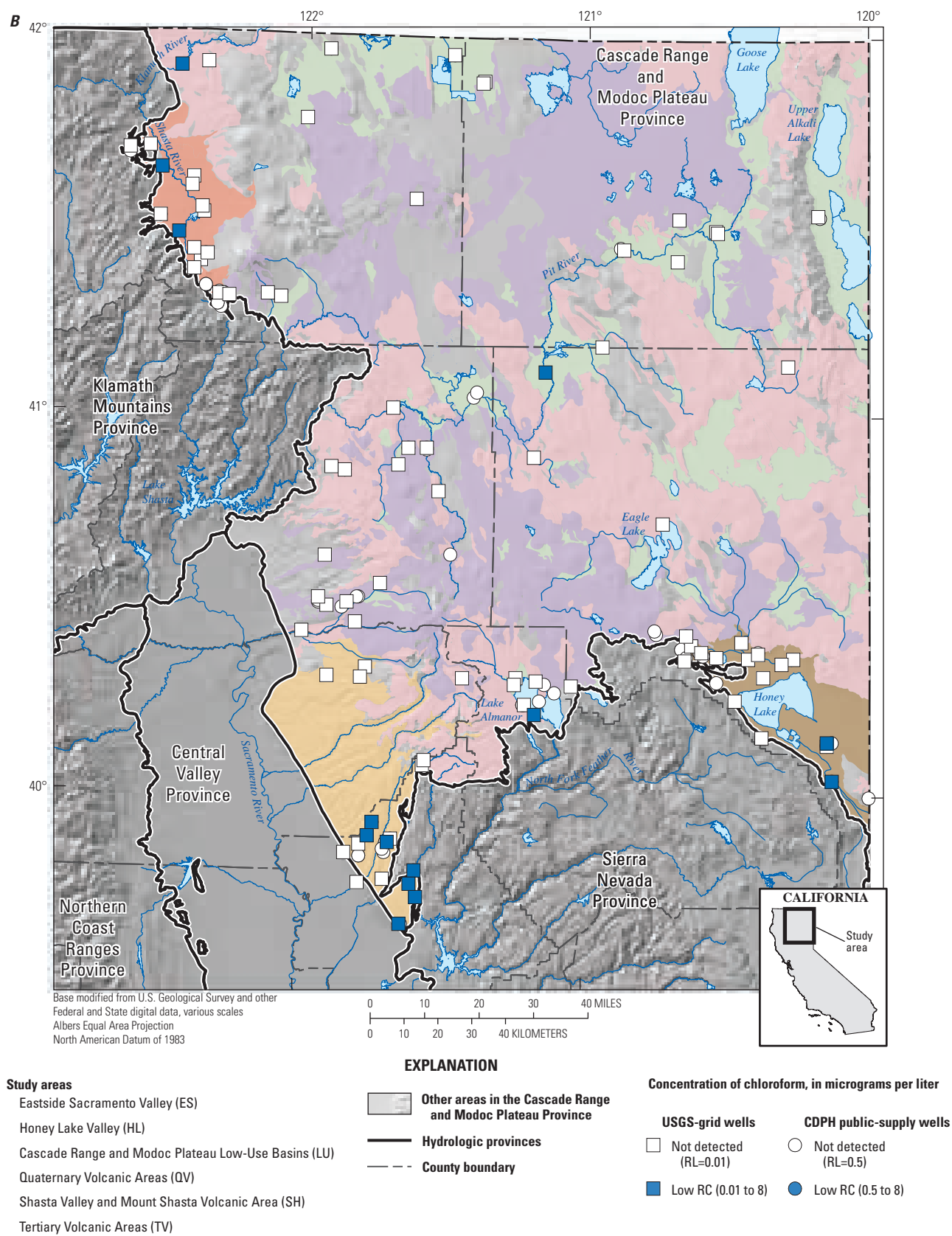


Figure 17. —Continued



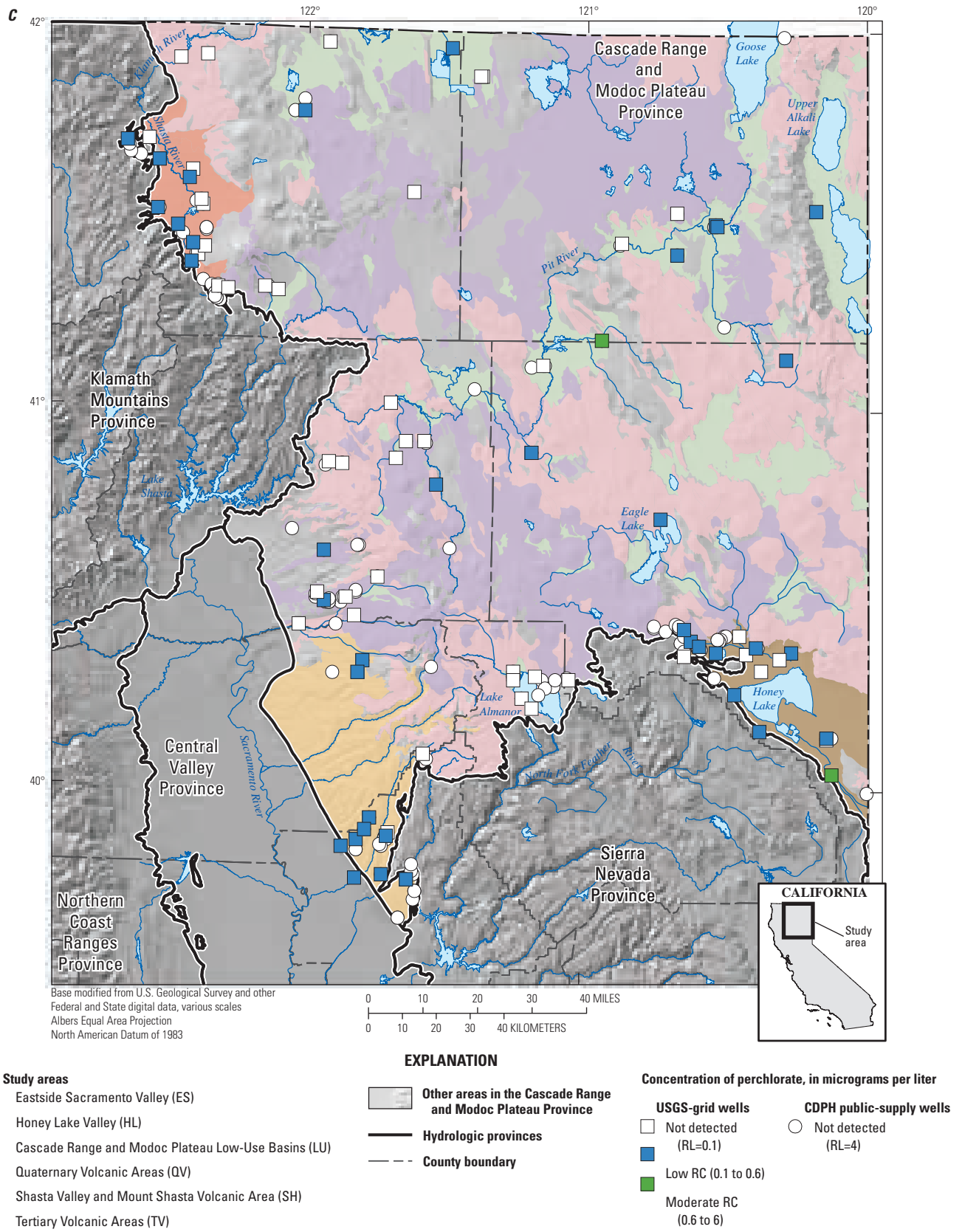


Figure 17. —Continued

Herbicide concentrations showed no significant correlations with depths to the top or the bottom of the screened or open interval in the well (*table 11B*) or to depth class (*table 11A*). Herbicide concentrations also showed no significant correlations with land use (*table 11B*). This absence of correlations was unexpected, given the positive correlation between herbicide concentrations and percentage of agricultural land use and negative correlation between herbicide concentrations and well depth or depth to the top of the screened or open interval observed in many other GAMA Priority Basin Project study units (for example, Landon and others, 2010).

The high detection frequency of herbicides in the SH study area compared to the other study areas (*table 13*; *fig. 16*)—and compared to most other areas investigated by the GAMA Priority Basin Project—and the lack of correlation between herbicide concentrations and land use or measures of well depth could be related to non-agricultural applications of herbicides and to specific features of the hydrology of the SH study area. The California Department of Pesticide Regulation (CDPR) maintains a database of registered pesticide applications at the scale of 1-mi<sup>2</sup> sections (California Department of Pesticide Regulation, 2013). Of the herbicides analyzed in this study, hexazinone has the greatest rate of registered usage in the CAMP study unit. The primary uses of hexazinone in the CAMP study unit are for timber-stand improvement in U.S. Forest Service and private timberlands and for weed management in grazing lands and alfalfa grown for forage (Kegley and others, 2011; California Department of Pesticide Regulation, 2013). Between 1991 and 2005, an average of 328 pounds per year (lb/yr) of hexazinone were applied in the SH study area, and another 832 lb/yr were applied in the forested watershed surrounding the study area. Use of herbicides in timberlands is of concern to the SWRCB and the Regional Water Quality Control Boards (for example, North Coast Regional Water Quality Control Board, 2005).

The other frequently detected herbicides in the CAMP study unit, atrazine and simazine, had few registered pesticide applications in specific 1-mi<sup>2</sup> sections between 1991 and 2005 (California Department of Pesticide Regulation, 2013). However, the database reports many registered non-agricultural uses of pesticides at the county level, rather than at the section level. Between 1991 and 1996, approximately 300 lb/yr of atrazine and 487 lb/yr of simazine were applied for weed control in rights-of-way in Siskiyou, Modoc, and Lassen counties (the three counties mostly or entirely within the CAMP study unit) (California Department of Pesticide Regulation, 2013). Herbicide use by the California Department of Transportation has decreased markedly since the mid-1990s as a result of changes in weed control strategies, and atrazine and simazine are no longer used (California Department of Transportation, 2014). No information is available about unregistered usage of herbicides in the CAMP study unit.

Of the six study areas, the SH study area had the greatest proportion of USGS-grid wells with modern or mixed age groundwater (*fig. 8C*). The combination of potential sources of herbicides (timberlands, agriculture, and roadside right-of-ways) and presence of modern groundwater could account for the greater detection frequency of herbicides in the SH study area compared to the other study areas.

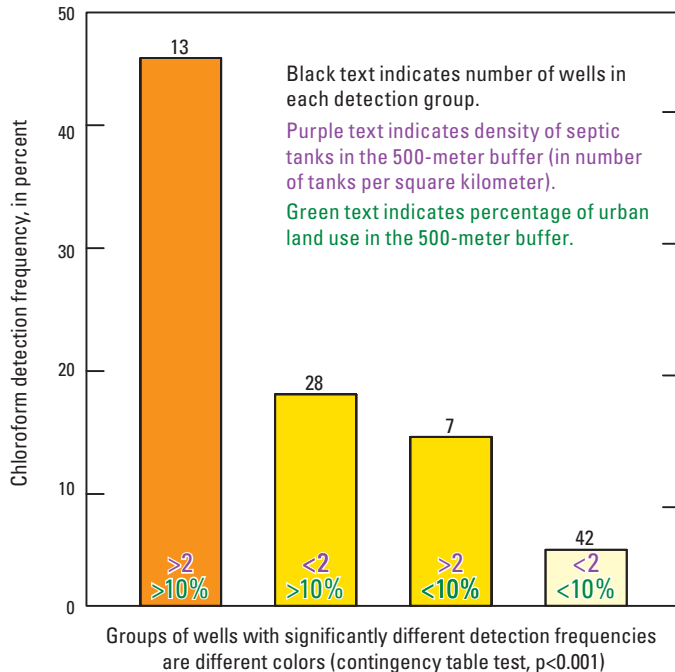
## Trihalomethanes

Water used for drinking and other household uses in domestic and public systems commonly is disinfected with chlorine solutions (for example, sodium hypochlorite [bleach], hypochlorous acid, chlorine gas, chloramines, or chlorine dioxide). In addition to disinfecting the water, the chlorine compounds can react with organic matter to produce trihalomethanes (THMs) and other chlorinated and (or) brominated disinfection byproducts (for example, Ivahnenko and Barbash, 2004). Chloroform was the most frequently detected VOC in groundwater across the USA (Zogorski and others, 2006).

The only THM detected in USGS-grid wells in the CAMP study unit was chloroform (*table 5*). Chloroform was not detected at high or moderate RCs in the CAMP study unit in samples from USGS-grid wells or reported at high or moderate RCs in the CDPH database. The area-weighted detection frequency of low RCs of chloroform in the CAMP study unit was 12 percent (*fig. 15*), and the detection frequencies in the six study areas ranged from zero in the QV study area to 47 percent in the ES study area (*table 13*, *figs. 16, 17B*).

Chloroform concentrations were significantly greater in the ES study area than in the LU and QV study areas (*table 11A*) and showed significant positive correlations with urban land use and septic-tank density (*table 11B*). The density of septic tanks was significantly greater in the ES study area than in the LU and QV study areas (*table 7A*). The significant negative correlations between chloroform concentrations and elevation and pH (*table 11B*) reflect that the ES study area has significantly lower elevation and pH compared to other study areas (*table 7A*). Chloroform concentrations showed no significant relations with groundwater age or with well depth (*tables 11A–B*); however, half of the wells with detections of chloroform were from the ES study area, which generally had deeper wells than the other study areas (*fig. 7*).

Urban land use and septic-tank density were not significantly correlated with each other (*table 7B*); thus, the fact that both are correlated with chloroform concentration indicates a more complex relation among the three variables. The 90 USGS-grid wells were divided into four groups on the basis of percentages of urban land use and septic-tank density. The detection frequency of chloroform in sites with urban land use greater than 10 percent and septic-tank density greater than 2 tanks/km<sup>2</sup> was significantly greater than the detection



**Figure 18.** Detection frequencies of chloroform in groundwater samples grouped by percentage of urban land use and density of septic tanks in the 500-meter buffer around the well, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. (>, greater than; <, less than, %, percent)

frequency in sites with less than 10 percent urban land use and septic-tank density less than 2 tanks/km<sup>2</sup> (contingency table test,  $p < 0.001$ ; *fig. 18*). Detection frequencies of chloroform in sites with either urban land use greater than 10 percent or septic-tank density greater than 2 tanks/km<sup>2</sup>, but not both, were in between the detection frequencies of chloroform in the other two groups (*fig. 18*).

Nationally, THMs have been strongly correlated with the percentage of urban land use (Zogorski and others, 2006). Potential urban sources of THMs include recharge from landscape irrigation with disinfected water, leakage from water distribution systems, and industrial and commercial usage of chlorinated disinfectants and reagents (Ivahnenco and Barbash, 2004). Septic systems can be a source of THMs to groundwater because they recharge water used for domestic purposes to the aquifer system, and this water may be disinfected for household use, or bleach and other cleaning products containing chlorine could have been used in the house. In addition, there could be a correlation between septic systems and domestic or small system wells—areas not part of large public water-supply systems may also not be part of sewage systems. 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 (U.S. Centers for Disease Control and Prevention, 2006), and could cause a reservoir of chlorinated water to form in the well bore and surrounding aquifer material. Smaller systems, such as schools, campgrounds, restaurants, small community associations, and domestic well owners, may be more likely to maintain their wells following guidelines for domestic wells than are large systems, such as municipalities. Of the 75 USGS-grid wells listed in the CDPH database, 53 (71 percent) served fewer than 1,000 people, and 37 (49 percent) served fewer than 200 people. The dominance of relatively small water systems could account for the relation between chloroform detections and septic-tank densities. There were no detections of chloroform in samples from the nine USGS-grid wells that were springs.

## 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 the CDPH was evaluating whether or not an MCL-CA should be established. The MCL-CA of 6 µg/L was promulgated in 2007. Perchlorate has both 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, 2009; 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 (U.S. Environmental Protection Agency, 2005b; Dasgupta and others, 2006). It also may 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 (Massachusetts Department of Environmental Protection, 2006; Greiner and others, 2008).

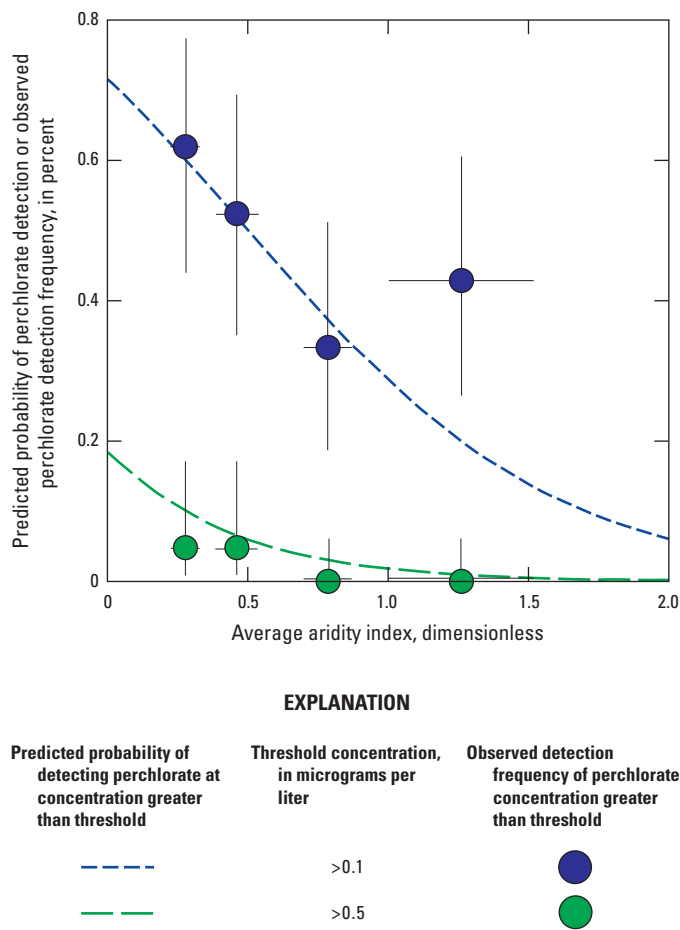
Perchlorate was not present at high RCs in the primary aquifer system of the CAMP study unit and was detected at moderate RCs in 2.2 percent and at low RCs in 41 percent of the system (*table 13*). The study-area detection frequency of perchlorate ranged from 21 percent in the QV study area to 91 percent in the ES study area (*table 13*; *figs. 16, 17C*). Concentrations of perchlorate showed significant negative correlations with the aridity index and pH and positive correlations with the percentage of agricultural land use (*table 11B*). Perchlorate concentrations were positively correlated with nitrate concentrations (spearman  $p < 0.001$ ,  $\rho = 0.63$ ).



Perchlorate detection frequencies in the CAMP study unit mostly were consistent with those expected from the distribution of perchlorate in California groundwater under natural conditions (Fram and Belitz, 2011). In the Fram and Belitz (2011) study, the observed occurrence frequencies of perchlorate at concentrations greater than threshold concentrations of 0.1 and 0.5 µg/L were compared to the predicted probability of perchlorate occurring under natural conditions as a function of aridity index. For the CAMP study unit, the 84 USGS-grid wells with perchlorate data were divided into 4 groups of 21 wells by the aridity index, and, for each group, the average aridity index and the detection frequencies of perchlorate at concentrations greater than 0.1 µg/L and greater than 0.5 µg/L were calculated. The observed detection frequencies were close to the predicted probabilities in all cases, except for the occurrence of perchlorate at concentrations greater than 0.1 µg/L in the group of samples from the wettest areas (greatest average aridity index) (fig. 19). This indicated that anthropogenic sources of perchlorate were not required to explain the pattern of perchlorate occurrence in most of the CAMP study unit, although contribution from anthropogenic sources cannot be ruled out.

The elevated occurrence frequency of low concentrations of perchlorate in the group of 21 USGS-grid wells from the wettest areas is not easily explained. There were no recorded sites of perchlorate production or use and no known sites of groundwater contamination from industrial sources of perchlorate near the nine USGS-grid wells in that group with perchlorate detections (U.S. Environmental Protection Agency, 2005b; California Department of Toxic Substances Control, 2007; California State Water Resources Control Board, 2007). There also were no significant differences in detection frequency of solvents and gasoline components among the four groups (contingency table test,  $p=0.36$ ), indicating an absence of industrial sources of perchlorate. The group from the wettest areas had significantly lower percentages of agricultural land use in the 500-m buffers around the USGS-grid wells than did the other three groups (Kruskal-Wallis test,  $p<0.001$ ), and there were no significant differences in nitrate concentrations among the four groups (Kruskal-Wallis test,  $p=0.26$ ). This indicates absence of agricultural sources of perchlorate. There were no significant differences in chloroform detection frequency among the four groups (contingency table test,  $p=0.30$ ), indicating absence of perchlorate derived from chlorine solutions. Of the nine samples with detections of perchlorate in the group of samples from the wettest areas, six samples were from the ES study

area. Of the 11 samples from the ES study area with data for perchlorate, 10 samples (91 percent) had a detection of perchlorate (Shelton and others, 2013). Further investigation of the increased occurrence of low concentrations of perchlorate in groundwater in the ES study area is beyond the scope of this report.



The 84 USGS-grid wells with perchlorate data were divided into 4 groups of 21 wells. Horizontal error bars equal plus or minus one standard deviation of the average aridity index. Vertical error bars are the 90-percent Jeffrey's confidence interval for the observed detection frequency.

**Figure 19.** Predicted probability of detecting perchlorate in groundwater as a function of aridity index and Anthropogenic Score and observed detection frequency and average aridity index in groups by aridity index, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

## Summary

Groundwater quality in the Cascade Range and Modoc Plateau (CAMP) study unit was investigated as part of the California State Water Resource Control Board's Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. The CAMP study unit covers an area of approximately 15,000 square miles (mi<sup>2</sup>) or 39,000 square kilometers (km<sup>2</sup>) in Siskiyou, Modoc, Shasta, Lassen, Tehama, Plumas, and Butte counties in the northeastern corner of the State.

The GAMA Priority Basin Project is designed to provide a statistically unbiased assessment of untreated groundwater quality in the primary aquifer system used for public drinking-water supplies statewide. The primary aquifer system was defined by the range of depths of the screened or open intervals of wells listed in the California Department of Public Health (CDPH) database of wells used for public drinking-water supply. [The CDPH Drinking Water Program which regulated water quality in public-supply wells was transferred to the SWRCB Division of Drinking Water on July 1, 2014, however the label "CDPH" is retained in this report for consistency with other GAMA Priority Basin Project publications and because the CDPH had jurisdiction over public-supply wells at the time that samples were collected for this study.] Two types of assessments were made for the CAMP study unit: (1) a *status assessment* yielding quantitative estimates of the current status of groundwater quality in the primary aquifer system and (2) an *understanding assessment* consisting of evaluation of relations between water quality and potential explanatory factors describing land use, geography, depth, geochemical conditions, groundwater age, and other characteristics of the primary aquifer system.

The assessments were based on data collected by the (U.S. Geological Survey (USGS) for the GAMA Priority Basin Project (USGS-GAMA) and data compiled from the CDPH database. The study unit was divided into six study areas on the basis of regional geology: Eastside Sacramento Valley (ES), Honey Lake Valley (HL), Cascade Range and Modoc Plateau Low Use Basins (LU), Quaternary Volcanic Areas (QV), Shasta Valley and Mount Shasta Volcanic Area (SH), and Tertiary Volcanic Areas (TV). Each study area was divided into 15 equal-area cells. The sizes of the grid cells ranged from 19 km<sup>2</sup> in the ES study area to 47 km<sup>2</sup> in the QV study area. Water-quality and ancillary data were collected by USGS-GAMA from a well or spring in each of the 90 grid cells during 2010 (referred to as USGS-grid wells in this report). Of the 90 USGS-grid wells, 82 were listed in the CDPH database of public-supply wells and springs, and the other 8 were screened or had open intervals similar to wells listed in the CDPH database. Samples from the USGS-grid wells were analyzed for organic constituents (volatile organic compounds and pesticides), inorganic constituents (major ions, trace elements, and radioactive constituents), special interest constituents (perchlorate) and geochemical and age-dating tracers. Additional water-quality data were obtained from

177 wells in the CDPH database having data for samples collected between September 16, 2007, and September 16, 2010.

Relative-concentrations (defined as sample concentration divided by benchmark concentration for the constituent) were used to evaluate groundwater quality for constituents that have Federal and (or) California regulatory or non-regulatory benchmarks for drinking-water quality. A relative-concentration (RC) greater than 1.0 indicates a concentration above a benchmark. Organic and special interest constituent RCs were classified as "high" (RCs greater than 1.0), "moderate" (RCs greater than 0.10, but less than or equal to 1.0), or "low" (RCs less than or equal to 0.1). For inorganic constituents, the boundary between low and moderate RCs was set at 0.5.

Aquifer-scale proportion was used as the primary metric in the *status assessment* to evaluate regional-scale groundwater quality. High-RC aquifer-scale proportion was defined as the areal percentage of the primary aquifer system that had a RC greater than 1.0 for a particular constituent or class of constituents; moderate-RC and low-RC aquifer-scale proportions were defined as the areal percentages of the primary aquifer system that had moderate and low RCs, respectively. Aquifer-scale proportions were calculated for the primary aquifer systems in each of the six study areas and on an area-weighted basis for the study unit as a whole. Both grid-based, which used data from one well per grid cell, and spatially weighted, which used data from multiple wells per grid cell, approaches were used to calculate aquifer-scale proportions.

The *status assessment* showed that inorganic constituents had greater high-RC and moderate-RC aquifer-scale proportions than did organic constituents and that there were significant differences in aquifer-scale proportions for many constituents among the six study areas. In the CAMP study unit as a whole, one or more inorganic constituents with health-based benchmarks (U.S. Environmental Protection Agency [USEPA] and CDPH maximum contaminant levels and action levels, CDPH notification levels, and USEPA lifetime health advisory levels) had high RCs in 9.4 percent of the primary aquifer system and moderate RCs in 14.7 percent. Arsenic and boron each were found at high RCs in approximately 3 percent of the primary aquifer system, and molybdenum, uranium, and vanadium each were found at high RCs in approximately 2 percent. The primary aquifer system of the HL study area had greater proportions with high or moderate RCs of arsenic, boron, molybdenum, and uranium than did primary aquifer systems in other study areas. In the CAMP study unit as a whole, one or more inorganic constituents with aesthetic-based benchmark (CDPH secondary maximum contaminant levels) had high RCs in 15.1 percent of the primary aquifer system and moderate RCs in 4.9 percent. Manganese, iron, and total dissolved solids (TDS) were found at high RCs in approximately 12 percent, 5 percent, and 2 percent of the primary aquifer system, respectively.



Organic constituents with health-based benchmarks were not found at high or moderate RCs in the CAMP study unit. Of the 148 organic constituents analyzed by USGS-GAMA, 27 were detected in at least one well, and of those 27 constituents, 18 have health-based benchmarks. One or more volatile organic compound (VOC) was detected at low RCs in 24 percent of the primary aquifer system, and one or more pesticide was detected at low RCs in 23 percent. Two organic constituents had detection frequencies greater than 10 percent: the trihalomethane chloroform and the herbicide atrazine. The special-interest constituent perchlorate was not found at high RCs in the CAMP study unit, but was found at moderate RCs in 2.2 percent of the primary aquifer system.

For the *understanding assessment*, statistical tests were used to evaluate relations between concentrations of constituents and potential explanatory factors descriptive of geologic, hydrologic, land use, and geochemical characteristics of the primary aquifer system at the 90 USGS-grid wells. The potential explanatory factors evaluated were study area; aquifer lithology class; the percentages of agricultural, natural, and urban land use within a radius 500-meters (m) around the USGS-grid well (500-m buffers); the densities of septic tanks and leaking or formerly leaking underground fuel tanks in the 500-m buffers; the aridity index and elevation at the well site; depths to the top and bottom of the screened, or open interval for wells, and depth class (spring, shallow well, overlapping well, deep well); groundwater age class (modern, mixed, pre-modern); and the water-quality indicators pH, dissolved oxygen concentration, and oxidation-reduction class (oxic, anoxic).

Concentrations of arsenic, boron, molybdenum, uranium, and TDS were significantly greater in USGS-grid well samples from the HL study area than in samples from other study areas. Many of the correlations between the concentrations of these constituents and values of other potential explanatory factors reflect associations between potential explanatory factors and location in the Honey Lake study area. Concentrations of arsenic, boron, molybdenum, uranium, and TDS generally were greater in pre-modern and mixed age groundwater compared to modern age groundwater and in sites with sedimentary aquifer lithology compared to sites

with volcanic aquifer lithology, and generally were positively correlated with percentage of agricultural land use and pH and negatively correlated with aridity index and dissolved oxygen concentration, consistent with the associations between values of these explanatory factors and location in the Honey Lake study area. The source of uranium was likely sediments derived from granitic rocks in the Sierra Nevada adjacent to the Honey Lake study area, and mixing with fluids from hydrothermal systems in the Honey Lake study area is likely a source of arsenic, boron, and other constituents to groundwater. Interaction between groundwater and Honey Lake playa sediments under high pH and low dissolved oxygen conditions may result in desorption of arsenic, molybdenum, and uranium from the sediments. Cumulative dissolution of aquifer materials over long time periods and evaporative concentration of groundwater in the playa may also contribute to increased concentrations of trace elements and TDS in Honey Lake groundwater.

Thermal springs are present in many parts of the CAMP study unit and could account for locally elevated concentrations of arsenic, boron, molybdenum, and TDS in the other study areas. Vanadium concentrations in USGS-grid wells were greater in oxic samples than in anoxic samples, but were not correlated with pH, contrary to expectations based on previous studies.

The SH study area had significantly greater occurrence of low RCs of herbicides than all of the other study areas, which could reflect the greater prevalence of modern groundwater in the SH study area and the presence of potential sources of herbicides from applications to timberlands and roadside rights-of-way. Chloroform occurrence was associated with the combination of septic-tank density greater than two tanks per square kilometer (km<sup>2</sup>) and urban land use greater than 10 percent within a radius of 500-meters of the well. These conditions were most prevalent in the ES study area. The detection frequency of low concentrations (0.1–0.5 µg/L) of perchlorate was consistent with probability of occurrence expected under natural conditions, except for in the ES study area where detection frequencies were much higher than expected, but could not be explained by known anthropogenic sources of perchlorate.

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## Appendix A: Attribution of Potential Explanatory Factors

The 90 U.S. Geological Survey (USGS)-grid wells (figs. A1A–G) were attributed with values for the following potential explanatory factors: aquifer lithology and study area, land use, densities of leaking (or formerly leaking) underground storage tanks and septic tanks, hydrologic conditions, well depth, groundwater age, and geochemical conditions. These factors were assumed to be the ones most likely to have causative relations with the concentrations of water-quality constituents in the groundwater.

### Aquifer Lithology and Study Area

Aquifer lithology was classified on the basis of lithologic information from California Department of Water Resources (CDWR) well completion reports and on the California State geologic map (Jennings, 1977; Saucedo and others, 2000). The State geologic map shows the lithologic unit exposed at the surface, which may not be the same as the lithologic unit at the depth range over which the well is screened or open. Therefore, if the lithologic category estimated from the geologic map disagreed with the lithology described in the CDWR well completion report, the category from the CDWR well completion report was used. The 90 wells sampled by Groundwater Ambient Monitoring and Assessment Program (USGS-GAMA) have screened or open intervals in 11 of the 66 geologic units defined on the California State geologic map (Jennings, 1977; Saucedo and others, 2000). These geologic units were grouped into four lithologic categories on the basis of rock type and age:

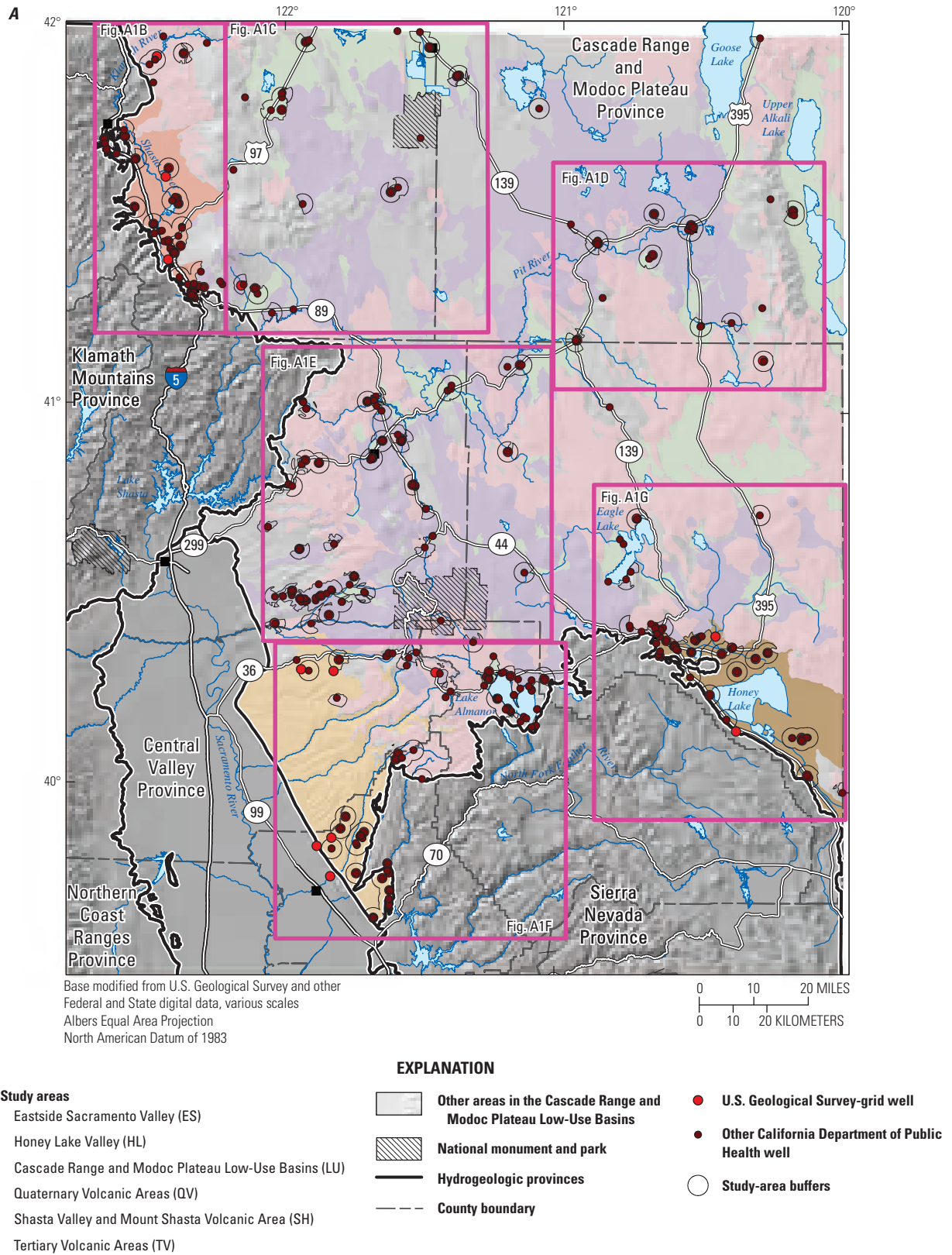
- G: Mesozoic granitic rocks (California State geologic map unit grMz).
- M: Mesozoic and Paleozoic metamorphic and marine sedimentary rocks. Metamorphic rocks are not exposed at the surface in the CAMP study unit, however, lithologic descriptions in CDWR well completion reports indicate that four wells in the SH study area have screened or open intervals in metamorphic rocks below the surface (table A1). The part of the Klamath Mountains adjacent to these four wells is mapped on the State geologic map as the following geologic units:

m, undivided Mesozoic, Paleozoic, and Precambrian metavolcanic and metasedimentary rocks; Ku, Mesozoic marine sedimentary and metasedimentary rocks; and SO, Paleozoic marine sedimentary and metasedimentary rocks.

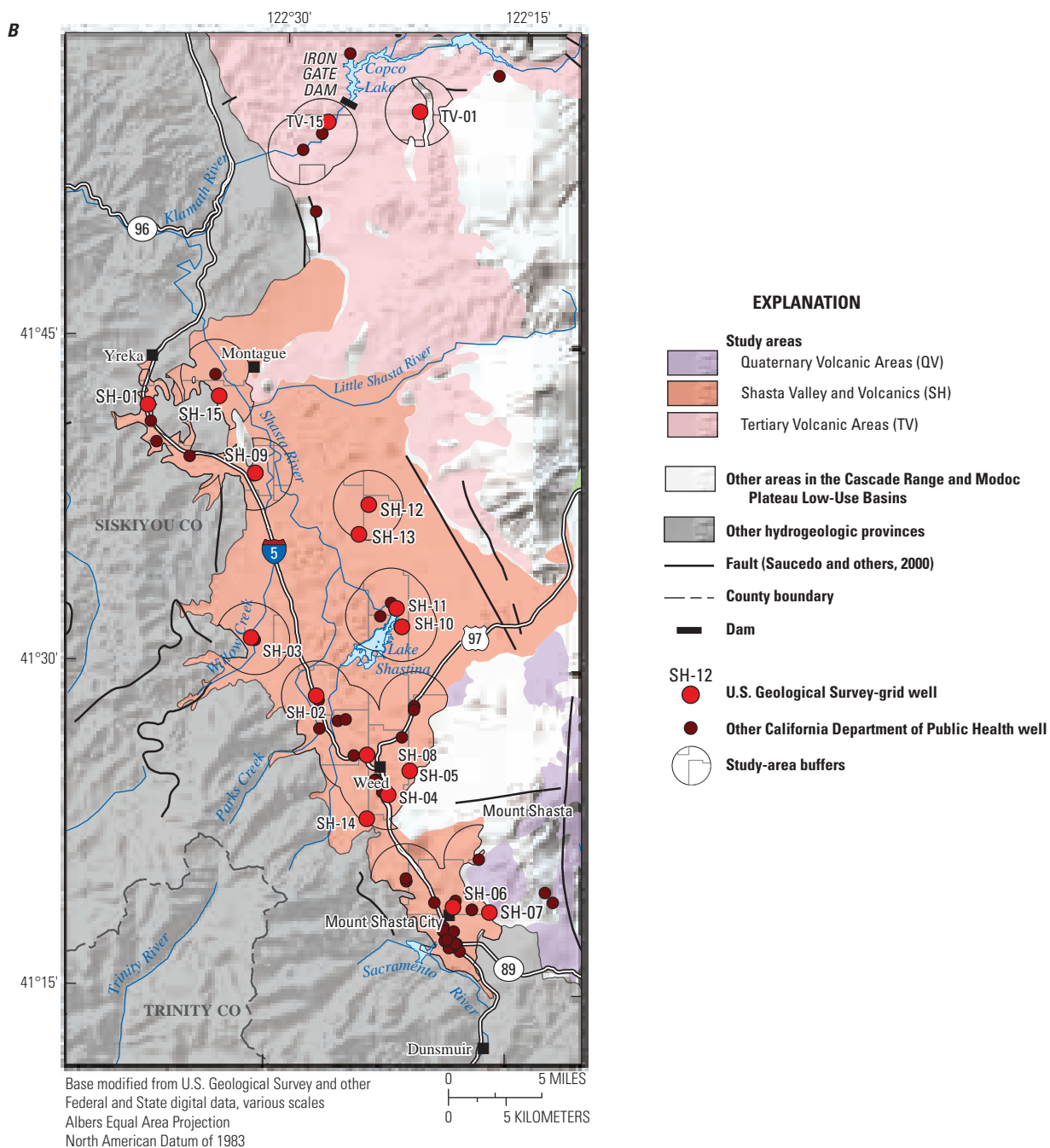
- S: Cenozoic sedimentary deposits, all of which are Quaternary age non-marine sedimentary deposits, including alluvial, consolidated alluvium, and sand dune sediments (California State geologic map units Q, QPc, and Qs). These deposits consist of Holocene age alluvial (Q) and eolian (Qs) deposits, and Plio-Pleistocene and Pliocene alluvial (QPc) deposits. The alluvial deposits include alluvial fan, fluvial, and lacustrine sediments.
- V: Cenozoic volcanic rocks. The Tertiary lava flows (Tv) and pyroclastic deposits (Tvp) are primarily Miocene and Pliocene in age, and the Quaternary lava flows are Pleistocene (Qv) and Holocene (Qrv) in age.

Geologic time is divided into four eras: Cenozoic (65.5 Ma to present), Mesozoic (251 Ma to 65.5 Ma), Paleozoic (542 Ma to 251 Ma), and Precambrian (approximately 3,900 Ma to 542 Ma) (Walker and Geissman, 2009). The Cenozoic Era consists of the Tertiary (65.5 Ma to 2.6 Ma) and Quaternary (2.6 Ma to present) periods. The Tertiary period consists of the Paleocene (65.5 Ma to 55.8 Ma), Eocene (55.8 Ma to 33.9 Ma), Oligocene (33.9 Ma to 23.0 Ma), Miocene (23.0 to 5.3 Ma), and Pliocene (5.3 Ma to 2.6 Ma) epochs. The Quaternary period consists of the Pleistocene (2.6 Ma to 10 ka) and Holocene (10 ka to present) epochs.

The lithologic categories assigned to the USGS-grid wells are listed in table A1: GS, 3 wells; MS, 3 wells; M, 1 well; S, 18 wells; V, 47 wells; VM, 1 well; and VS, 17 wells. Wells assigned to two categories (GS, MS, VM, or VS) have screened or open intervals in two different lithologic units. The CAMP study unit was divided into six study areas on the basis of geologic characteristics to investigate potential differences in groundwater quality among these geologically distinct aquifer systems.



**Figure A1.** Boundaries of the six study areas and study area buffers and locations of U.S. Geological Survey (USGS)-grid wells and California Department of Public Health (CDPH) wells for A, the entire study unit; B, the northwestern; C, north-central; D, northeastern; E, west-central; F, southwestern; and G, southeastern parts of the Cascades Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



**Figure A1.** —Continued

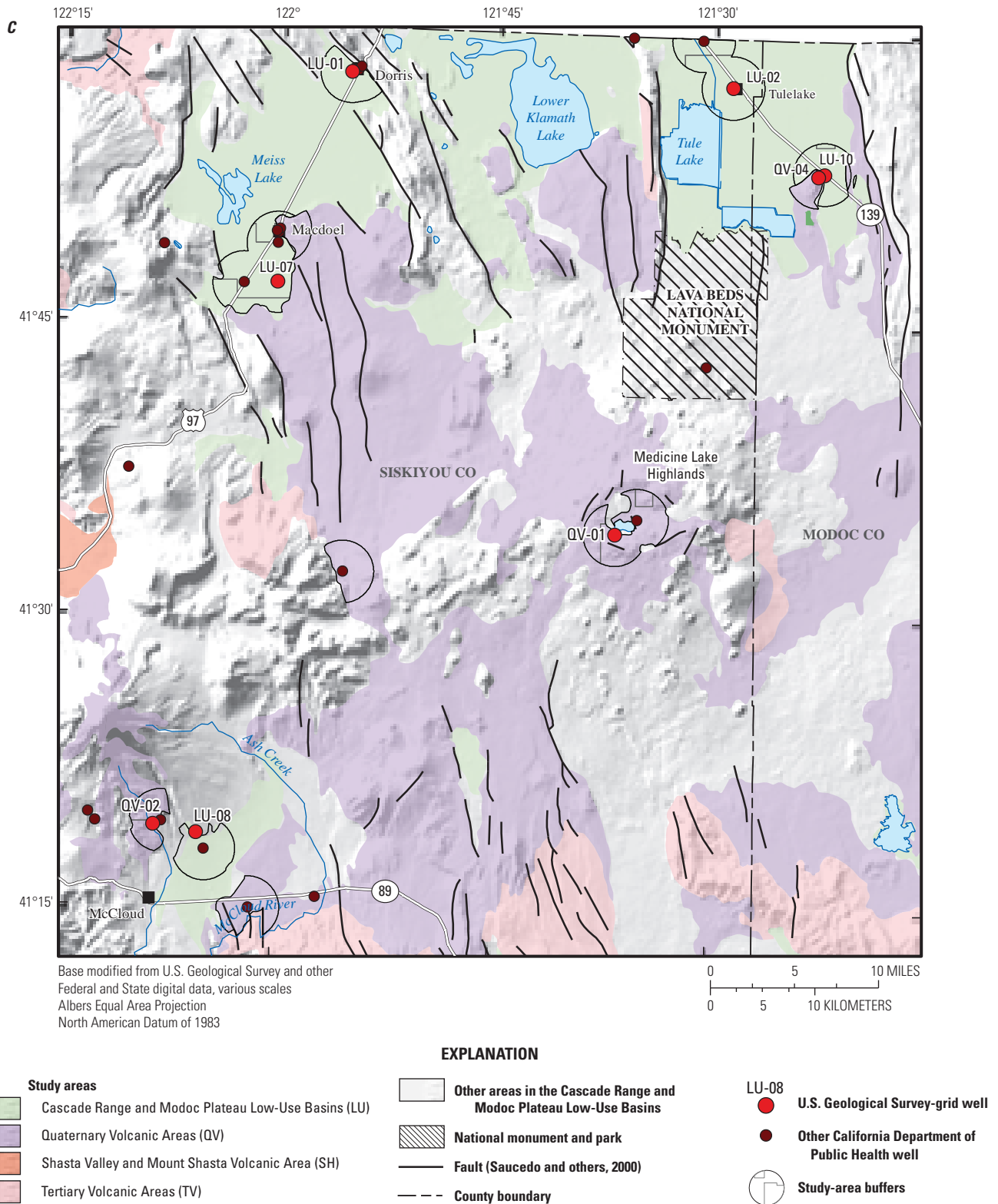


Figure A1. —Continued



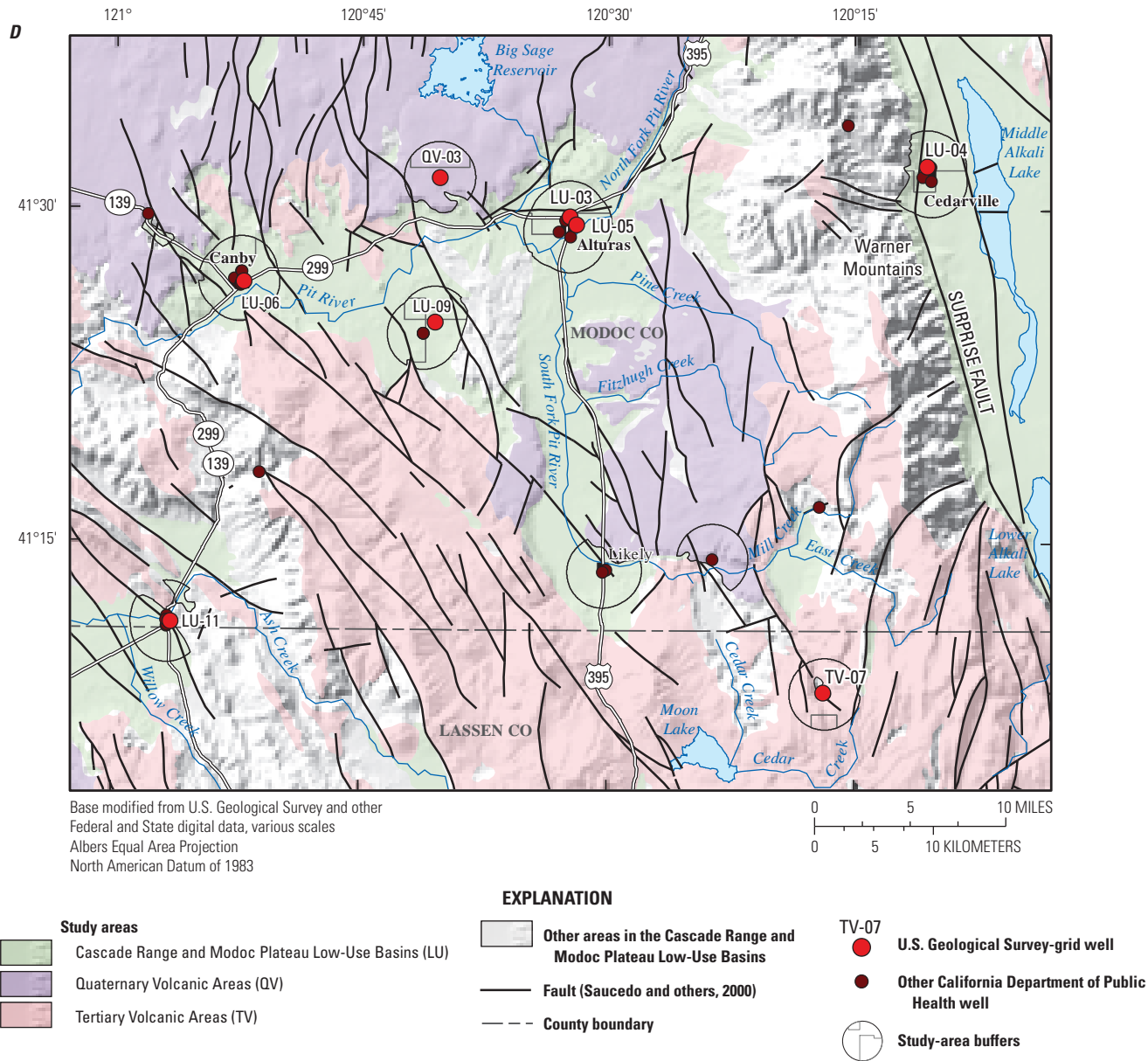


Figure A1. —Continued



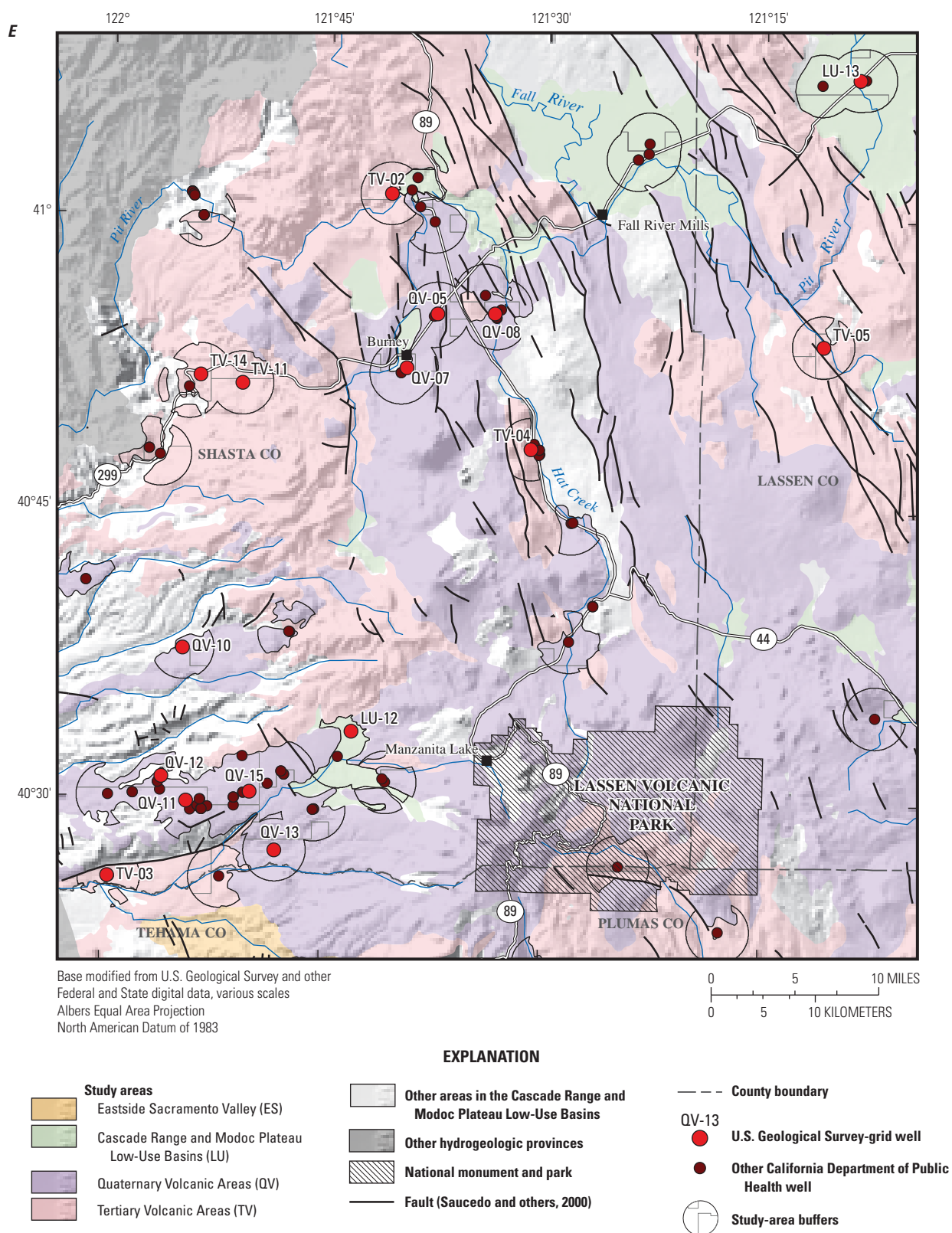


Figure A1. —Continued

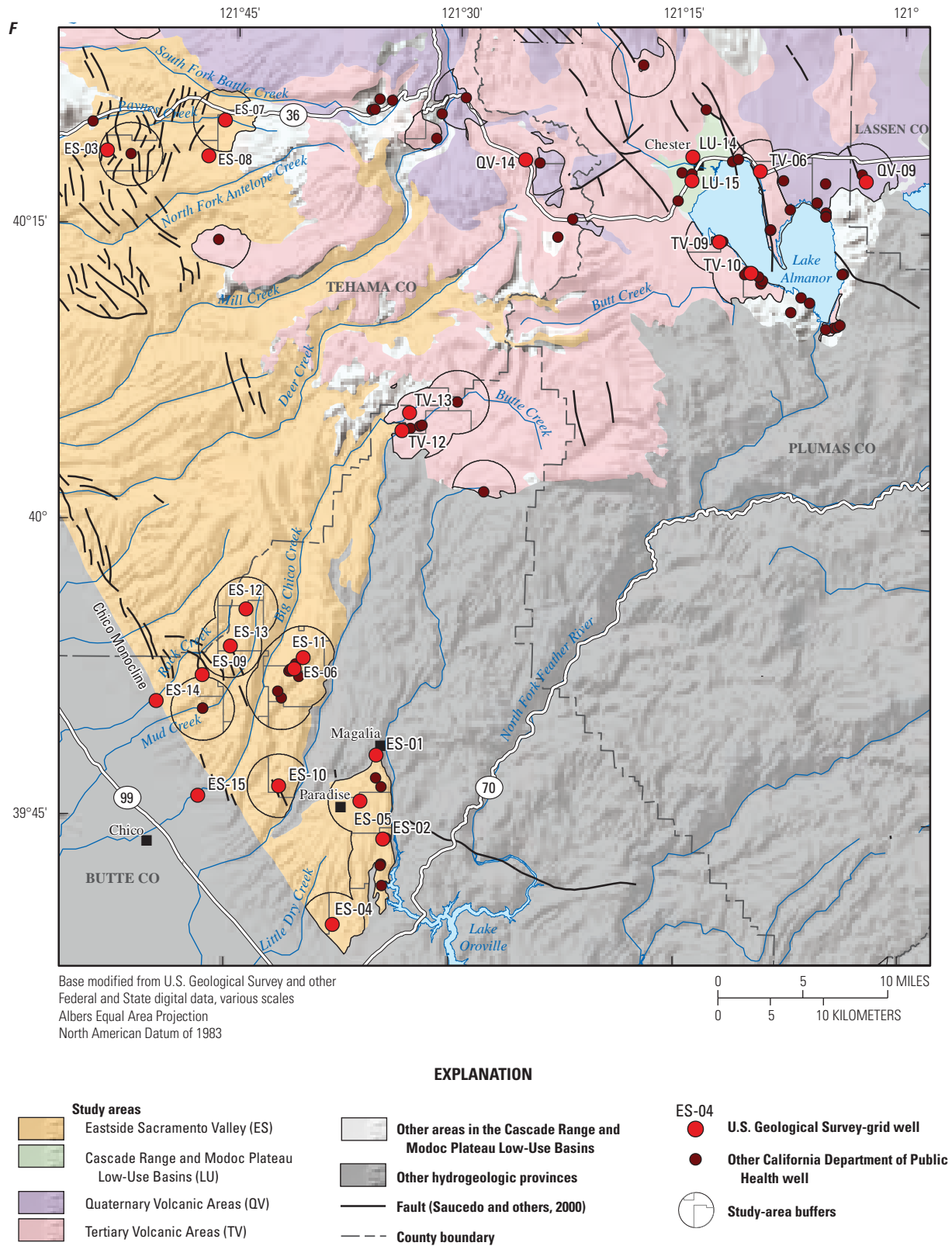


Figure A1. —Continued

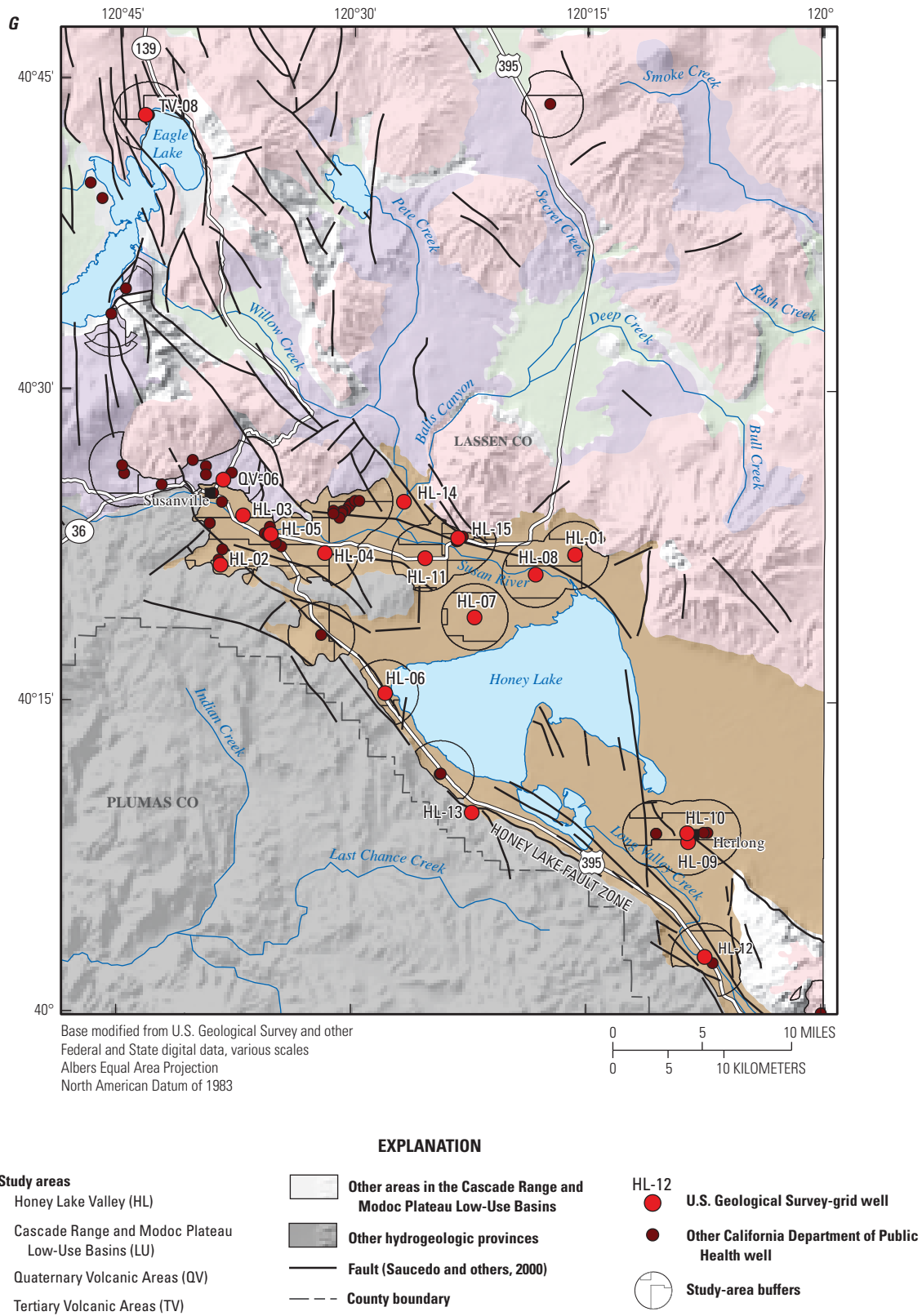


Figure A1. —Continued

**Table A1.** Land use percentages, septic-tank density, underground storage tank density and geology classification for U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Well identification numbers: ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Other abbreviations:** tanks/km<sup>2</sup>, number of tanks per square kilometer; UST, leaking or formerly leaking underground-storage tank; WCR, well completion report]

Well identification number	Geology classification <sup>1</sup>		Land-use percentages <sup>2</sup>			Septic density <sup>3</sup> (tanks/km <sup>2</sup> )	UST density <sup>4</sup> (tanks/km <sup>2</sup> )
	Aquifer lithology class	Source of data <sup>1</sup>	Agricultural (percent)	Natural (percent)	Urban (percent)		
Sacramento Valley Eastside study area							
CAMP-ES-01	V	WCR	0	44	56	112	0.06
CAMP-ES-02	V	WCR	0	36	64	39.8	0.04
CAMP-ES-03	V	field	0	92	8	0.4	0.00
CAMP-ES-04	S	WCR	21	58	21	4.7	0.01
CAMP-ES-05	S	WCR	0	0	100	256	0.87
CAMP-ES-06	V	WCR	0	99	1	3.1	0.01
CAMP-ES-07	V	WCR	0	99	1	0.4	0.00
CAMP-ES-08	V	WCR	0	100	0	0.4	0.00
CAMP-ES-09	VS	WCR	0	100	0	1.7	0.02
CAMP-ES-10	S	WCR	0	100	0	4.0	0.04
CAMP-ES-11	V	WCR	0	92	8	2.9	0.01
CAMP-ES-12	VS	WCR	0	76	24	1.7	0.02
CAMP-ES-13	VS	map	0	100	0	1.7	0.02
CAMP-ES-14	VS	map	0	100	0	1.7	0.02
CAMP-ES-15	V	WCR	5	61	34	1.7	0.03
Honey Lake Valley study area							
CAMP-HL-01	S	WCR	0	100	0	0.4	0.00
CAMP-HL-02	GS	WCR	2	93	5	2.2	0.01
CAMP-HL-03	S	map	27	43	30	1.7	0.01
CAMP-HL-04	S	WCR	63	14	23	4.2	0.01
CAMP-HL-05	S	WCR	27	42	31	4.2	0.01
CAMP-HL-06	S	WCR	37	54	9	4.2	0.00
CAMP-HL-07	S	WCR	4	94	2	1.3	0.00
CAMP-HL-08	S	WCR	12	88	0	1.1	0.00
CAMP-HL-09	S	WCR	0	42	58	0.0	0.00
CAMP-HL-10	S	WCR	0	66	34	0.0	0.00
CAMP-HL-11	S	WCR	27	52	21	1.3	0.00
CAMP-HL-12	GS	WCR	1	69	30	0.7	0.00
CAMP-HL-13	GS	map	0	100	0	1.1	0.00
CAMP-HL-14	S	map	36	64	0	1.1	0.00
CAMP-HL-15	S	WCR	1	63	36	0.5	0.00
Cascade Range and Modoc Plateau Low-Use Basins study area							
CAMP-LU-01	V	WCR	44	10	46	0.2	0.61
CAMP-LU-02	V	WCR	64	1	36	0.2	0.00
CAMP-LU-03	VS	WCR	0	13	87	1.2	0.00
CAMP-LU-04	S	WCR	38	20	43	0.4	0.00
CAMP-LU-05	VS	WCR	40	7	53	1.2	1.82

Well identification number	Geology classification <sup>1</sup>		Land-use percentages <sup>2</sup>			Septic density <sup>3</sup> (tanks/km <sup>2</sup> )	UST density <sup>4</sup> (tanks/km <sup>2</sup> )
	Aquifer lithology class	Source of data <sup>1</sup>	Agricultural (percent)	Natural (percent)	Urban (percent)		
Cascade Range and Modoc Plateau Low-Use Basins study area—Continued							
CAMP-LU-06	V	WCR	55	19	26	0.1	0.00
CAMP-LU-07	V	WCR	72	4	24	0.2	0.01
CAMP-LU-08	VS	map	0	96	4	0.1	0.02
CAMP-LU-09	VS	map	24	75	1	0.2	0.00
CAMP-LU-10	VS	map	1	78	21	0.1	0.05
CAMP-LU-11	VS	map	27	44	29	0.2	0.00
CAMP-LU-12	V	WCR	0	87	13	1.3	0.00
CAMP-LU-13	S	WCR	13	42	46	0.2	0.00
CAMP-LU-14	VS	WCR	0	93	7	0.7	0.00
CAMP-LU-15	VS	map	0	73	27	1.9	0.01
Quaternary Volcanic area study area							
CAMP-QV-01	V	field	0	100	0	0.0	0.00
CAMP-QV-02	V	field	0	100	0	0.1	0.02
CAMP-QV-03	V	map	0	93	7	0.1	0.00
CAMP-QV-04	VS	WCR	0	100	0	0.1	0.05
CAMP-QV-05	V	map	0	17	83	39.1	0.00
CAMP-QV-06	V	map	1	87	11	1.2	0.04
CAMP-QV-07	V	WCR	0	97	3	0.3	0.01
CAMP-QV-08	V	WCR	0	66	34	0.5	0.00
CAMP-QV-09	V	field	0	84	16	1.0	0.00
CAMP-QV-10	V	WCR	0	100	0	1.1	0.01
CAMP-QV-11	V	WCR	0	62	38	1.8	0.00
CAMP-QV-12	VS	WCR	0	100	0	1.5	0.00
CAMP-QV-13	V	WCR	0	100	0	0.7	0.01
CAMP-QV-14	V	WCR	0	100	0	0.4	0.00
CAMP-QV-15	V	WCR	0	95	5	1.4	0.00
Shasta Valley and Mount Shasta Volcanic Area study area							
CAMP-SH-01	M	WCR	0	45	55	6.3	0.29
CAMP-SH-02	V	WCR	1	81	18	1.2	0.02
CAMP-SH-03	MS	map	55	43	2	1.6	0.01
CAMP-SH-04	V	WCR	0	84	16	2.1	0.01
CAMP-SH-05	V	field	0	100	0	1.8	0.36
CAMP-SH-06	S	WCR	0	7	93	18.8	0.62
CAMP-SH-07	V	field	0	100	0	1.9	0.03
CAMP-SH-08	V	map	15	74	11	1.1	0.02
CAMP-SH-09	MS	WCR	14	63	23	2.4	0.02
CAMP-SH-10	VS	WCR	0	97	3	1.3	0.02



Well identification number	Geology classification <sup>1</sup>		Land-use percentages <sup>2</sup>			Septic density <sup>3</sup> (tanks/km <sup>2</sup> )	UST density <sup>4</sup> (tanks/km <sup>2</sup> )
	Aquifer lithology class	Source of data <sup>1</sup>	Agricultural (percent)	Natural (percent)	Urban (percent)		
Shasta Valley and Mount Shasta Volcanic Area study area—Continued							
CAMP-SH-11	VS	map	75	22	3	1.3	0.02
CAMP-SH-12	V	map	37	63	0	0.8	0.01
CAMP-SH-13	V	field	7	93	0	1.3	0.01
CAMP-SH-14	V	WCR	0	98	2	1.1	0.01
CAMP-SH-15	MS	map	90	10	1	3.3	0.02
Tertiary Volcanic Areas study area							
CAMP-TV-01	V	map	24	76	0	0.6	0.00
CAMP-TV-02	V	map	0	100	0	0.3	0.00
CAMP-TV-03	V	field	0	100	0	1.8	0.01
CAMP-TV-04	V	map	19	81	0	0.3	0.00
CAMP-TV-05	V	WCR	2	72	26	0.1	0.00
CAMP-TV-06	V	WCR	0	94	6	10.8	0.02
CAMP-TV-07	V	WCR	0	100	0	0.0	0.00
CAMP-TV-08	V	map	0	96	4	1.3	0.00
CAMP-TV-09	VS	WCR	0	73	27	18.4	0.03
CAMP-TV-10	V	map	0	66	34	5.7	0.00
CAMP-TV-11	V	WCR	0	88	12	1.5	0.00
CAMP-TV-12	V	WCR	0	100	0	1.2	0.02
CAMP-TV-13	V	map	0	100	0	1.2	0.02
CAMP-TV-14	V	WCR	0	98	2	1.2	0.00
CAMP-TV-15	VM	WCR	0	98	2	0.5	0.01

<sup>1</sup>Classification based on lithology of screened or open interval as described in the California Department of Water Resources well completion report (WCR), if available. For wells without WCRs, lithology was inferred from geologic map of California (Jennings, 1977; Saucedo and others, 2000) and well depth information, if available (map). For most springs, lithology was estimated from field observations (field). Wells can have screened or open intervals in more than one lithology.

<sup>2</sup>Land-use percentages within 500 meters of well site (Johnson and others, 2009).

<sup>3</sup>Septic-tank density within 500 meters of well site, based on 1990 U.S. Census data.

<sup>4</sup>Leaking (or formerly leaking) underground-storage tank density within a 500-meter radius of well site (California State Water Resources Control Board, 2007).

## Land Use

Land use was classified by using an enhanced version of the satellite-derived (30-meter pixel resolution), nationwide 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. About two-thirds of the Cascade Range and Modoc Plateau (CAMP) study-unit wells had groundwater classified as mixed or pre-modern age, indicating presence of groundwater recharged many decades to perhaps thousands of years ago (see ‘Well Depth and Groundwater Age’ section); therefore, land use patterns from several decades ago were thought more likely to be relevant to the groundwater samples than current land-use patterns. The imagery was classified into 25 land-cover classifications (Nakagaki and Wolock, 2005). For this study, these 25 land-cover classifications were condensed into 3 principal land-use categories: urban, agricultural, and natural. Land-use statistics for the study unit, study areas, and areas within a 500-meter radius around each well (500-meter buffers) were calculated for each category by using ArcGIS. Buffers consisting of a 500-meter radius circle centered on each well have been shown to be effective at correlating land use with occurrence of volatile organic compounds (VOCs), pesticides, and nitrate for the purposes of statistical characterization (for example, Rupert, 2003; Johnson and Belitz, 2009). Land-use data for USGS-grid wells are listed in [table A1](#).

The 25 land-cover classes defined by Nakagaki and Wolock (2005) were based on features distinguishable in Level II remote-sensing data (high-elevation aerial photography; Anderson and others, 1976). Urban land use includes high-, moderate-, and low-intensity development and developed open space. Agricultural land includes cultivated crops and land used for pasture or hay. Natural land includes everything else. In this classification, open-range grazing, such as that practiced on U.S. Forest Service and U.S. Bureau of Land Management lands in the Cascade Range and Modoc Plateau (CAMP) study unit, was classified as natural land, not agricultural land.

## Septic Systems and Underground Storage Tanks

Septic-tank density was determined from housing characteristics data from the 1990 U.S. Census (U.S. Census Bureau, 1990). The density of septic tanks in each housing census block was calculated from the number of tanks and block area. The density of septic tanks around each well was then calculated from the area-weighted mean of the block densities for blocks within a 500-m buffer around the well location (Tyler Johnson, USGS, written commun., 2009) ([table A1](#)).

The density of leaking or formerly leaking underground storage tanks (USTs) was determined from the locations

of tanks in the State Water Resources Control Board’s (SWRCB’s) GeoTracker database of environmental cleanup sites (California State Water Resources Control Board, 2007). The density of USTs was calculated by using Theissen polygons (Tyler Johnson, USGS, written commun., 2007). The boundaries 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 ([table A1](#)).

## Well Construction Information and Hydrologic Conditions

Well-construction data were obtained primarily from CDWR well completion reports. In locations where CDWR well completion reports were not available, well-construction data were obtained from ancillary records of well owners or the USGS National Water Information System database (<http://waterdata.usgs.gov/nwis>). Well-identification verification procedures are described by Shelton and others (2013). Well depths and depths to the top and bottom of the screened or open interval for USGS-grid wells are listed in [table A2](#). Wells drilled in hard rock commonly do not have casings; the borehole is left open. For these wells, the top of the screened or open interval was defined as the base of the sanitary seal, and the bottom was defined as the depth of the well. Springs were not assigned a value for well depth or depths to top and bottom of the screened or open interval.

Eleven wells had data for well depth, but not for depth to the bottom of the screened or open interval ([table A2](#)). For these wells, the depth to the bottom of the screened interval was assumed to be the same as the well depth for statistical tests and for graphical presentations of the data. Of the 63 wells having data for well depth and depth to the bottom of the screened or open intervals, the two depths were equal for 48 of the wells (76 percent).

Wells were classified as production wells or springs, and production wells were further classified as shallow, overlapping, or deep wells ([table A2](#)). Production wells pump the groundwater from the aquifer to a distribution system. Wells with depths less than 200 feet below land surface (ft bls) were defined as shallow; wells with depth to the top of the screened or open interval greater than 200 ft bls were defined as deep; and wells with depth to the top of the screened or open interval less than 200 ft bls and total depth of greater than 200 ft bls were defined as overlapping. The name ‘overlapping’ refers to the fact that these wells were screened or open in both the shallow and deep parts of the primary aquifer system. Wells were classified as springs if water could flow from the aquifer into the distribution system without a pump, and if the well was either drilled horizontally or had no borehole.

**Table A2.** Hydrologic conditions and well construction information for U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[**Depth class:** deep, top of screened or open interval >200 ft; overlapping, top of screened or open interval <200 ft and bottom of screened or open interval >200 ft; shallow, bottom of screened or open interval <200 ft; unknown, no construction information available for the well. **Other abbreviations:** >, greater than; <, less than; ft; feet; LSD, land-surface datum; na, no data available; —, depths not defined for springs]

Well identification number	Hydrologic conditions		Well construction			
	Aridity index <sup>1</sup> (dimensionless)	Elevation of LSD (ft above NAVD88) <sup>2</sup>	Depth class <sup>3</sup>	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD) <sup>4</sup>
Eastside Sacramento Valley study area (ES)						
CAMP-ES-01	1.35	2,351	Overlapping	400	65	400
CAMP-ES-02	1.14	1,686	Overlapping	325	60	325
CAMP-ES-03	0.75	2,267	Spring	—	—	—
CAMP-ES-04	0.62	383	Overlapping	475	160	475
CAMP-ES-05	1.25	1,934	Deep	550	395	525
CAMP-ES-06	1.37	2,602	Deep	930	823	930
CAMP-ES-07	0.83	3,089	Shallow	80	60	80
CAMP-ES-08	0.87	3,328	Deep	386	346	386
CAMP-ES-09	0.99	1,524	Deep	730	500	730
CAMP-ES-10	1.02	1,520	Deep	770	495	760
CAMP-ES-11	1.33	2,306	Deep	480	440	480
CAMP-ES-12	1.28	2,821	Overlapping	995	93	995
CAMP-ES-13	1.16	2,054	Shallow	96	na	na
CAMP-ES-14	0.67	413	Overlapping or deep	<sup>5</sup> >285	na	na
CAMP-ES-15	0.62	294	Deep	480	206	470
Honey Lake Valley study area (HL)						
CAMP-HL-01	0.19	4,031	Overlapping	300	50	300
CAMP-HL-02	0.38	4,344	Overlapping	240	140	240
CAMP-HL-03	0.36	4,144	Unknown	<sup>5</sup> >180	na	na
CAMP-HL-04	0.33	4,097	Overlapping	600	55	600
CAMP-HL-05	0.36	4,139	Shallow	190	190	190
CAMP-HL-06	0.32	4,106	Shallow	56	40	56
CAMP-HL-07	0.21	4,011	Overlapping	200	60	200
CAMP-HL-08	0.20	4,006	Overlapping	208	60	208
CAMP-HL-09	0.22	4,133	Deep	530	220	520
CAMP-HL-10	0.22	4,123	Overlapping or deep	545	na	na
CAMP-HL-11	0.23	4,050	Overlapping	225	165	205
CAMP-HL-12	0.26	4,223	Overlapping	246	50	246
CAMP-HL-13	0.41	4,474	Shallow	130	na	na
CAMP-HL-14	0.27	4,093	Shallow	102	na	na
CAMP-HL-15	0.24	4,058	Shallow	120	110	120
Cascade Range and Modoc Plateau Low-Use Basins study area (LU)						
CAMP-LU-01	0.39	4,247	Deep	1,236	840	1,236
CAMP-LU-02	0.29	4,038	Deep	2,664	2,546	2,664
CAMP-LU-03	0.30	4,379	Deep	670	350	670
CAMP-LU-04	0.32	4,666	Overlapping	353	126	350

**Table A2.** Hydrologic conditions and well construction information for U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.—Continued

[**Depth class:** deep, top of screened or open interval >200 ft; overlapping, top of screened or open interval <200 ft and bottom of screened or open interval >200 ft; shallow, bottom of screened or open interval <200 ft; unknown, no construction information available for the well. **Other abbreviations:** >, greater than; <, less than; ft, feet; LSD, land-surface datum; na, no data available; —, depths not defined for springs]

Well identification number	Hydrologic conditions		Well construction			
	Aridity index <sup>1</sup> (dimensionless)	Elevation of LSD (ft above NAVD88) <sup>2</sup>	Depth class <sup>3</sup>	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD) <sup>4</sup>
Cascade Range and Modoc Plateau Low-Use Basins study area (LU)—Continued						
CAMP-LU-05	0.30	4,391	Deep	500	220	500
CAMP-LU-06	0.40	4,317	Overlapping	220	180	220
CAMP-LU-07	0.32	4,259	Shallow	87	59	87
CAMP-LU-08	1.53	4,184	Spring	—	—	—
CAMP-LU-09	0.34	4,400	Overlapping	310	100	310
CAMP-LU-10	0.29	4,052	Overlapping	343	100	338
CAMP-LU-11	0.39	4,225	Shallow	184	na	na
CAMP-LU-12	1.11	4,127	Shallow	146	54	146
CAMP-LU-13	0.45	4,124	Shallow	<sup>6</sup> 345	95	110
CAMP-LU-14	0.80	4,549	Overlapping	235	162	222
CAMP-LU-15	0.80	4,528	Deep	371	228	360
Quaternary Volcanic Areas study area (QV)						
CAMP-QV-01	1.38	6,887	Spring	—	—	—
CAMP-QV-02	1.74	4,919	Spring	—	—	—
CAMP-QV-03	0.32	5,014	Deep	740	400	740
CAMP-QV-04	0.31	4,090	Deep	325	211	325
CAMP-QV-05	0.54	3,200	Deep	226	226	226
CAMP-QV-06	0.37	4,197	Deep	<sup>5</sup> ≥800	<sup>5</sup> 800	<sup>5</sup> ≥800
CAMP-QV-07	0.67	3,258	Deep	300	250	300
CAMP-QV-08	0.48	3,218	Overlapping	244	184	244
CAMP-QV-09	0.81	4,985	Spring	—	—	—
CAMP-QV-10	1.01	2,260	Shallow	174	47	174
CAMP-QV-11	0.93	3,338	Shallow	170	110	170
CAMP-QV-12	0.85	2,588	Overlapping	232	3	232
CAMP-QV-13	0.90	2,957	Shallow	184	164	184
CAMP-QV-14	1.31	4,715	Deep	465	240	465
CAMP-QV-15	1.09	3,728	Shallow	150	22	150
Shasta Valley and Mount Shasta Volcanic Area study area (SH)						
CAMP-SH-01	0.48	2,744	Shallow	120	12	120
CAMP-SH-02	0.82	2,952	Overlapping	232	80	232
CAMP-SH-03	0.81	2,779	Shallow	107	na	na
CAMP-SH-04	0.90	3,721	Deep	450	200	450
CAMP-SH-05	0.79	3,778	Spring	—	—	—
CAMP-SH-06	1.07	3,684	Deep	328	288	328
CAMP-SH-07	1.32	4,465	Spring	—	—	—
CAMP-SH-08	0.70	3,302	Unknown	<sup>5</sup> >40	na	na

**Table A2.** Hydrologic conditions and well construction information for U.S. Geological Survey (USGS)-grid wells, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.—Continued

[Depth class: deep, top of screened or open interval >200 ft; overlapping, top of screened or open interval <200 ft and bottom of screened or open interval >200 ft; shallow, bottom of screened or open interval <200 ft; unknown, no construction information available for the well. Other abbreviations: >, greater than; <, less than; ft, feet; LSD, land-surface datum; na, no data available; —, depths not defined for springs]

Well identification number	Hydrologic conditions		Well construction			
	Aridity index <sup>1</sup> (dimensionless)	Elevation of LSD (ft above NAVD88) <sup>2</sup>	Depth class <sup>3</sup>	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD) <sup>4</sup>
Shasta Valley and Mount Shasta Volcanic Area study area (SH)—Continued						
CAMP-SH-09	0.55	2,576	Overlapping	230	30	225
CAMP-SH-10	0.71	2,841	Overlapping	309	132	267
CAMP-SH-11	0.65	2,762	Shallow or overlapping	<sup>9</sup> >52	52	na
CAMP-SH-12	0.47	2,642	Shallow	150	na	na
CAMP-SH-13	0.49	2,604	Spring	—	—	—
CAMP-SH-14	1.02	3,844	Shallow	140	120	140
CAMP-SH-15	0.49	2,568	Shallow	<sup>7</sup> 121	na	na
Tertiary Volcanic Areas study area (TV)						
CAMP-TV-01	0.51	2,690	Overlapping	218	175	218
CAMP-TV-02	0.67	2,953	Overlapping or deep	<sup>7</sup> >450	na	na
CAMP-TV-03	0.68	978	Spring <sup>8</sup>	—	—	—
CAMP-TV-04	0.83	3,455	Overlapping or deep	290	na	na
CAMP-TV-05	0.44	4,266	Deep	300	210	290
CAMP-TV-06	0.90	4,823	Deep	380	305	380
CAMP-TV-07	0.63	6,262	Overlapping	230	50	230
CAMP-TV-08	0.43	5,173	Overlapping	200	na	na
CAMP-TV-09	0.89	4,564	Overlapping	403	158	400
CAMP-TV-10	0.95	4,551	Overlapping or deep	<sup>5</sup> >300	na	na
CAMP-TV-11	1.60	3,767	Overlapping	202	87	202
CAMP-TV-12	1.79	4,321	Overlapping	210	170	210
CAMP-TV-13	1.73	4,220	Shallow	<sup>5</sup> 135	na	na
CAMP-TV-14	1.61	3,284	Shallow	175	155	170
CAMP-TV-15	0.43	2,273	Overlapping	275	54	275

<sup>1</sup>Aridity index is average annual precipitation divided by average annual evapotranspiration.

<sup>2</sup>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 the North American Vertical Datum 1988.

<sup>3</sup>Springs have no vertically drilled hole, and groundwater reaches the surface without a pump. The classes shallow, overlapping, and deep apply to wells. Depth class is given as 'overlapping or deep' when the well depth is greater than 200 ft, and no data are available for depth to top of screened or open interval. Depth class is given as 'overlapping or shallow' when depth to top of screened or open interval is less than 200 ft, and no data are available for well depth.

<sup>4</sup>Eleven wells did not have data for depth to the bottom of the screened or open interval, but did have data for well depth. Well-depth data were used to represent data for the depth of the bottom of the screened or open interval for these wells for statistical tests and for graphical presentations.

<sup>5</sup>Estimated from well-owner records; no driller's log available.

<sup>6</sup>Driller's log (1978) gives initial well depth as 500 ft; well owner provided video log (2005) showing depth of 345 ft.

<sup>7</sup>Estimated from measurement of well depth by USGS; no driller's log available.

<sup>8</sup>Conveyance from the TV-03 spring source to the point of use is an open channel.

<sup>9</sup>Driller's log (1972) reports installation of sanitary seal to depth of 52 ft. Owner reports hole depth and well depth greater than 52 ft.



The climate at each well site was represented by an aridity index (United Nations Environment Programme, 1997; United Nations Educational, Scientific, and Cultural Organization, 1979; [table A2](#)):

$$\text{aridity index} = \frac{\text{average annual precipitation}}{\text{average annual evapotranspiration}} \quad (\text{A1})$$

Greater values of the index correspond to wetter conditions. Values less than 0.05 are defined as hyper-arid, 0.05–0.20 as arid, 0.20–0.50 as semi-arid, 0.50–0.65 as dry sub-humid, 0.65–1.00 as humid, and greater than 1.00 as wet. 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, 2007). 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 reference evapotranspiration values (California Irrigation Management Information System, 2005; Alan Flint, California Water Science Center, commun., 2009).

Elevation of the intersection of the well or spring and the land surface was used as a proxy for relative position in the groundwater-flow system. The study unit had a large range in elevation of well sites—approximately 300 ft to 7,000 ft. Elevations were obtained from U.S. Geological Survey digital elevation GIS coverage and are reported in feet relative to NAVD 88 ([table A2](#)).

## Groundwater Age Classification

Groundwater dating techniques provide estimates of the time elapsed since a given parcel of groundwater entered the saturated zone and was no longer in contact with the atmosphere. The techniques used in this report to estimate groundwater residence times or ‘age’ were those based on tritium ( $^3\text{H}$ ) (for example, Tolstikhin and Kamensky, 1969; Torgersen and others, 1979), and carbon-14 ( $^{14}\text{C}$ ) activity (for example, Vogel and Ehhalt, 1963; Plummer and others, 1993).

Tritium ( $^3\text{H}$ ) is a short-lived radioactive isotope of hydrogen with a half-life of 12.32 years (Lucas and Unterweger, 2000). It is produced naturally in the atmosphere from the interaction of cosmogenic radiation with nitrogen (Craig and Lal, 1961), or, anthropogenically, by above-ground nuclear weapons testing (peak 1952 to 1963, Michel, 1989) and by the operation of nuclear reactors. Tritium enters the hydrologic cycle following exchange with protium ( $^1\text{H}$ ) in water to form tritiated water. Above-ground nuclear testing resulted in a large increase in tritium values in precipitation, beginning in about 1952 and peaking in 1963 at values of over

1,000 tritium units (TU) in the northern hemisphere (Michel, 1989).

Previous investigations have used a range of tritium values from 0.2 to 1.0 TU as minimum thresholds for indicating the presence of water that has been in contact with the atmosphere since 1952 (Michel, 1989; Plummer and others, 1993; Michel and Schroeder, 1994; Clark and Fritz, 1997; Manning and others, 2005; Landon and others, 2010). For samples collected for the CAMP study unit in 2010, tritium values greater than 0.5 TU were defined as indicating a predominance of groundwater recharged since 1952. The threshold value of 0.5 TU was selected because background tritium values in California precipitation at the latitudes and longitudes corresponding to the CAMP study unit are approximately 4 to 5 TU (Robert Michel, USGS, written commun., 2012). Radioactive decay of tritium in water with a tritium value of 5 TU in 1950 would result in a tritium value of 0.2 TU in 2010.

Carbon-14 ( $^{14}\text{C}$ ) is a widely used chronometer that is based on the radiocarbon content of organic and inorganic carbon.  $^{14}\text{C}$  is formed in the atmosphere by the interaction of cosmic-ray neutrons with nitrogen and, to a lesser degree, with oxygen and carbon.  $^{14}\text{C}$  is incorporated into carbon dioxide and mixed throughout the atmosphere. The carbon dioxide dissolves in precipitation, which eventually recharges the aquifer. As a result, dissolved inorganic carbon species (primarily carbonic acid, bicarbonate, and carbonate) are commonly used for  $^{14}\text{C}$  dating of groundwater.  $^{14}\text{C}$  activity in groundwater reflects the time elapsed since groundwater was last exposed to the atmospheric  $^{14}\text{C}$  source.  $^{14}\text{C}$  has a half-life of 5,730 years and can be used to estimate groundwater ages ranging from 1,000 to approximately 30,000 years before the present (Clark and Fritz, 1997).

$^{14}\text{C}$  data can be reported in units of percent Modern (pM) or in units of percent modern carbon (pmc).  $^{14}\text{C}$  data for the CAMP study unit in Shelton and others (2013) are given in pM units, as reported by the analyzing laboratory, and have been normalized for carbon isotopic fractionation based on a  $\delta^{13}\text{C}$  value of  $-25$  per mil (parts per thousand). The un-normalized  $^{14}\text{C}$  data in pmc units are used in this report. Data were converted from pM to pmc by using this equation, derived from Plummer and others (2004):

$$\text{pmc} = \frac{\text{pM} \left( 1 + \frac{\delta^{13}\text{C}}{1000} \right)^2}{0.975^2} \quad (\text{A2})$$

where

$\text{pM}$  is the  $^{14}\text{C}$  value in units of pM, and  
 $\delta^{13}\text{C}$  is the measured  $^{13}\text{C}$  composition in units of per mil

The  $^{14}\text{C}$  pmc values in this study are referred to as “uncorrected” because they are not adjusted to consider water-rock interactions, such as exchanges with sedimentary sources of carbon (Fontes and Garnier, 1979). Measured values of percent modern carbon can be greater than 100 pmc because the definition of the  $^{14}\text{C}$  content in “modern” carbon does not include the excess  $^{14}\text{C}$  produced in the atmosphere by above-ground nuclear weapons testing. For samples collected for the CAMP study unit in 2010,  $^{14}\text{C}$  values greater than 90 pmc were defined as indicating the presence of some groundwater recharged since 1952. This threshold of 90 pmc was selected because nearly all samples with tritium values less than 0.50 TU also had  $^{14}\text{C}$  values less than 90 pmc.

The age distributions in groundwater samples were classified as pre-modern, modern, or mixed, by using the thresholds for tritium and  $^{14}\text{C}$  values as shown in [table A3](#). Samples with tritium greater than 0.5 TU and  $^{14}\text{C}$  greater than or equal to 90 pmc were classified as modern; samples with tritium less than 0.5 TU were classified as pre-modern; all other samples were classified as mixed. Tritium concentrations, uncorrected  $^{14}\text{C}$  percent modern carbon, and age classifications for the samples are listed in [table A4](#).

**Table A3.** Tritium and carbon-14 threshold values used for groundwater age classification for the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[**Groundwater age classification:** mixed, groundwater containing components recharged before and after 1952; modern, groundwater recharged since 1952; pre-modern, groundwater recharged before 1952. **Abbreviations:** pmc, percent modern carbon; TU, tritium units; <, less than; ≥, greater than or equal to]

Age class	Number of samples	Threshold values	
		Tritium (TU)	Carbon-14 (pmc)
Pre-modern	33	<0.5	Any
Mixed	20	≥0.5	<90
Modern	34	≥0.5	≥90
Modern or mixed	3	≥0.5	No data

**Table A4.** Tritium, carbon-14 data, and groundwater age classes, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[**Well identification numbers:** ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Groundwater age classification:** mixed, groundwater containing components recharged before and after 1952; modern, groundwater recharged since 1952; pre-modern, groundwater recharged before 1952. **Other abbreviations:** ID, identification; na, not available; pmc, percent modern carbon; TU, tritium units; <, less than]

Well ID number	Tritium (TU)	Carbon-14 (pmc)	Groundwater age classification
Eastside Sacramento Valley study area (ES)			
CAMP-ES-01	2.03	106	Modern
CAMP-ES-02	2.13	112	Modern
CAMP-ES-03	0.15	79	Pre-modern
CAMP-ES-04	1.56	88	Mixed
CAMP-ES-05	0.37	91	Pre-modern
CAMP-ES-06	0.47	97	Pre-modern
CAMP-ES-07	1.06	94	Modern
CAMP-ES-08	0.84	94	Modern
CAMP-ES-09	0.34	86	Pre-modern
CAMP-ES-10	0.15	89	Pre-modern
CAMP-ES-11	1.44	100	Modern
CAMP-ES-12	1.91	115	Modern
CAMP-ES-13	2.78	115	Modern
CAMP-ES-14	0.12	95	Pre-modern
CAMP-ES-15	0.87	98	Modern
Honey Lake Valley study area (HL)			
CAMP-HL-01	0.00	26	Pre-modern
CAMP-HL-02	0.50	55	Pre-modern
CAMP-HL-03	0.47	68	Pre-modern
CAMP-HL-04	0.21	65	Pre-modern
CAMP-HL-05	1.78	81	Mixed
CAMP-HL-06	2.63	102	Modern
CAMP-HL-07	<0.03	34	Pre-modern
CAMP-HL-08	0.12	56	Pre-modern
CAMP-HL-09	<0.03	59	Pre-modern
CAMP-HL-10	0.31	69	Pre-modern
CAMP-HL-11	1.50	83	Mixed
CAMP-HL-12	0.53	92	Modern
CAMP-HL-13	0.59	101	Modern
CAMP-HL-14	0.03	51	Pre-modern
CAMP-HL-15	0.43	86	Pre-modern

**Table A4.** Tritium, carbon-14 data, and groundwater age classes, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.—Continued

[**Well identification numbers:** ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Groundwater age classification:** mixed, groundwater containing components recharged before and after 1952; modern, groundwater recharged since 1952; pre-modern, groundwater recharged before 1952. **Other abbreviations:** ID, identification; na, not available; pmc, percent modern carbon; TU, tritium units; <, less than]

Well ID number	Tritium (TU)	Carbon-14 (pmc)	Groundwater age classification	Well ID number	Tritium (TU)	Carbon-14 (pmc)	Groundwater age classification
Cascade Range and Modoc Plateau Low-Use Basins study area (LU)				Shasta Valley and Mount Shasta Volcanic Area study area (SH)			
CAMP-LU-01	0.00	25	Pre-modern	CAMP-SH-01	3.07	84	Mixed
CAMP-LU-02	0.09	10	Pre-modern	CAMP-SH-02	0.87	60	Mixed
CAMP-LU-03	0.50	59	Pre-modern	CAMP-SH-03	2.66	101	Modern
CAMP-LU-04	3.19	95	Modern	CAMP-SH-04	0.12	49	Pre-modern
CAMP-LU-05	0.37	58	Pre-modern	CAMP-SH-05	0.75	50	Mixed
CAMP-LU-06	0.03	33	Pre-modern	CAMP-SH-06	1.50	73	Mixed
CAMP-LU-07	0.94	99	Modern	CAMP-SH-07	2.53	110	Modern
CAMP-LU-08	4.10	112	Modern	CAMP-SH-08	1.12	69	Mixed
CAMP-LU-09	<0.03	71	Pre-modern	CAMP-SH-09	2.13	98	Modern
CAMP-LU-10	0.09	85	Pre-modern	CAMP-SH-10	2.00	76	Mixed
CAMP-LU-11	0.68	90	Modern	CAMP-SH-11	2.63	94	Modern
CAMP-LU-12	3.32	na	Mixed or modern	CAMP-SH-12	1.69	94	Modern
CAMP-LU-13	1.97	92	Modern	CAMP-SH-13	1.75	48	Mixed
CAMP-LU-14	2.35	85	Mixed	CAMP-SH-14	3.57	101	Modern
CAMP-LU-15	2.47	98	Modern	CAMP-SH-15	1.88	100	Modern
Quaternary Volcanic Areas study area (QV)				Tertiary Volcanic Areas study area (TV)			
CAMP-QV-01	2.85	112	Modern	CAMP-TV-01	14.32	43	Mixed
CAMP-QV-02	2.72	113	Modern	CAMP-TV-02	1.09	89	Mixed
CAMP-QV-03	<0.03	6	Pre-modern	CAMP-TV-03	1.69	56	Mixed
CAMP-QV-04	1.84	86	Mixed	CAMP-TV-04	0.15	72	Pre-modern
CAMP-QV-05	0.62	na	Mixed or modern	CAMP-TV-05	0.03	78	Pre-modern
CAMP-QV-06	3.19	51	Mixed	CAMP-TV-06	2.13	80	Mixed
CAMP-QV-07	1.88	91	Modern	CAMP-TV-07	<0.03	87	Pre-modern
CAMP-QV-08	0.90	89	Mixed	CAMP-TV-08	0.28	53	Pre-modern
CAMP-QV-09	1.03	92	Modern	CAMP-TV-09	0.09	52	Pre-modern
CAMP-QV-10	0.47	95	Pre-modern	CAMP-TV-10	1.15	98	Modern
CAMP-QV-11	1.19	96	Modern	CAMP-TV-11	2.88	94	Modern
CAMP-QV-12	2.57	110	Modern	CAMP-TV-12	2.72	na	Mixed or modern
CAMP-QV-13	1.25	49	Mixed	CAMP-TV-13	2.31	104	Modern
CAMP-QV-14	0.06	59	Pre-modern	CAMP-TV-14	2.31	109	Modern
CAMP-QV-15	3.63	78	Mixed	CAMP-TV-15	0.25	54	Pre-modern

Although more sophisticated lumped parameter models that incorporate mixing could have been used for analyzing groundwater age distributions (for example, Cook and Böhlke, 2000; Jurgens and others, 2012), use of these models to understand age mixtures was beyond the scope of this report.

Instead, classification into modern (primarily recharged after 1952), mixed, and pre-modern (primarily recharge before 1952) groundwater age classes was sufficient to provide an appropriate and useful characterization for examining groundwater quality at the study area and study unit scale.

## Geochemical Conditions

Geochemical conditions investigated as potential explanatory factors in this report include oxidation-reduction characteristics and pH. Oxidation-reduction (redox) conditions can influence the mobility of many organic and inorganic constituents (McMahon and Chapelle, 2008). Redox conditions along groundwater flow paths commonly proceed along a well-documented sequence of Terminal Electron Acceptor Processes (TEAP), in which a single TEAP typically dominates at a particular time and aquifer location (Chapelle and others, 1995; Chapelle, 2001). As electron acceptors are depleted along groundwater flow paths, the typical TEAP sequence is oxygen reduction (oxic), followed, in turn, by nitrate reduction, manganese reduction, iron reduction, sulfate reduction, and methanogenesis. This sequence is the order predicted from equilibrium thermodynamics and corresponds to progressively decreasing oxidation-reduction potentials. However, the kinetics of many TEAPs are slow, and the reactions typically only proceed at significant rates when mediated by biological catalysis (Stumm and Morgan, 1996; Appelo and Postma, 2005). Microbes present in groundwater and on aquifer sediment or rock produce enzymes that catalyze the reactions (Stumm and Morgan, 1996; Appelo and Postma, 2005). The microbes couple reduction of these inorganic species to oxidation of organic matter to produce energy needed for metabolism and growth. Groundwater samples can contain redox-active chemical species that indicate more than

one TEAP is operating. Evidence for more than one TEAP may indicate mixing of waters from different redox zones upgradient of the well, a well that is screened across more than one redox zone, or spatial heterogeneity in microbial activity in the aquifer. In addition, different redox couples sometimes are not consistent with one another, indicating the presence of electrochemical disequilibrium, complicating the assessments of redox conditions (Lindberg and Runnells, 1984; Appelo and Postma, 2005).

In this report, oxidation-reduction conditions were represented in two ways: by dissolved oxygen (DO) concentrations and by classified oxidation-reduction condition. The DO concentrations were measured at USGS-grid wells (Shelton and others, 2013). Oxidation-reduction conditions were classified on the basis of the DO, nitrate, manganese, and iron concentrations by using a modified version of the classification scheme of McMahon and Chapelle (2008) and Jurgens and others (2009) (*tables A5, A6*). The modification was that the DO threshold for separating oxic from anoxic groundwater was increased from 0.5 milligrams per liter (mg/L) to 1 mg/L. Anoxic conditions were further classified as suboxic, nitrate-reducing, manganese-reducing, or manganese- and iron-reducing. Samples were classified as mixed if the DO concentration was greater than or equal to 1 mg/L, and manganese or iron concentrations were greater than the thresholds for indicating manganese-reducing or iron-reducing conditions (*table A5, A6*).

**Table A5.** Oxidation-reduction classification system applied to U.S. Geological Survey (USGS)-grid wells from the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Anoxic sub-classes: NO<sub>3</sub>-red, nitrate-reducing; Mn-red, manganese-reducing; Fe-red, iron-reducing. Units: mg/L, milligrams per liter; µg/L, micrograms per liter. Other abbreviations: ≥, greater than or equal to; >, greater than; ≤, less than or equal to; <, less than; Any, any concentration]

Category	Number of samples	Dissolved oxygen (mg/L)	Nitrate, as nitrogen (mg/L)	Manganese (µg/L)	Iron (µg/L)
Oxic class					
Oxic	72	≥1	Any	<50	<100
Anoxic classes					
Suboxic	7	<1	<0.5	<50	<100
NO <sub>3</sub> -red	0	<1	≥0.5	<50	<100
NO <sub>3</sub> -red, Mn-red	1	<1	≥0.5	≥50	<100
Mn-red	2	<1	<0.5	≥50	<100
Fe-red	1	<1	<0.5	<50	≥100
Mn-red, Fe-red	2	<1	<0.5	≥50	<100
Mixed classes					
Mixed (oxic - anoxic Mn-red)	2	≥1	Any	≥50	<100
Mixed (oxic - anoxic Fe-red)	1	≥1	Any	Any	≥100
Mixed (oxic - anoxic Mn-red, Fe-red)	2	≥1	Any	≥50	≥100

**Table A6.** Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic and iron, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Well identification numbers: CAMP, Cascade Range and Modoc Plateau study unit; ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Oxidation-reduction classification:** See table A5. Anoxic sub-classes: Mn-red, manganese-reducing; Fe-red, iron-reducing; NO<sub>3</sub>-red, nitrate-reducing. **Units:** mg/L, milligrams per liter; µg/L, micrograms per liter. **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:** >, greater than; <, less than; —, concentration too low to measure ratio]

Well identification number	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification <sup>1</sup>		Ratios of oxidized and reduced species of metals	
			Redox class	Subclass of anoxic/mixed	Fe(III)/ Fe(II)	As(V)/ As(III)
Eastside Sacramento Valley study area (ES)						
CAMP-ES-01	6.2	5.6	Oxic	—	—	>10
CAMP-ES-02	6.2	9.8	Oxic	—	—	—
CAMP-ES-03	7.2	4.7	Oxic	—	—	>10
CAMP-ES-04	7.2	1.3	Oxic	—	—	>10
CAMP-ES-05	6.7	9.8	Oxic	—	—	—
CAMP-ES-06	6.8	10.3	Oxic	—	—	—
CAMP-ES-07	6.6	6.6	Oxic	—	—	>10
CAMP-ES-08	6.6	6.2	Oxic	—	—	—
CAMP-ES-09	7.5	6.0	Oxic	—	—	>10
CAMP-ES-10	6.7	7.4	Oxic	—	na	na
CAMP-ES-11	6.6	7.4	Oxic	—	—	—
CAMP-ES-12	5.8	5.3	Mixed	Fe-red	>10	—
CAMP-ES-13	6.0	5.5	Oxic	—	—	—
CAMP-ES-14	7.2	6.2	Oxic	—	—	>10
CAMP-ES-15	7.1	6.8	Oxic	—	—	>10
Honey Lake Valley study area (HL)						
CAMP-HL-01	8.8	6.7	Oxic	—	—	<sup>2</sup> >10
CAMP-HL-02	7.6	1.0	Oxic	—	<0.01	>10
CAMP-HL-03	7.7	0.9	Anoxic	Suboxic	—	<sup>2</sup> >10
CAMP-HL-04	7.6	4.2	Oxic	—	—	>10
CAMP-HL-05	7.0	8.3	Oxic	—	—	>10
CAMP-HL-06	6.4	7.8	Oxic	—	—	>10
CAMP-HL-07	7.9	0.6	Anoxic	Mn-red	0.03	<sup>2</sup> 0.4
CAMP-HL-08	9.2	0.4	Anoxic	Suboxic	<0.01	<0.01
CAMP-HL-09	7.6	6.4	Mixed	Mn-red	>10	0.8
CAMP-HL-10	7.0	1.5	Mixed	Mn-red, Fe-red	0.13	>10
CAMP-HL-11	7.8	<0.2	Anoxic	NO <sub>3</sub> -red, Mn-red	0.08	<sup>3</sup> >10
CAMP-HL-12	7.3	4.4	Oxic	—	—	>10
CAMP-HL-13	6.5	7.5	Oxic	—	—	—
CAMP-HL-14	7.8	0.4	Anoxic	Suboxic	—	>10
CAMP-HL-15	8.0	1.1	Oxic	—	—	<sup>3</sup> >10
Cascade Range and Modoc Plateau Low-Use Basins study area (LU)						
CAMP-LU-01	8.4	<sup>2</sup> 0.2	Anoxic	Suboxic	—	—
CAMP-LU-02	7.3	<0.2	Anoxic	Fe-red	<0.01	—
CAMP-LU-03	8.0	1.5	Oxic	—	—	>10



**Table A6.** Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic and iron, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Well identification numbers: CAMP, Cascade Range and Modoc Plateau study unit; ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Oxidation-reduction classification:** See table A5. Anoxic sub-classes: Mn-red, manganese-reducing; Fe-red, iron-reducing; NO<sub>3</sub>-red, nitrate-reducing. **Units:** mg/L, milligrams per liter; µg/L, micrograms per liter. **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:** >, greater than; <, less than; —, concentration too low to measure ratio]

Well identification number	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification <sup>1</sup>		Ratios of oxidized and reduced species of metals	
			Redox class	Subclass of anoxic/mixed	Fe(III)/ Fe(II)	As(V)/ As(III)
Cascade Range and Modoc Plateau Low-Use Basins study area (LU)—Continued						
CAMP-LU-04	7.8	8.5	Oxic	—	—	>10
CAMP-LU-05	7.5	1.9	Oxic	—	—	<sup>2</sup> >10
CAMP-LU-06	7.9	0.2	Anoxic	Suboxic	<0.01	—
CAMP-LU-07	7.0	5.7	Oxic	—	—	—
CAMP-LU-08	6.3	10.9	Oxic	—	—	—
CAMP-LU-09	8.0	1.6	Oxic	—	1.22	>10
CAMP-LU-10	7.8	0.2	Anoxic	Mn-red, Fe-red	0.19	—
CAMP-LU-11	7.0	7.0	Oxic	—	—	>10
CAMP-LU-12	6.6	8.9	Oxic	—	—	>10
CAMP-LU-13	6.9	1.0	Mixed	Mn-red, Fe-red	>10	>10
CAMP-LU-14	7.1	7.9	Oxic	—	—	>10
CAMP-LU-15	7.3	7.2	Oxic	—	—	>10
Quaternary Volcanic Areas study area (QV)						
CAMP-QV-01	5.7	12.0	Oxic	—	—	—
CAMP-QV-02	6.3	11.0	Oxic	—	—	—
CAMP-QV-03	7.3	0.8	Anoxic	Mn-red, Fe-red	0.20	—
CAMP-QV-04	7.9	1.0	Mixed	Mn-red	0.09	<sup>2</sup> 1.8
CAMP-QV-05	7.5	10.4	Oxic	—	—	—
CAMP-QV-06	8.5	3.0	Oxic	—	—	>10
CAMP-QV-07	7.6	9.8	Oxic	—	—	—
CAMP-QV-08	7.4	7.3	Oxic	—	—	>10
CAMP-QV-09	7.2	10.0	Oxic	—	—	—
CAMP-QV-10	6.8	7.4	Oxic	—	—	—
CAMP-QV-11	6.4	6.3	Oxic	—	—	—
CAMP-QV-12	6.3	4.6	Oxic	—	—	—
CAMP-QV-13	6.7	8.7	Oxic	—	—	>10
CAMP-QV-14	8.5	3.6	Oxic	—	4.55	>10
CAMP-QV-15	6.5	9.8	Oxic	—	—	>10
Shasta Valley and Mount Shasta Volcanic Area study area (SH)						
CAMP-SH-01	6.8	5.0	Oxic	—	—	—
CAMP-SH-02	6.6	4.7	Oxic	—	—	<sup>3</sup> >10
CAMP-SH-03	7.3	4.7	Oxic	—	—	>10

**Table A6.** Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic and iron, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Well identification numbers: CAMP, Cascade Range and Modoc Plateau study unit; ES, Sacramento Valley Eastside study area; HL, Honey Lake Valley study area; LU, Cascade Range and Modoc Plateau Low-Use Basins study area; QV, Quaternary Volcanic Areas study area; SH, Shasta Valley and Mount Shasta Volcanic Area study area; TV, Tertiary Volcanic Areas study area. **Oxidation-reduction classification:** See *table A5*. Anoxic sub-classes: Mn-red, manganese-reducing; Fe-red, iron-reducing; NO<sub>3</sub>-red, nitrate-reducing. **Units:** mg/L, milligrams per liter; µg/L, micrograms per liter. **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:** >, greater than; <, less than; —, concentration too low to measure ratio]

Well identification number	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification <sup>1</sup>		Ratios of oxidized and reduced species of metals	
			Redox class	Subclass of anoxic/mixed	Fe(III)/ Fe(II)	As(V)/ As(III)
Shasta Valley and Mount Shasta Volcanic Area study area (SH)—Continued						
CAMP-SH-04	7.2	4.4	Oxic	—	—	>10
CAMP-SH-05	6.4	10.6	Oxic	—	—	>10
CAMP-SH-06	6.5	9.3	Oxic	—	—	—
CAMP-SH-07	6.3	10.8	Oxic	—	—	—
CAMP-SH-08	6.7	4.0	Oxic	—	—	>10
CAMP-SH-09	6.9	5.8	Oxic	—	—	—
CAMP-SH-10	6.8	3.2	Oxic	—	—	>10
CAMP-SH-11	7.2	0.3	Anoxic	Suboxic	—	>10
CAMP-SH-12	7.1	7.2	Oxic	—	—	<sup>2</sup> >10
CAMP-SH-13	6.6	9.3	Oxic	—	—	>10
CAMP-SH-14	6.3	10.5	Oxic	—	0.32	—
CAMP-SH-15	7.3	0.2	Anoxic	Mn-red	0.21	—
Tertiary Volcanic Areas study area (TV)						
CAMP-TV-01	7.9	0.8	Anoxic	Suboxic	—	>10
CAMP-TV-02	7.2	8.2	Oxic	—	<0.01	>10
CAMP-TV-03	6.9	11.2	Oxic	—	—	>10
CAMP-TV-04	7.6	7.4	Oxic	—	—	>10
CAMP-TV-05	7.5	6.9	Oxic	—	—	—
CAMP-TV-06	8.0	9.4	Oxic	—	—	—
CAMP-TV-07	7.8	7.5	Oxic	—	—	—
CAMP-TV-08	8.3	5.9	Oxic	—	—	>10
CAMP-TV-09	7.5	4.9	Oxic	—	—	>10
CAMP-TV-10	6.2	8.1	Oxic	—	—	—
CAMP-TV-11	7.0	7.9	Oxic	—	—	—
CAMP-TV-12	6.8	8.6	Oxic	—	0.15	—
CAMP-TV-13	6.6	8.6	Oxic	—	—	—
CAMP-TV-14	5.8	7.8	Oxic	—	1.48	—
CAMP-TV-15	9.3	4.9	Oxic	—	—	0.29

<sup>1</sup>Oxidation-reduction classification criteria are given in *table A5*.

<sup>2</sup>Arsenic concentration between 5 and 10 µg/L (moderate relative-concentration).

<sup>3</sup>Arsenic concentration greater than 10 µg/L (high relative-concentration).

Arsenic and iron occur as different species depending on the redox state of the groundwater. The ratio of the amount of the more oxidized species to the amount of the more reduced species for each constituent can provide information about the progress of the TEAP involving the constituent. The following ratios are reported in *table A6*:

$$As^{+5} / As^{+3} \quad (A3)$$

where

$As^{+5}$  is the amount of arsenic present in the more oxidized +5 oxidation state (arsenate), and  
 $As^{+3}$  is the amount of arsenic present in the more reduced +3 oxidation state (arsenite);

$$Fe^{+3} / Fe^{+2} \quad (A4)$$

where

$Fe^{+3}$  is the amount of iron present in the more oxidized +3 oxidation state (ferric iron), and  
 $Fe^{+2}$  is the amount of iron present in the more reduced +2 oxidation state (ferrous iron).

Total concentrations of As and Fe and concentrations of  $As^{+3}$  and  $Fe^{+2}$  were reported by Shelton and others (2013). The concentrations of  $As^{+5}$  and  $Fe^{+3}$  were calculated from these data by difference.  $As^{+5}/As^{+3}$  was reported as greater than 10 if the total arsenic concentration was above the reporting limit and  $As^{+3}$  was not detected and as less than 0.01 if the total arsenic concentration equaled the  $As^{+3}$  concentration. Similarly,  $Fe^{+3}/Fe^{+2}$  was reported as greater than 10 if the total iron concentrations was above the reporting limit and  $Fe^{+2}$  was not detected and as less than 0.01 if the total iron concentration equaled the  $Fe^{+2}$  concentration.

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## Appendix B: Comparison of California Department of Public Health and U.S. Geological Survey-Groundwater Ambient Monitoring and Assessment Program Data

Major-ion data for the 90 U.S. Geological Survey (USGS)-grid wells were compared with major ion data from wells in the California Department of Public Health (CDPH) database for the Cascade Range and Modoc Plateau (CAMP) study unit to evaluate whether the USGS-grid wells were representative of the range of groundwater types pumped by wells used for municipal and community drinking-water supply in the CAMP study unit. The CDPH well dataset consisted of all wells with a complete major ion analysis between September 16, 2007, and September 16, 2010. If multiple analyses were available, the most recent one with an acceptable cation-anion balance was selected. The datasets were compared by using Piper diagrams (Piper, 1944; Hem, 1985). Groundwater types were defined on a Piper diagram according to the cations and anions present in the greatest proportions (*fig. B1A*).

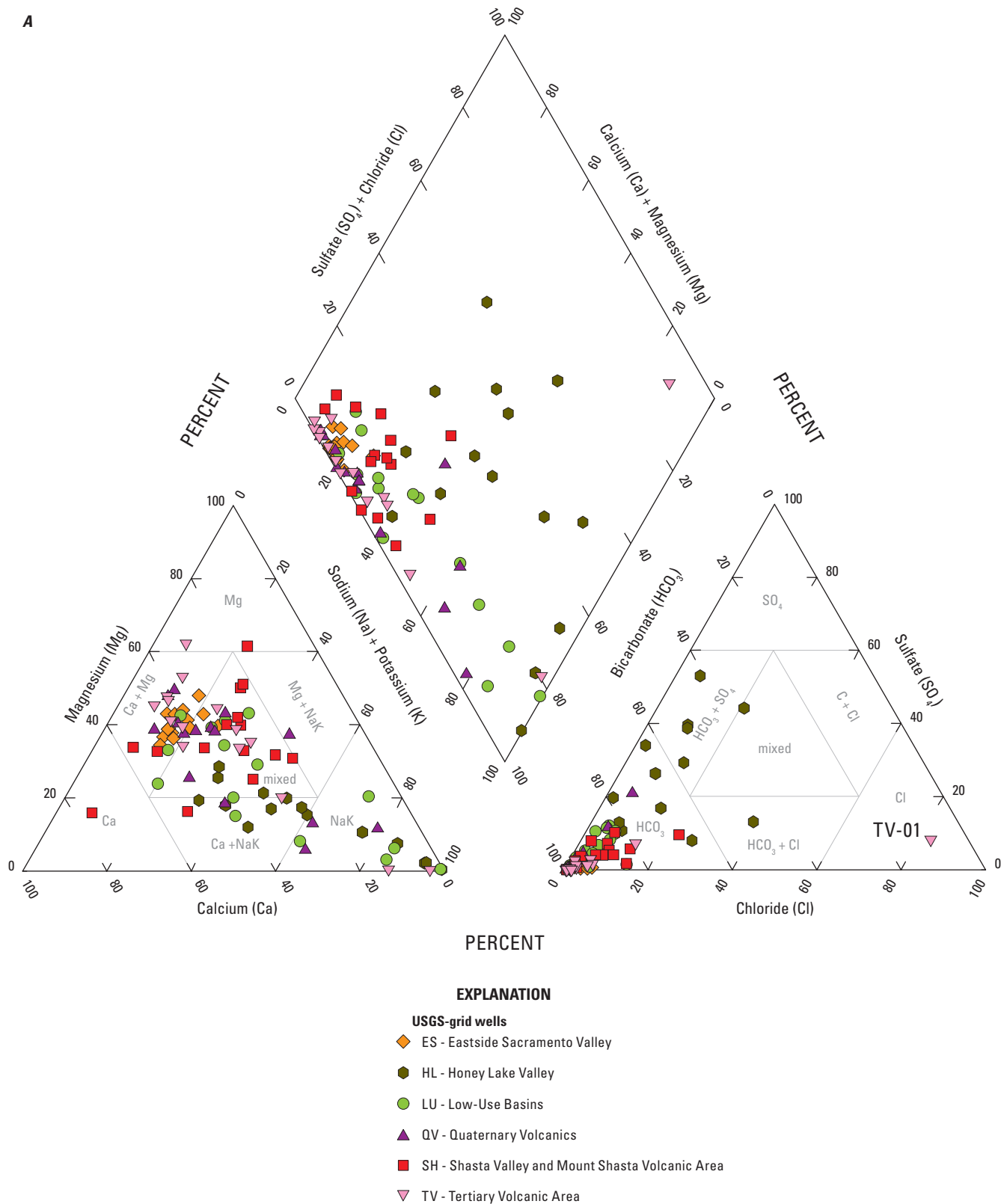
For electroneutrality, the total concentrations of positive charges in a water sample, expressed as milliequivalents of cations per liter, must equal the total concentration of negative charges, expressed as milliequivalents of anions per liter; thus, cation-anion balance is a test of the internal consistency of a major-ion analysis (Hem, 1985). An acceptable cation-anion balance was defined as one for which the difference between the total cation and anion concentrations, both expressed in milliequivalents per liter, was no greater than 10 percent of the total. Of the 234 CDPH wells with data available in the 3-year period, 45 had major-ion analyses, and 44 of those had major-ion analyses with acceptable cation-anion balance. The major-ion analyses for all 90 USGS-grid wells had acceptable cation-anion balance.

The anion compositions of most of the CDPH wells (93 percent) and the USGS-grid wells (92 percent) were classified as bicarbonate-type ( $\text{HCO}_3^-$ ) waters (*fig. B1B*). The median fraction of sulfate ( $\text{SO}_4^{2-}$ ) in the anions was greater in the USGS-grid wells than in the CDPH wells (Wilcoxon rank-sum test,  $p=0.019$ ; Helsel and Hirsch, 2002), reflecting sampling of  $\text{HCO}_3^-$ - $\text{SO}_4^{2-}$ -type groundwater in the HL study area by USGS-GAMA that was not present in the CDPH dataset. The cation compositions of a majority of the CDPH wells (82 percent) and the USGS-grid wells (69 percent) were classified as calcium-magnesium (Ca-Mg)-type or mixed-cation-type waters (*fig. B1B*). A greater proportion of USGS-grid wells had more than 40 percent sodium-potassium (NaK) in the cations than did CDPH wells (contingency table test,  $p=0.029$ ; Helsel and Hirsch, 2002), primarily reflecting sampling of NaK-type and Ca-NaK-type groundwaters in the HL, LU, QV, and TV study areas by USGS-GAMA that were not present in the CDPH dataset. The reason for the differences between the two datasets is unknown.

Trace element, nutrient, and radioactive constituent data from the USGS-grid wells were compared to the most recent data from the CDPH database for samples collected between September 16, 2007, and September 16, 2010, from the same wells. The purpose of this comparison was to evaluate the quality of the data in the CDPH database. If data from USGS and CDPH for the same wells showed acceptable agreement, then the quality of the CDPH data from wells without USGS data were considered acceptable for use in the spatially weighted calculations of aquifer-scale proportions. Only constituents having one or more detections with a RC greater than 0.5 in either dataset were examined. Sixty-one USGS-grid wells had data for one or more constituents in the CDPH database; however, the number of wells with data in the CDPH database varied considerably among the constituents. Nitrate was the only constituent for which there were more than 35 wells with data from both datasets. Both datasets were recensored to the most common reporting limit used in the CDPH database (*table B1*) for each constituent for these comparisons.

The comparisons for each constituent were made in two ways: linear regression and percentage of wells with concentration above a threshold (*table B1*). The slope, intercept, and coefficient of determination ( $r^2$ ) of the linear regression were compared to values for one-to-one line (slope = 1, intercept = 0,  $r^2 = 1$ ) to evaluate the agreement between the two datasets. The percentage of wells with concentrations above a threshold in each dataset was compared to evaluate whether use of one dataset or the other would affect results for aquifer-scale proportions. In most cases, the threshold used for this test corresponded to a RC equal to 0.5. A threshold corresponding to a RC equal to 0.333 was used for the trace-element lead in order to have a sufficient number of samples with concentrations above the threshold. The 90 percent confidence interval for the percentage above the threshold calculated from USGS data was determined by using the Jeffrey's interval for the binomial proportion (Belitz and others, 2010).

Sufficient data were available to make comparisons for 10 constituents. For nitrate, arsenic, vanadium, chloride, manganese, and TDS, the two datasets had acceptable agreement. The percentages of wells with concentration above the threshold based on CDPH data were within the 90 percent confidence intervals around the percentages of wells with concentration above the threshold based on USGS data (*table B1*). The slopes of the linear regressions were between 0.75 and 1.1, the intercepts were close to zero, and the  $r^2$  values were greater than 0.85 (*table B1*; *fig. B2*).



**Figure B1.** Piper diagrams showing *A*, samples collected by the U.S. Geological Survey (USGS) for the study unit; and *B*, wells in the California Department of Public Health (CDPH) database having major-ion chemical analyses with acceptable cation-anion balance during the time period September 16, 2007, through September 17, 2010, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

***B***



**Table B1.** Results of comparisons between concentrations of constituents in samples from wells with U.S. Geological Survey (USGS) data and data in the California Department of Public Health (CDPH) database during the time period September 16, 2007, through September 17, 2010, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project

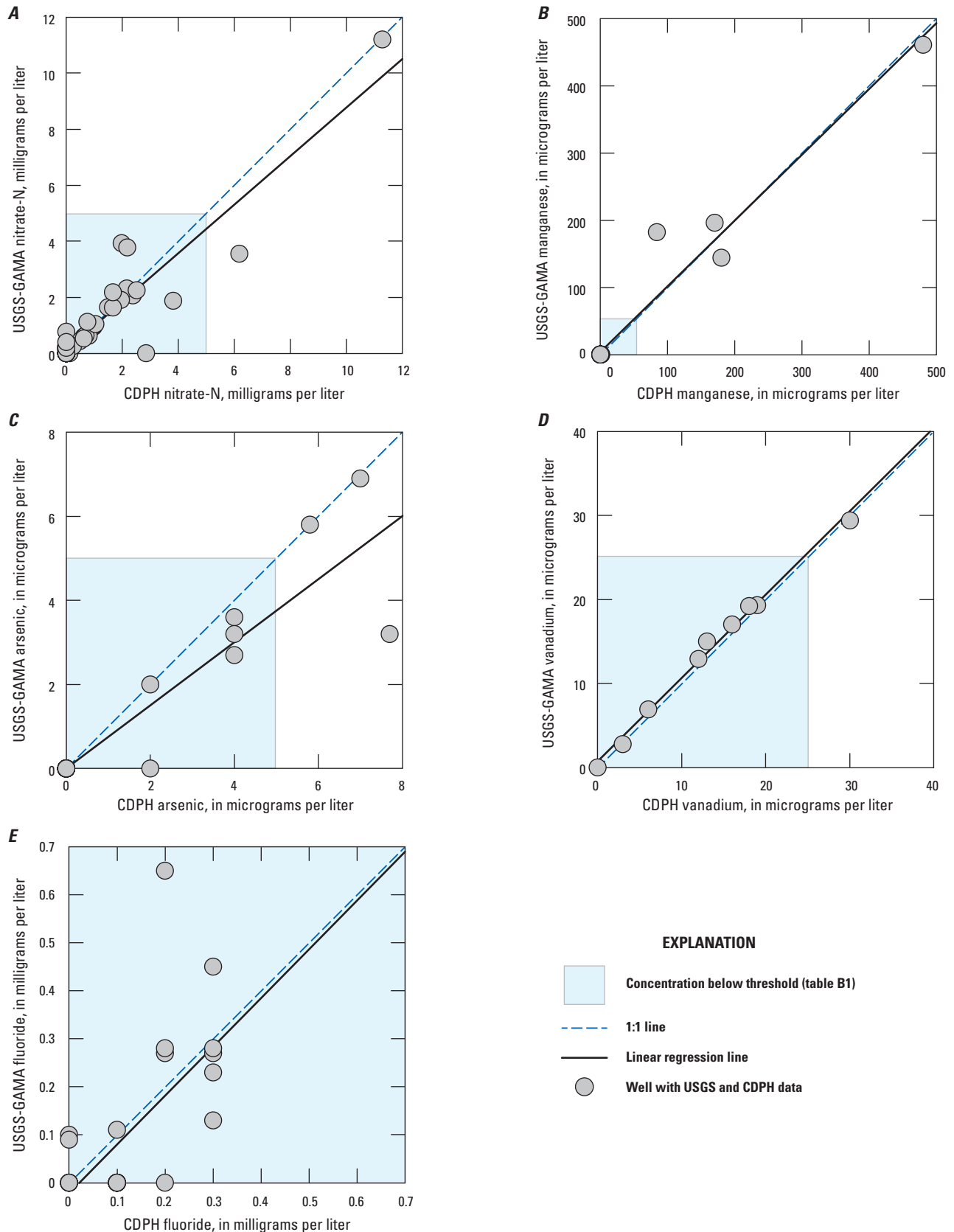
[Both datasets were censored to the most common reporting limit for data from the CDPH database (RL). **Abbreviations:** mg/L, milligrams per liter; na, not available; pCi/L, picocuries per liter;  $r^2$ , coefficient of determination; SMCL, secondary maximum contaminant level;  $\mu\text{g/L}$ , micrograms per liter]

Constituent	Number of wells with a detection greater than RL/total number of wells with USGS and CDPH data	RL	Linear regression			Threshold concentration	Percentage of wells with concentration above threshold		90-percent confidence interval for USGS (percent)
			Slope	Intercept	r <sup>2</sup>		USGS	CDPH	
Nutrients									
Ammonia	0/0	na	na	na	na	na	na	na	na
Nitrate	39/59	0.1 mg/L	0.87	0.1	0.86	5 mg/L	1.7	3.4	0.3–6.4
Trace elements and minor ions with health-based benchmarks									
Arsenic	8/32	2 µg/L	0.75	0	0.86	5 µg/L	6.3	9.4	1.8–16
Boron	0/9	100 µg/L	na	na	na	na	na	na	na
Fluoride	16/28	0.1 mg/L	0.96	0	0.48	2 mg/L	0	0	0–4.7
Lead	13/21	0.2 µg/L	0.09	0.2	0.13	5 µg/L	0	9.5	0–6.2
Molybdenum	0/0	na	na	na	na	na	na	na	na
Strontium	0/0	na	na	na	na	na	na	na	na
Vanadium	8/9	2 µg/L	0.99	0.7	0.99	25 µg/L	11	11	2.0–36
Radioactive constituents									
Gross-alpha particle activity	6/25	3 pCi/L	0.86	−0.5	0.61	7.5 pCi/L	4.0	12	0.7–12
Radon-222	0/0	na	na	na	na	na	na	na	na
Uranium	3/5	na	na	na	na	na	na	na	na
Inorganic constituents with SMCL benchmarks									
Chloride	13/20	1 mg/L	1.1	−0.2	0.88	250 mg/L	0	0	0–6.5
Iron	8/27	50 µg/L	0.41	−7	0.91	150 µg/L	7.4	19	2.2–19
Manganese	6/24	10 µg/L	0.98	4	0.96	50 µg/L	17	17	7.2–32
Total dissolved solids (TDS)	23/23	na	0.94	14	0.86	500 mg/L	0	0	0–5.7

Agreement between the two datasets was also considered acceptable for fluoride, despite the comparatively poorer linear regression fit than the others, because the percentage of wells with concentrations above the threshold was the same for both datasets (*table B1*; *fig. B2*). Thus, poor agreement between the USGS and CDPH data would be unlikely to affect results of aquifer-scale proportion calculations.

The USGS and CDPH datasets did not show acceptable agreement for lead, gross-alpha particle activity, or iron. For these three constituents, the percentages of wells with concentrations above the thresholds based on CDPH data were at or above the upper 90 percent confidence interval

limit for the percentages of wells with concentrations above the thresholds based on USGS data (*table B1*). This indicated that use of CDPH data could bias the results for aquifer-scale proportions toward greater high-RC and moderate-RC proportions. The linear regressions for these three constituents diverged markedly from the one-to-one line (*table B1*; *fig. B3*). Because of the poor agreement between USGS and CDPH data for lead, gross-alpha particle activity, and iron, the high-RC and moderate-RC aquifer-scale proportions calculated with the spatially weighted method were considered less reliable than those calculated with the grid-based method.



**Figure B2.** Comparison of data collected by the U.S. Geological Survey (USGS) and data reported in the California Department of Public Health (CDPH) database during the time period September 16, 2007, through September 17, 2010, for *A*, nitrate; *B*, manganese; *C*, arsenic; *D*, vanadium; *E*, fluoride, *F*, chloride, and; *G*, total dissolved solids, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.



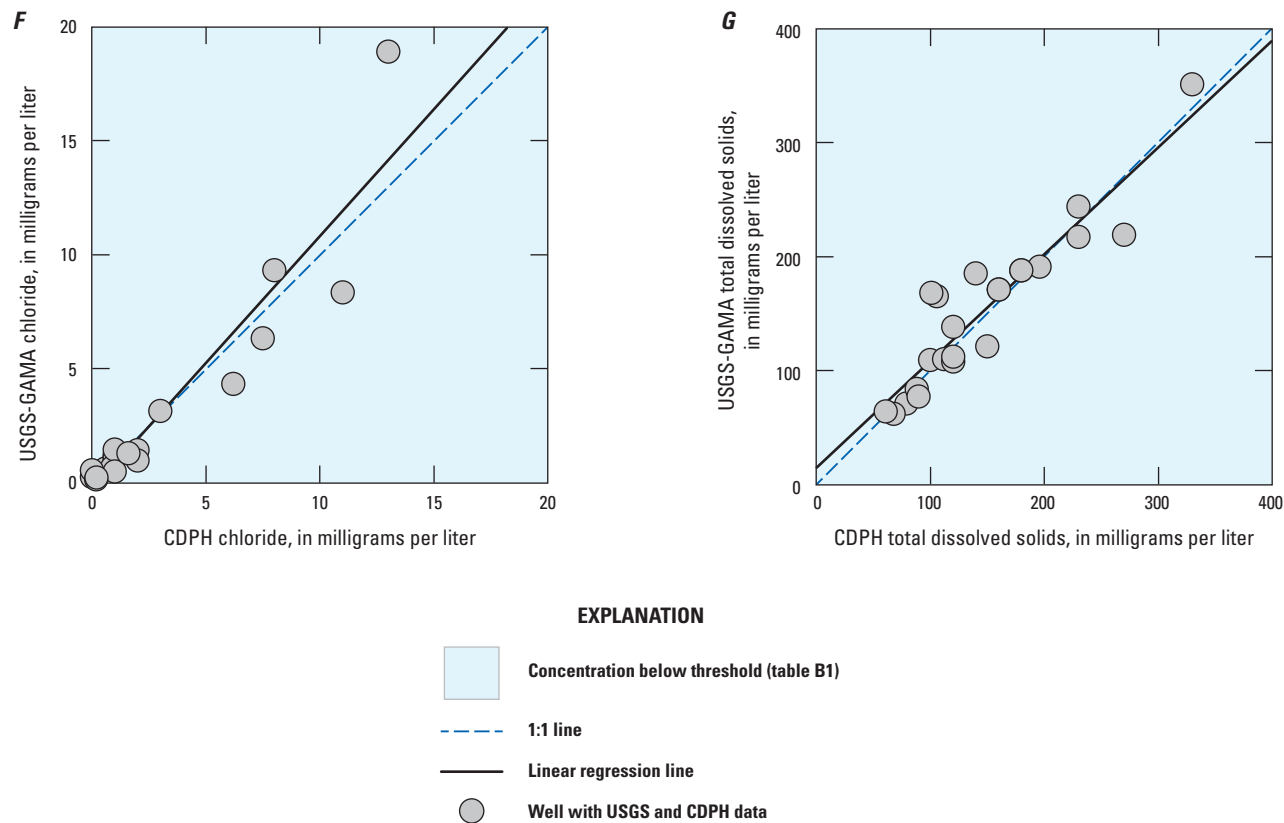
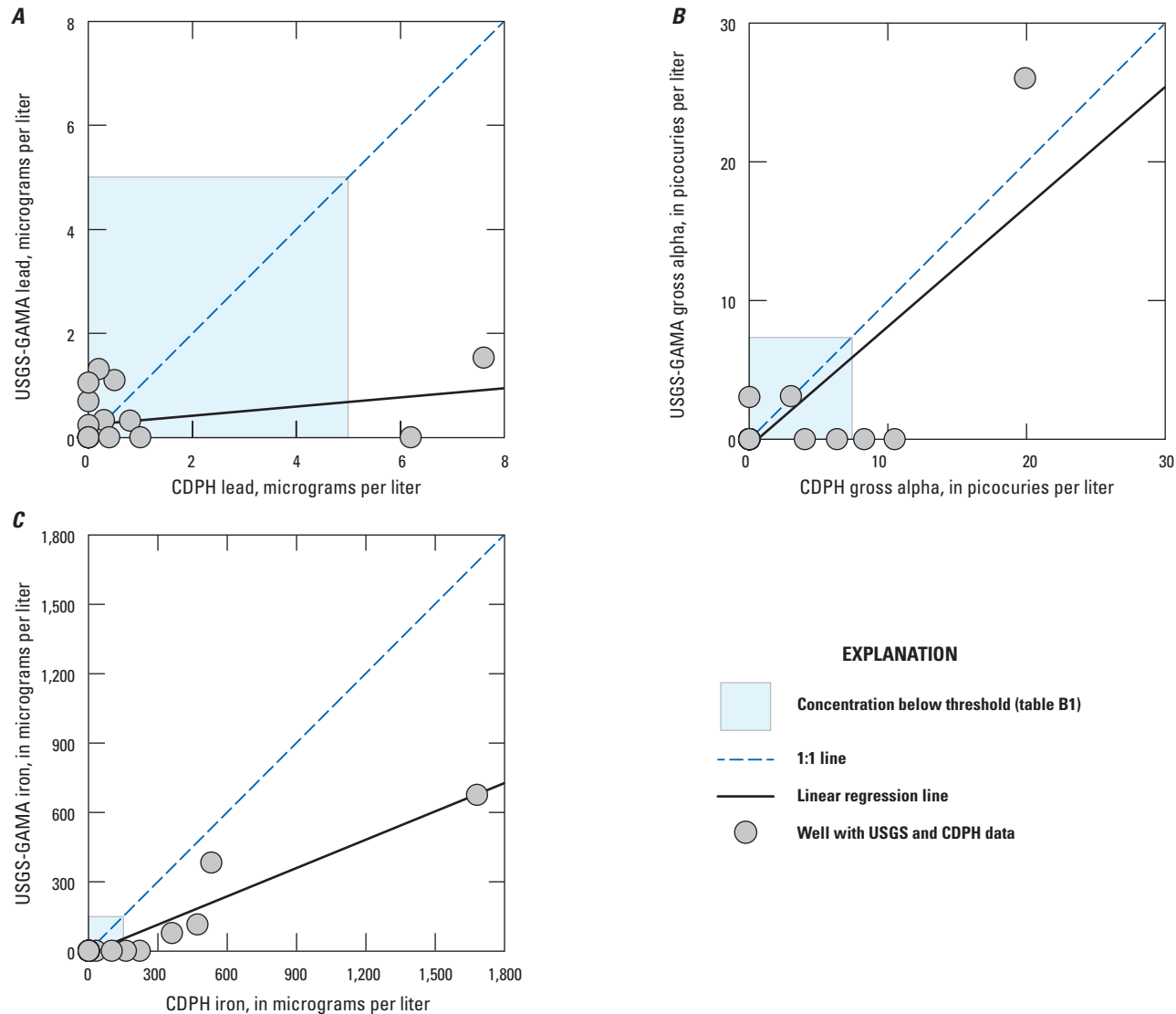


Figure B2. —Continued

Lead detections (greater than or equal to 1 µg/L) were reported in 10 CDPH wells during the period September 16, 2007, through September 17, 2010. Two wells had high-RCs, and three had moderate-RCs of lead. Three of the CDPH wells with detections of lead also were sampled by USGS, and the agreement between the two datasets was poor (table B1; fig. B3A), with concentrations reported by CDPH as much higher than those measured by USGS. This pattern indicates that use of the CDPH data could result in observations of high-RCs or moderate-RCs of lead where none would be observed if USGS data were used. In addition, of the 10 CDPH wells with lead detections, 7 wells had historical data for lead, and of those 7 wells, only 1 had a previous detection of lead (at a low-RC). Based on this poor agreement between the USGS and CDPH results for wells with data in both datasets and the lack of confirmation of detections of lead in the CDPH dataset,

the CDPH data for lead were considered suspect. Use of the CDPH data for lead in the *status assessment* could result in erroneous results. Spatially weighted aquifer-scale proportions for lead are listed in tables 8 and CIA-F, but lead was not included in the calculations of aquifer-scale proportions for trace elements as a class or for inorganic constituents as a class (table 9A).

The higher concentrations of iron and lead reported in the CDPH database compared to the concentrations measured by the USGS could reflect the difference in sample collection and analysis methods. Samples for analysis of trace elements by USGS are filtered during sample collection, whereas, the analytical methods used for regulatory compliance sampling for trace elements can use unfiltered samples. The source of particulate iron and lead in water samples could be particles from piping in wells and distribution systems.



**Figure B3.** Comparison of data collected by the U.S. Geological Survey (USGS) and data reported in the California Department of Public Health (CDPH) database during the time period September 16, 2007, through September 17, 2010, for *A*, lead; *B*, gross-alpha particle activity; and *C*, iron, Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

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## Appendix C: Aquifer-Scale Proportions in Study Areas

Grid-based and spatially weighted aquifer-scale proportions in the six study areas for individual relative concentrations (RC) inorganic constituents detected at high or moderate in the U.S. Geological Survey (USGS)-grid wells or reported at high or moderate RCs in the California Department of Public Health (CDPH) database in samples collected between September 2007 and September 2010 are listed in *tables C1A–F*.

Aquifer-scale proportion results are not tabulated for organic constituents because there were no high-RC or moderate-RC detections of these constituents; hence, the proportions were 100 percent low-RCs. Four herbicides (atrazine, hexazinone, prometon, and simazine), the trihalomethane chloroform, the solvents 1,1-dichloroethene and tetrachloroethene (PCE), and the gasoline oxygenate methyl *tert*-butyl ether (MTBE) each were detected in greater than 10 percent of the 15 USGS-grid wells in 1 or more of the 6 study areas (Shelton and others, 2013). All detections had low RCs. The CDPH database contained no pesticide data for

samples collected in the Cascade Range and Modoc Plateau (CAMP) study unit between September 2008 and September 2010. The CDPH database contained data for volatile organic compounds (VOCs) in samples from 71 wells, and, of those 71 wells, 24 also had USGS-Groundwater Ambient Monitoring and Assessment (GAMA) VOC data. Chloroform was the only VOC with a detection reported in the CDPH database between September 2008 and September 2010. One CDPH well had one detection of chloroform at a low RC.

### References Cited

Shelton, J.L., Fram, M.S., and Belitz, Kenneth, 2013, Groundwater-quality data in the Cascade Range and Modoc Plateau study unit, 2010, Results from the California GAMA Program: U.S. Geological Survey Data Series 688, 124 p., <http://pubs.er.usgs.gov/publication/ds688>.

**Table C1A.** Aquifer-scale proportions for the Sacramento Valley Eastside (ES) study area for inorganic constituents detected at high or moderate relative-concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Sacramento Valley Eastside study area covers 10.38 percent of the Cascade Range and Modoc Plateau study unit. **Relative-concentration (RC) categories for inorganic constituents:** High, RC 1.0, RC less than or equal to 1.0 and greater than 0.5; low, RC less than 0.5. RC defined as measured value divided by benchmark value. Inorganic 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 4A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)			
					Spatially weighted		Grid-based	
	Wells	Cells	Moderate-RC	High-RC	Moderate-RC	High-RC	Moderate-RC	High-RC
Nutrients								
Ammonia	15	15	0	0	0	0	0	0
Nitrate	30	15	0	0	0	0	0	0
Trace elements								
Arsenic	27	15	0	0	0	0	0	0
Boron	22	15	0	0	0	0	0	0
Fluoride	24	15	0	0	0	0	0	0
Lead	23	15	4.3	0	3.3	0	0	0
Molybdenum	15	15	0	0	0	0	0	0
Strontium	15	15	0	0	0	0	0	0
Vanadium	23	15	8.7	0	10.0	0	13.3	0
Radioactive constituents								
Gross alpha particle activity	24	15	0	0	0	0	0	0
Adjusted gross alpha particle activity	24	15	0	0	0	0	0	0
Radon-222 activity	15	15	0	0	0	0	0	0
Uranium	15	15	0	0	0	0	0	0
Inorganic constituents with SMCL benchmarks								
Chloride	22	15	0	0	0	0	0	0
Iron	24	15	8.3	8.3	3.6	8.9	0	6.7
Manganese	23	15	0	8.7	0	4.4	0	0
Total dissolved solids (TDS)	24	15	0	0	0	0	0	0

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health (CDPH) well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 15 grid wells during September 13, 2007, through October 12, 2010.

**Table C1B.** Aquifer-scale proportions for the Honey Lake Valley (HL) study area for inorganic constituents detected at high or moderate relative concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Honey Lake Valley study area covers 13.41 percent of the Cascade Range and Modoc Plateau study unit. **Relative-concentration (RC) categories for inorganic constituents:** high, RC greater than 1.0, RC less than or equal to 1.0 and greater than 0.5; low, RC less than 0.5. RC defined as measured value divided by benchmark value. Inorganic 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 4A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)			
					Spatially weighted		Grid-based	
	Wells	Cells	Moderate-RC	High-RC	Moderate-RC	High-RC	Moderate-RC	High-RC
Nutrients								
Ammonia	15	15	0	0	0	0	0	0
Nitrate	35	15	2.9	2.9	1.1	6.7	0	6.7
Trace elements								
Arsenic	31	15	25.8	19.4	21.7	16.4	26.7	13.3
Boron	21	15	28.6	0	36.7	0	40.0	0
Fluoride	23	15	8.7	0	10.0	0	13.3	0
Lead	21	15	0	0	0	0	0	0
Molybdenum	15	15	0	6.7	0	6.7	0	6.7
Strontium	15	15	0	0	0	0	0	0
Vanadium	27	15	7.4	3.7	8.3	3.3	6.7	6.7
Radioactive constituents								
Gross alpha particle activity	22	15	0	13.6	0	15.6	6.7	13.3
Adjusted gross alpha particle activity	22	15	4.5	4.5	2.2	4.5	6.7	0
Radon-222 activity	15	15	0	6.7	0	6.7	0	6.7
Uranium	19	15	0	15.8	0	15.0	0	13.3
Inorganic constituents with SMCL benchmarks								
Chloride	26	15	0	0	0	0	0	0
Iron	31	15	0	3.2	0	3.3	0	6.7
Manganese	31	15	0	22.6	0	28.9	0	26.7
Total dissolved solids (TDS)	30	15	23.3	0	34.4	0	40.0	0

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health (CDPH) well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 15 grid wells during July through October 2010.



**Table C1C.** Aquifer-scale proportions for the Cascade Range and Modoc Plateau Low Use Basins (LU) study area for inorganic constituents detected at high or moderate relative concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Cascade Range and Modoc Plateau Low Use Basins study area covers 18.44 percent of the Cascade Range and Modoc Plateau study unit. **Relative-concentration (RC) categories for inorganic constituents:** high, RC greater than 1.0, RC less than or equal to 1.0 and greater than 0.5; low, RC less than or equal to 0.5. RC defined as measured value divided by benchmark value. Inorganic 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 4A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)			
					Spatially weighted		Grid-based	
	Wells	Cells	Moderate-RC	High-RC	Moderate-RC	High-RC	Moderate-RC	High-RC
Nutrients								
Ammonia	15	15	6.7	0	6.7	0	6.7	0
Nitrate	44	15	2.3	0	1.3	0	0	0
Trace elements								
Arsenic	25	15	8.0	4.0	8.9	3.3	6.7	0
Boron	17	15	5.9	0	6.7	0	6.7	0
Fluoride	22	15	0	0	0	0	0	0
Lead	22	15	0	0	0	0	0	0
Molybdenum	15	15	0	0	0	0	0	0
Strontium	15	15	0	0	0	0	0	0
Vanadium	17	15	5.9	0	6.7	0	6.7	0
Radioactive constituents								
Gross alpha particle activity	27	15	3.7	0	3.3	0	0	0
Adjusted gross alpha particle activity	27	15	0	0	0	0	0	0
Radon-222 activity	15	15	0	0	0	0	0	0
Uranium	15	15	0	0	0	0	0	0
Inorganic constituents with SMCL benchmarks								
Chloride	24	15	0	0	0	0	0	0
Iron	23	15	13.0	21.7	12.2	15.6	6.7	13.3
Manganese	23	15	17.4	17.4	13.3	15.6	6.7	13.3
Total dissolved solids (TDS)	30	15	3.3	3.3	6.7	3.3	6.7	0

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health (CDPH) well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 15 grid wells during July through October 2010.

**Table C1D.** Aquifer-scale proportions for the Quaternary Volcanic Areas (QV) study area for inorganic constituents detected at high or moderate relative concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Quaternary Volcanic Areas study area covers 25.72 percent of the Cascade Range and Modoc Plateau study unit. **Relative-concentration (RC) categories for inorganic constituents:** High, RC greater than 1.0, RC less than or equal to 1.0 and greater than 0.5; low, RC less than or equal to 0.5. RC defined as measured value divided by benchmark value. Inorganic 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 4A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)			
					Spatially weighted		Grid-based	
	Wells	Cells	Moderate-RC	High-RC	Moderate-RC	High-RC	Moderate-RC	High-RC
Nutrients								
Ammonia	15	15	0	0	0	0	0	0
Nitrate	64	15	0	0	0	0	0	0
Trace elements								
Arsenic	26	15	3.8	0	6.7	0	6.7	0
Boron	22	15	0	0	0	0	0	0
Fluoride	30	15	0	0	0	0	0	0
Lead	25	15	4.0	8.0	2.2	4.4	0	0
Molybdenum	15	15	0	0	0	0	0	0
Strontium	15	15	0	0	0	0	0	0
Vanadium	21	15	14.3	0	15.0	0	20.0	0
Radioactive constituents								
Gross alpha particle activity	28	15	0	0	0	0	0	0
Adjusted gross alpha particle activity	28	15	0	0	0	0	0	0
Radon-222 activity	15	15	0	0	0	0	0	0
Uranium	15	15	0	0	0	0	0	0
Inorganic constituents with SMCL benchmarks								
Chloride	27	15	0	0	0	0	0	0
Iron	28	15	0	0	0	0	0	0
Manganese	28	15	0	7.1	0	13.3	0	13.3
Total dissolved solids (TDS)	27	15	3.7	0	6.7	0	6.7	0

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health (CDPH) well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 15 grid wells during July through October 2010.

**Table C1E.** Aquifer-scale proportions for the Shasta Valley and Mount Shasta Volcanic Area (SH) study area for inorganic constituents detected at high or moderate relative concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Shasta Valley and Mount Shasta Volcanic Area study area covers 13.35 percent of the Cascade Range and Modoc Plateau study unit. **Relative-concentration (RC) categories for inorganic constituents:** High, RC greater than 1.0, RC less than or equal to 1.0 and greater than 0.5; low, RC less than or equal to 0.5. RC defined as measured value divided by benchmark value. Inorganic 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 4A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)			
					Spatially weighted		Grid-based	
	Wells	Cells	Moderate-RC	High-RC	Moderate-RC	High-RC	Moderate-RC	High-RC
Nutrients								
Ammonia	15	15	0	0	0	0	0	0
Nitrate	42	15	7.1	0	11.1	0	13.3	0
Trace elements								
Arsenic	29	15	3.4	3.4	6.7	6.7	6.7	6.7
Boron	15	15	6.7	0	6.7	0	6.7	0
Fluoride	29	15	0	0	0	0	0	0
Lead	28	15	0	0	0	0	0	0
Molybdenum	15	15	0	0	0	0	0	0
Strontium	15	15	6.7	0	6.7	0	6.7	0
Vanadium	15	15	20.0	6.7	20.0	6.7	20.0	6.7
Radioactive constituents								
Gross alpha particle activity	27	15	0	0	0	0	0	0
Adjusted gross alpha particle activity	27	15	0	0	0	0	0	0
Radon-222 activity	15	15	0	0	0	0	0	0
Uranium	15	15	0	0	0	0	0	0
Inorganic constituents with SMCL benchmarks								
Chloride	26	15	0	0	0	0	0	0
Iron	27	15	3.7	3.7	1.7	2.2	0	0
Manganese	27	15	0	3.7	0	6.7	0	6.7
Total dissolved solids (TDS)	26	15	7.7	0	13.3	0	13.3	0

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health (CDPH) well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 15 grid wells during July through October 2010.

**Table C1F.** Aquifer-scale proportions for the Tertiary Volcanic Areas (TV) study area for inorganic constituents detected at high or moderate relative concentrations in the Cascade Range and Modoc Plateau study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[Tertiary Volcanic Areas study area covers 18.70 percent of the Cascade Range and Modoc Plateau study unit. **Relative-concentration (RC) categories for inorganic constituents:** High, RC greater than 1.0, RC less than or equal to 1.0 and greater than 0.5; low, RC less than or equal to 0.5. RC defined as measured value divided by benchmark value. Inorganic 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 4A](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Number		Raw occurrence frequency (percent)		Aquifer-scale proportions (percent)			
					Spatially weighted		Grid-based	
	Wells	Cells	Moderate-RC	High-RC	Moderate-RC	High-RC	Moderate-RC	High-RC
Nutrients								
Ammonia	15	15	0	0	0	0	0	0
Nitrate	38	15	0	0	0	0	0	0
Trace elements								
Arsenic	21	15	0	0	0	0	0	0
Boron	18	15	5.6	11.1	2.2	13.3	0	13.3
Fluoride	23	15	0	0	0	0	0	0
Lead	18	15	0	0	0	0	0	0
Molybdenum	15	15	0	6.7	0	6.7	0	6.7
Strontium	15	15	0	0	0	0	0	0
Vanadium	17	15	0	0	0	0	0	0
Radioactive constituents								
Gross alpha particle activity	22	14	0	0	0	0	0	0
Adjusted gross alpha particle activity	22	15	0	0	0	0	0	0
Radon-222 activity	15	15	0	0	0	0	0	0
Uranium	16	15	0	0	0	0	0	0
Inorganic constituents with SMCL benchmarks								
Chloride	21	15	0	4.5	0	6.7	0	6.7
Iron	22	15	0	9.1	0	5.6	0	0
Manganese	22	15	0	4.5	0	3.3	0	0
Total dissolved solids (TDS)	22	15	0	4.5	0	6.7	0	6.7

<sup>1</sup>Based on the most recent analyses for each California Department of Public Health (CDPH) well during September 16, 2007, through September 16, 2010, combined with data from U.S. Geological Survey (USGS)-grid wells.

<sup>2</sup>Grid-based aquifer-scale proportions are based on samples collected by the USGS from 15 grid wells during July through October 2010.

## Appendix D. Radioactivity

The class of radioactive constituents includes constituents with abundances commonly measured as activities rather than concentrations. Activity is measured in units of picocuries per liter (pCi/L), and one picocurie equals approximately two atoms decaying per minute. When atoms decay, they release alpha or beta particles, and (or) gamma radiation. 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 (MCL-US) (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 (USGS) Groundwater Ambient Monitoring and Assessment (GAMA) and data compiled in the California Department of Public Health (CDPH) 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 Department of Public Health, 2013b); therefore, the CDPH database contains substantially more data for gross alpha particle activity than for uranium. As a result, it is not always possible to calculate 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 the USGS-GAMA for Priority Basin Project study units. Results for adjusted gross alpha particle activity also are given in this report for comparison (*tables 8* and *C1A–F*).

USGS-GAMA reports data for two measurements of gross alpha particle activity, counted 72 hours and 30 days after sample collection. Regulatory sampling for gross alpha particle activity permits use of quarterly composite samples (California Department of Public Health, 2013b). The composite samples sent by water agencies to laboratories for

analysis may be mixtures of four samples collected 9 months, 6 months, 3 months, and a few days before submission. Because of these long holding times for CDPH data, the USGS-GAMA gross alpha 30-day count data could be more appropriate to use when combining USGS-GAMA and CDPH datasets. The 30-day count data were used in this study. Gross alpha particle activity in a groundwater sample can change with time after sample collection because of the radioactive decay of parent isotopes and ingrowth and subsequent decay of radioactive daughter isotopes (activity can increase or decrease depending on sample composition and holding time) (Arndt, 2010).

Most uranium results in the CDPH databases are reported as activities because the maximum contaminant level (MCL-CA) for uranium is 20 pCi/L. Uranium activities for CDPH wells, reported in pCi/L, were converted to uranium concentrations, reported in micrograms per liter (µg/L), by using a conversion factor derived from data collected by USGS-GAMA for the CAMP study unit. Activities of the three dominant uranium isotopes, uranium-234, -235, and -238, were measured in 20 CAMP study unit USGS-grid wells (Shelton and others, 2013). Total uranium activity is equal to the sum of the activities of these three isotopes (Arndt, 2010). Linear regression of the uranium concentration and uranium activity data from these 20 samples yield the following relation with  $r^2=0.998$ , and the slope of the regression equation was used as the conversion factor.

$$U_{mass} = 1.35 \times U_{act} - 0.28 \quad (D1)$$

where

$U_{mass}$  is the concentration of uranium in µg/L, and  
 $U_{act}$  is the activity of uranium in pCi/L.

Total uranium activity is assumed to equal the sum of the activities of the three uranium isotopes, uranium-234, -235, and -238.



## References Cited

- Arndt, M.F., 2010, Evaluation of gross alpha and uranium measurements for MCL compliance: Water Research Foundation, Denver, Colorado, 299 p., accessed January 10, 2012, <http://www.waterrf.org/PublicReportLibrary/3028.pdf>.
- California Department of Public Health, 2013, California Code of Regulation, Title 22, Division 4 Environmental Health, Chapter 15 Domestic water quality and monitoring regulations, Article 4 Primary standards—Inorganic chemicals, §64431 Maximum contaminant levels—Inorganic chemicals; Article 5 Radioactivity, §64442 MCLs and monitoring—Gross alpha particle activity, radium-226, radium-228, and uranium; Article 5.5 Primary standards—Organic chemicals, §64444 Maximum contaminant levels—Organic chemicals; and Article 16 Secondary drinking water standards, §64449 Secondary maximum contaminant levels and compliance, accessed December 2013, [http://www.waterboards.ca.gov/laws\\_regulations/](http://www.waterboards.ca.gov/laws_regulations/).
- Shelton, J.L., Fram, M.S., and Belitz, Kenneth, 2013, Groundwater-quality data in the Cascade Range and Modoc Plateau study unit, 2010, Results from the California GAMA Program: U.S. Geological Survey Data Series 688, 124 p., <http://pubs.er.usgs.gov/publication/ds688>.
- U.S. Environmental Protection Agency, 2000, National primary drinking water regulations; radionuclides; final rule, accessed January 2014 <https://www.federalregister.gov/articles/2000/12/07/00-30421/national-primary-drinking-water-regulations-radionuclides-final-rule>.

## Appendix E: Additional Water-Quality Data

Noble gas data provided by the Lawrence Livermore National Laboratory that were not available at the time of publication of the Data-Series Report (Shelton and others, 2013) are tabulated in this appendix (*table E1*).

### References Cited

Shelton, J.L., Fram, M.S., and Belitz, Kenneth, 2013, Groundwater-quality data in the Cascade Range and Modoc Plateau study unit, 2010, Results from the California GAMA Program: U.S. Geological Survey Data Series 688, 124 p., <http://pubs.er.usgs.gov/publication/ds688>.

**Table E1.** Results for analyses of noble gases by Lawrence Livermore National Laboratory for samples collected for the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project.

[The five digit number in parentheses below the constituent name is the U.S. Geological Survey parameter code used to uniquely identify a specific constituent or property. **Other abbreviations:** cm<sup>3</sup>STP/gH<sub>2</sub>O, cubic centimeters at standard temperature and pressure per gram of water; x, times; na, not available]

GAMA identification number	Helium-3/ Helium-4 (atom ratio)	Helium-4 (85561)	Neon (61046)	Argon (85563)	Krypton (85565)	Xenon (85567)
	(61040)	x 10 <sup>-7</sup>	x 10 <sup>-7</sup>	x 10 <sup>-4</sup>	x 10 <sup>-8</sup>	x 10 <sup>-8</sup>
	x 10 <sup>-6</sup>	(cm³STP/gH₂O)				
Eastside Sacramento Valley study area (ES)						
CAMP-ES-01	1.51	0.42	1.84	3.39	7.76	1.12
CAMP-ES-02	1.07	19.80	41.09	7.94	27.21	2.51
CAMP-ES-03	1.30	0.22	1.00	2.43	5.34	0.84
CAMP-ES-04	0.84	10.02	14.48	8.59	13.55	1.50
CAMP-ES-05	1.46	0.52	2.10	3.82	8.40	1.18
CAMP-ES-06	0.96	0.91	2.18	3.37	8.24	1.18
CAMP-ES-07	1.42	0.48	2.06	3.43	8.35	1.17
CAMP-ES-08	1.39	0.52	2.19	3.64	8.16	1.18
CAMP-ES-09	1.26	0.61	1.97	3.11	6.94	0.97
CAMP-ES-10	1.38	0.49	2.11	3.29	7.25	1.03
CAMP-ES-11	1.40	0.48	2.10	3.57	7.92	1.14
CAMP-ES-12	1.38	0.42	1.84	3.33	7.91	1.12
CAMP-ES-13	1.40	0.46	2.10	3.48	7.94	1.15
CAMP-ES-14	1.32	0.49	1.91	3.12	7.10	0.99
CAMP-ES-15	1.19	0.62	1.94	3.17	7.13	1.01
Honey Lake Valley study area (HL)						
CAMP-HL-01	1.68	3.77	7.25	5.46	9.27	1.02
CAMP-HL-02	0.90	0.98	2.65	4.05	8.78	1.17
CAMP-HL-03	2.66	44.18	1.99	3.37	7.91	1.11
CAMP-HL-04	1.15	0.62	2.13	3.57	8.22	1.13
CAMP-HL-05	1.62	0.46	1.91	3.25	7.50	1.04
CAMP-HL-06	0.96	3.10	5.30	4.62	9.14	1.15
CAMP-HL-07	na	na	na	na	na	na
CAMP-HL-08	1.26	0.84	2.56	7.07	6.21	1.21
CAMP-HL-09	1.03	3.30	8.36	5.77	11.15	1.27
CAMP-HL-10	0.94	0.87	2.18	3.30	7.33	0.97
CAMP-HL-11	1.64	1.88	2.91	4.46	7.73	1.09

**Table E1.** Results for analyses of noble gases by Lawrence Livermore National Laboratory for samples collected for the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project. —Continued

[The five digit number in parentheses below the constituent name is the U.S. Geological Survey parameter code used to uniquely identify a specific constituent or property. **Other abbreviations:** cm<sup>3</sup>STP/gH<sub>2</sub>O, cubic centimeters at standard temperature and pressure per gram of water; x, times; na, not available]

GAMA identification number	Helium-3/ Helium-4 (atom ratio)	Helium-4 (85561) x 10 <sup>-7</sup>	Neon (61046) x 10 <sup>-7</sup>	Argon (85563) x 10 <sup>-4</sup>	Krypton (85565) x 10 <sup>-8</sup>	Xenon (85567) x 10 <sup>-8</sup>
	(61040) x 10 <sup>-6</sup>	(cm <sup>3</sup> STP/gH <sub>2</sub> O)				
Honey Lake Valley study area (HL)						
CAMP-HL-12	0.99	0.69	2.07	3.26	7.35	1.06
CAMP-HL-13	1.33	0.94	3.39	4.01	8.46	1.14
CAMP-HL-14	2.38	3.23	1.97	3.31	7.72	1.03
CAMP-HL-15	1.35	0.60	2.30	3.49	7.63	1.03
Cascade Range and Modoc Plateau Low-Use Basins study area (LU)						
CAMP-LU-01	2.61	0.74	2.02	3.51	8.01	1.15
CAMP-LU-02	2.38	0.51	1.53	3.09	5.58	0.81
CAMP-LU-03	1.68	2.19	2.15	3.37	7.36	1.04
CAMP-LU-04	2.10	0.69	2.87	4.12	8.68	1.17
CAMP-LU-05	1.76	2.58	1.94	3.34	6.90	0.99
CAMP-LU-06	2.97	4.81	2.10	3.62	8.06	1.21
CAMP-LU-07	1.39	0.63	2.72	4.17	9.28	1.22
CAMP-LU-08	1.32	0.49	1.80	2.27	4.92	0.65
CAMP-LU-09	2.30	3.00	1.79	3.10	7.19	1.01
CAMP-LU-10	1.58	0.52	2.34	3.55	8.13	1.14
CAMP-LU-11	1.39	0.47	1.83	3.14	7.09	1.03
CAMP-LU-12	1.93	0.43	1.84	3.39	7.97	1.17
CAMP-LU-13	1.22	0.52	1.98	3.79	8.17	1.14
CAMP-LU-14	2.41	0.83	2.30	3.79	8.55	1.33
CAMP-LU-15	1.85	0.53	2.24	3.76	8.83	1.26
Quaternary Volcanic Areas study area (QV)						
CAMP-QV-01	1.40	0.37	1.73	3.54	8.69	1.28
CAMP-QV-02	1.35	0.39	1.78	3.59	8.92	1.33
CAMP-QV-03	2.44	1.48	2.03	3.51	7.99	1.17
CAMP-QV-04	na	na	na	na	na	na
CAMP-QV-05	1.61	0.46	1.92	3.62	8.72	1.29
CAMP-QV-06	1.00	0.78	1.83	3.07	6.97	0.97
CAMP-QV-07	1.39	0.42	1.91	3.60	8.81	1.26
CAMP-QV-08	2.56	0.53	1.98	3.50	8.34	1.19
CAMP-QV-09	na	na	na	na	na	na
CAMP-QV-10	1.46	0.55	2.10	3.57	8.18	1.19
CAMP-QV-11	1.50	0.54	2.42	4.07	8.79	1.27
CAMP-QV-12	1.77	0.71	3.02	4.28	9.28	1.29
CAMP-QV-13	3.76	0.59	1.85	3.58	7.49	1.15
CAMP-QV-14	1.04	0.97	2.71	4.07	9.23	1.31
CAMP-QV-15	1.62	0.41	1.87	3.25	8.47	1.29

**Table E1.** Results for analyses of noble gases by Lawrence Livermore National Laboratory for samples collected for the Cascade Range and Modoc Plateau (CAMP) study unit, 2010, California Groundwater Ambient Monitoring and Assessment Program (GAMA) Priority Basin Project. —Continued

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	(61040) x 10 <sup>-6</sup>	(cm³STP/gH₂O)				
Shasta Valley and Mount Shasta Volcanic Area study area (SH)						
CAMP-SH-01	0.68	1.43	2.49	3.81	8.42	1.15
CAMP-SH-02	1.58	5.09	1.98	3.25	7.23	1.04
CAMP-SH-03	1.20	0.96	2.27	3.61	8.08	1.13
CAMP-SH-04	6.61	2.92	2.75	3.91	8.79	1.25
CAMP-SH-05	1.45	0.40	1.80	3.45	8.12	1.22
CAMP-SH-06	7.14	1.40	1.97	3.65	8.75	1.24
CAMP-SH-07	1.35	0.41	1.88	3.68	8.68	1.30
CAMP-SH-08	6.56	1.39	2.41	4.60	6.41	1.11
CAMP-SH-09	1.00	0.99	2.07	3.33	7.60	1.02
CAMP-SH-10	3.20	1.18	2.41	3.75	8.17	1.19
CAMP-SH-11	2.95	1.01	2.62	3.85	8.18	1.19
CAMP-SH-12	1.34	0.69	1.90	3.43	7.55	1.08
CAMP-SH-13	1.62	0.47	1.76	3.17	7.57	1.07
CAMP-SH-14	1.57	0.74	3.38	4.80	10.99	1.63
CAMP-SH-15	0.15	8.25	2.91	4.04	8.76	1.24
Tertiary Volcanic Areas study area (TV)						
CAMP-TV-01	2.31	104.0	1.93	3.33	7.33	1.02
CAMP-TV-02	1.39	0.42	1.83	3.19	6.70	1.01
CAMP-TV-03	1.78	0.46	1.82	3.28	7.72	1.17
CAMP-TV-04	5.51	1.34	1.95	3.55	8.34	1.20
CAMP-TV-05	1.32	0.52	1.99	3.21	7.39	0.98
CAMP-TV-06	2.77	1.01	1.94	3.59	8.57	1.28
CAMP-TV-07	1.43	0.54	2.28	3.65	8.25	1.24
CAMP-TV-08	1.34	0.38	1.55	2.65	5.94	0.87
CAMP-TV-09	1.99	3.25	2.26	3.84	8.96	1.38
CAMP-TV-10	1.54	0.73	3.08	4.54	10.12	1.42
CAMP-TV-11	1.36	5.06	15.93	8.68	16.51	1.95
CAMP-TV-12	1.59	0.47	2.04	3.75	8.98	1.31
CAMP-TV-13	1.60	0.68	2.67	4.18	9.19	1.33
CAMP-TV-14	1.40	0.80	3.39	4.39	9.80	1.36
CAMP-TV-15	0.90	7.71	1.73	8.55	5.80	0.89





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# CALIFORNIA GAMA PROGRAM

