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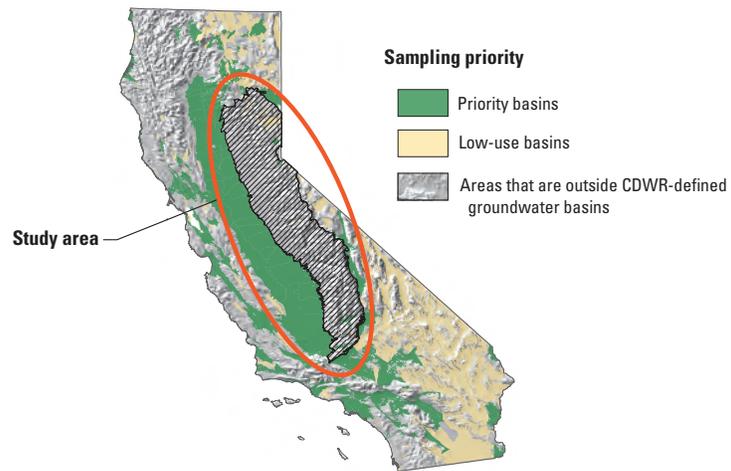
A product of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program

Status and Understanding of Groundwater Quality in the Sierra Nevada Regional Study Unit, 2008: California GAMA Priority Basin Project



Scientific Investigations Report 2014–5174

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: Wellhouse and holding tank near Angels Camp, California. (Photograph taken by Barbara J. Dawson, U.S. Geological Survey.)

Back cover: View near Tuolumne Meadows in Yosemite National Park, California. (Photograph taken by George L. Bennett, U.S. Geological Survey.)

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By Miranda S. Fram and Kenneth Belitz

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Conversion Factors, Datums, and 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		
acre	4,047	square meter (m ²)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm ²)
acre	0.004047	square kilometer (km ²)
square foot (ft ²)	0.09290	square meter (m ²)
square mile (mi ²)	2.590	square kilometer (km ²)
Flow rate		
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)
picocurie per liter (pCi/L)	0.313	tritium units (TU)

SI to Inch/Pound

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
Area		
square kilometer (km ²)	0.3861	square mile (mi ²)

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Datums

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 the distance above the vertical datum.

Selected Terms and Symbols

α	significance level
>	greater than
\geq	greater than or equal to
<	less than
\leq	less than or equal to

Abbreviations and Acronyms

AL-US	U.S. Environmental Protection Agency action level
BQ	benchmark quotient
ft bls	feet below land surface
G	granitic aquifer lithology
GAMA	California Groundwater Ambient Monitoring and Assessment Program
HAL-US	U.S. Environmental Protection Agency lifetime health advisory level
HBSL	health-based screening level
LUFT	leaking (or formerly leaking) underground fuel tank
M	metamorphic aquifer lithology
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
NAWQA	National Water-Quality Assessment Program (USGS)
NL-CA	California Department of Public Health notification level
p	p-value (probability)
pmC	percent modern carbon
RC	relative-concentration
RSD5-US	U.S. Environmental Protection Agency risk-specific dose at a risk factor of 10^{-5}
S	sedimentary aquifer lithology

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

SNR	Sierra Nevada Regional study unit
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 process
TT-US	U.S. Environmental Protection Agency treatment technique
TU	tritium unit
V	volcanic aquifer lithology

Organizations

CDPH	California Department of Public Health (Department of Health Services <i>prior to July 1, 2007</i>)
CDWR	California Department of Water Resources
LLNL	Lawrence Livermore National Laboratory
SWRCB	State Water Resources Control Board (California)
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Selected Chemical Names

^{14}C	carbon-14
$\delta^{13}\text{C}$	ratio of carbon-13 to carbon-12 in the sample relative to the ratio of carbon-13 to carbon-12 in the PeeDee belemnite standard, in units of per mil
DO	dissolved oxygen
MTBE	methyl <i>tert</i> -butyl ether
NDMA	<i>N</i> -nitrosodimethylamine
PCE	tetrachloroethene (perchloroethene)
1,2-DCA	1,2-dichloroethane
TDS	total dissolved solids
THM	trihalomethane
VOC	volatile organic compound

Status and Understanding of Groundwater Quality in the Sierra Nevada Regional Study Unit, 2008: California GAMA Priority Basin Project

By Miranda S. Fram and Kenneth Belitz

Abstract

Groundwater quality in the Sierra Nevada Regional (SNR) study unit was investigated as part of the California State Water Resources Control Board's Groundwater Ambient Monitoring and Assessment Program Priority Basin Project. The study was designed to provide statistically unbiased assessments of the quality of untreated groundwater within the primary aquifer system of the Sierra Nevada. The primary aquifer system for the SNR study unit was delineated by the depth intervals over which wells in the State of California's database of public drinking-water supply wells are open or screened. Two types of assessments were made: (1) a status assessment that described the current quality of the groundwater resource, and (2) an evaluation of relations between groundwater quality and potential explanatory factors that represent characteristics of the primary aquifer system. The assessments characterize untreated groundwater quality, rather than the quality of treated drinking water delivered to consumers by water distributors.

The status assessment was based on water-quality data collected by the U.S. Geological Survey from 83 wells in the SNR study unit in 2008 and from 117 wells in 3 small study units within the SNR study unit in 2006–07 and on water-quality data compiled in the State's database for 1,066 wells sampled in 2006–08. To provide some context for the results, water-quality data were converted to relative-concentrations (RCs), which are the sample concentrations divided by the concentrations of Federal or California regulatory and non-regulatory benchmarks for drinking-water quality. RCs for inorganic constituents (major ions, trace elements, nutrients, and radioactive constituents) were classified as "high" ($RC > 1.0$, indicating that concentration is above the benchmark), "moderate" ($1.0 \geq RC > 0.5$), or "low" ($RC \leq 0.5$). For organic constituents (volatile organic compounds and pesticides) and special-interest constituents (perchlorate and *N*-nitrosodimethylamine [NDMA]), the boundary between moderate and low RCs was set at 0.1. All benchmarks used for organic constituents were health-based, whereas health-based and aesthetic-based benchmarks were used for inorganic constituents.

The primary metric used for quantifying regional-scale groundwater quality was "aquifer-scale proportion." Aquifer-scale proportions were calculated as the areal percentages of the primary aquifer system having high, moderate, and low RCs for a given constituent or class of constituents. The SNR study unit area was classified into four aquifer lithologic types—granitic rocks, metamorphic rocks, sedimentary deposits, and volcanic rocks—and aquifer-scale proportions were calculated on an area-weighted basis for each of the four aquifer lithologies and for the study unit as a whole (aggregated system).

The results of the status assessment indicated that inorganic constituents were present at high and moderate RCs in greater proportions in the SNR study unit aggregated primary aquifer system than were organic constituents and that there were significant differences ($p < 0.05$) between the four aquifer lithologies. One or more inorganic constituents with health-based benchmarks were present at high RCs in 16 percent of the aggregated primary aquifer system and at moderate RCs in 21 percent. Arsenic (9.7 percent), uranium (2.9 percent), boron (2.0 percent), fluoride (1.8 percent), and nitrate (1.4 percent) were the constituents most commonly present at high RCs.

For inorganic constituents with aesthetic-based benchmarks, 18 percent of the aggregated primary aquifer system had high RCs of one or more constituent, and 6.8 percent had moderate RCs. Iron (15.8 percent), manganese (15.1 percent), and total dissolved solids (1.3 percent) were the constituents most commonly present at high RCs.

Organic constituents were not detected in 72 percent of the primary aquifer system. One or more organic constituents had high RCs in 0.1 percent of the primary aquifer system, moderate RCs in 3.0 percent, and low RCs in 25 percent. Proportions of the four lithologic primary aquifer systems with high or moderate concentrations of organic constituents were not significantly different. Three organic constituents had area-weighted detection frequencies greater than 10 percent in the primary aquifer system as a whole or at least one of the four lithologic primary aquifer systems: the gasoline oxygenate methyl *tert*-butyl ether, the trihalomethane chloroform, and the herbicide simazine. The special-interest constituent

perchlorate was detected at high RCs in 0.01 percent of the primary aquifer system and at moderate RCs in 1.0 percent, and detection frequencies could be accounted for by the distribution of perchlorate under natural conditions.

Statistical tests were used to evaluate relations between constituent concentrations and potential explanatory factors descriptive of land use, geography, depth, geochemical conditions, and groundwater age. Higher concentrations of trace elements, radioactive constituents, and constituents with aesthetic-based benchmarks generally were associated with anoxic conditions, higher pH, and location within a particular compositional band in the Sierra Nevada batholith corresponding to the southwestern part of the study unit. High concentrations of organic constituents generally were associated with greater proportions of urban land use. No significant relations were observed between the concentrations of organic constituents and measures of well depth or groundwater age, perhaps because of the high proportions of springs and modern groundwater in the dataset.

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 collaboration 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 statewide GAMA Program currently consists of four projects: (1) the GAMA Priority Basin Project, conducted by the USGS (website at <http://ca.water.usgs.gov/gama/>); (2) the GAMA Domestic Well Project, conducted by the SWRCB; (3) the GAMA Special Studies, conducted by LLNL; and (4) the GeoTracker GAMA online groundwater information system, operated by the SWRCB. On a statewide basis, the GAMA Priority Basin Project primarily focused on the deep portion of the groundwater resource, and the SWRCB Domestic Well Project generally focused on the shallow aquifer systems.

The SWRCB initiated the GAMA Program in 2000 in response to a legislative mandate (State of California, 1999, 2001a). 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) and is a comprehensive assessment of statewide groundwater quality designed to help better understand and identify risks to groundwater resources and to increase the availability of information about groundwater quality to the public. For the GAMA Priority Basin Project, the USGS, in collaboration 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, 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 that exist in California were considered in this state-wide assessment of groundwater quality. Belitz and others (2003) partitioned the state into 10 hydrogeologic provinces, each with distinctive hydrologic, geologic, and climatic characteristics (fig. 1A). These hydrogeologic provinces include groundwater basins defined by the CDWR (California Department of Water Resources, 2003). Groundwater basins in California generally consist of relatively permeable, unconsolidated deposits of alluvial origin. Eighty percent of the approximately 16,000 active and standby public drinking-water supply wells listed in the State's database (hereinafter referred to as CDPH wells) are located in CDWR-defined groundwater basins. The CDPH Drinking Water Program 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.

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 1-square-mile (mi²) sections having registered pesticide applications (Belitz and others, 2003). Of the 472 basins defined by the CDWR, 116 contained approximately 95 percent of the CDPH wells located in basins. These 116 basins were defined as "priority basins," and the remaining 356 basins were defined as "low-use" basins. 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. The 35 study units together represent approximately 95 percent of all CDPH wells. Of the 10 hydrogeologic provinces, the Sierra Nevada province contains the largest number of CDPH wells outside of the CDWR-defined groundwater basins. About 97 percent of the total area and approximately 85 percent of the CDPH wells in the province are outside of the CDWR-defined groundwater basins. The entire Sierra Nevada hydrogeologic province was defined as the Sierra Nevada Regional (SNR) study unit (fig. 1A).

The GAMA Priority Basin Project was designed to produce three types of water-quality assessments for each study unit: (1) status: assessment of the current quality of the groundwater resource, (2) understanding: identification of the natural and human factors affecting groundwater quality and explanation of the relations between water quality



Figure 1. (A) Location of the California hydrogeologic provinces and the Sierra Nevada Regional study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project and (B) selected major geologic features in California.

4 Status and Understanding of Groundwater Quality in the Sierra Nevada Regional Study Unit, 2008



Shaded relief derived from U.S. Geological Survey
National Elevation Dataset, 2006.
Albers Equal Area Conic Projection
North American Datum of 1983 (NAD 83)

Geology simplified from Saucedo and others (2000).

EXPLANATION

- | | |
|---|--|
| Geologic units | |
|  | Mesozoic granitic rocks |
|  | Cenozoic sedimentary deposits |
|  | Paleozoic and Mesozoic metamorphic and sedimentary rocks and non-granitic plutonic rocks |
|  | Cenozoic volcanic and volcanoclastic rocks |

Figure 1. —Continued

and selected explanatory factors, and (3) trends: 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 GAMA Priority Basin Project assessments are intended to characterize the quality of groundwater within 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 those for cities, towns, and mobile-home parks), “non-transient, non-community” (such as those for schools, workplaces, and restaurants), and “transient, non-community” (such as those for campgrounds, parks, and highway rest areas) (California Department of Public Health, 2013a). Groundwater quality in shallower or deeper parts of the aquifer system may differ from that in the primary aquifer system. In particular, shallower groundwater may be more vulnerable to surface-derived contamination.

The purposes of this report are to provide (1) a *study unit description*: description of the hydrogeologic setting of the SNR study unit, (2) a *status assessment*: assessment of the status of the current quality of groundwater in the primary aquifer system in the study unit, and (3) an *understanding assessment*: discussion of statistical tests of correlations between water quality and potential explanatory factors. Trends in groundwater quality are not discussed in this report.

In this report, features of the hydrogeologic setting are described on the scale of the entire SNR study unit; features of specific alluvial basins and delineated hard-rock aquifers are not discussed. Geology, land-use patterns, and hydrology of the study unit are summarized. Characteristics of the primary aquifer system, including geology, land use, climate, depth, groundwater age distribution, and geochemical conditions are described by using ancillary data compiled for the 83 sites sampled by USGS-GAMA for the study unit.

GAMA status assessments are 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 having groundwater of defined quality. Water-quality data for samples collected by the USGS for the SNR study unit and details of sample collection, analysis, and quality-assurance procedures are reported by Shelton and others (2010).

Water-quality data from 1,266 wells from 3 sources were used in the status assessment: (1) the 83 wells sampled by

USGS-GAMA for the SNR study unit ([appendix A](#); Shelton and others, 2010), (2) the 117 wells sampled in 2006–07 by USGS-GAMA for the Tahoe-Martis, Central Sierra Nevada, and Southern Sierra Nevada study units that are within the SNR (Fram and Belitz, 2012), and (3) the 1,066 wells in the CDPH database that had water-quality data during the period May 1, 2006, through October 31, 2008. The Tahoe-Martis, Central Sierra Nevada, and Southern Sierra Nevada study units are three small study units that are entirely contained within the SNR study unit ([fig. 2](#)). Two methods were used to calculate aquifer-scale proportions from these data, both of which were based on a 30-cell grid covering the SNR study unit: the methods either used data from one well per aquifer lithology per cell (grid-based method) or from many wells per aquifer lithology per cell (spatially weighted method) (Belitz and others, 2010). Aquifer-scale proportions for constituents and classes of constituents were computed for the SNR primary aquifer system as a whole and for the primary aquifer systems in granitic, metamorphic, sedimentary, and volcanic aquifer lithologies.

To provide context, the water-quality data discussed in this report are 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 units, 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.

Relations between water quality and potential explanatory factors were evaluated by using statistical tests for correlations and associations. Two types of evaluations were made. The first type examined differences in aquifer-scale proportions for constituents and classes of constituents between the granitic, metamorphic, sedimentary, and volcanic primary aquifer systems. The second type examined correlations between constituent concentrations and values of potential explanatory factors and differences in median concentrations of constituents between samples grouped into categories by potential explanatory factors. Results of these statistical tests have been tabulated and are briefly discussed and compared to results for the Tahoe-Martis, Central Sierra, and Southern Sierra study units. Detailed discussions of the factors affecting groundwater quality in the Sierra Nevada were presented by Fram and Belitz (2012) and thus are not repeated in this report.

6 Status and Understanding of Groundwater Quality in the Sierra Nevada Regional Study Unit, 2008

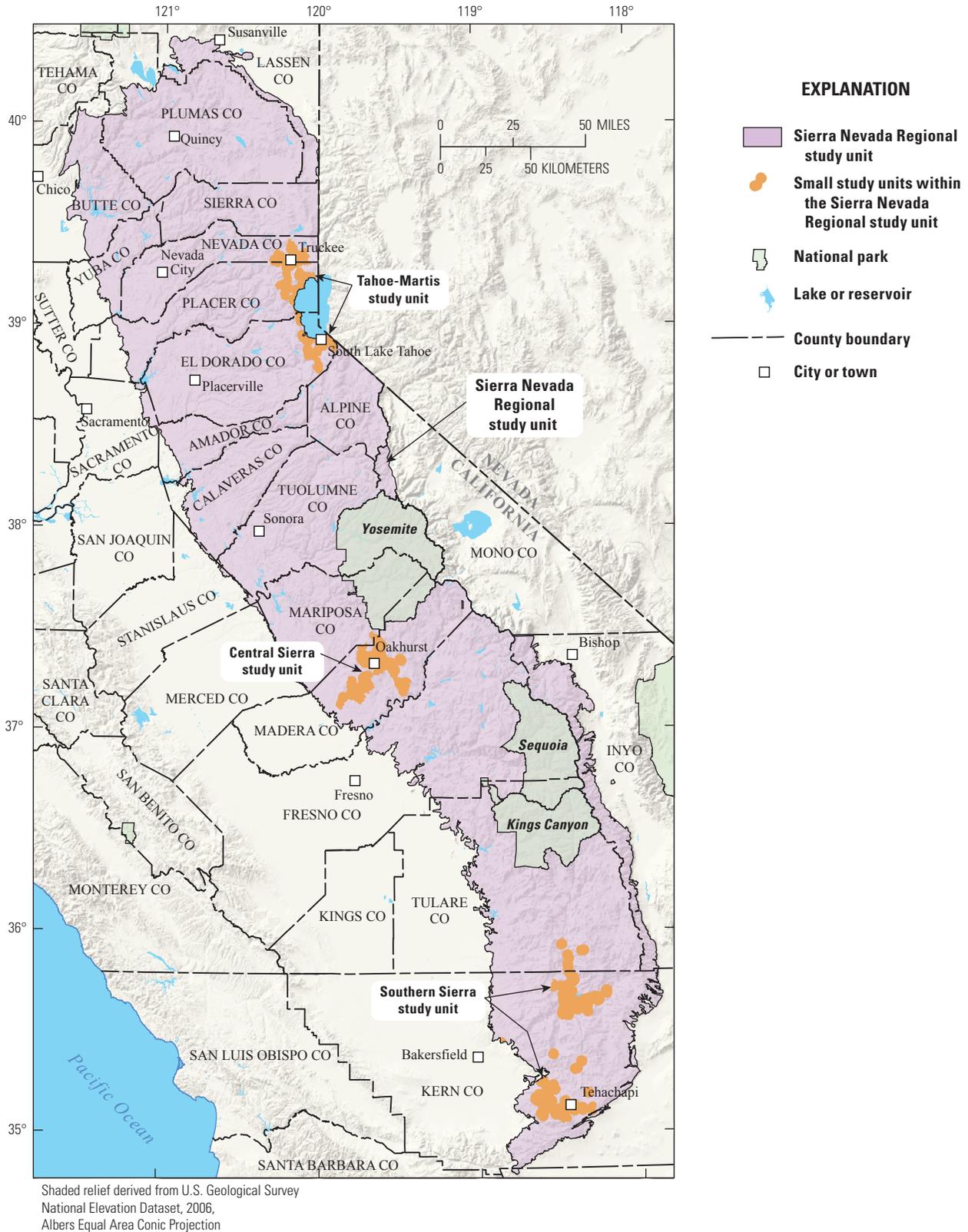


Figure 2. County, national park, and California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project, Sierra Nevada Regional (SNR) study unit boundaries.

Hydrogeologic Setting of the SNR Study Unit

The SNR study unit covers an area of approximately 25,000 mi² (66,000 square kilometers [km²]) and includes all or parts of 20 California counties: Lassen, Plumas, Butte, Sierra, Yuba, Nevada, Placer, El Dorado, Sacramento, Amador, Alpine, Calaveras, Tuolumne, Mono, Mariposa, Madera, Fresno, Inyo, Tulare, and Kern Counties ([fig. 2](#)). The study unit includes the Sierra Nevada, which is the mountain range extending along the eastern side of California, and the foothills on the western slope of the Sierra Nevada. The western boundary of the study unit is defined by the limit of late Tertiary and Quaternary sediments of the Central Valley ([figs. 1A,B](#)). The eastern boundary is defined by the limits of late Tertiary and Quaternary sediments in the Owens Valley, the Nevada State line, and the watersheds of the basins between the Owens Valley and the Nevada State line. The study unit is terminated at the southern end by the Garlock Fault ([fig. 1B](#)) and at the northern end by the Cascades Range and Modoc Plateau ([fig. 1A](#)). The SNR study unit encompasses a broad range of geologic, hydrologic, climatic, and land-use settings. Settings are described on the scale of the entire SNR study unit; features of specific alluvial basins and delineated hard-rock aquifers are not discussed.

Geology

The dominant geologic feature of the SNR study unit is the Sierra Nevada batholith, a complex of Mesozoic tonalite, granodiorite, quartz diorite, and granite plutons that intruded the North American Plate above the subducting Farallon Plate, mostly between 80 and 150 mega annum (Ma; million years ago) (Evernden and Kistler, 1970; Saleeby and others, 2008). The batholith has regional variations in chemical and mineralogical composition that are in part due to variations in the composition of the terrain into which the plutons intruded (Ague and Brimhall, 1987, 1988).

The Western Metamorphic Belt occupies the foothills in the northern half of the study unit ([fig. 1B](#)) and consists of a deformed package of imbricate thrust slices of Mesozoic and Paleozoic ophiolites and oceanic sedimentary rocks that were accreted onto the western margin of the North American Plate as subduction proceeded (Day and others, 1985). The Mother Lode gold deposits are hosted by quartz veins injected along the Melones Fault zone, a major structural feature that likely marks the Mesozoic subduction plate boundary (Böhlke and Kistler, 1986). Roof pendants of older Mesozoic and Paleozoic metamorphic rocks, remnants of the terrain into which the plutons intruded, are scattered throughout the batholith, particularly in the southern part of the province ([fig. 1B](#)).

Late Cenozoic (approximately 35 Ma to 1 Ma) volcanism covered parts of the Sierra Nevada, particularly in the northern part of the study unit (Christiansen and others, 1992). Geologic evidence suggests that by the Late Miocene

(16 Ma to 12 Ma), areas to the east of the Sierra Nevada were in prominent rain shadow, indicating that most of the uplift of the modern Sierra Nevada range had occurred by that time (Crowley and others, 2008; Mulch and others, 2008). Continued uplift has occurred within the last 5 Ma (Wakabayashi and Sawyer, 2001). Parts of the Sierra Nevada were glaciated in the multiple major glacial advances during the Pleistocene (Birkeland, 1964; Raub and others, 2006).

The organizing feature for SNR study-unit design was aquifer lithology. Public drinking-water supply wells in the SNR study unit are located in fractured hard-rock aquifers and in alluvial basins. In contrast, in nearly all other GAMA Priority Basin Project study units, the primary aquifer system consists solely of alluvial basins. For the purpose of examining broad relations between aquifer lithology and groundwater quality, aquifer lithology was classified into four categories: the fractured hard-rock aquifers were classified as granitic, metamorphic, or volcanic rocks, and the alluvial basins and other accumulations of sediment were classified as sedimentary deposits. The SNR study unit is approximately 50 percent granitic rocks, 30 percent metamorphic rocks, 13 percent volcanic rocks, and 7 percent sedimentary deposits ([fig. 3A](#)). These four rock types have different geochemical and hydrologic characteristics, and thus may host groundwater with different water-quality characteristics. The classifications were made from the California State geologic map (Jennings, 1977; Saucedo and others, 2000) and are described in greater detail in [appendix B](#).

Hydrology and Climate

The hydrologic features and the climate within the SNR study unit are closely related to the topography. The western side of the Sierra Nevada slopes gradually from the crest towards the Central Valley, and the eastern side is a steep escarpment that marks the western edge of active extension in the Basin and Range province. The elevation of the Sierra Nevada crest is highest in the south, with several peaks over 14,000 feet (ft) (4,270 meters [m]), and decreases northward, with the highest peaks north of Lake Tahoe only about 8,000 ft in elevation (2,440 m) ([fig. 3B](#)).

Like much of California, the Sierra Nevada has a Mediterranean climate, with warm, dry summers and cool, wet winters. Annual precipitation ranges from 10 to 80 inches per year (in/yr) (25 to 200 centimeters per year [cm/yr]), and most of the precipitation falls in the winter season, between October and April (PRISM Climate Group, Oregon State University, 2007). At elevations above about 6,500 ft (about 2,000 m), most of the precipitation falls as snow. Precipitation generally increases with elevation and latitude, reflecting the orographic effect in which moisture is drawn out of weather systems as they travel from west to east, up the western slope of the Sierra Nevada, and the regional north to south gradient. The eastern edge of the study unit is in the rain shadow of the Sierra Nevada crest and receives less precipitation than the west side.

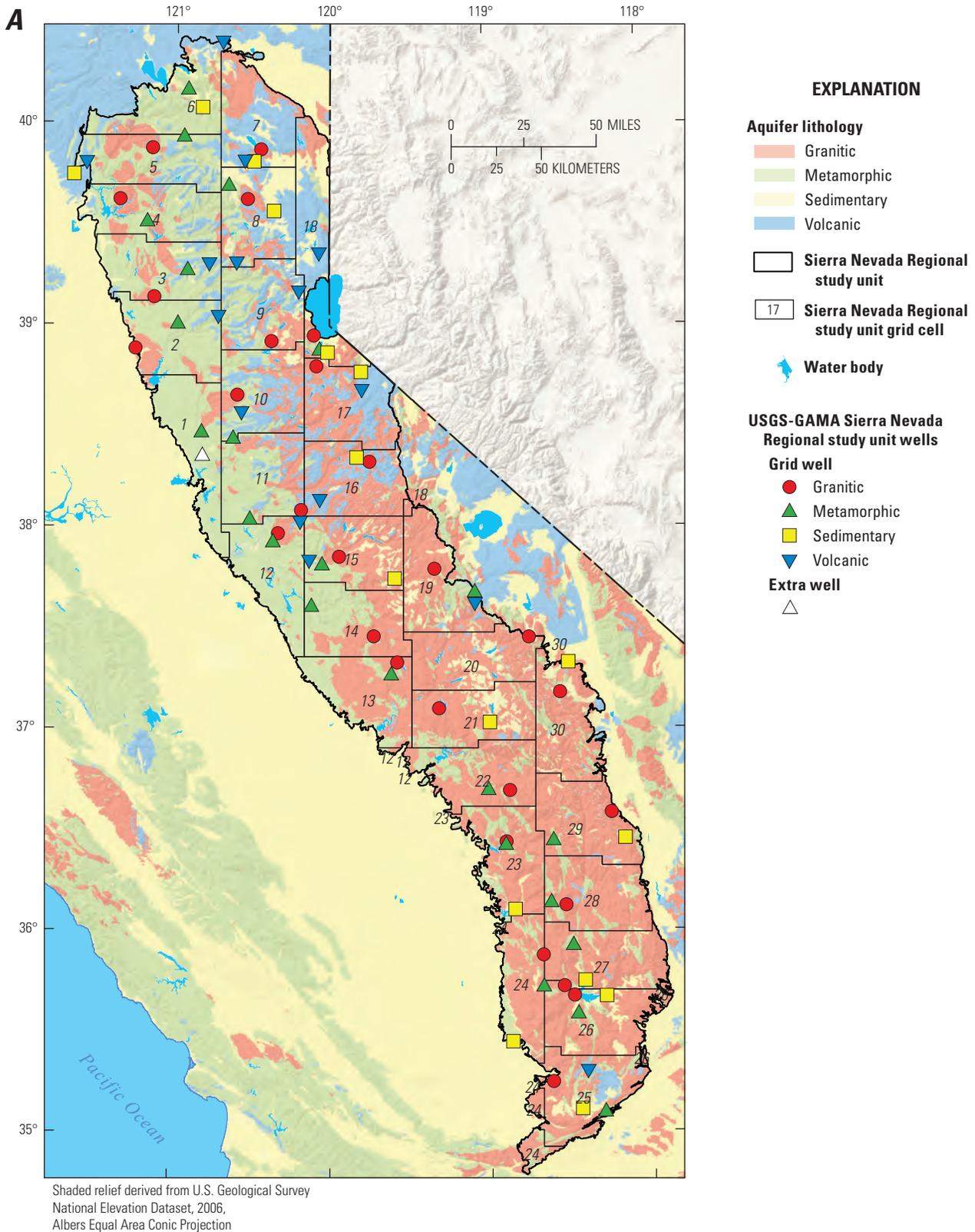


Figure 3. (A) Simplified geology, (B) elevation and major hydrologic features, and (C) land use for the Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

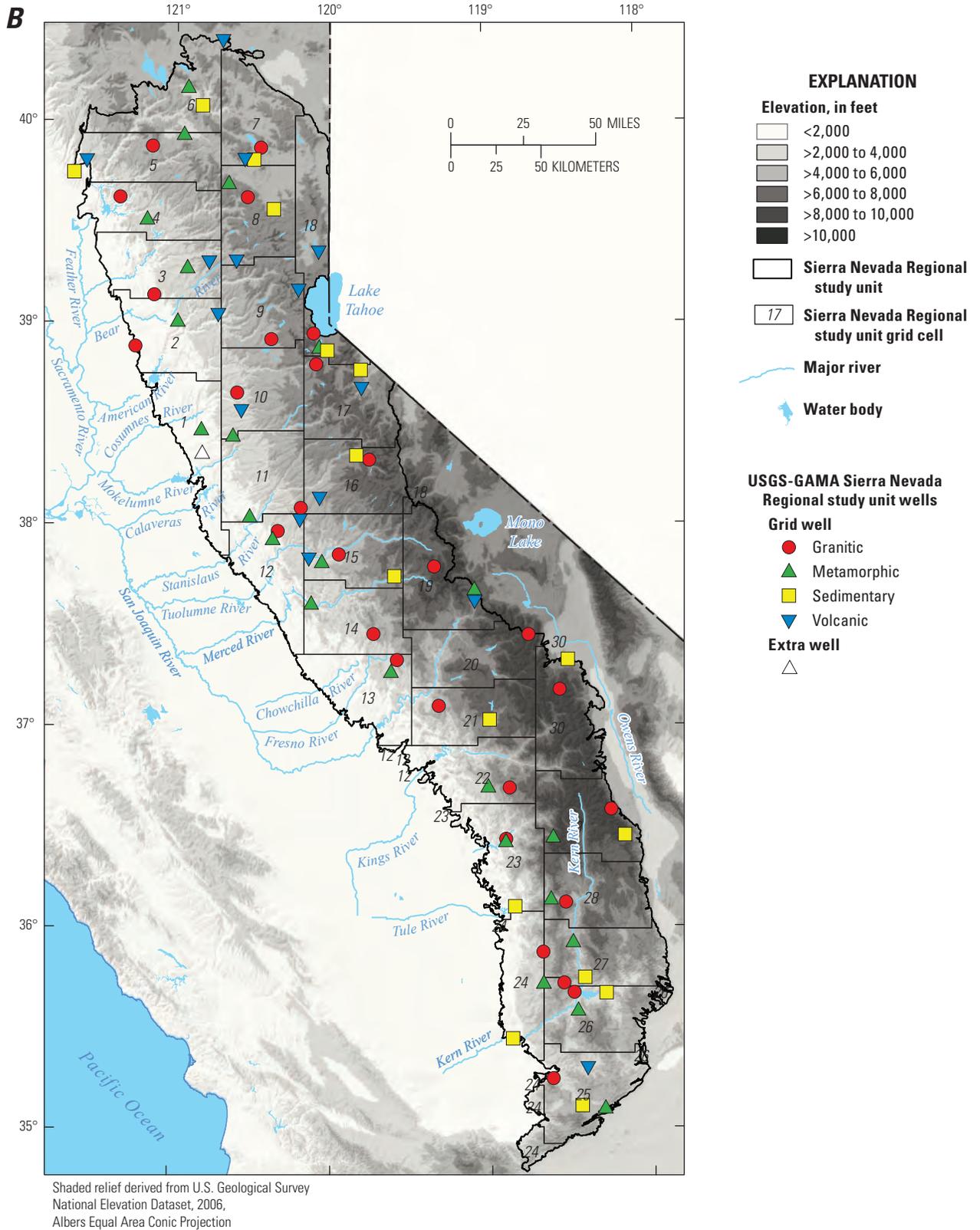


Figure 3. —Continued

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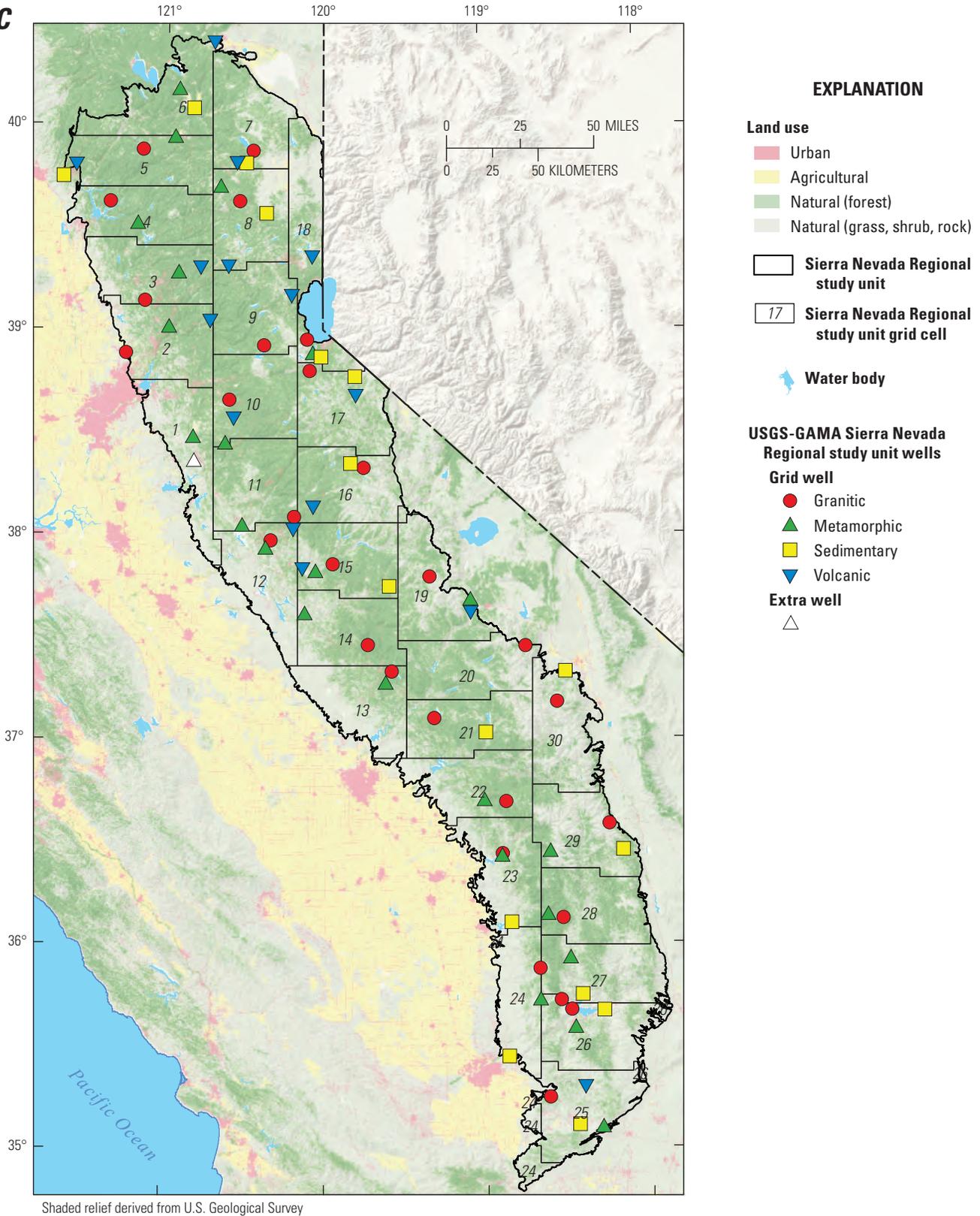


Figure 3. —Continued

Runoff from Sierra Nevada watersheds, primarily in the form of snow melt, provides approximately 50 percent of California's developed water (Carle, 2004). River systems on the western slope of the Sierra Nevada drain into the Sacramento River, the San Joaquin River, or the Tulare Basin. Streams on the eastern side primarily feed Lake Tahoe or the Owens River ([fig. 3B](#)). Nearly all of the river systems have large dams and reservoirs that are operated to provide water supplies and (or) to control flooding outside of the Sierra Nevada.

Groundwater is used extensively for public and domestic drinking-water supplies in the Sierra Nevada, and much of this groundwater comes from granitic-, metamorphic-, or volcanic-rock aquifers, rather than from sediment deposits in groundwater basins. Granitic and metamorphic rocks of the Sierra Nevada have low permeability except where they are extensively fractured. Fractures and joints typically are most extensive in size and number in the upper few hundred feet of bedrock and typically decrease with depth (Page and others, 1984; Borchers, 1996). Fracture permeability tends to decrease with depth because of increased lithostatic pressure (Ingebritsen and Sanford, 1998); however, because crystalline rocks remain brittle to depths of several kilometers, some fracture permeability may persist to great depths (Freeze and Cherry, 1979). The three-dimensional complexity and variability of fracture systems can cause well yields and water quality to vary widely on a local scale. Recharge to fractured hard-rock aquifers of the SNR study unit occurs by direct infiltration of precipitation and snow melt and by infiltration from lakes and streams.

Although groundwater basins compose a small part of the SNR study unit, they typically have a greater density of groundwater use than other areas because they commonly contain greater population densities and (or) greater amounts of agricultural land compared to other areas. In addition, wells in groundwater basins typically have greater yields than those in the surrounding fractured-rock aquifers (for example, California Department of Water Resources, 2003). Recharge to groundwater basins of the Sierra Nevada occurs through two primary mechanisms: (1) mountain-front recharge, which is runoff from precipitation on the mountain that percolates into the basin through the coarser alluvial fan deposits along the basin margin and through stream channels crossing the basin; and (2) mountain-block recharge, which is water that has percolated through the mountain bedrock aquifer and enters the basin from the sub-surface (for example, Wilson and Guan, 2004). Precipitation falling directly on the basin percolates vertically downward through the sediments of the basin or enters stream channels.

Land Use

Land use in the entire SNR study unit is 91.2 percent natural, 4.6 percent agricultural, and 4.2 percent urban ([fig. 3C](#)). Land use was classified using an enhanced version of the satellite-derived (30-m pixel resolution), nationwide

USGS National Land Cover Dataset (Nakagaki and others, 2007; [appendix B](#)). Natural land in the Sierra Nevada consists mainly of shrub lands and grasslands at lower elevations, forests at higher elevations, and bare rock at the highest elevations. Approximately 40 percent of the area is managed by the U.S. Forest Service, and approximately 20 percent is under the jurisdiction of the National Park Service or the Bureau of Land Management (Sierra Nevada Ecosystem Project, 1996). Most of the remaining 40 percent is privately owned.

Agricultural land constitutes less than 5 percent of total land use and is concentrated in the valleys of the southern Sierra Nevada and areas of the foothills adjacent to the Central Valley ([fig. 3C](#)). Urban land also constitutes less than 5 percent of total land use, but this category is growing rapidly. The permanent population of the province rose from 0.3 million in 1970 to 0.8 million in 2000 and is predicted to grow to 1.7–2.0 million by 2040 (Duane, 1996; Sierra Nevada Ecosystem Project, 1996). Much of the population growth has occurred along the Interstate 80 and Highway 50 corridors (highways that connect Sacramento to Reno, Nevada, and to the southern end of Lake Tahoe, respectively; [fig. 3C](#)). As of 1990, 80 percent of the permanent population lived on 3 percent of the land area (Sierra Nevada Ecosystem Project, 1996). Recreation and tourism are the primary industries in the Sierra Nevada, and the resulting transient population is much larger than the permanent population.

Methods

This section describes the methods used for the status assessment and for evaluating data for potential explanatory factors (the understanding assessment). Methods used to collect and analyze groundwater samples and results for the quality-control assessment are described by Shelton and others (2010).

Status Assessment

The status assessment was designed to quantify groundwater quality in areal proportions of the primary aquifer system. This section describes the methods used for (1) defining groundwater quality, (2) assembling the data used for the assessment, and (3) 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 sub-cell and a “spatially weighted” approach that used many wells to represent each grid sub-cell (Belitz and others, 2010).

The 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 SNR study unit, the historical CDPH database contains more than 500,000 records from about 1,500 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), the concentrations of constituents measured in groundwater relative to regulatory and non-regulatory benchmarks 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 within a toxicological context (for example, U.S. Environmental Protection Agency, 1986; Toccalino and others, 2004; Toccalino and Norman, 2006; Rowe and others, 2007). RC is defined as:

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

An RC value less than 1 (<1.0) indicates that the sample concentration is less than the benchmark, and an RC value greater than 1 (>1.0) indicates that the sample concentration is greater than the benchmark. The use of RCs permits comparison on a single scale of multiple constituents 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. However, to place the results in a human-health context, concentrations of constituents measured in the untreated groundwater were compared to benchmarks established by the U.S. Environmental Protection Agency (USEPA) and CDPH (U.S. Environmental Protection Agency, 1999a, 2009, 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 USEPA: maximum contaminant levels (MCL-CA and MCL-US, where the prefix MCL indicates maximum contaminant level, and the suffixes “-CA” and “-US” indicate CDPH and USEPA, respectively), action levels (AL-US), and treatment technique levels (TT-US).
2. Non-regulatory, non-health-based, aesthetic-based levels established by the CDPH and USEPA: secondary maximum contaminant levels (SMCL-CA and SMCL-US). For constituents with both recommended and upper SMCL-CA levels, the values for the upper levels were used.
3. Non-regulatory, health-based levels established by the CDPH and USEPA: CDPH notification levels (NL-CA), USEPA lifetime health advisory levels (HAL-US), and USEPA risk-specific doses for 1:100,000 (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 listings of the benchmark values for all constituents analyzed are provided by Shelton and others (2010).

Toccalino and others (2004), Toccalino and Norman (2006), and Rowe and others (2007) previously used the ratio of the 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 were not used in this report because HBSLs are not currently used as benchmarks by California drinking-water regulatory agencies. Because different water-quality benchmarks are used to calculate RCs and BQs, the terms are not interchangeable. For example, the RC and BQ values were different from one another for approximately half of the constituents detected in samples from USGS-GAMA study units in the Sierra Nevada hydrogeologic province (Fram and Belitz, 2012).

For ease of discussion, RCs of constituents were classified into low, moderate, and high categories ([table 1](#)). RC values >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 >0.5 and ≤1.0 were defined as “moderate,” and RC values ≤0.5 were defined as “low.” For organic and special-interest constituents, RC values >0.1 and ≤1.0 were defined as “moderate,” and RC values ≤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 a 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

Table 1. Relative-concentration categories used for assessing groundwater quality in the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Relative-concentration (RC) is defined as the measured value divided by a benchmark value. **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

others, 2010). The primary reason for using a higher boundary value for inorganic constituents in this study was to focus attention on the inorganic constituents most prevalent at concentrations closest to benchmark concentrations. In a national survey of water quality in aquifers used for public drinking-water supply, Toccalino and others (2010) found that organic constituents (pesticides and volatile organic compounds [VOCs]) were present at $BQ > 0.1$ in approximately 10 percent of the samples and that inorganic constituents (nutrients, trace elements, and radioactive constituents) were present at $BQ > 0.1$ 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 (intentional, such as pesticide applications, and unintentional, such as leaks and spills) at the land surface. Concentrations of the organic constituents may change rapidly in groundwater; therefore, such early warning may be vital for planning and implementing measures to protect aquifer systems from further contamination and to mitigate existing contamination. Resources may be appropriately focused on the 10 percent of wells that have $BQ > 0.1$ of organic constituents; however, a similar focusing of resources would be less feasible for the inorganic constituents because most of the wells (80 percent) have inorganic constituents present at $BQ > 0.1$. Inorganic constituents typically are naturally occurring 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 BQs) of 0.5 allows identification of inorganic constituents—from among the many that may be present—that are most prevalent at concentrations close to benchmarks and therefore may warrant more immediate attention from water-resource managers.

The boundary between low and moderate RCs is not intended as a demarcation of the presence of contamination from anthropogenic sources. For example, concentrations of nitrate in groundwater greater than 1 milligram per liter (mg/L) generally are considered to indicate contamination from anthropogenic sources (Nolan and Hitt, 2003; 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) allows some contamination from anthropogenic sources in groundwater with a low RC for nitrate. Nitrate and the other nutrient constituents were treated as inorganic constituents, with the boundary between low and moderate RCs set at an RC of 0.5 for this study. Similarly, groundwater containing human-made anthropogenic organic constituents with RCs less than 0.1 is classified as having low RC for organic constituents, even though contamination from anthropogenic sources is present.

Setting the boundary between moderate and low RCs at 0.5 for inorganic constituents, rather than 0.1, also facilitated the use of water-quality data from the CDPH database in the status assessment. Twenty-three inorganic constituents with health-based benchmarks had data from both the CDPH database and USGS-GAMA. RCs of reporting limits used by USGS-GAMA were <0.1 for all 23 constituents (Fram and Belitz, 2012); thus, the difference between low and moderate RCs in groundwater samples could be distinguished whether the boundary was set at 0.1 or 0.5. In contrast, the median RC of the most prevalent reporting limit reported in the CDPH database was 0.1, and 11 of the constituents had reporting limits with RCs >0.1 (Fram and Belitz, 2012). If the boundary were set at 0.1, then data from the CDPH database would yield only minimum estimates of the prevalence of groundwater with moderate RCs of these 11 constituents; therefore, the boundary value was set at 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. Although other organizations also collect water-quality data, the CDPH data are the only data available from a Statewide database of groundwater chemistry that are suitable for comprehensive analysis.

Data for Grid-Based Calculations of Aquifer-Scale Proportions

The data used for the grid-based calculations of aquifer-scale proportions were from wells sampled by USGS-GAMA. Detailed descriptions of the methods used to identify wells for sampling are given in Shelton and others (2010). Briefly, the SNR study unit was divided into 30 equal-area grid cells (2,200 km² each; [fig. 3A](#)) (Scott, 1990), and each cell was subdivided into 1 to 4 sub-cells, 1 for each of the 4 aquifer lithologies (granitic rock, metamorphic rock, sedimentary deposits, and volcanic rock) present in the cell. All the CDPH wells in a cell were assigned random ranks, and the highest ranked well in each sub-cell for which permission to sample could be obtained and which met basic sampling criteria was selected as the lithologic-grid well to represent that sub-cell. Not all cells contained areas of all four aquifer lithologies, and not all aquifer lithologies present in a cell contained wells. The 30 grid cells each had 2 to 4 aquifer lithologies containing CDPH wells, resulting in total of 91 possible lithologic-grid sub-cells. USGS-GAMA sampled wells in 82 of the 91 possible lithologic-grid sub-cells ([table 2](#)). One additional non-grid well was sampled in one sub-cell. Of the 83 wells sampled by USGS-GAMA, 76 were listed in the CDPH database, and 7 were unlisted public drinking-water supply wells.

Table 2. Summary of numbers of wells used in the calculations of aquifer-scale proportions for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[A total of 132 wells were sampled by USGS-GAMA for the Tahoe-Martis, Central Sierra, and Southern Sierra study units; 11 of these wells were also sampled by USGS-GAMA for the Sierra Nevada Regional study unit, and 4 wells were monitoring wells not considered representative of the primary aquifer system. A total of 1,238 wells had data for at least one constituent in the CDPH database; 172 of those wells were also sampled by USGS-GAMA. **Abbreviations:** CDPH, California Department of Public Health; USGS, U.S. Geological Survey]

Aquifer lithology	Number of sub-cells	Grid wells sampled by USGS-GAMA for SNR study unit	Additional wells sampled by USGS-GAMA for SNR study unit	Wells sampled by USGS-GAMA for Tahoe-Martis, Central Sierra, Southern Sierra study units	Other wells in CDPH database
Granitic rocks	29	28	0	41	568
Metamorphic rocks	24	23	1	11	221
Sedimentary rocks	22	16	0	45	202
Volcanic rocks	19	15	0	20	75
Total	91	82	1	117	1,066

The top-ranked lithologic-grid well in each cell also was member of a second network, the fundamental-grid network. These 30 wells were named with an alphanumeric GAMA_ID consisting of an initial prefix identifying the study unit (SIERRA), a second prefix indicating aquifer lithology (G, M, S, and V for granitic, metamorphic, sedimentary, and volcanic aquifer lithologies), and a number indicating the order of sample collection ([appendix A](#); [figs. A14,B](#); [table A1](#)). The other 52 lithologic-grid wells (and the 1 extra well) were named in the same way, except that the second prefix included an “L” for lithologic grid (GL, ML, SL, and VL for granitic, metamorphic, sedimentary, and volcanic aquifer lithologies). The fundamental grid was used for data analysis by Shelton and others (2010), but was not used for data analysis in this report.

Samples collected from USGS-grid wells were analyzed for 211 or 214 constituents ([table 3](#)). Water-quality data collected by USGS-GAMA are tabulated in Shelton and others (2010) and also are available from the SWRCB’s online groundwater information system GeoTracker GAMA (website at http://www.waterboards.ca.gov/gama/geotracker_gama.shtml). Twenty of the sites were developed springs, and 63 were wells. For ease of discussion, all sites are referred to as wells unless the difference between wells and springs is important to the discussion.

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

The spatially weighted calculations of aquifer-scale proportions used data from 1,266 wells having data for at least 1 water-quality constituent: 83 wells sampled by USGS-GAMA for the SNR study unit, 117 wells sampled by USGS-GAMA for the Tahoe-Martis, Central Sierra Nevada, and Southern Sierra Nevada study units (Fram and Belitz, 2012), and 1,066 wells in the CDPH database having water-quality data for samples collected between May 1, 2006, and October 31, 2008 ([table 2](#)). This count of 1,066 CDPH wells

does not include the 172 CDPH wells that were among the 190 wells sampled by USGS-GAMA. Water-quality data collected by the CDPH are available from the SWRCB’s online groundwater information system GeoTracker GAMA (website at http://www.waterboards.ca.gov/gama/geotracker_gama.shtml). Eleven of the wells sampled by USGS-GAMA for the SNR study unit also were sampled for the Tahoe-Martis, Central Sierra Nevada, or Southern Sierra Nevada study units; the data from the sampling for the SNR study unit in 2008 were used. For the 172 wells sampled by USGS-GAMA that also had CDPH data for 1 or more constituents, the USGS-GAMA data were used.

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 SNR study unit ([table 3](#)). This subset was selected by using the following criteria:

- Constituents present at high or moderate RCs ([table 1](#)) in any well sampled by USGS-GAMA for the SNR study unit or the Tahoe-Martis, Central Sierra Nevada, or Southern Sierra Nevada study units, or in the CDPH database for any sample collected between May 1, 2006, and October 31, 2008.
- Organic constituents having area-weighted detection frequencies >10 percent in the USGS-GAMA samples collected for the SNR study unit for the study unit as a whole or for one or more of the four aquifer lithologies.

These criteria identified 27 inorganic constituents, 7 organic constituents, and 1 special-interest constituent ([table 4A](#)). An additional 20 inorganic constituents and 15 organic constituents were detected by USGS-GAMA in samples from the SNR study unit, but these constituents either have no drinking-water-quality benchmarks or were only

Table 3. Summary of constituent groups and number of wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[na, not analyzed]

Constituent groups	Analytical schedule ¹	
	Regular	Enhanced
Number of wells	55	28
Number of constituents		
Inorganic constituents		
Specific conductance	1	1
Nutrients	5	5
Major ions, alkalinity, and total dissolved solids	12	12
Trace elements ²	24	24
Uranium activity ³ or uranium concentration ²	1	1
Radon-222 activity	na	1
Radium activity ⁴	na	1
Gross alpha and beta particle activities ⁵	2	2
Organic constituents⁶		
Volatile organic compounds (VOCs) ⁷	85	85
Pesticides and degradates	63	63
Constituents of special interest		
Perchlorate	1	1
<i>N</i> -Nitrosodimethylamine (NDMA)	na	1
Geochemical and age-dating tracers		
Dissolved oxygen, pH, and temperature	3	3
Arsenic and iron redox species ratios	2	2
Carbon-14 and $\delta^{13}\text{C}$ of dissolved carbonates	2	2
Tritium	1	1
Noble gases (helium, neon, argon, krypton, xenon) and $^3\text{He}/^4\text{He}$ ⁽⁸⁾	6	6
$\delta^2\text{H}$ and $\delta^{18}\text{O}$ stable isotopes of water	2	2
$^{87}\text{Sr}/^{86}\text{Sr}$ of dissolved strontium	1	1
Sum:	211	214

¹“Regular” and “enhanced” schedules correspond to the “intermediate” and “slow” schedules of Shelton and others (2010). Tiered sampling schedules were used to reduce costs.

²Uranium was measured in two ways, as uranium concentration by the same analytical method used to measure trace elements, and as uranium activity. Uranium is not counted as a trace element.

³Uranium activity equals the sum of the three isotopes measured: uranium-234, uranium-235, and uranium-238.

⁴Radium activity equals the sum of the two isotopes measured: radium-226 and radium-228.

⁵Both gross alpha particle and gross beta particle radiation were measured after 72-hour and 30-day holding times; data from the 72-hour measurement are used in this report.

⁶The enhanced schedule also had 14 pharmaceutical compounds analyzed. Results are presented in Fram and Belitz (2011b).

⁷Includes 10 constituents classified as fumigants or fumigant synthesis byproducts.

⁸Noble gas and helium isotope data are presented in [appendix F](#).

Table 4A. Benchmark type and value and reporting levels for constituents detected at moderate or high relative-concentrations and organic constituents detected with more than 10 percent detection frequency in at least one primary aquifer system, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Inorganic constituents selected if maximum value measured in USGS-GAMA samples or reported in CDPH database between May 2006 and October 2008 had RC > 0.5. Organic and special-interest constituents selected if maximum value had RC > 0.1, or if detection frequency at any concentration was greater than 10 percent. Relative-concentration (RC) is defined as the measured value divided by the benchmark value. **Benchmark type:** Non-regulatory, aesthetic-based benchmarks: SMCL-CA, California Department of Public Health (CDPH) secondary maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; Prop AMCL-US, proposed USEPA alternative maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. **Units:** µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; pCi/L, picocuries per liter. **Abbreviations:** USGS, U.S. Geological Survey; USEPA, U.S. Environmental Protection Agency; N, nitrogen; na, not available; ssLc, sample-specific critical level; >, greater than]

Constituent ¹	Benchmarks		Units	Reporting levels ³		Relations to explanatory factors tested
	Type ²	Value		USGS	CDPH	
Trace elements						
Aluminum ⁴	MCL-CA	1,000	µg/L	¹¹ 1.6	50	No
Antimony	MCL-US	6	µg/L	0.02	6	No
Arsenic	MCL-US	10	µg/L	0.03	2	Yes
Beryllium ⁴	MCL-US	4	µg/L	0.01	1	No
Boron	NL-CA	1,000	µg/L	2	na	Yes
Cadmium ⁴	MCL-US	5	µg/L	0.01	1	No
Chromium ⁴	MCL-CA	50	µg/L	¹¹ 0.42	1	No
Copper ⁴	AL-US	1,300	µg/L	¹¹ 1.7	50	No
Fluoride	MCL-CA	2	mg/L	0.04	0.1	Yes
Lead ^{4,5}	AL-US	15	µg/L	¹¹ 0.65	5	No
Mercury ⁴	MCL-US	2	µg/L	¹¹ 0.012	0.5	No
Molybdenum	HAL-US	40	µg/L	0.02	na	No
Nickel ⁴	MCL-CA	100	µg/L	¹¹ 0.36	10	No
Selenium	MCL-US	50	µg/L	0.02	5	No
Strontium ⁵	HAL-US	4,000	µg/L	0.4	na	No
Uranium and radioactive constituents						
Gross alpha particle activity	MCL-US	15	pCi/L	ssL _c	3	Yes
Radium activity	MCL-US	5	pCi/L	ssL _c	1	No
Radon-222 activity	Prop AMCL-US	4,000	pCi/L	ssL _c	na	Yes
Uranium ⁶ activity	MCL-CA	20	pCi/L	ssL _c	1	Yes
Nutrients						
Nitrate, as N ⁷	MCL-US	10	mg/L	0.02	0.45	Yes
Inorganic constituents with secondary maximum contaminant levels (SMCL)						
Specific conductance ⁸	SMCL-CA	1,600	µS/cm	5	na	No
Chloride ^{4,5}	SMCL-CA	500	mg/L	0.06	2	No
Total dissolved solids ⁸ (TDS)	SMCL-CA	1,000	mg/L	5	na	No
Sulfate	SMCL-CA	500	mg/L	0.09	2	No
Iron	SMCL-CA	300	µg/L	¹¹ 6	100	Yes
Manganese	SMCL-CA	50	µg/L	¹¹ 0.2	20	Yes
Zinc ^{4,5}	SMCL-CA	5,000	µg/L	¹¹ 4.8	50	No

Table 4A. Benchmark type and value and reporting levels for constituents detected at moderate or high relative-concentrations and organic constituents detected with more than 10 percent detection frequency in at least one primary aquifer system, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Inorganic constituents selected if maximum value measured in USGS-GAMA samples or reported in CDPH database between May 2006 and October 2008 had RC > 0.5. Organic and special-interest constituents selected if maximum value had RC > 0.1, or if detection frequency at any concentration was greater than 10 percent. Relative-concentration (RC) is defined as the measured value divided by the benchmark value. **Benchmark type:** Non-regulatory, aesthetic-based benchmarks: SMCL-CA, California Department of Public Health (CDPH) secondary maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; Prop AMCL-US, proposed USEPA alternative maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. **Units:** µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; pCi/L, picocuries per liter. **Abbreviations:** USGS, U.S. Geological Survey; USEPA, U.S. Environmental Protection Agency; N, nitrogen; na, not available; ssLc, sample-specific critical level; >, greater than]

Constituent ¹	Benchmarks		Units	Reporting levels ³		Relations to explanatory factors tested
	Type ²	Value		USGS	CDPH	
Volatile organic compounds						
Chloroform ⁹	MCL-US	80	µg/L	0.01	0.5	Yes ¹²
Benzene ¹⁰	MCL-CA	1	µg/L	0.008	0.5	No
Methyl <i>tert</i> -butyl ether ^{4,9} (MTBE)	MCL-CA	13	µg/L	0.05	3	Yes ¹²
Carbon tetrachloride ¹⁰	MCL-CA	0.5	µg/L	0.03	0.5	No
1,2-Dichloroethane	MCL-CA	0.5	µg/L	0.03	0.5	No
Tetrachloroethene (PCE)	MCL-US	5	µg/L	0.02	0.5	Yes ¹²
Pesticides						
Simazine ⁹	MCL-US	4	µg/L	0.003	1	Yes ¹²
Special-interest constituent						
Perchlorate ^{4,9}	MCL-CA	6	µg/L	0.1	4	Yes

¹Typical uses and (or) potential sources of constituents to groundwater are briefly discussed in the text for some constituents. Additional information may be obtained from Hem (1985), U.S. Environmental Protection Agency (2014), and California Department of Public Health (2014).

²Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks:

MCL-CA, SMCL-CA:	California Department of Public Health (2013b)
MCL-US, AL-US:	U.S. Environmental Protection Agency (2009)
NL-CA:	California Department of Public Health (2010)
HAL-US:	U.S. Environmental Protection Agency (2012)
Prop AMCL-US:	U.S. Environmental Protection Agency (1999a)

³USGS reporting level for most constituents is the long-term method detection level (Shelton and others, 2010). CDPH reporting level is the most common reporting level used to report non-detections for the study unit.

⁴Selected on the basis of concentrations reported in CDPH database. Constituent also detected in samples from the SNR study unit at low relative-concentrations.

⁵Selected on the basis of concentrations reported in samples from the Tahoe-Martis, Central Sierra, or Southern Sierra study units. Constituent also detected in samples from the SNR study unit at low relative-concentrations.

⁶The MCL-US for uranium is 30 µg/L. Uranium data in the CDPH database generally are reported in units of picocuries per liter, and most USGS-GAMA samples also were analyzed for uranium isotope activity. For samples having only uranium measured in units of micrograms per liter, the data were converted to activities using a conversion factor of 0.79 (see [appendix D](#)).

⁷Concentrations of nitrate, as nitrate, reported in the CDPH data are converted to concentrations of nitrate, as nitrogen (nitrate-N), for comparison with USGS-GAMA data.

⁸Aquifer-scale proportions were not calculated for specific conductance (SC). For the 198 wells that had data for SC, but not TDS, SC was converted to TDS.

⁹Selected on the basis of detection frequency in the Sierra Nevada Regional study unit.

¹⁰Selected on the basis of concentrations reported in samples from the Tahoe-Martis, Central Sierra, or Southern Sierra study units.

¹¹USGS reporting level is a study reporting level (Olsen and others, 2010).

¹²The organic constituents are evaluated as constituent classes rather than as individual constituents because none of the individual organic constituents were present at high RC in greater than 2 percent of the primary aquifer system, but at least one member of the class had an area-weighted detection frequency >10 percent in at least one of the four aquifer lithologies or in the study unit as a whole. The four qualifying classes are: trihalomethanes (chloroform was the only constituent detected), gasoline oxygenates (MTBE was the only constituent detected), solvents (8 solvents detected), and pesticides (3 herbicides detected).

Table 4B. Benchmark type and value and reporting levels for constituents detected only at low relative-concentrations and constituents that were detected and did not have benchmarks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Low concentrations are defined as $RC \leq 0.5$ for inorganic constituents and as $RC \leq 0.1$ for organic constituents. Relative-concentration (RC) is defined as the measured value divided by the benchmark value. **Benchmark type:** Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; Prop AMCL-US, proposed USEPA alternative maximum contaminant level; AL-US, USEPA action level; MCL-CA, California Department of Public Health (CDPH) maximum contaminant level. **Units:** $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; $\mu\text{S/cm}$, microsiemens per centimeter; pCi/L , picocuries per liter. **Abbreviations:** N, nitrogen; na, not available.; P, phosphorus; ssL_c , sample-specific critical level; \leq , less than or equal to]

Constituent ¹	Benchmarks		Units	Reporting levels ³	
	Type ²	Value		USGS	CDPH
Inorganic constituents detected only at low concentrations					
Ammonia, as N	HAL-US	24.7	mg/L	0.01	1
Nitrite, as N	MCL-US	1	mg/L	0.001	0.4
Barium	MCL-CA	1,000	$\mu\text{g/L}$	0.1	100
Silver	SMCL-CA	100	$\mu\text{g/L}$	0.1	10
Thallium	MCL-US	2	$\mu\text{g/L}$	0.02	1
Vanadium	NL-CA	50	$\mu\text{g/L}$	0.05	3
Gross beta particle activity	MCL-US	50	pCi/L	ssL_c	3
Detected inorganic constituents without benchmarks					
Total nitrogen	na	na	mg/L	0.03	na
Orthophosphate, as P	na	na	mg/L	0.003	na
Calcium	na	na	mg/L	0.01	1
Magnesium	na	na	mg/L	0.006	2
Potassium	na	na	mg/L	0.01	2
Sodium	na	na	mg/L	0.06	na
Alkalinity	na	na	mg/L	1	20
Bromide	na	na	mg/L	0.01	na
Iodide	na	na	mg/L	0.001	na
Silica	na	na	mg/L	0.009	na
Cobalt	na	na	$\mu\text{g/L}$	0.02	na
Lithium	na	na	$\mu\text{g/L}$	0.3	na
Tungsten	na	na	$\mu\text{g/L}$	0.03	na
Organic constituents detected only at low concentrations and detection frequency less than 10 percent					
Carbon disulfide	NL-CA	160	$\mu\text{g/L}$	0.02	na
1,4-Dichlorobenzene	MCL-CA	5	$\mu\text{g/L}$	0.01	0.5
1,1-Dichloroethane	MCL-CA	5	$\mu\text{g/L}$	0.02	0.5
1,1-Dichloroethene	MCL-CA	6	$\mu\text{g/L}$	0.01	0.5
<i>cis</i> -1,2-Dichloroethene	MCI-CA	6	$\mu\text{g/L}$	0.01	0.5
1,1,1-Trichloroethane	MCL-US	200	$\mu\text{g/L}$	0.01	0.5
Trichloroethene (TCE)	MCL-US	5	$\mu\text{g/L}$	0.01	0.5
Trichlorofluoromethane	MCL-CA	150	$\mu\text{g/L}$	0.04	5
Atrazine	MCL-CA	1	$\mu\text{g/L}$	0.003	0.5
Hexazinone	HAL-US	400	$\mu\text{g/L}$	0.004	na

Table 4B. Benchmark type and value and reporting levels for constituents detected only at low relative-concentrations and constituents that were detected and did not have benchmarks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Low concentrations are defined as $RC \leq 0.5$ for inorganic constituents and as $RC \leq 0.1$ for organic constituents. Relative-concentration (RC) is defined as the measured value divided by the benchmark value. **Benchmark type:** Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; Prop AMCL-US, proposed USEPA alternative maximum contaminant level; AL-US, USEPA action level; MCL-CA, California Department of Public Health (CDPH) maximum contaminant level. **Units:** $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; $\mu\text{S/cm}$, microsiemens per centimeter; pCi/L , picocuries per liter. **Abbreviations:** N, nitrogen; na, not available.; P, phosphorus; ssLc, sample-specific critical level; \leq , less than or equal to]

Constituent ¹	Benchmarks		Units	Reporting levels ³	
	Type ²	Value		USGS	CDPH
Detected organic constituents without benchmarks					
Deethylatrazine	na	na	$\mu\text{g/L}$	0.007	na
3,4-Dichloroaniline	na	na	$\mu\text{g/L}$	0.002	na
Fipronil	na	na	$\mu\text{g/L}$	0.01	na
Desulfinylfipronil	na	na	$\mu\text{g/L}$	0.006	na
Fipronil sulfone	na	na	$\mu\text{g/L}$	0.026	na

¹Typical uses and (or) potential sources of constituents to groundwater are briefly discussed in the text for some constituents. Additional information may be obtained from Hem (1992), U.S. Environmental Protection Agency (2014), and California Department of Public Health (2014).

²Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks:

MCL-CA, SMCL-CA:	California Department of Public Health (2013b)
MCL-US, AL-US:	U.S. Environmental Protection Agency (2009)
NL-CA:	California Department of Public Health (2010)
HAL-US:	U.S. Environmental Protection Agency (2012)
Prop AMCL-US:	U.S. Environmental Protection Agency (1999a)

³USGS reporting level for most constituents is the long-term method detection level (Shelton and others, 2010). CDPH reporting level is the most common reporting level used to report non-detections for the study unit.

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 18 of the geochemical and age-dating tracers examined also were detected (table 3). The remaining 126 constituents were not detected by USGS-GAMA in the SNR study unit (Shelton and others, 2010).

The CDPH database also was used to identify constituents that have been reported at high RCs historically but not currently (table 5). 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: January 12, 1977, to April 30, 2006. Constituent concentrations may have been higher in the past than at the present for several reasons, such as a general improvement of groundwater quality with time or the abandonment of wells with high concentrations of

constituents. Constituents with historically high constituents that did not otherwise meet the criteria previously listed were not considered to be representative of potential groundwater-quality concerns in the study unit during the current period of interest (May 2006 through October 2008).

The SNR study unit had 20 historically high constituents (table 5). Of the five inorganic constituents, two also were reported at moderate RCs in the CDPH database between May 1, 2006, and October 31, 2008 (aluminum and mercury). Of the 10 VOCs, 2 also were reported at moderate RCs in the CDPH database between May 1, 2006, and October 31, 2008, or were detected at greater than 10 percent area-weighted detection frequency in the wells sampled by USGS-GAMA for the SNR study unit (chloroform, and methyl *tert*-butyl ether). Of the five other organic constituents, four are semi-volatile organic compounds that were not analyzed by USGS-GAMA. Eleven of the 20 historically high constituents were detected at high concentrations in only 1 well each.

Table 5. Constituents reported at concentrations greater than benchmarks in the California Department of Public Health (CDPH) database prior to May 2006 but not during the time period used for the status assessment (May 2006 through October 2008), Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

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

Constituent ¹	Benchmark			Date of most recent value above benchmark	Number of wells with data prior to status assessment period	Number of wells with a value above benchmark
	Type ²	Value	Units			
Inorganic constituents						
Aluminum ³	MCL-CA	1,000	µg/L	11/04/2005	1,136	16
Barium	MCL-CA	1,000	µg/L	04/27/2005	1,159	2
Mercury ³	MCL-US	2	µg/L	08/27/1996	1,156	6
Thallium	MCL-US	2	µg/L	08/17/2004	1,018	5
Vanadium	NL-CA	50	µg/L	11/16/2005	490	12
Volatile organic compounds						
1,1,1-Trichloroethane	MCL-US	200	µg/L	12/19/1988	1,183	1
1,1,2,2-Tetrachloroethane	MCL-CA	1	µg/L	09/11/2002	1,184	1
1,1-Dichloroethane	MCL-CA	5	µg/L	03/17/1993	1,183	2
1,1-Dichloroethene	MCL-CA	6	µg/L	06/15/1989	1,179	1
Chloroform ⁴	MCL-US	80	µg/L	07/16/1996	1,182	1
Dibromochloropropane (DBCP)	MCL-US	0.2	µg/L	09/03/2004	411	1
Dichloromethane	MCL-US	5	µg/L	03/16/2001	1,182	4
Methyl <i>tert</i> -butyl ether ^{3,4} (MTBE)	MCL-CA	13	µg/L	05/28/2004	998	4
Trichloroethene (TCE)	MCL-US	5	µg/L	01/17/1990	1,183	1
Vinyl chloride	MCL-CA	0.5	µg/L	05/12/2003	1,183	1
Other organic compounds						
Alachlor	MCL-US	2	µg/L	11/28/2001	541	1
Aldrin ⁵	RSD5-US	0.02	µg/L	07/17/2003	247	1
Di(2-ethylhexyl)phthalate ⁵	MCL-CA	4	µg/L	08/22/1997	217	1
Diazinon ⁵	HAL-US	1	µg/L	10/27/2004	495	1
Heptachlor epoxide ⁵	MCL-CA	0.01	µg/L	11/25/1997	358	2

¹Typical uses and (or) potential sources of constituents to groundwater are briefly discussed in the text for some constituents. Additional information may be obtained from Hem (1992), U.S. Environmental Protection Agency (2013), and California Department of Public Health (2013).

²Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks:

MCL-CA, SMCL-CA:	California Department of Public Health (2013b)
MCL-US, AL-US:	U.S. Environmental Protection Agency (2009)
NL-CA:	California Department of Public Health (2010)
HAL-US, RSD5-US:	U.S. Environmental Protection Agency (2012)
Prop AMCL-US:	U.S. Environmental Protection Agency (1999a)

³Constituent detected at moderate relative-concentrations in the CDPH database or in the Sierra Nevada Regional Tahoe-Martis, Central Sierra, or Southern Sierra study units between May 2006 and October 2008. Reporting limits are in [table 4A](#), and results for aquifer-scale proportions are in [tables 7A](#), [7B](#), or [12](#).

⁴Constituent detected at greater than 10 percent detection frequency in the Sierra Nevada Regional study unit. Reporting limits are in [table 4A](#), and results for aquifer-scale proportions are in [table 12](#).

⁵Constituent not analyzed by USGS-GAMA.

Calculation of Aquifer-Scale Proportions

The status assessment is intended to characterize the current quality of groundwater resources within the primary aquifer system of the SNR study unit. 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 mean that there exists a discrete aquifer unit. In most groundwater basins, public drinking-water supply wells typically are screened or open at greater depths than are domestic drinking-water supply 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 tapped by public drinking-water supply wells. However, this segregation between the depths of public drinking-water supply wells and domestic drinking-water supply wells commonly does 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; Page and others, 1984; Borchers, 1996; Ingebritsen and Sanford, 1998). Nearly all of the wells used in the status assessment for the SNR study unit are listed in the CDPH database, and are therefore classified as public drinking-water supply wells. To the extent that domestic drinking-water supply wells in the study unit are screened or open over the same depth intervals as the CDPH wells, the assessments presented in this report will also be applicable to the parts of the aquifer system used for domestic drinking-water supplies.

Five primary aquifer systems were defined for the SNR study unit: one to represent each of the four aquifer lithologies (granitic, metamorphic, sedimentary, and volcanic) and an aggregated system to represent the study unit as a whole. The proportions of these primary aquifer systems with high, moderate, and low RCs of constituents were calculated using a modified version of the grid-based and spatially weighted approaches of Belitz and others (2010). The modification consisted of area-weighting to account for the size differences among the sub-cells for a given aquifer lithology. Calculations of aquifer-scale proportions were made for individual constituents and for classes of constituents.

The grid-based calculations used data from one well per lithologic-grid sub-cell. Aquifer-scale proportions were calculated for each of the four aquifer lithologies separately. High-RC aquifer-scale proportion was calculated as the fraction of the area of the aquifer lithology in the study unit represented by lithologic-grid wells having high RCs for a constituent (eq. 1). The contribution of each cell to the aquifer-scale proportion for a given lithology was weighted according to the area of the sub-cell occupied by that lithology. The moderate-RC aquifer-scale proportion was calculated similarly.

$$P_{Lg, high} = \frac{\sum_c N_{L,high,c} A_{L,c}}{\sum_c A_{L,c}}, \quad (1)$$

where

- $P_{Lg,high}$ is the grid-based high-RC aquifer-scale proportion for the lithologic type L primary aquifer system (granitic, metamorphic, sedimentary, or volcanic) in the SNR study unit,
- $N_{L,high,c}$ is the number of wells in a given lithologic sub-cell of type L having high RC for the constituent (for the grid-based calculation, there is only one well per lithologic sub-cell, so the value of this parameter is either 1 or 0),
- $A_{L,c}$ is the area of a given lithologic sub-cell of type L , and
- \sum_c refers to summation over all sub-cells having data for the constituent.

The spatially weighted calculations used the dataset of 1,266 wells assembled from wells sampled by USGS-GAMA for the SNR, Tahoe-Martis, Central Sierra, and Southern Sierra study units and wells with data in the CDPH database (table 2). Aquifer-scale proportions were calculated for each of the four aquifer lithologies separately. High-RC aquifer-scale proportion was calculated for each constituent by computing the proportion of high RC wells in each sub-cell and then calculating the area-weighted average proportion for the sub-cells (eq. 2; Isaaks and Srivastava, 1989). The moderate-RC aquifer-scale proportion was calculated similarly.

$$P_{Ls,high} = \frac{\sum_c \frac{N_{L,high,c}}{N_{L,total,c}} A_{L,c}}{\sum_c A_{L,c}}, \quad (2)$$

where

- $P_{Ls,high}$ is the spatially weighted high-RC aquifer-scale proportion for the lithologic type L primary aquifer system (granitic, metamorphic, sedimentary, or volcanic) in the SNR study unit, and
- $N_{L,total,c}$ is the number of wells in a given lithologic sub-cell of type L having data for the constituent.

The results for the granitic, metamorphic, sedimentary, and volcanic primary aquifer systems were combined to create an aggregated system that represents the study unit as a whole. High-RC aquifer-scale proportions for the aggregated system were calculated by combining either the grid-based (eq. 3) or the spatially weighted (eq. 4) results for the four aquifer lithologies. Moderate-RC aquifer-scale proportions for the aggregated system were calculated similarly.

$$P_{SUg,high} = \frac{\sum_L (P_{Lg,high} \sum_c A_{L,c})}{\sum_L \sum_c A_{L,c}} \quad (3)$$

where

$P_{SUg,high}$ is the grid-based high-RC aquifer-scale proportion for the aggregated primary aquifer system, and \sum_L refers to summation over the four aquifer lithologies.

$$P_{SUs,high} = \frac{\sum_L (P_{Ls,high} \sum_c A_{L,c})}{\sum_L \sum_c A_{L,c}} \quad (4)$$

where

$P_{SUs,high}$ is the spatially weighted high-RC aquifer-scale proportion for the aggregated primary aquifer system.

Aquifer-scale proportions for constituent classes were calculated 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. Datasets for wells commonly were incomplete; for example, of the 1,224 wells having data for at least 1 inorganic constituent with a health-based benchmark, 553 wells had data only for nutrients and had no data for any trace elements or radioactive constituents (fig. 4). Of the 530 wells having data for at least 1 trace element with a health-based benchmark, 95 wells had data for only 1 of the 18 trace elements. The effects of these data gaps on calculated aquifer-scale proportions for constituent classes are discussed in appendix C.

For inorganic constituents, the spatially weighted aquifer-scale proportions were used to represent proportions in the primary aquifer systems; results for grid-based aquifer-scale proportions are not presented. Results from status assessments for other GAMA Priority Basin Project study units indicated that the spatially weighted high-RC aquifer-scale proportion was within the 90 percent confidence interval for the grid-based high-RC aquifer-scale proportion in almost all cases (for example, Burton and others, 2012; Fram and Belitz, 2012). The largest differences between the grid-based and spatially weighted aquifer-scale proportions for inorganic constituents were found in the SNR study unit.

For organic constituents, the grid-based aquifer-scale proportions were used to represent proportions in the primary aquifer systems, unless the grid-based high-RC or moderate-RC proportion was zero and the spatially weighted high-RC or moderate-RC proportion was non-zero. Both the grid-based and spatially weighted calculations have the potential to underestimate the proportions of the primary aquifer systems

with high RCs or moderate RCs for organic constituents—but for different reasons. The grid-based method can miss constituents present at high RCs or moderate RCs in a small proportion of the primary aquifer system. For equal-area cells, Belitz and others (2010) showed that a target of size $0.7/n$, where n is the number of cells, has a 50 percent probability of being missed by the grid sampling. Organic constituents generally had high-RC and moderate-RC aquifer-scale proportions of less than 1 percent, and thus, had a substantial probability of being missed in the grid well sampling (each lithology was represented by 15 to 28 grid wells, table 2). The spatially weighted method can miss constituents present at high RCs or moderate RCs because the RCs of the reporting limits in the CDPH database were greater than 0.1 for many organic constituents (Fram and Belitz, 2012; tables 4A,B). Using the spatially weighted high-RC or moderate-RC proportion in cases where the grid-based high-RC or moderate-RC proportion was zero and the spatially weighted high-RC or moderate-RC proportion was non-zero may mitigate the tendency of the results to underestimate the high-RC and moderate-RC proportions.

Calculated aquifer-scale proportions were used for constituent classes unless the high-RC or moderate-RC aquifer-scale proportion for any individual constituent in the class was greater than the calculated high-RC or moderate-RC aquifer-scale proportion for the class as a whole. The high-RC aquifer-scale proportion for an individual constituent may be greater than the calculated high-RC aquifer-scale proportion for the class in the case of data gaps (see appendix C). In such cases, the greatest high-RC or moderate-RC aquifer-scale proportion for an individual constituent in the class was assigned as the high-RC or moderate-RC aquifer-scale proportion for the class as a whole.

Area-weighted detection frequencies for organic constituents were calculated using data from the 82 USGS-grid wells:

$$D_L = \frac{\sum_c N_{L,det,c} A_{L,c}}{\sum_c A_{L,c}} \text{ and } D_{SU} = \frac{\sum_L (D_L \sum_c A_{L,c})}{\sum_L \sum_c A_{L,c}}, \quad (5)$$

where

D_L is the area-weighted detection frequency for an organic constituent for the lithologic type L primary aquifer system (granitic, metamorphic, sedimentary, or volcanic) in the SNR study unit,

D_{SU} is the area-weighted detection frequency for an organic constituent in the aggregated primary aquifer system, and

$N_{L,det,c}$ is the number of wells in a given lithologic sub-cell of type L having a detection of the constituent (there is only one well per lithologic sub-cell, so the value of this parameter is either 1 or 0).

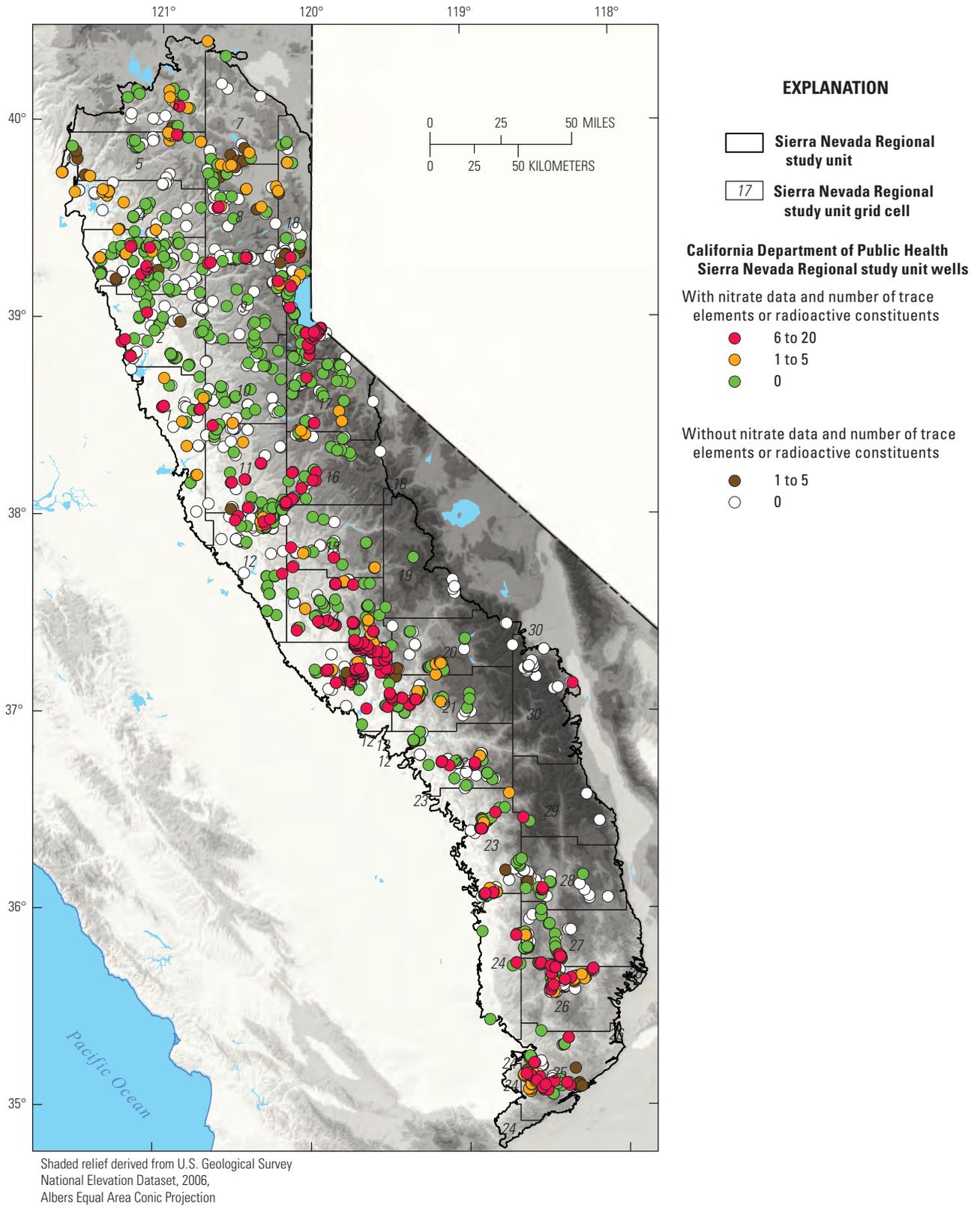


Figure 4. Locations of public-supply wells from the California Department of Public Health database, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

Understanding Assessment

The evaluation of relations between potential explanatory factors and groundwater quality included three types of evaluations: (1) correlations among potential explanatory factors; (2) correlations between potential explanatory factors and constituent concentrations; and (3) differences in aquifer-scale proportions for individual constituents and constituent classes among the four aquifer lithologies.

A subset of constituents was selected for evaluation of relations between potential explanatory factors and groundwater quality. The constituents were selected on the basis of aquifer-scale proportions using the following approach:

- Constituents present at high RCs in greater than approximately 2 percent of the aggregated primary aquifer system (eqs. 3, 4); and
- Organic constituent classes and special-interest constituents having area-weighted detection frequency greater than 10 percent for the granitic, metamorphic, sedimentary, volcanic, or aggregated primary aquifer systems (eq. 5).

These criteria resulted in selection of nine individual inorganic constituents, four classes of organic constituents, and one special-interest constituent (table 4A). Relations for the following classes also were examined: any VOC, any organic constituent, any nutrient, any trace element, any radioactive constituent, any inorganic constituent with health-based benchmarks, any metal with an SMCL benchmark, any salinity indicator, and any constituent with an SMCL benchmark.

Tests of Correlations Among Potential Explanatory Factors and Between Potential Explanatory Factors and Water Quality

The purpose of examining potential explanatory factors is to improve understanding of the natural and anthropogenic factors that affect groundwater quality. The potential explanatory factors evaluated were geology, land-use characteristics, hydrologic conditions, well depth, groundwater age distribution, and geochemical conditions. Correlations among these factors that could affect apparent relations between aquifer lithology and water quality are also described. Data were compiled for the 83 wells sampled by USGS-GAMA. Other CDPH wells were not used because data for many of the potential explanatory factors were not available. Wells sampled for the Tahoe-Martis, Central Sierra, and Southern Sierra study units were not included to avoid adding spatial bias to the dataset.

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 (α) of 5 percent ($\alpha = 0.05$) to evaluate whether the relation was statistically significant ($p < \alpha$).

Three different statistical tests were used because the set of potential explanatory factors included categorical and continuous variables. Groundwater age class, aquifer-lithology class, 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 fuel tank (LUFT) density, aridity index, elevation, latitude, well depth, depth to top of screened or open interval, dissolved oxygen (DO), and pH were treated as continuous variables; for example, land use was represented by percentages of land-use types. Well depth and oxidation-reduction status were treated as continuous (depth in feet below land surface and DO concentration, respectively) and categorical (depth classified into four groups, and oxidation-reduction status as oxic or anoxic; appendix B) variables.

- Correlations between continuous variables were evaluated using the Spearman's rho test to calculate the rank-order coefficient (ρ , rho) and the significance level of the correlation (p).
- Relations among categorical variables and continuous variables were evaluated 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 four groups is $\alpha = 0.26$ (Helsel and Hirsch, 2002). If the Kruskal-Wallis test showed 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 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 entry in each cell of the matrix represents the number of observations which are in the categories corresponding to the i th row and j th column of the matrix. A test statistic is computed by comparing the observed counts to the counts expected if the two variables are independent, and statistical significance is determined by comparing the test statistic to the $(1-\alpha)$ th quantile of a chi-square distribution (Helsel and Hirsch, 2002). If the contingency table test detected a significant difference between the observed

counts and the expected counts, then the matrix cell(s) contributing most to the difference was determined by comparing magnitudes of the components of the test statistic. Contingency tables were constructed by assigning the groups for one categorical variable as the columns and the groups for the other as the rows; entries in the table correspond to the number of wells with each combination of characteristics.

Comparison of Aquifer-Scale Proportions Among Primary Aquifer Systems

Aquifer-scale proportions for the granitic, metamorphic, sedimentary, and volcanic primary aquifer systems also were compared by using contingency table tests. For inorganic constituents, the sum of the proportions of the primary aquifer system having high RCs or moderate RCs was compared to the proportion having low RCs. A 4×2 contingency table was constructed, with the four aquifer lithologies as the rows and the two proportions being compared as the columns. The entries in the table were the adjusted numbers of samples in each category. These adjusted numbers of samples in each category were calculated by applying the spatially weighted aquifer-scale proportions to the number of wells used in the spatially weighted calculations. For example, if 223 wells with granitic aquifer lithology were used in the calculation of aquifer-scale proportions and the resulting spatially weighted proportions for a constituent were 7.8 percent with high RCs, 11.5 percent with moderate RCs, and 80.7 percent with low RCs, the granitic aquifer lithology row of the contingency table for that constituent would be [43.0, 180.0].

For organic constituents, the proportion with detection of any organic constituent was compared to the proportions with no detections. The adjusted numbers of samples were calculated using the numbers of wells having USGS-GAMA data for organic constituents. The RCs of USGS-GAMA reporting limits were <0.1 for all 16 of the detected organic constituents and <0.01 for 14 of the 16 (tables 4A,B). Because the USGS-GAMA reporting limits are so much lower than the CDPH reporting limits, the two datasets could not be combined for this comparison of detections.

If the contingency table test indicated a significant difference in aquifer-scale proportions among the four lithologies, then the pairs with significant differences were identified by pair-wise 2×2 contingency table tests.

Characteristics of the Primary Aquifer System

Characteristics of the primary aquifer system, including geology, land use, climate, depth, groundwater age distribution, and geochemical conditions are described using data compiled for the 83 sites sampled by USGS-GAMA for the SNR study unit. The methods used to compile the data are described in [appendix B](#). Correlations between explanatory factors are important to identify because an apparent

correlation between an explanatory factor and a water-quality constituent could reflect correlations among explanatory factors.

Geology

The 83 wells sampled for the SNR study unit were assigned one of four aquifer lithologic classes ([appendix B](#)):

- Granitic rocks (28 wells): Mesozoic granitic rocks of the Sierra Nevada batholith;
- Metamorphic rocks (24 wells): Mesozoic and Paleozoic metavolcanic, metasedimentary, mafic, and ultramafic rocks;
- Sedimentary deposits (16 wells): Cenozoic alluvial, glacial, fluvial, and lacustrine sediments; and
- Volcanic rocks (15 wells): Cenozoic volcanic and volcanoclastic rocks.

Because the study design called for sampling one well in each lithologic sub-cell present in a cell, the numbers of wells representing each aquifer lithology are not proportional to the areal percentages of the four geologic units in the study unit. The 82 sub-cells in which USGS sampled a well for the SNR study unit represent 94 percent of the area of the study unit ([fig. 5](#)). In comparison, the sub-cells containing wells with data in the CDPH database for 10 or more inorganic constituents represent less than two-thirds of the area of the study unit. The combination of the two datasets covers 95 percent of the area of the study unit ([fig. 5](#)).

Land Use

Land use was classified using an enhanced version of the satellite-derived (30-m-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. 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 B](#)).

Average land use around wells differs from the overall land use in the study unit because wells are preferentially located where people are living, working, or recreating. The average amount of urban land use in the 500-m buffers around all of the CDPH wells and around the USGS-GAMA wells was more urban than for overall land use ([fig. 6A](#)). The difference between the average land use around the CDPH wells and around the grid wells reflects the spatially distributed nature of the grid wells. The CDPH wells are more biased towards urban land use because urbanized areas typically have a higher density of CDPH wells.

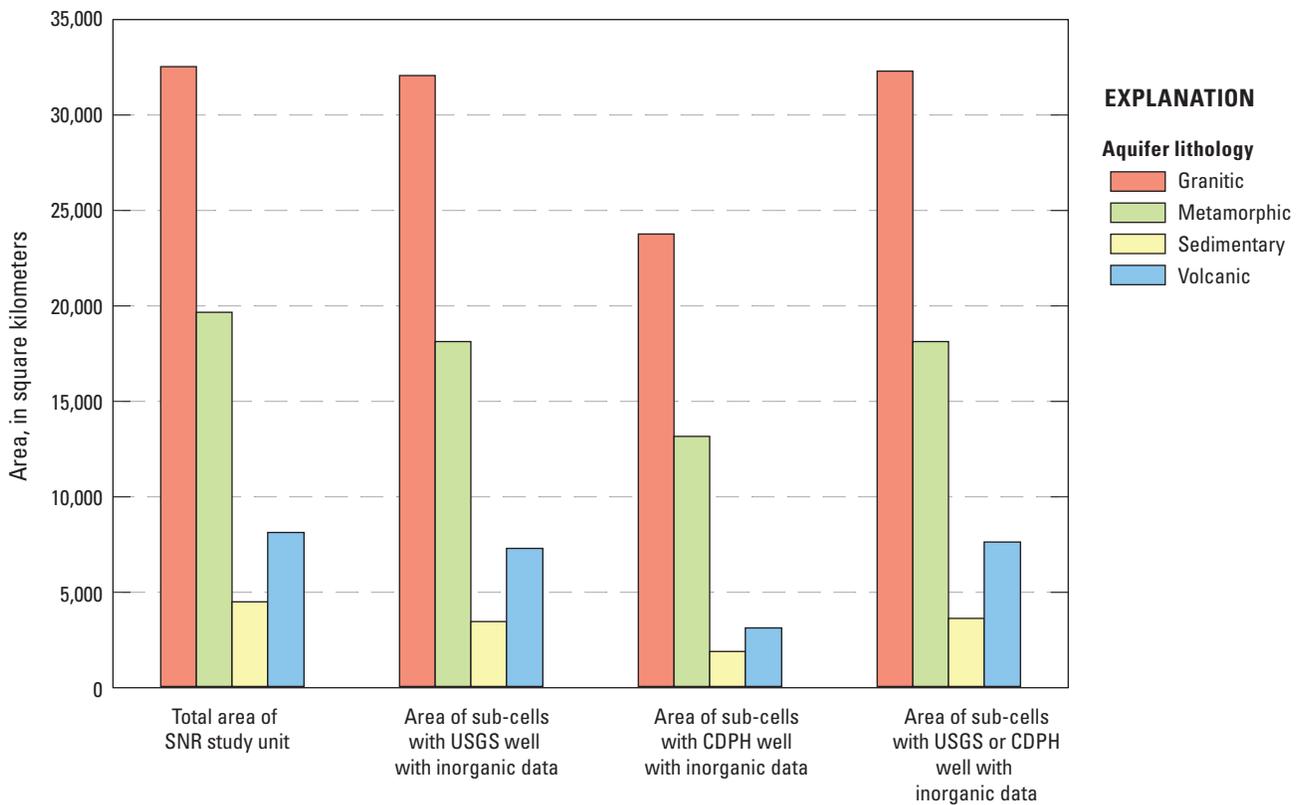


Figure 5. Area assigned to the four aquifer lithologies in the study unit as a whole, and the areas represented by wells sampled by the U.S. Geological Survey (USGS) having data for 24 or more inorganic constituents with health-based benchmarks, by wells in the California Department of Public Health (CDPH) database having data for 10 or more inorganic constituents with health-based benchmarks, and by any well having data for 10 or more inorganic constituents with health-based benchmarks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

Land use and aquifer lithology are correlated. Agricultural land use is significantly associated with sedimentary aquifer lithology compared to the other lithologies for the study unit area as a whole (contingency table test, $p < 0.001$) and for the area within the 500-m buffers around the USGS-GAMA wells (table 6A; fig. 6A). Natural land use and aquifer lithology also are significantly associated for the area within the 500-m buffers around the USGS-GAMA wells: areas with granitic aquifer lithology have significantly more natural land use than areas with sedimentary aquifer lithology.

The percentage of natural land within the 500-m buffers around the USGS-GAMA wells was expected to be lower than the percentage of natural land for the study unit as a whole because wells are preferentially located in areas with developed land. While this is the case for areas with granitic, sedimentary, and volcanic aquifer lithologies, it is not true for areas with metamorphic aquifer lithology (fig. 6A). For the study unit as a whole, areas with metamorphic aquifer lithology have the greatest percentage of urban land because the Western Metamorphic Belt, which composes the majority of the area occupied by metamorphic rocks in the SNR study unit (fig. 3A), is adjacent to the major population

centers in the Central Valley that extend into the foothills (Sacramento, Stockton, Modesto; fig. 3C). However, wells with metamorphic aquifer lithology were sampled in 24 cells, and the Western Metamorphic Belt is in only 4 of those cells (cells 1, 2, 3, and 12; figs. 3A,B).

Of the 83 USGS-GAMA wells, 73 have more than 80 percent natural land in the 500-m buffer around the well, and for most of those wells, the remainder consists of urban land (table B1). Land use surrounding the other 10 wells ranges from more than 80 percent urban or agricultural land to nearly an equal mixture of the three land-use types (fig. 6B). Half of the wells with less than 80 percent natural land have sedimentary aquifer lithology, reflecting that most of the areas with sedimentary aquifer lithology are groundwater basins that are conducive to agricultural and urban development.

Septic tanks and LUFTs are also markers of land-use patterns. Septic systems generally are associated with dispersed residences and may occur in areas classified as natural or agricultural land in addition to areas classified as urban land. The density of septic tanks in the 500-m buffers around the USGS-GAMA wells in the study unit ranged from 0 to 117 tanks per square kilometer (tanks/km²) (table B1). The wells with septic tank density greater than 7 tanks/km² were

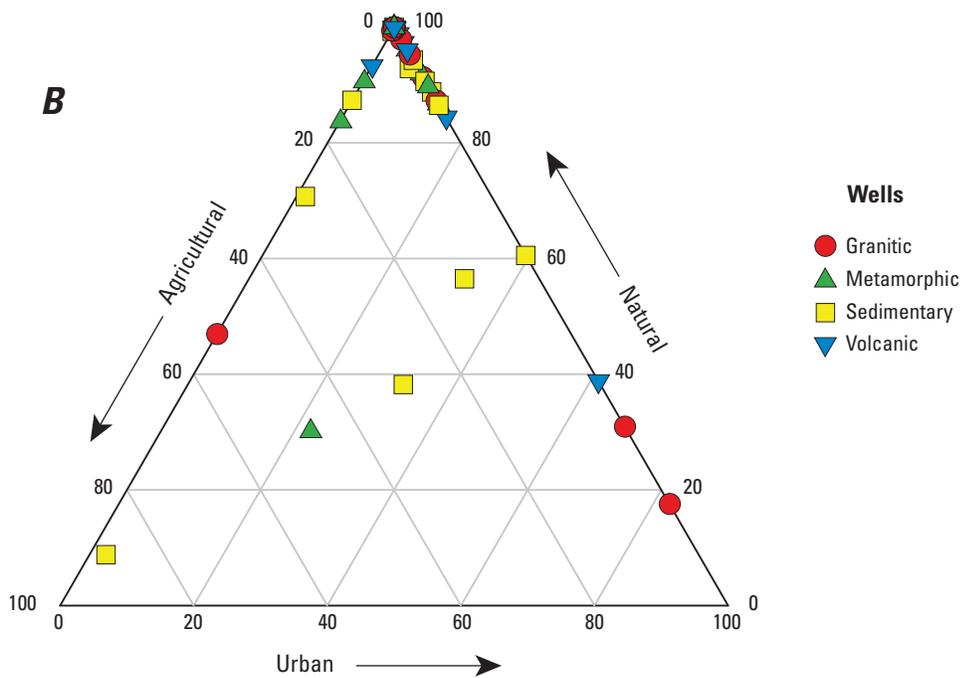
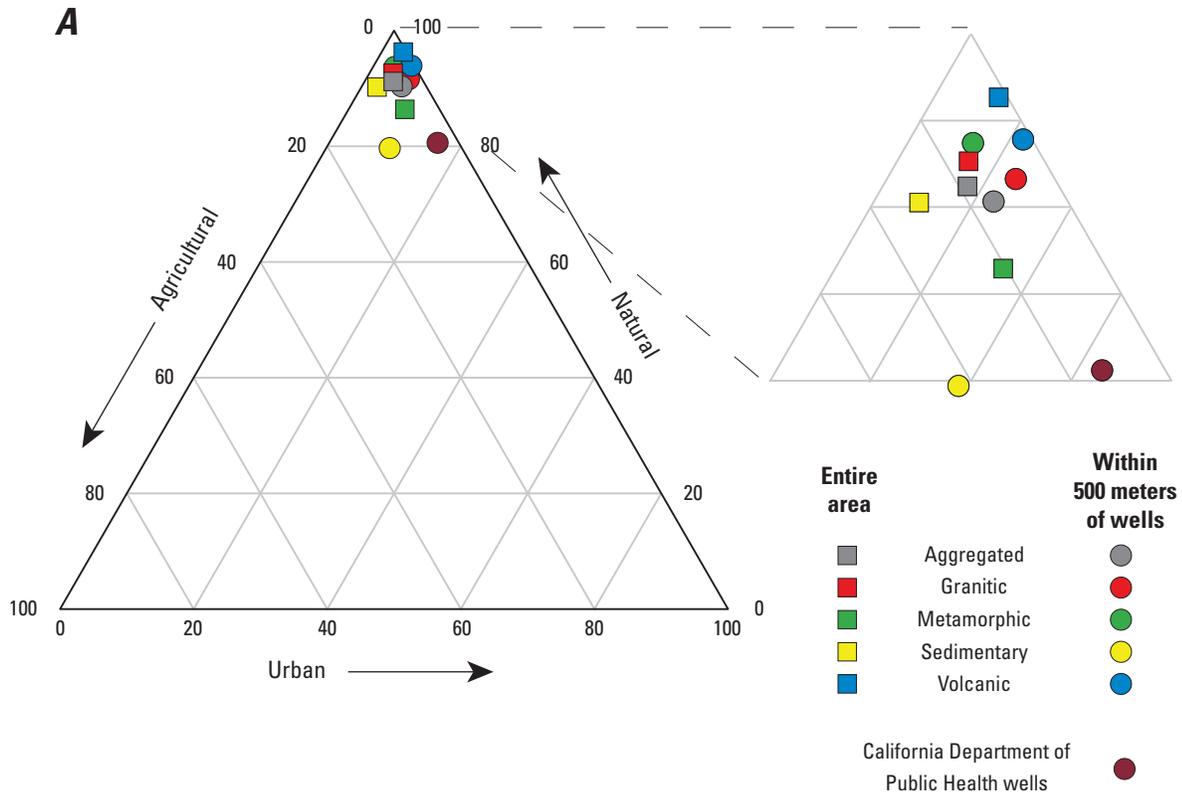


Figure 6. Percentage of urban, agricultural, and natural land use in the Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project in (A) the aquifer lithologic units, and (B) the areas surrounding each USGS-GAMA well.

Table 6A. Results from multi-stage Kruskal-Wallis tests for differences in median values of selected potential explanatory factors among samples classified into groups by aquifer lithology class, oxidation-reduction class, depth class, or groundwater age class, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Factors yielding a result of significance in the Kruskal-Wallis test were evaluated with Tukey’s test on the single-factor analysis of variance of the ranks. Significance defined as p-value less than threshold value (α) of 0.05. **Aquifer lithology class:** G, granitic; M, metamorphic; S, sedimentary; V, volcanic (see [appendix B](#)). **Oxidation-reduction class:** see [appendix B](#) for definitions of oxic and anoxic. **Depth class:** deep, well depth > 170 ft bls and top of perforations > 170 ft bls; overlapping, top of perforations < 170 ft bls and well depth > 170 ft bls; shallow, well depth < 170 ft bls; spring, site is a spring. **Age class:** see [appendix B](#) for explanation of classes. **Abbreviations:** ft bls, feet below land surface; LUFT, leaking or formerly leaking underground fuel tank; ns, no significant differences; >, greater than; <, less than]

Potential explanatory factors	Aquifer lithology class (G, M, S, V)		Oxidation-reduction class (oxic, anoxic)		Depth class [spring (SP), shallow (SH), overlapping (OL), deep (DP)]		Age class [modern (MOD), mixed (MIX), pre-modern (PRE)]	
	p	Significant differences	p	Significant differences	p	Significant differences	p	Significant differences
Land-use characteristics								
Percent agricultural land use	0.013	S > G S > M S > V	0.425	ns	0.063	ns	0.381	ns
Percent natural land use	0.027	G > S	0.776	ns	0.007	SP > SH SP > OL	0.705	ns
Percent urban land use	0.090	ns	0.484	ns	0.003	SH > SP OL > SP	0.209	ns
Density of septic tanks	0.380	ns	0.259	ns	0.079	ns	0.813	ns
Density of LUFTs	0.839	ns	0.874	ns	0.131	ns	0.244	ns
Climate and hydrology variables								
Aridity index	0.046	G > S	0.050	oxic > anoxic	0.029	SP > SH	0.069	ns
Elevation	0.128	ns	0.004	oxic > anoxic	<0.001	SP > SH SP > OL SP > DP	0.635	ns
Latitude	0.132	ns	ns	ns	0.282	ns	0.048	MIX > PRE
Characteristics of primary aquifer system								
Depth to top of open or screened interval	0.225	ns	0.889	ns	<0.001	DP > SH DP > OL	0.015	PRE > MOD
Depth to bottom of open or screened interval	0.685	ns	0.987	ns	<0.001	DP > OL > SH	0.122	ns
pH	0.057	ns	0.001	anoxic > oxic	0.019	DP > SP DP > SH DP > OL	<0.001	MIX > MOD PRE > MOD
Dissolved oxygen concentration	0.333	ns	<0.001	oxic > anoxic	<0.001	SP > SH SP > OL SP > DP	0.003	MOD > PRE MIX > PRE

Table 6C. Results of contingency table tests for association between selected potential explanatory factors, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[For factors determined to be significantly associated on the basis of p-values less than threshold value (α) of 0.05 for contingency table test, the association or absence of association that contributes most to significance of the test statistic is described. **Aquifer lithology class:** G, granitic; M, metamorphic; S, sedimentary; V, volcanic. **Depth class:** deep, well depth > 170 ft bls and top of perforations > 170 ft bls; overlapping top of perforations < 170 ft bls and well depth > 170 ft bls; shallow, well depth < 170 ft bls; spring, site is a spring. **Groundwater age class:** See [appendix B](#) for explanation of classes. **Oxidation-reduction class:** See [appendix B](#) for explanation of classes. **Abbreviations:** ft bls, feet below land surface; <, less than; >, greater than]

Factor	Groundwater age (modern, mixed, pre-modern)	Oxidation-reduction (oxic, anoxic)	Depth class (spring, shallow, overlapping, deep)	Site type (spring, well)
Aquifer lithology (G, M, S, V)	0.092	0.614	0.227	0.568
Groundwater age (modern, mixed, pre-modern)		0.003 Modern groundwater is not associated with anoxic conditions	<0.001 Deep wells are associated with pre-modern groundwater	0.268
Oxidation-reduction (oxic, anoxic)			0.089	0.009 Springs are not associated with anoxic conditions

located in the foothills east of the Central Valley population centers of Sacramento, Stockton, Modesto, and Fresno and in the Lake Isabella area of the southern Sierra Nevada. The foothills east of the Central Valley population centers and the Lake Isabella area are among the few areas in California that have population densities of greater than 100 people per square mile, yet have almost no cities with populations greater than 5,000 people (U.S. Census Bureau, 1990). Dispersed residential developments outside of cities are more likely to have individual septic systems rather than a collective sewer system because of the large costs associated with constructing sewage collection and treatment systems. The density of documented LUFTs in the 500-m buffers around the USGS-GAMA wells in the study unit ranges from 0 to 0.7 tanks/km² ([table B1](#)). Most of the wells with LUFT densities greater than 0.05 tank/km² were located in the foothills or along major roads leading from Central Valley urban centers into the Sierra Nevada or around Lake Tahoe. As expected from these occurrence patterns, the densities of septic tanks and LUFTs were positively correlated with each other and with percentage of urban land use and negatively correlated with elevation and percentage of natural land use ([table 6B](#)).

Climate and Hydrology

Climate and hydrologic conditions were represented by the United Nations Educational, Scientific, and Cultural Organization aridity index (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997), latitude, and elevation at the well site ([table B3](#)). Aridity index is average annual precipitation divided by average annual evapotranspiration; higher values correspond to wetter conditions. As expected,

aridity index showed significant positive correlations with elevation and latitude ([table 6B](#)). Values of aridity index were greater for wells in granitic aquifer lithology compared to sedimentary aquifer lithology ([table 6A](#)).

Elevation may be used as a proxy for relative position in a generalized regional groundwater flow system. Given the fact that water moves from higher elevations to lower elevations, elevation is generally expected to be inversely related to residence time in many groundwater flow systems. This is approximately true in areas like the eastern San Joaquin Valley where natural recharge primarily occurs on the eastern margin and groundwater flows through alluvial aquifer systems towards the central part of the valley (Landon and others, 2010, 2011). In the Sierra Nevada, however, most of the aquifer systems consist of fractured hard rock with variable porosity and permeability and may not be interconnected, and recharge is not limited to the highest elevations. Because of the topographic and geologic complexity of the Sierra Nevada, there are likely to be many local flow cells of different scales superimposed on the regional groundwater flow system (Tóth, 1963). Thus, the relation between elevation and relative position in the regional groundwater flow system in the SNR study unit is likely to be more complex than a simple, inverse proportionality.

Depth and Groundwater Age

As noted earlier, the primary aquifer system in the SNR study unit is defined as the depth interval over which wells in the CDPH database are screened or open. Because the wells sampled by USGS-GAMA for the SNR study unit were considered representative of wells in the CDPH database, the depth and groundwater age characteristics of these wells were

used to define the depth and groundwater age characteristics of the primary aquifer system.

Groundwater age refers to residence time in the aquifer system, which is the amount of time elapsed since the water was last in contact with the atmosphere (either directly, while it was at the ground surface, or indirectly, as it passed through the vadose zone). Data for the age-dating tracers tritium and carbon-14 (^{14}C) were used to classify groundwater age into three categories: modern, mixed, and pre-modern (appendix B). Of the 83 wells sampled by USGS-GAMA, 42 were classified as having modern groundwater, 31 as having mixed groundwater, and 7 as having pre-modern groundwater (table B5). Three samples were classified as modern or mixed because they had insufficient data to confirm the presence or absence of pre-modern groundwater, either because ^{14}C data were not collected or because the $\delta^{13}\text{C}$ values suggested that substantial interaction with sedimentary carbon may have occurred (table B5).

Twenty of the 83 USGS-GAMA sites were springs, and all 4 aquifer lithologies included springs (fig. 7). Sites that were springs had significantly higher elevations, wetter conditions, and greater percentages of natural land use around the sites than did sites that were wells (table 6A). Springs emerge at the land surface, but the geometry of the fracture networks in the subsurface from which their water is derived is usually unknown. For the sites that were wells, the median depth to the bottom of the screened or open interval was

300 ft, and the median depth to the top of the open or screened interval was 77 ft (table B3). There were no significant relations between aquifer lithology and either measure of well depth (tables 6A,C).

Groundwater ages typically increase with depth below the water table, and thus, in general with well depth and the depth to the top of the screened or open interval. Pre-modern groundwater came from wells with significantly greater depths to the top and the bottom of the screened or open interval compared to modern or mixed groundwater (tables 6A,C). There were no significant associations between aquifer lithology and groundwater age class (table 6C).

Groundwater age categories were combined with information on well depths to create a system for classifying different types of sites. Wells with depth less than a critical value were defined as shallow; wells with screened or open intervals beginning above the critical depth and ending below the critical value were defined as overlapping; and wells with screened or open intervals entirely below the critical value were defined as deep. The critical depth value of 170 feet below land surface (ft bls) was selected by optimizing the segregation of modern groundwater into shallow wells, mixed-age groundwater into overlapping wells, and pre-modern groundwater into deep wells and was selected for consistency with previous work (Fram and Belitz, 2012). Springs were considered a separate class.

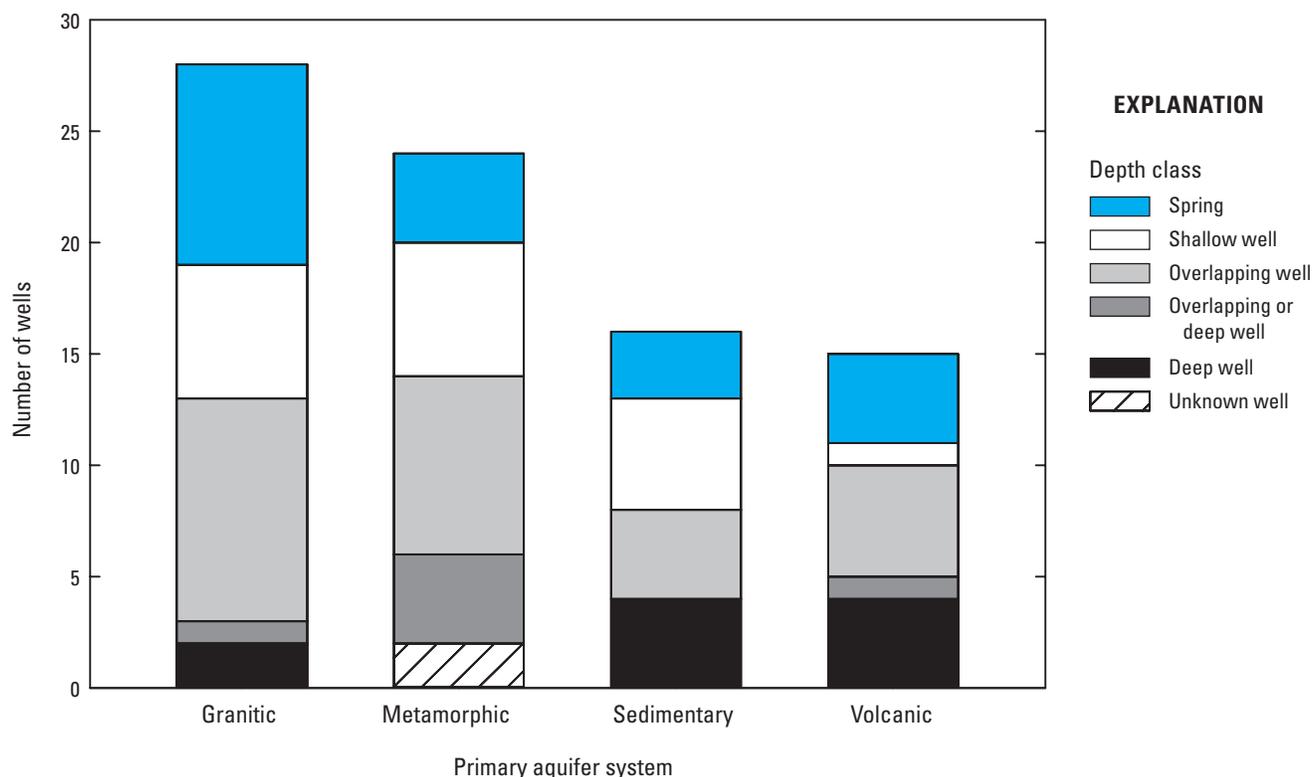


Figure 7. Numbers of sites sampled by the U.S. Geological Survey (USGS) in each aquifer lithologic class and depth class, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

Springs, shallow wells, and overlapping wells were represented in all four aquifer lithologies, and deep wells occurred in three of the four aquifer lithologies (fig. 7). Most springs, shallow wells, and overlapping wells yielded modern groundwater, and a majority of deep wells yielded pre-modern groundwater (fig. 8). Mixed-age groundwater was found in 30–45 percent of sites in all four well depth classes. Pre-modern groundwater was not found in springs or shallow wells, but modern groundwater was found in deep wells.

Comparison between the wells sampled for the SNR study unit and the wells sampled for the Tahoe-Martis, Central Sierra, and Southern Sierra study units indicated that the two studies sampled different populations of wells in granitic aquifer lithology. The SNR study unit sites in granitic aquifer lithology included a significantly greater proportion of sites that were springs or shallow wells (54 percent) than did the sites in granitic aquifer lithology in the Tahoe-Martis, Central Sierra, and Southern Sierra study units (17 percent) (contingency table test, $p = 0.002$). In addition, the SNR study unit sites in granitic aquifer lithology included a significantly smaller proportion of sites with pre-modern groundwater (4 percent) than did the sites in granitic aquifer lithology in the Tahoe-Martis, Central Sierra, and Southern Sierra study units (23 percent) (contingency table test, $p = 0.025$). The difference reflects the occurrence of relatively deep wells in the Central Sierra study unit; deep wells in granitic lithology are not typical in the SNR study unit.

Geochemical Conditions

Oxidation-reduction conditions were classified on the basis of 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) (appendix B). 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 (66 of the 83 sites [80 percent]), the groundwater was classified as oxic ($DO \geq 1$ mg/L). Anoxic conditions ($DO < 1$ mg/L), present in 17 of the 83 wells (20 percent), were further classified as either suboxic, nitrate-reducing, manganese-reducing, or manganese- and iron-reducing (table B7).

DO concentrations were greater in samples from springs than in samples from shallow, overlapping, or deep wells and were greater in modern and mixed groundwater than in pre-modern groundwater (table 6A). In contrast, pH values were greater in samples from deep wells than in samples from springs or shallow and overlapping wells and were greater in pre-modern groundwater than in modern or mixed groundwater. Neither DO concentration nor pH was significantly related to aquifer lithology, which was expected given the lack of significant relations between aquifer lithology and depth class or groundwater age (table 6C).

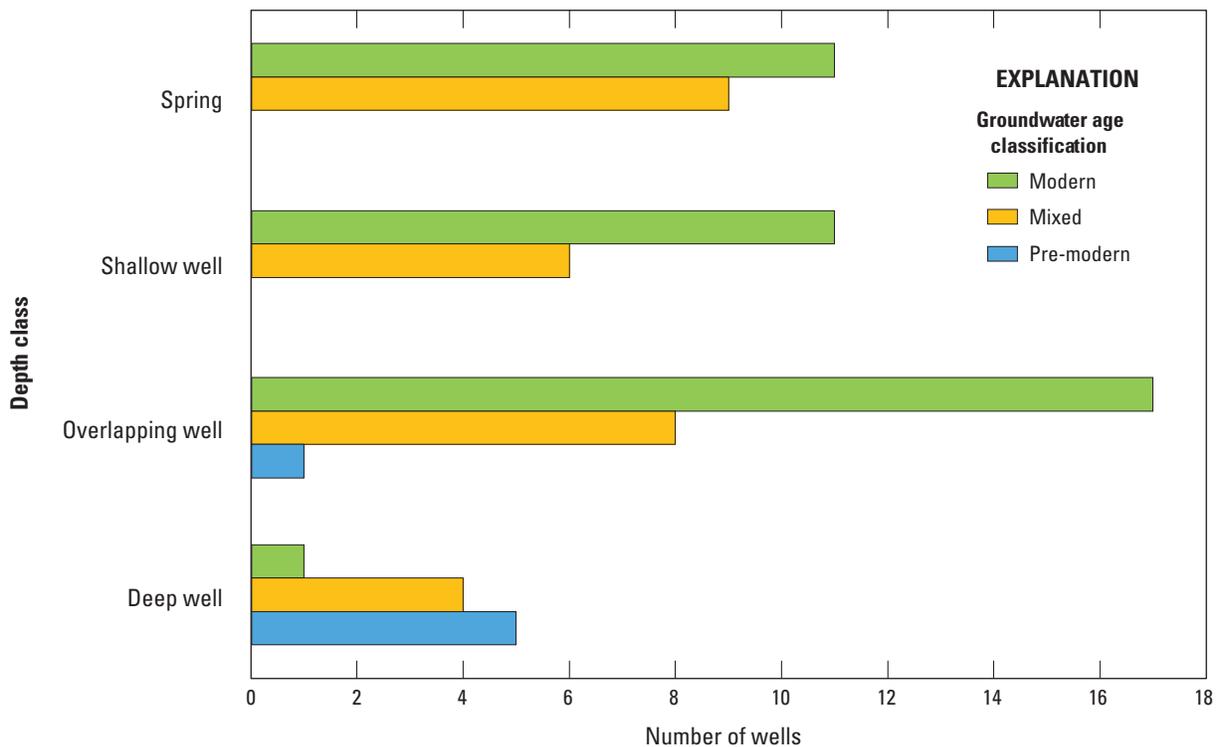


Figure 8. Relation between depth classification and groundwater age classification for the Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

The positive correlations among DO concentration, elevation, and springs may be related to the fact that springs commonly represent the intersection of the water table with the land surface, discharging water that tends to have 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 would not have had its DO consumed.

pH values were significantly higher in deep wells compared to other site types, in anoxic groundwater compared to oxic groundwater, and in mixed or pre-modern groundwater compared to modern groundwater ([table 6A](#)). Precipitation in the Sierra Nevada is dilute: median specific conductance values were less than 5 microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$), and median pH values were approximately 5.6 for annual wet deposition at National Atmospheric Deposition Program sites within the boundaries of the SNR study unit (National Atmospheric Deposition Program, 2012). These low pH values are primarily controlled by the equilibrium between atmospheric carbon dioxide and dissolved carbonate species. 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).

Status and Understanding of Groundwater Quality

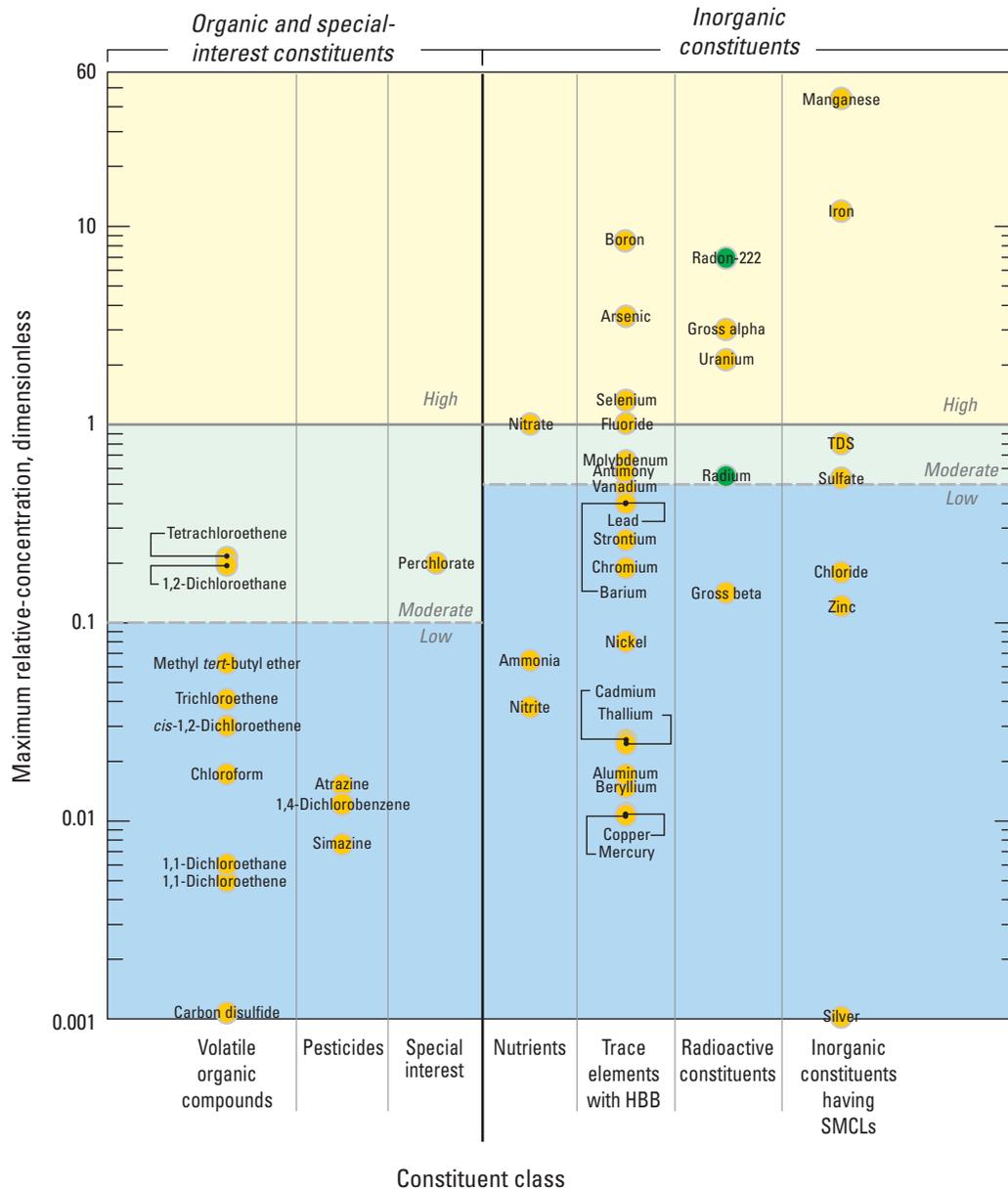
The following discussion is divided into two parts, one for inorganic constituents and the other for organic constituents, and each part has a tiered structure. Each part begins with a summary of the number of constituents that were detected at any concentration in USGS-GAMA samples compared to the number analyzed and graphical summaries of the RCs of constituents detected in the lithologic-grid wells. Aquifer-scale proportions then are presented for constituent classes and individual constituents. Lastly, results of statistical tests for relations between water quality and potential explanatory factors are presented for a subset of individual constituents and constituent classes. Discussions of the geochemical and hydrologic processes that may affect constituent concentrations are beyond the scope of this report and can be found in Fram and Belitz (2012) for many of the constituents evaluated here.

Inorganic Constituents

Inorganic constituents generally occur naturally in groundwater, although their concentrations may be influenced by human activities as well as by natural factors. Of the 47 inorganic constituents analyzed by USGS-GAMA, 26 had regulatory or non-regulatory health-based benchmarks, 8 had non-regulatory aesthetic-based benchmarks, and 13 had no established benchmarks. Of these 34 constituents with benchmarks, 27 were detected at moderate or high RCs in samples collected by USGS-GAMA for the SNR study unit or the Tahoe-Martis, Central Sierra, and Southern Sierra study units, or were reported in the CDPH database at moderate or high RCs in samples collected between May 1, 2006, and October 31, 2008 ([table 4A](#)). The other 20 inorganic constituents either had no established benchmarks or were only detected at low RCs ([table 4B](#)). Most of the inorganic constituents without benchmarks are ions that are present in nearly all groundwater.

Sixteen of the 27 inorganic constituents were detected at moderate or high RCs in samples collected by USGS-GAMA for the SNR study unit: the trace elements antimony, arsenic, boron, fluoride, molybdenum, and selenium; the radioactive constituents gross alpha particle activity, radium, radon-222, and uranium; the nutrient nitrate; and the constituents having SMCL benchmarks (hereinafter referred to as SMCL constituents)—specific conductance, total dissolved solids, sulfate, iron, and manganese ([table 4A](#); [figs. 9, 10A–C](#)). The majority of these 16 constituents were detected at moderate or high RCs in more than 10 percent of the wells in at least 1 of the 4 lithologic-grid well networks ([figs. 10A–C](#)). The remaining 11 inorganic constituents (the trace elements aluminum, beryllium, cadmium, chromium, copper, lead, mercury, nickel, and strontium and the SMCL constituents chloride and zinc) were included because they were reported at high or moderate RCs in the CDPH database between May 1, 2006, and October 31, 2008, or in the USGS-GAMA Tahoe-Martis, Central Sierra, and Southern Sierra study units ([table 4A](#)). Aquifer-scale proportions are summarized in [tables 7A,B](#) for the individual inorganic constituents listed in [table 4A](#), and in [tables 8A,B](#) for classes of inorganic constituents.

Inorganic constituents with health-based benchmarks, as a group, were present at high RCs in 16 percent of the primary aquifer system and at moderate RCs in 21 percent ([table 8A](#)). The proportion of the primary aquifer system having high or moderate RCs of any inorganic constituent was greater for the granitic and sedimentary systems than for the metamorphic system, and for the granitic system compared to the volcanic system ([tables 8A, 9](#)). Inorganic constituents with SMCL benchmarks, as a group, were present at high RCs in 18 percent of the primary aquifer system and at moderate RCs in 6.8 percent ([table 8B](#)). The proportion of the primary aquifer system having high or moderate RCs was greater for the metamorphic system than for the granitic, sedimentary, and volcanic systems ([tables 8B, 9](#)).



EXPLANATION

- Constituent with analyses in 82 grid wells**—Name and center of symbol is location of data unless indicated by following location line:
- Constituent with analyses in 28 grid wells**—Name and center of symbol is location of data.

HBB, health-based benchmark; SMCL, secondary maximum contaminant level; upper water-quality benchmark used for calculating relative-concentrations for constituents with an upper and recommended SMCL

Figure 9. Maximum relative-concentrations of constituents detected in lithologic-grid wells by constituent class for the Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project. [HBB, health-based benchmarks; SMCL, secondary maximum contaminant level]

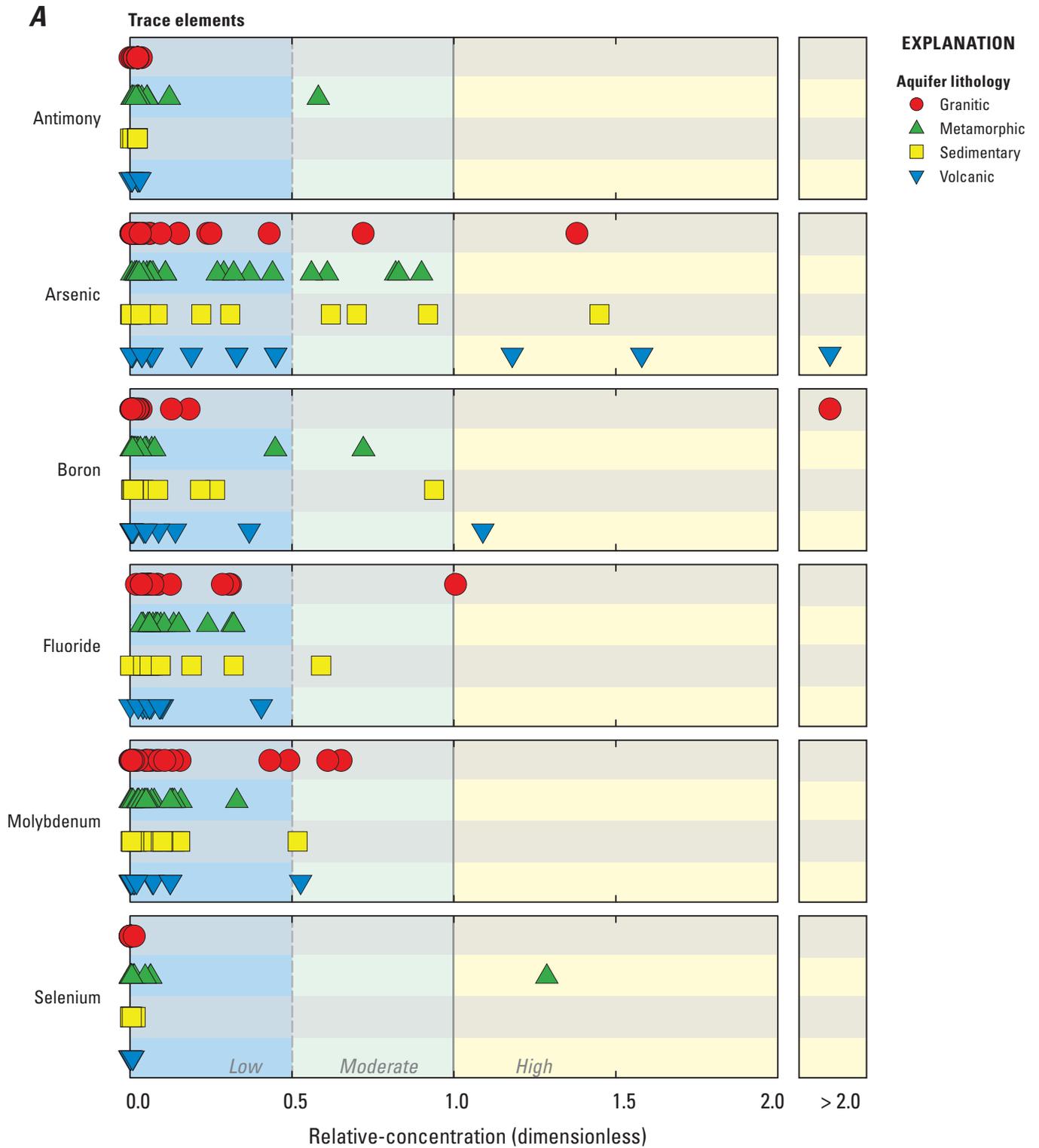


Figure 10. Relative-concentrations of selected (A) trace elements with regulatory and non-regulatory health-based benchmarks, (B) nutrients and radioactive constituents with regulatory health-based benchmarks, and (C) salinity indicators and trace elements with non-regulatory secondary maximum contaminant level (SMCL) benchmarks, in USGS-grid wells, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

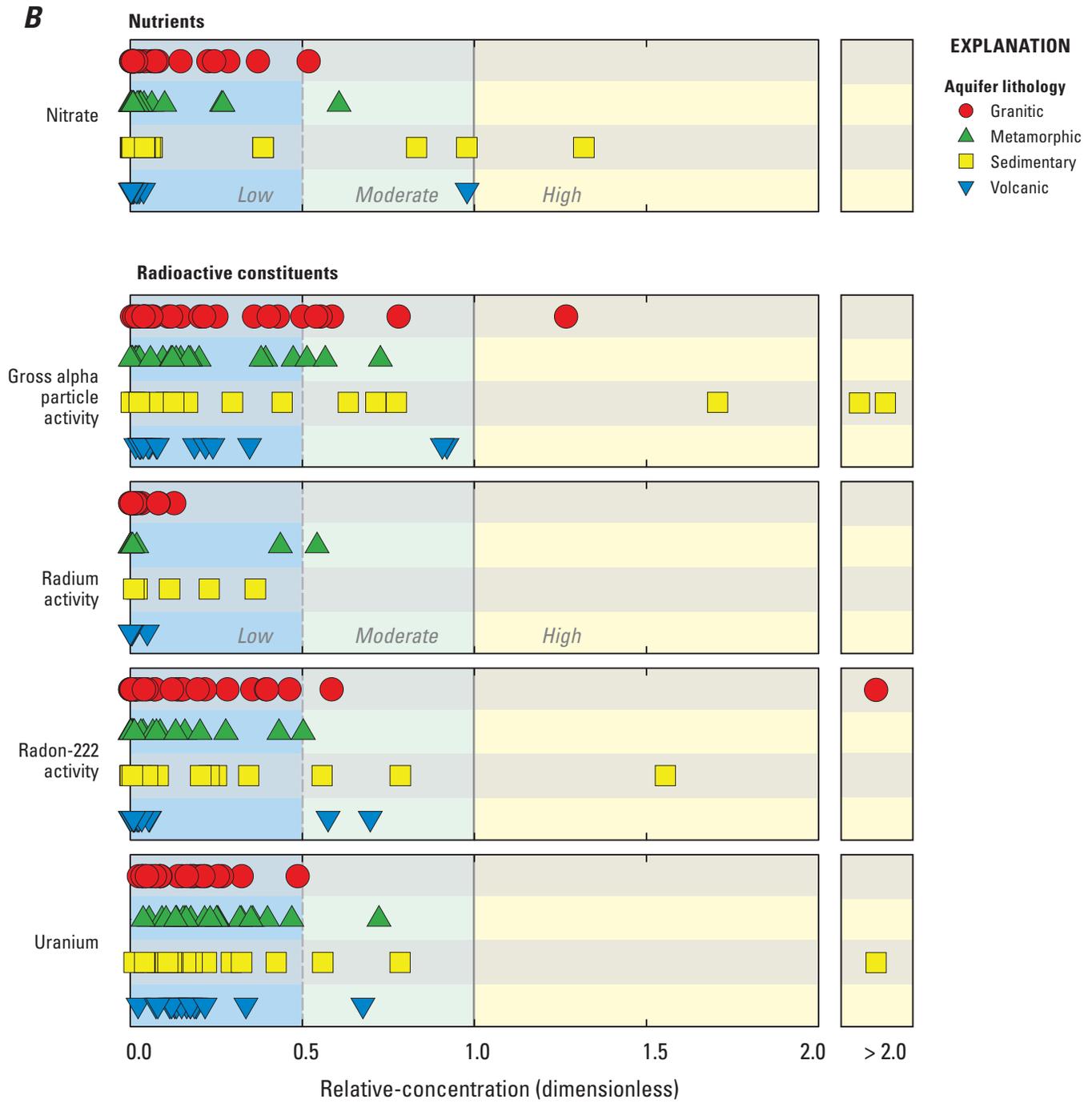


Figure 10. —Continued

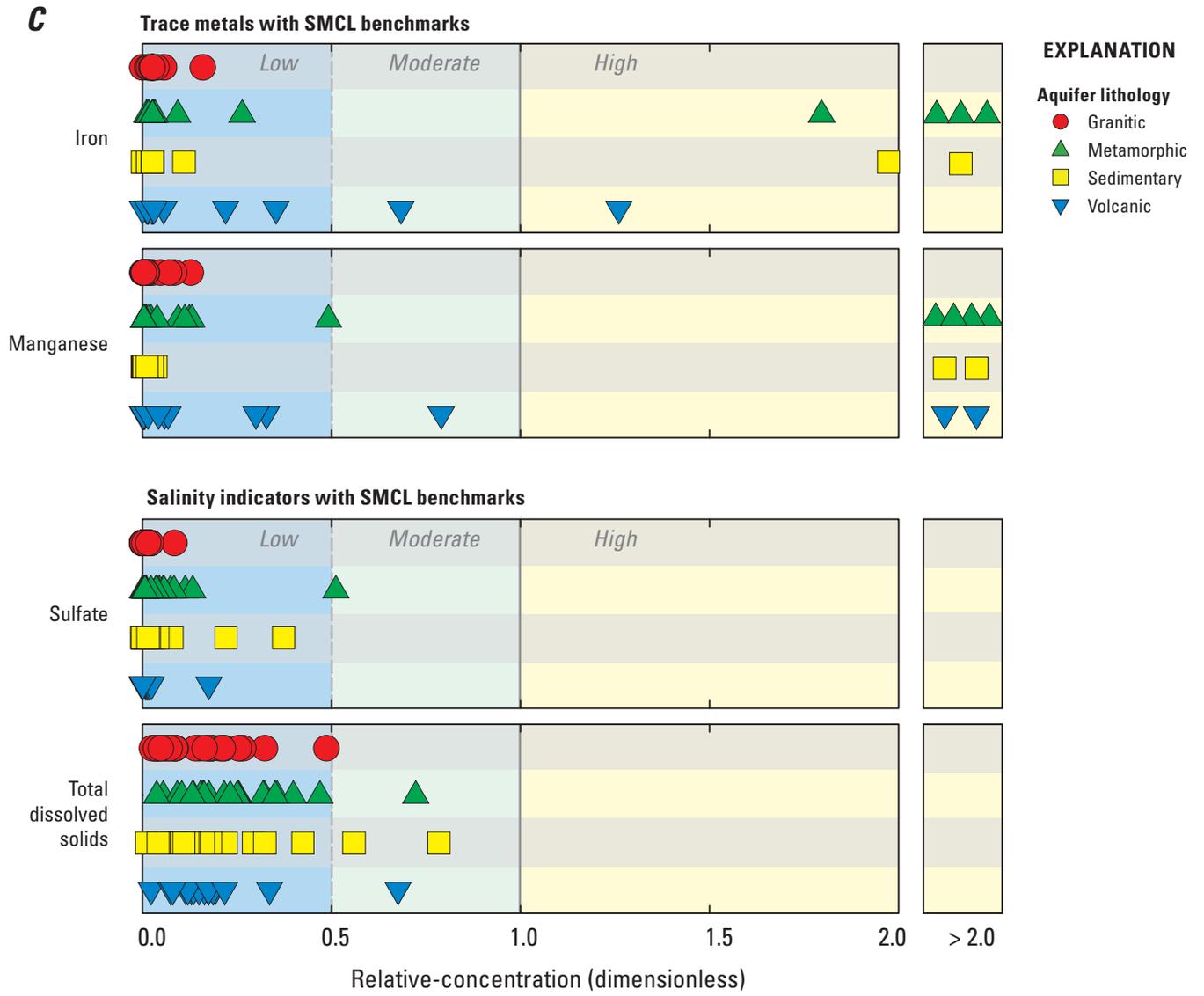


Figure 10. —Continued

Table 7A. Aquifer-scale proportions for inorganic constituents for the granitic, metamorphic, sedimentary, and volcanic primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—C

[Aquifer-scale proportions calculated with the spatially weighted method (equation 2). **Relative-concentration (RC) categories:** high, $RC > 1.0$, moderate, $RC > 0.5$ and $RC \leq 1.0$; low, $RC \leq 0.5$. 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](#). **Abbreviations:** CDPH, California Department of Public Health; SMCL, secondary maximum contaminant level; USGS, U.S. Geological Survey; >, greater than; \leq , less than or equal to]

Constituent	Granitic primary aquifer system			Metamorphic primary aquifer system			Sedimentary primary aquifer system			Volcanic primary aquifer system						
	Number	Aquifer-scale proportion (in percent)		Number	Aquifer-scale proportion (in percent)		Number	Aquifer-scale proportion (in percent)		Number	Aquifer-scale proportion (in percent)					
		Wells	Cells		Moderate RC	High RC		Wells	Cells		Moderate RC	High RC	Wells	Cells	Moderate RC	High RC
Trace elements with health-based benchmarks																
Aluminum	204	29	3.1	0	70	23	0.4	0	91	17	0	0	42	16	0	0
Antimony	202	29	0	0.3	64	23	0.9	0	89	17	0	0.8	39	16	0	0
Arsenic	223	29	11.5	7.8	79	23	9.7	8.6	118	18	17.7	5.8	45	16	1.4	22.1
Beryllium	202	29	0	0	65	23	0	0.7	90	17	0	0	39	16	0	0
Boron	74	28	2.5	2.3	38	23	1.2	1.2	58	16	7.1	0	34	15	0.7	3.6
Cadmium	202	29	0	0.3	66	23	0	0	90	17	0	0.5	40	16	0	0
Chromium	209	29	0.5	0	66	23	0	0	92	17	0	0	39	16	0	0
Copper	190	29	0	0	59	23	0	0	97	18	0	17.3	42	16	0	12.4
Fluoride	220	29	0.2	2.1	70	23	0	1.7	100	18	7.1	3.7	44	16	0	0
Lead	199	29	1.5	1.6	59	23	0.8	0.4	93	16	0	0	38	16	0	0
Mercury	197	29	0	0	67	23	0.3	0	71	17	0	0	22	16	0	0
Molybdenum	61	28	12.9	1.5	29	23	0	0	52	16	7.3	0.8	34	15	9.8	0
Nickel	201	29	0.1	0	66	23	0	0	90	17	0	0	39	16	0	0
Selenium	203	29	0	0	66	23	0	11.2	91	17	0	0	40	16	0	0
Strontium	61	28	0	0	29	23	0	0	52	16	0	0	34	15	0	12.9
Uranium and radioactive constituents with health-based benchmarks																
Gross alpha particle activity	171	28	20.9	12.9	66	23	6.4	0	92	16	11.9	10.6	23	16	7.9	3.2
Adjusted gross alpha particle activity	171	28	1.0	1.4	66	23	3.4	0	92	16	3.5	2.2	23	16	0	0
Radium activity	150	17	2.6	0.3	49	9	2.5	0	83	5	0	0.8	22	5	0	0
Radon-222 activity	36	17	41.8	19.9	7	5	0	0	38	4	6.2	11.4	23	4	0	0
Uranium activity	147	29	11.1	5.2	32	23	0.8	0	87	16	11.5	3.8	35	16	7.9	0

Table 7A. Aquifer-scale proportions for inorganic constituents for the granitic, metamorphic, sedimentary, and volcanic primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Aquifer-scale proportions calculated with the spatially weighted method (equation 2). **Relative-concentration (RC) categories:** high, $RC > 1.0$, moderate, $RC > 0.5$ and $RC \leq 1.0$; low, $RC \leq 0.5$. 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. **Abbreviations:** CDPH, California Department of Public Health; SMCL, secondary maximum contaminant level; USGS, U.S. Geological Survey; >, greater than; \leq , less than or equal to]

Constituent	Granitic primary aquifer system				Metamorphic primary aquifer system				Sedimentary primary aquifer system				Volcanic primary aquifer system			
	Number		Aquifer-scale proportion (in percent)		Number		Aquifer-scale proportion (in percent)		Number		Aquifer-scale proportion (in percent)		Number		Aquifer-scale proportion (in percent)	
	Wells	Cells	Moderate RC	High RC	Wells	Cells	Moderate RC	High RC	Wells	Cells	Moderate RC	High RC	Wells	Cells	Moderate RC	High RC
Nutrients with health-based benchmarks																
Nitrate	576	29	3.7	2.2	227	24	1.6	0.7	230	22	8.1	1.3	98	16	1.7	0
Inorganic constituents with SMCL benchmarks																
Chloride	197	29	0.7	0.1	63	23	0	0	98	18	0	0	43	16	0	0
Total dissolved solids (TDS)	297	29	2.5	1.3	101	23	2.0	1.4	142	18	7.6	0	58	16	3.4	1.2
Sulfate	196	29	0	0	64	23	0.8	0	96	18	0	0	42	16	0	1.7
Iron	224	29	4.7	13.0	70	23	5.8	25.9	100	18	0.8	8.5	45	16	2.2	7.5
Manganese	218	29	3.8	7.6	62	23	3.7	32.2	95	18	0.9	8.4	45	16	1.5	9.9
Zinc	191	29	0.1	0.1	58	23	0.8	1.0	92	18	0	0	42	16	0	0

¹Selenium was detected at high RC by USGS-GAMA in one metamorphic aquifer lithology well, and the other 399 wells with USGS-GAMA or CDPH data for selenium had low RCs. Strontium was detected at high RC by USGS-GAMA in 1 volcanic aquifer lithology well, and the other 175 wells with USGS-GAMA data for strontium had low RCs. Copper was reported at high RCs by the CDPH in 1 sedimentary and 1 volcanic aquifer lithology well, and the other 386 wells with USGS-GAMA or CDPH data for copper had low RCs. In all of these cases, the 1 well with high RC was located in a cell having few wells in that particular lithology and having a relatively large area for the lithology.

Table 7B. Aquifer-scale proportions for inorganic constituents for the aggregated primary aquifer system, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Aquifer-scale proportions calculated with the spatially weighted method (equation 4). **Relative-concentration (RC) categories:** high, $RC > 1.0$; moderate, $RC > 0.5$ and $RC \leq 1.0$; low, $RC \leq 0.5$. 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](#). **Abbreviations:** SMCL, secondary maximum contaminant level; >, greater than; \leq , less than or equal to]

Constituent	Aggregated lithologic primary aquifer system			
	Number		Aquifer-scale proportion (in percent)	
	Wells	Cells	Moderate RC	High RC
Trace elements with health-based benchmarks				
Aluminum	407	30	1.7	0
Antimony	394	30	0.3	0.2
Arsenic	465	30	10.1	9.7
Beryllium	396	30	0	0.2
Boron	204	30	2.2	2.0
Cadmium	398	30	0	0.2
Chromium	406	30	0.3	0
Copper	388	30	0	0.8
Fluoride	434	30	0.5	1.8
Lead	389	30	1.0	1.0
Mercury	357	30	0.1	0
Molybdenum	176	30	8.4	0.9
Nickel	396	30	0.03	0
Selenium	400	30	0	0.3
Strontium	176	30	0	0.3
Uranium and radioactive constituents with health-based benchmarks				
Gross alpha particle activity	352	30	14.5	7.8
Adjusted gross alpha particle activity	352	30	1.7	0.9
Radium activity	304	30	2.2	0.2
Radon-222 activity	104	30	28.8	14.1
Uranium activity	301	30	7.7	2.9
Nutrients with health-based benchmarks				
Nitrate	1,131	30	3.1	1.4
Inorganic constituents with SMCL benchmarks				
Chloride	401	30	0.4	0.1
Total dissolved solids (TDS)	598	30	2.8	1.3
Sulfate	398	30	0.2	0.2
Iron	439	30	4.4	15.8
Manganese	420	30	3.3	15.1
Zinc	383	30	0.3	0.3

Table 8A. Summary of aquifer-scale proportions in the granitic, metamorphic, sedimentary, volcanic, and aggregated primary aquifer systems for inorganic constituent classes with health-based benchmarks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Aquifer-scale proportions calculated with the spatially weighted method (equations 2 and 4). **Relative-concentration (RC) categories for inorganic constituents:** high, $RC > 1.0$; moderate, $RC > 0.5$ and $RC \leq 1.0$; low, $RC \leq 0.5$. RC defined as measured value divided by benchmark value. **Abbreviations:** >, greater than; \leq , less than or equal to]

Constituent class and primary aquifer system	Number of wells	Aquifer-scale proportion (in percent)		
		Low	Moderate	High
Nutrients				
Granitic	579	93	3.7	2.2
Metamorphic	233	98	1.6	0.7
Sedimentary	232	91	8.1	1.3
Volcanic	99	98	1.7	0
Aggregated	1,143	95	3.1	1.4
Trace elements				
Granitic	252	68	22	10
Metamorphic	97	81	¹ 9.7	9.5
Sedimentary	130	67	18	15
Volcanic	51	68	¹ 9.8	¹ 22
Aggregated	530	73	16	11
Uranium and radioactive constituents²				
Granitic	239	54	32	14
Metamorphic	82	94	¹ 6.4	0
Sedimentary	133	76	¹ 12	12
Volcanic	48	89	7.9	¹ 3.2
Aggregated	502	72	20	8.2
Any inorganic constituent^{2,3}				
Granitic	327	50	30	20
Metamorphic	120	79	12	9.5
Sedimentary	167	60	20	20
Volcanic	57	68	¹ 9.8	¹ 22
Aggregated	671	63	21	16

¹Moderate or high aquifer-scale proportion for the constituent class was set equal to the greatest moderate or high aquifer-scale proportion for an individual component of the class. The calculated proportion for the class was smaller than the greatest proportion for an individual component in the class. This situation may occur when not all wells have data for all components of the class (see [appendix C](#) for discussion).

²Aquifer-scale proportions for radioactive constituents and any inorganic constituent with health-based benchmarks were calculated using unadjusted gross alpha particle activity. If adjusted gross alpha particle activity is used instead of unadjusted gross alpha particle activity, the results are:

Lithology	Radioactive constituents		Any inorganic constituent	
	Moderate	High	Moderate	High
Granitic	22	11	29	17
Metamorphic	3.7	0	11	10
Sedimentary	¹ 11	8.3	22	17
Volcanic	7.9	0	¹ 9.8	¹ 22
Aggregated	14	6.2	21	15

³Aquifer-scale proportions for any inorganic constituent were calculated with wells having data for trace elements or radioactive constituents. Wells having data only for nutrients were not included ([appendix C](#)).

Table 8B. Summary of aquifer-scale proportions in the granitic, metamorphic, sedimentary, volcanic, and aggregated primary aquifer systems for inorganic constituent classes with secondary maximum contaminant level (SMCL) benchmarks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Aquifer-scale proportions calculated with the spatially weighted method (equations 2 and 4). **Relative-concentration (RC) categories for inorganic constituents:** high, RC > 1.0; moderate, RC > 0.5 and RC ≤ 1.0; low, RC ≤ 0.5. RC defined as measured value divided by benchmark value. **Abbreviations:** >, greater than; ≤, less than or equal to]

Constituent class and aquifer lithology	Number of wells	Aquifer-scale proportion (in percent)		
		Low	Moderate	High
Salinity indicators with SMCL benchmarks¹				
Granitic	297	96	2.6	1.3
Metamorphic	104	96	2.0	1.4
Sedimentary	144	92	7.4	0
Volcanic	59	95	3.4	1.2
Aggregated	604	96	2.8	1.3
Trace metals with SMCL benchmarks²				
Granitic	231	78	7.2	15
Metamorphic	73	62	5.2	⁴ 32
Sedimentary	102	90	0	8.9
Volcanic	45	88	2.1	9.9
Aggregated	451	76	5.5	18
Any inorganic constituent with SMCL benchmarks³				
Granitic	212	77	7.9	15
Metamorphic	67	62	5.2	⁴ 32
Sedimentary	99	84	7.3	⁴ 8.9
Volcanic	45	85	5.5	9.9
Aggregated	423	76	6.8	18

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

²Trace metals with SMCL benchmarks: iron, manganese, and zinc.

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

⁴High-RC aquifer-scale proportion for the constituent class was set equal to the greatest high-RC aquifer-scale proportion for an individual component of the class. The calculated proportion for the class was smaller than the greatest proportion for an individual component in the class. This situation may occur when not all wells have data for all components of the class (see [appendix C](#) for discussion).

Table 9. Results of contingency table tests for differences in aquifer-scale proportions of selected inorganic constituents and constituent classes between granitic, metamorphic, sedimentary, and volcanic primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Significance defined as p-value less than threshold value (α) of 0.05. **Aquifer lithology class:** G, granitic; M, metamorphic; S, sedimentary; V, volcanic. **Abbreviations:** ns, no significant differences; SMCL, secondary maximum contaminant levels; >, greater than; <, less than]

Constituent	Proportion high or moderate compared to proportion low	Significant differences
	p-value	
Individual inorganic constituents with health-based benchmarks		
Arsenic	0.725	ns
Boron	0.774	ns
Fluoride	0.001	S > G, S > M, S > V
Gross alpha particle activity ¹	<0.001	G > M, G > V, S > M
Radon-222	<0.001	G > M, G > S, G > V, S > V
Uranium	0.050	G > M, S > M
Individual inorganic constituents with SMCL benchmarks		
Iron	0.001	M > G, M > S, M > V
Manganese	<0.001	M > G, M > S, M > V
Classes of inorganic constituents with health-based benchmarks²		
Nutrients (nitrate)	0.003	G > M, S > M, S > V
Trace elements	0.079	ns
Uranium and radioactive constituents ¹	<0.001	G > M, G > S, G > V, S > M
Any inorganic constituent ¹	<0.001	G > M, G > V, S > M
Classes of inorganic constituents with SMCL benchmarks²		
Salinity indicators	0.472	ns
Metals	<0.001	M > G, M > S, M > V, G > S
Any inorganic SMCL constituent	<0.001	M > S, M > V

¹Aquifer-scale proportions for gross alpha particle activity, uranium and radioactive constituents, and any inorganic constituent with health-based benchmarks were calculated using unadjusted gross alpha particle activity and without radon-222 data. If adjusted gross alpha particle activity is used instead of unadjusted gross alpha particle activity, the results are:

Constituent or class	p-value	Significant differences
Adjusted gross alpha particle activity	0.435	ns
Uranium and radioactive constituents	<0.001	G > M, G > S, G > V, S > M
Any inorganic constituent	<0.001	G > M, S > M

²For classes of constituents, statistical test performed with the maximum relative-concentration for any constituent in the class for each sample.

Trace Elements

The trace element 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 had high-RC aquifer-scale proportion of 11 percent and moderate-RC aquifer-scale proportion of 16 percent in the SNR study unit (table 8A). The sum of the proportions of the primary aquifer system with high RCs or moderate RCs of any trace element was not significantly different among the four aquifer lithologies (table 9). Arsenic, boron, and fluoride were the only trace elements having high-RC aquifer-scale proportions of greater than approximately 2 percent for the SNR study unit as a whole (table 7B). Twelve other trace elements were detected at high RCs in less than 2 percent of the primary aquifer system or were only detected at moderate RCs (table 7B).

Arsenic

Arsenic is a semi-metallic trace element. Natural sources to groundwater include dissolution of arsenic-bearing minerals and desorption of arsenic from mineral surfaces. Pyrite, an iron-sulfide mineral, is a common accessory mineral in aquifer materials and may contain up to several percent (by weight) of arsenic (Smedley and Kinniburgh, 2002). Potential anthropogenic sources of arsenic 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 may increase the rate of dissolution of naturally occurring arsenic-bearing minerals (Smedley and Kinniburgh, 2002). The MCL-US for arsenic was lowered from 50 micrograms per liter ($\mu\text{g/L}$) 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 ($>10 \mu\text{g/L}$) (Focazio and others, 2000; 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).

In the SNR study unit, arsenic was present at high RCs in 9.7 percent of the aggregated primary aquifer system and at moderate RCs in 10.1 percent of the system (table 7B; fig. 11A) and was present at high and moderate RCs in all four lithologic primary aquifer systems (table 7A; fig. 11A). The sum of the proportions of the primary aquifer system with high RCs or moderate RCs of arsenic was not significantly different among the four aquifer lithologies (table 9). However, the high-RC aquifer-scale proportion for arsenic in the volcanic system was significantly greater than the high-RC aquifer-scale proportions in the granitic, metamorphic, and sedimentary systems (contingency table test, $p = 0.010$; table 7A; fig. 11A).

The cells contributing most to the high-RC and moderate-RC aquifer-scale proportions of arsenic were different for the four aquifer lithologic types. For the granitic system, the greatest contribution to high-RC and moderate-RC aquifer-scale proportions of arsenic came from cells located in the southern half of the SNR study unit (cells 26, 30, 13, 23, 24; fig. 12A). This region includes the Central Sierra study unit and Lake Isabella area of the Southern Sierra study unit, which are areas known to have high and moderate RCs of arsenic in groundwater from granitic aquifers (Fram and Belitz, 2012). The majority of the cells contributing most to the high and moderate RCs of arsenic in the metamorphic system contained metamorphic rocks of the Western Metamorphic Belt (cells 1, 2, 12, 11). The cells contributing most to the high-RC and moderate-RC aquifer-scale proportions of arsenic in the volcanic system were located near Lake Tahoe (cells 17, 18, 9). High and moderate RCs of arsenic in the sedimentary system were located near areas with high and moderate RCs of arsenic in the hard-rock areas; the cells contributing most to high-RC and moderate-RC aquifer-scale proportions in the sedimentary system were cell 26 in the southern part of the study unit, which presumably is dominated by sediments derived from the surrounding granitic rocks in cell 26, and cells 8 and 18 near Lake Tahoe, where sediments are presumably dominated by the nearby volcanic rocks.

Arsenic concentrations showed significant negative correlations with aridity index, elevation, and latitude (table 10B). These correlations likely reflect the positive correlations between aridity index and both elevation and latitude (table 6B) and the association between higher arsenic concentrations and location in a particular compositional band in the Sierra Nevada batholith that is along the southwestern side of the SNR study unit (Fram and Belitz, 2012; fig. 12A). In this part of the Sierra Nevada batholith, granitic magmas appear to have assimilated reduced sedimentary materials (reduced phylites and pelitic schists) (Ague and Brimhall, 1987, 1988). The sedimentary protoliths for these materials, black shales, commonly contain higher concentrations of many trace elements, such as arsenic, boron, copper, chromium, molybdenum, vanadium, selenium, uranium, and zinc (Tourtelot, 1970).

Arsenic concentrations also were significantly correlated with geochemical conditions: arsenic concentration was positively correlated with pH and negatively correlated with DO (table 10B). These correlations between arsenic and geochemical conditions are consistent with the two primary mechanisms affecting arsenic concentrations in groundwater (Smedley and Kinniburgh, 2002; Welch and others, 2006; Fram and Belitz, 2012). One mechanism is release of arsenic resulting from reductive dissolution of iron or manganese oxyhydroxides under reducing conditions, and the other is pH-dependent desorption of arsenic from the oxyhydroxides in alkaline, oxic groundwater. Fram and Belitz (2012) observed a significant relation between arsenic concentration and groundwater age class in the Tahoe-Martis, Central Sierra, and Southern Sierra study units (higher arsenic in pre-modern groundwater) that was not seen in the SNR study unit, likely because

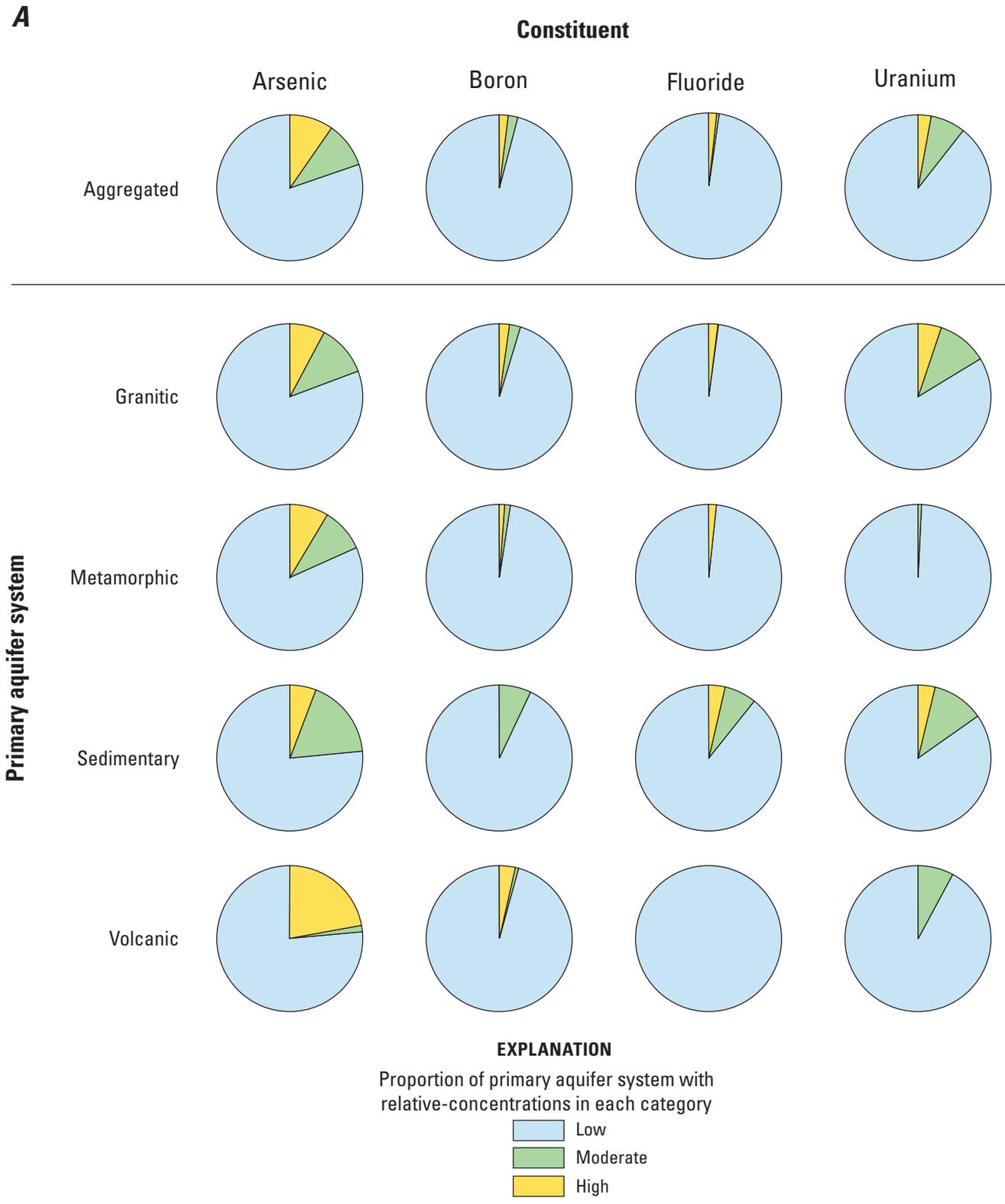


Figure 11. Aquifer-scale proportions for (A) arsenic, boron, fluoride, and uranium and for (B) nitrate, total dissolved solids, manganese, and organic constituents in the aggregated, granitic, metamorphic, sedimentary, and volcanic primary aquifer systems, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

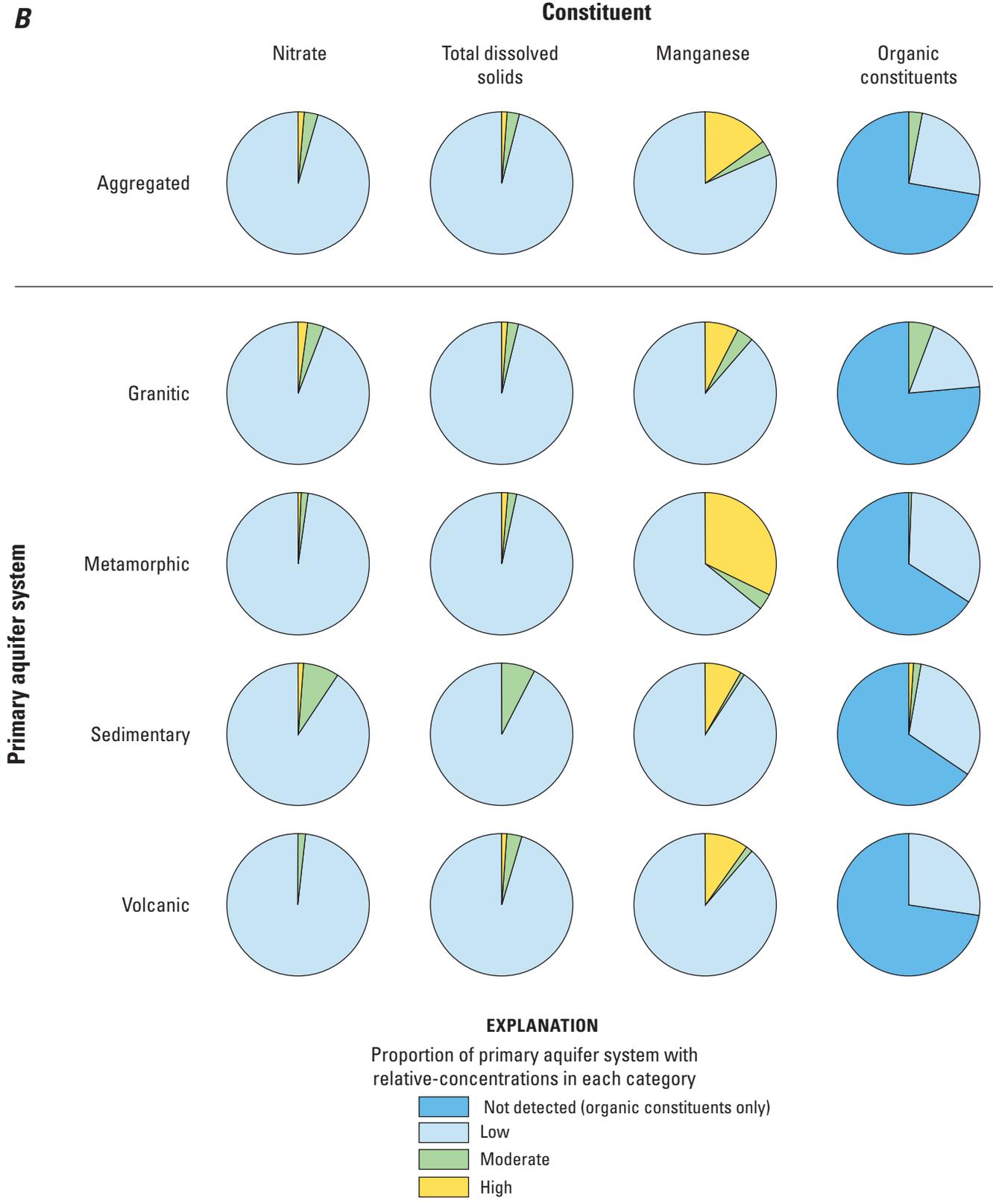


Figure 11. —Continued

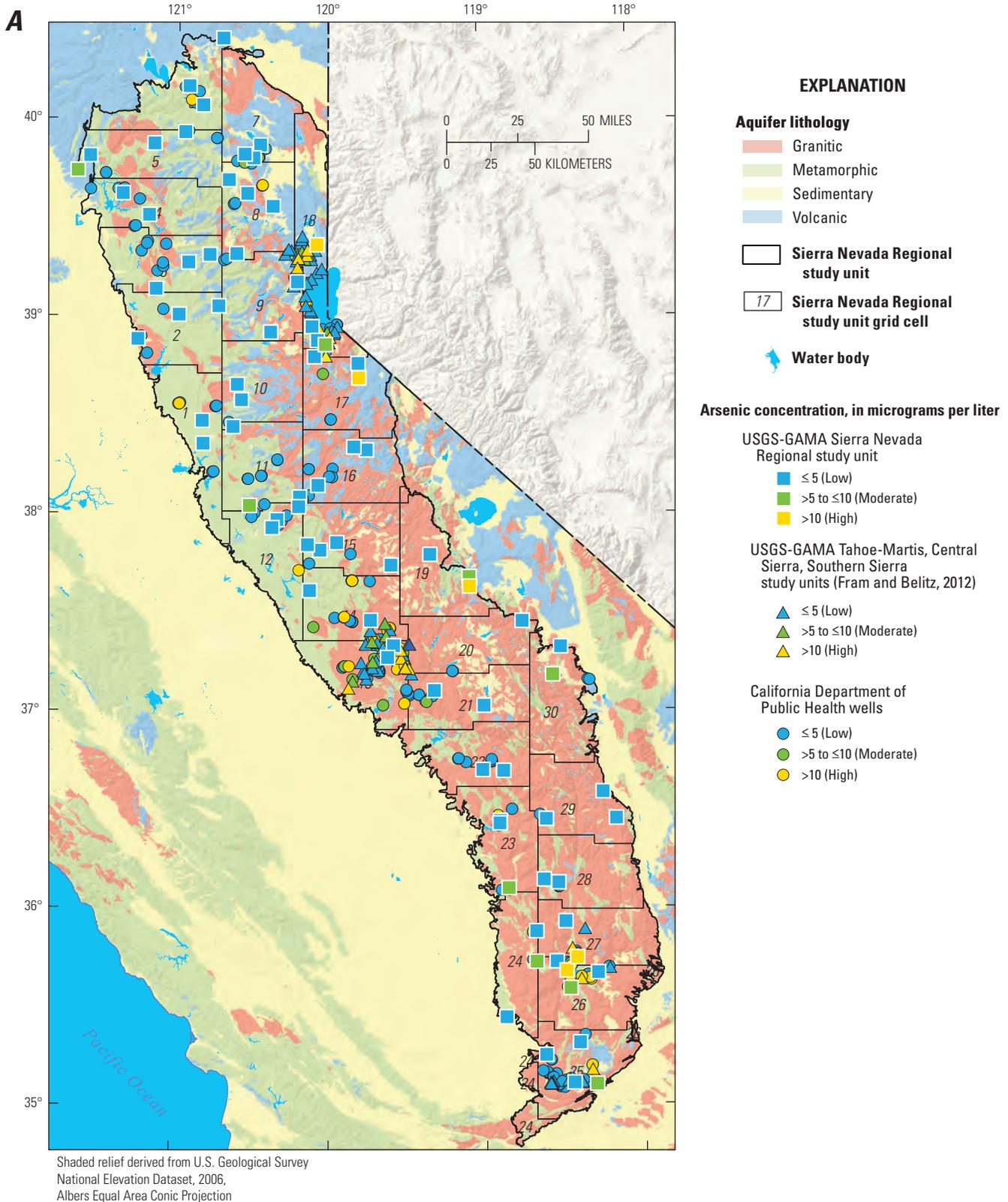


Figure 12. Concentrations of (A) arsenic, (B) boron, (C) fluoride, (D) nitrate, (E) uranium, and (F) manganese for wells sampled by USGS-GAMA for the Sierra Nevada Regional study unit in 2008, the Tahoe-Martis study unit in 2007, and the Central Sierra and Southern Sierra study units in 2006 and all wells in the California Department of Public Health (CDPH) database with data during the period May 2006 through October 2008, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

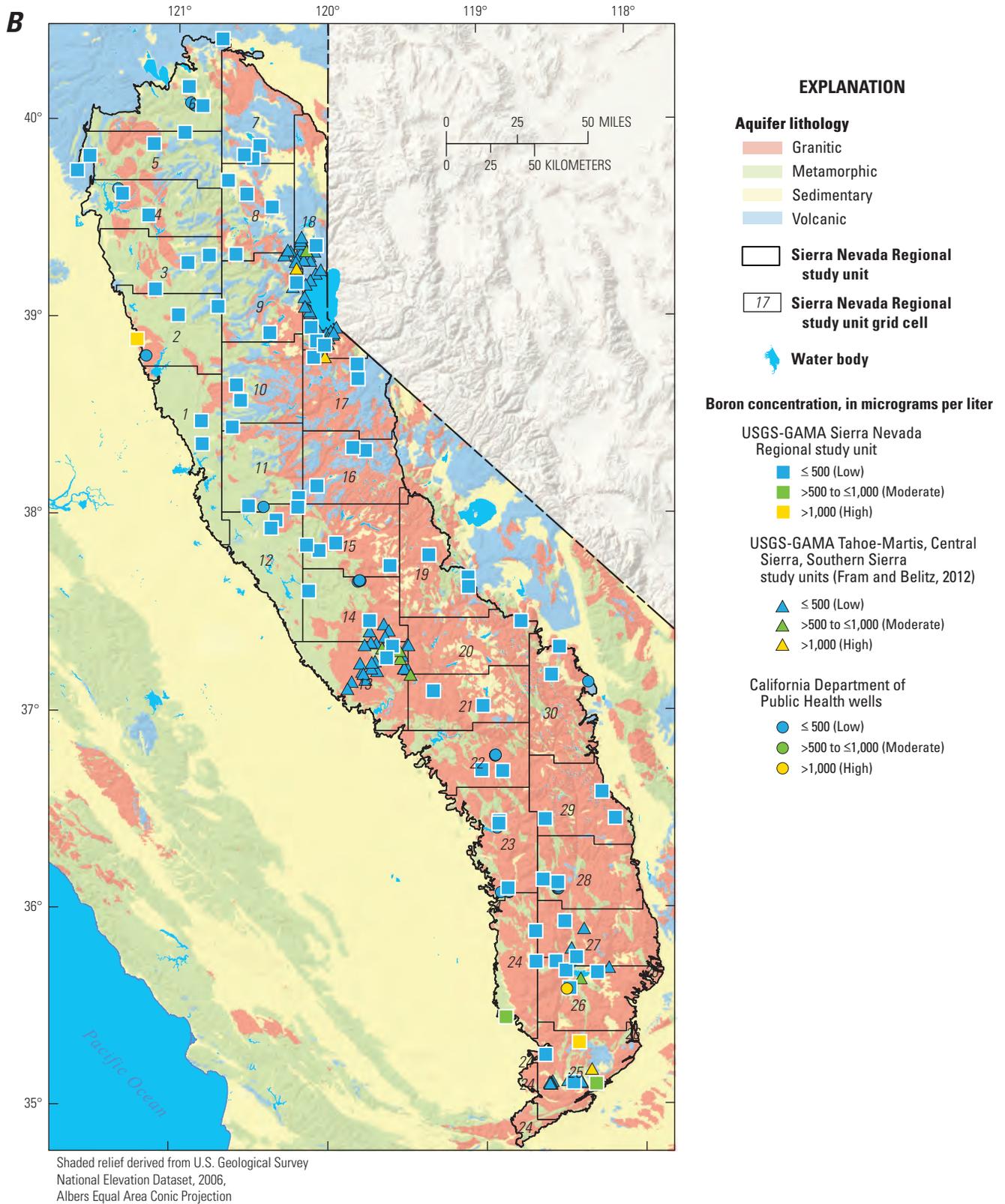


Figure 12. —Continued

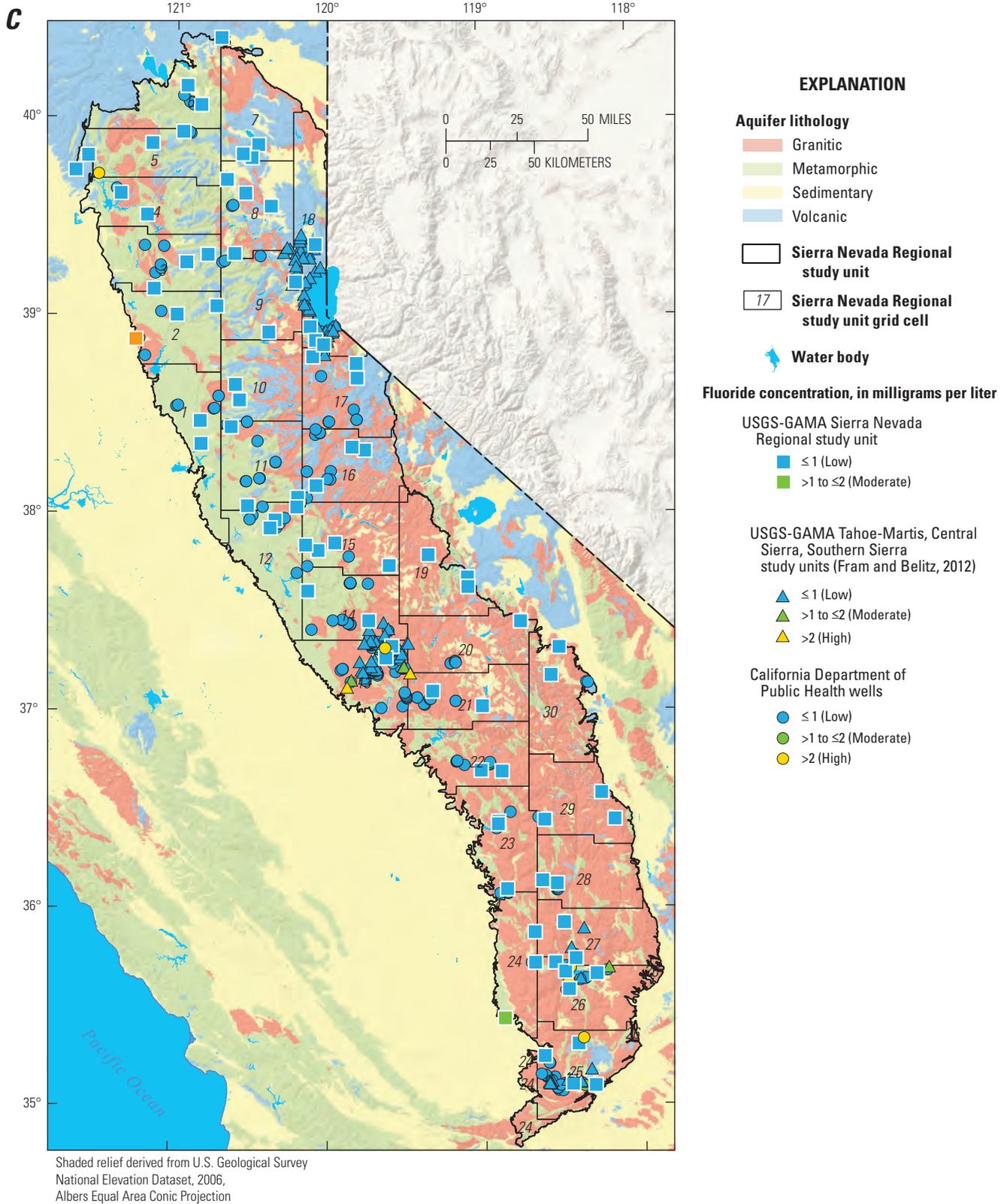


Figure 12. —Continued

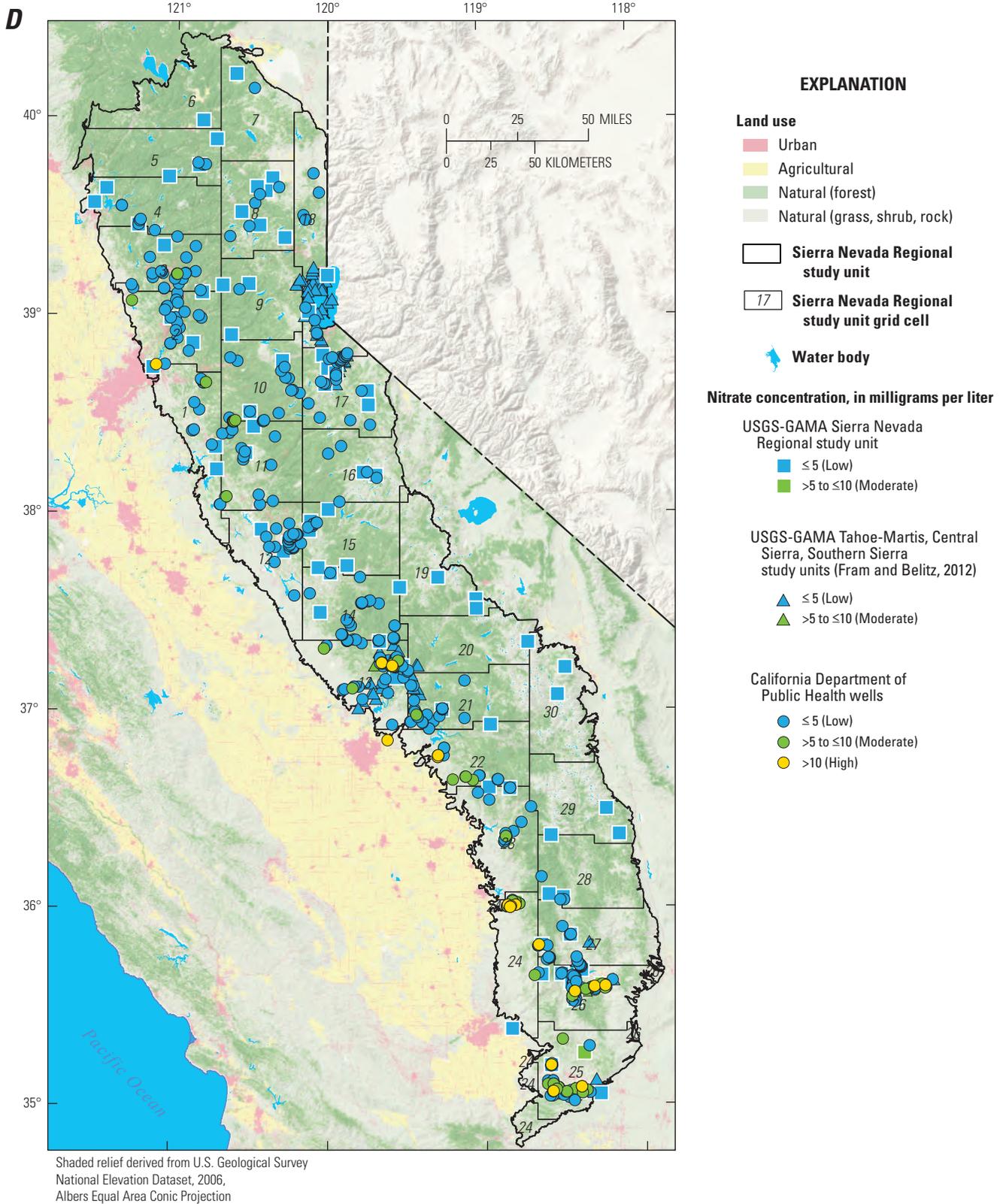


Figure 12. —Continued

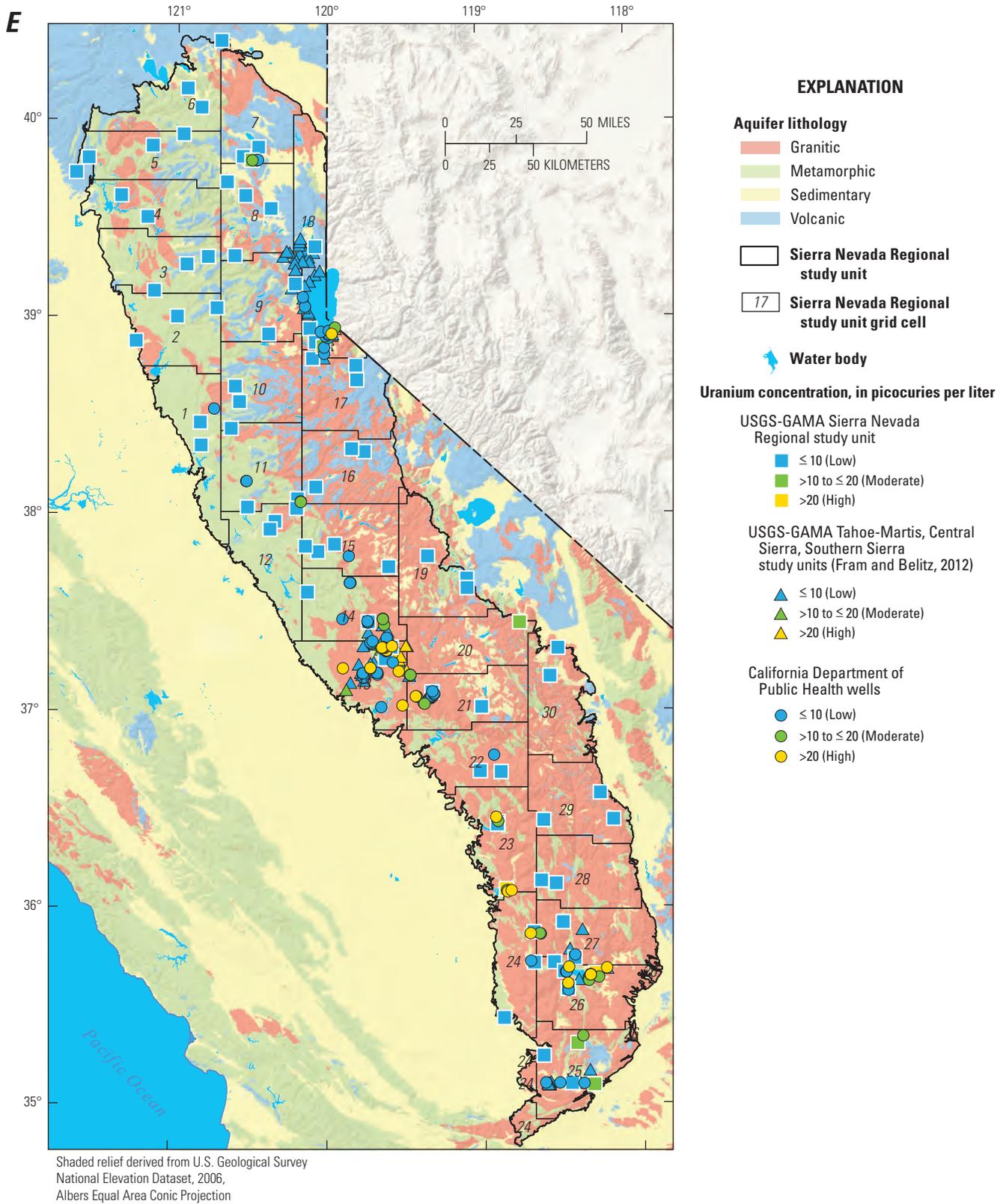


Figure 12. —Continued

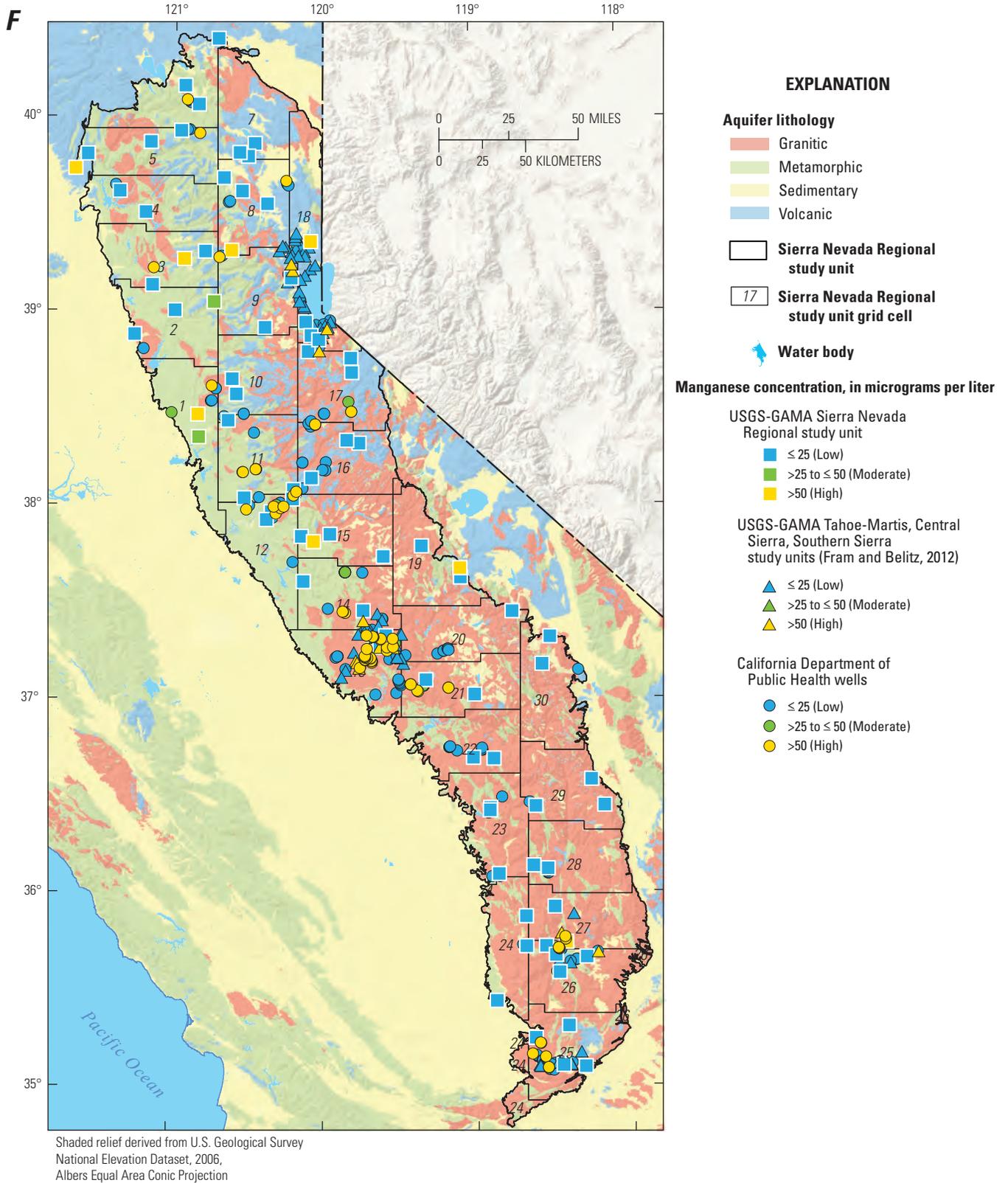


Figure 12. —Continued

Table 10A. Results of multi-stage Kruskal-Wallis tests for differences in median values of selected potential explanatory factors and water-quality constituents between samples classified into groups by aquifer lithologic class, oxidation-reduction class, site type class, or groundwater age class, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Factors yielding a result of significance in the Kruskal-Wallis test were evaluated with Tukey's test on the single-factor analysis of variance of the ranks. Significance defined as p-value less than threshold value (α) of 0.05. **Aquifer lithology class:** G, granitic; M, metamorphic; S, sedimentary; V, volcanic (see [appendix B](#)). **Oxidation-reduction class:** see [appendix B](#) for definitions of oxic and anoxic. **Depth class:** spring (SP), site is a spring; shallow (SH), well depth < 170 ft bls; overlapping (OL), top of perforations < 170 ft bls and well depth > 170 ft bls; Deep (DP), well depth > 170 ft bls and top of perforations > 170 ft bls. **Age class:** see [appendix B](#) for explanation of classes. **Abbreviations:** ft bls, feet below land surface; ns, no significant differences; SMCL, secondary maximum contaminant levels; >, greater than; <, less than; ns, no significant differences]

Constituent	Aquifer lithology class (G, M, S, V)		Oxidation-reduction class [oxic (OX), anoxic (AN)]		Depth class [spring (SP), shallow (SH), overlapping (OL), deep (DP)]		Age class [modern (MOD), mixed (MIX), pre-modern (PRE)]	
	p	Significant differences	p	Significant differences	p	Significant differences	p	Significant differences
Individual inorganic constituents								
Fluoride	0.133	ns	<0.001	AN > OX	<0.001	SH > SP OL > SP DP > SP	0.036	PRE > MOD
Arsenic	0.036	M > G, V > G	0.013	AN > OX	0.065	ns	0.139	ns
Boron	0.119	ns	<0.001	AN > OX	0.003	SH > SP OL > SP DP > SP	0.002	PRE > MOD PRE > MIX
Gross alpha particle activity	0.295	ns	0.289	ns	0.281	ns	0.279	ns
Radon-222 activity	0.004	G > V	0.185	ns	0.258	ns	0.370	ns
Uranium activity	0.087	ns	0.059	ns	0.678	ns	0.575	ns
Individual inorganic constituents with SMCL benchmarks								
Iron	0.223	ns	<0.001	AN > OX	0.108	ns	0.300	ns
Manganese	0.180	ns	<0.001	AN > OX	0.037	OL > SP	0.055	ns
Classes of inorganic constituents¹								
Trace elements with health-based benchmarks	0.031	M > G, S > G	<0.001	AN > OX	0.002	SH > SP OL > SP DP > SP	0.008	PRE > MOD PRE > MIX
Nutrients (nitrate)	0.312	ns	0.001	OX > AN	0.029	SH > SP	0.111	ns
Uranium and radioactive constituents	0.375	ns	0.370	ns	0.398	ns	0.221	ns
Any inorganic constituent with health-based benchmarks	0.380	ns	0.001	AN > OX	0.054	ns	0.056	ns
Classes of inorganic constituents with SMCL benchmarks¹								
Metals	0.090	ns	<0.001	AN > OX	0.087	ns	0.143	ns
Salinity indicators	0.072	ns	<0.001	AN > OX	<0.001	SH > SP OL > SP DP > SP	0.035	PRE > MOD
Any inorganic constituent with SMCL benchmarks	0.008	M > G, V > G	<0.001	AN > OX	<0.001	SH > SP OL > SP DP > SP	0.021	PRE > MOD

Table 10A. Results of multi-stage Kruskal-Wallis tests for differences in median values of selected potential explanatory factors and water-quality constituents between samples classified into groups by aquifer lithologic class, oxidation-reduction class, site type class, or groundwater age class, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Factors yielding a result of significance in the Kruskal-Wallis test were evaluated with Tukey’s test on the single-factor analysis of variance of the ranks. Significance defined as p-value less than threshold value (α) of 0.05. **Aquifer lithology class:** G, granitic; M, metamorphic; S, sedimentary; V, volcanic (see [appendix B](#)). **Oxidation-reduction class:** see [appendix B](#) for definitions of oxic and anoxic. **Depth class:** spring (SP), site is a spring; shallow (SH), well depth < 170 ft bls; overlapping (OL), top of perforations < 170 ft bls and well depth > 170 ft bls; Deep (DP), well depth > 170 ft bls and top of perforations > 170 ft bls. **Age class:** see [appendix B](#) for explanation of classes. **Abbreviations:** ft bls, feet below land surface; ns, no significant differences; SMCL, secondary maximum contaminant levels; >, greater than; <, less than; ns, no significant differences]

Constituent	Aquifer lithology class (G, M, S, V)		Oxidation-reduction class [oxic (OX), anoxic (AN)]		Depth class [spring (SP), shallow (SH), overlapping (OL), deep (DP)]		Age class [modern (MOD), mixed (MIX), pre-modern (PRE)]	
	p	Significant differences	p	Significant differences	p	Significant differences	p	Significant differences
Classes of organic and special-interest constituents¹								
Trihalomethanes (chloroform)	0.918	ns	0.110	ns	0.097	ns	0.251	ns
Gasoline oxygenates (methyl <i>tert</i> -butyl ether)	0.810	ns	0.504	ns	0.169	ns	0.233	ns
Solvents	0.050	ns	0.802	ns	0.324	ns	0.687	ns
Any VOC	0.508	ns	0.374	ns	0.003	OL > SP	0.060	ns
Pesticides	0.534	ns	0.640	ns	0.057	ns	0.169	ns
Any organic constituent	0.605	ns	0.460	ns	0.003	OL > SP	0.026	MOD > PRE MIX > PRE
Special-interest constituent								
Perchlorate	0.374	ns	0.086	ns	0.007	SH > SP OL > SP	0.017	MOD > MIX

¹For classes of constituents, statistical test performed with the maximum relative-concentration for any constituent in the class for each sample.

Table 10B. Results of Spearman's rho tests for correlations between selected potential explanatory factors and selected water-quality constituents, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[ρ (rho), Spearman's correlation statistic. Significance defined as p-value less than threshold value (α) of 0.05. Tests in which the variables were determined to be significantly correlated on the basis of p-values (not shown) have p-values underlined and in bold font. Black values, positive correlation; red values, negative correlation. Abbreviations: LUFT, leaking or formerly leaking underground fuel tank; SMCL, secondary maximum contaminant level; VOC, volatile organic compound]

ρ	Land-use factors				Geography factors				Primary aquifer system factors			
	Percentage agricultural land use	Percentage natural land use	Percentage urban land use	Density of septic tanks	Density of LUFTs	Aridity Index	Elevation	Latitude	Depth to top of open or screen ¹	Depth to bottom of open or screen ¹	pH	Dissolved oxygen concentration
Individual inorganic constituents												
Fluoride	<u>0.29</u>	<u>-0.22</u>	0.11	0.18	0.03	<u>-0.69</u>	<u>-0.55</u>	<u>-0.53</u>	<u>-0.02</u>	<u>-0.16</u>	<u>0.33</u>	<u>-0.64</u>
Arsenic	0.02	<u>-0.10</u>	0.11	0.02	0.03	<u>-0.38</u>	<u>-0.23</u>	<u>-0.23</u>	0.10	<u>-0.09</u>	<u>0.41</u>	<u>-0.34</u>
Boron	<u>0.32</u>	<u>-0.33</u>	<u>0.23</u>	0.14	0.03	<u>-0.52</u>	<u>-0.41</u>	<u>-0.33</u>	0.00	<u>-0.06</u>	<u>0.41</u>	<u>-0.59</u>
Gross alpha particle activity	0.07	<u>-0.12</u>	0.11	<u>-0.19</u>	<u>-0.22</u>	<u>-0.38</u>	0.01	<u>-0.36</u>	<u>-0.09</u>	<u>-0.06</u>	0.19	<u>-0.22</u>
Radon-222 activity ¹	<u>-0.10</u>	0.12	<u>-0.05</u>	<u>-0.08</u>	<u>-0.38</u>	<u>-0.04</u>	0.33	<u>-0.36</u>	<u>-0.75</u>	<u>-0.03</u>	<u>-0.54</u>	0.21
Uranium activity	0.18	<u>-0.19</u>	0.11	<u>-0.11</u>	<u>-0.16</u>	<u>-0.43</u>	0.06	<u>-0.44</u>	<u>-0.15</u>	0.02	0.17	0.02
Individual inorganic constituents with SMCL benchmarks												
Iron	<u>-0.17</u>	0.00	0.12	<u>0.22</u>	0.13	0.06	<u>-0.11</u>	0.11	<u>-0.09</u>	0.03	0.03	<u>-0.47</u>
Manganese	<u>-0.12</u>	0.06	0.01	0.15	0.05	<u>-0.05</u>	<u>-0.26</u>	0.06	<u>-0.02</u>	0.05	0.08	<u>-0.61</u>
Classes of inorganic constituents ²												
Trace elements with health-based benchmarks	0.16	<u>-0.19</u>	0.15	0.05	0.06	<u>-0.53</u>	<u>-0.39</u>	<u>-0.35</u>	0.18	<u>-0.10</u>	<u>0.50</u>	<u>-0.49</u>
Nutrients (nitrate)	0.20	<u>-0.33</u>	<u>0.31</u>	0.16	0.08	<u>-0.40</u>	<u>-0.30</u>	<u>-0.32</u>	<u>-0.28</u>	<u>-0.22</u>	<u>-0.17</u>	0.11
Uranium and radioactive constituents	0.08	<u>-0.11</u>	0.09	<u>-0.18</u>	<u>-0.22</u>	<u>-0.37</u>	0.04	<u>-0.38</u>	<u>-0.11</u>	<u>-0.05</u>	<u>0.22</u>	<u>-0.20</u>
Any inorganic constituent with health-based benchmarks	0.22	<u>-0.17</u>	0.10	<u>-0.07</u>	<u>-0.07</u>	<u>-0.56</u>	<u>-0.25</u>	<u>-0.38</u>	0.11	<u>-0.11</u>	<u>0.45</u>	<u>-0.37</u>
Classes of inorganic constituents with SMCL benchmarks ²												
Metals	<u>-0.16</u>	0.09	0.01	0.17	0.07	<u>-0.01</u>	<u>-0.21</u>	0.03	0.07	0.04	0.03	<u>-0.54</u>
Salinity indicators	<u>0.28</u>	<u>-0.32</u>	<u>0.24</u>	<u>0.36</u>	<u>0.22</u>	<u>-0.64</u>	<u>-0.70</u>	<u>-0.35</u>	<u>-0.05</u>	<u>-0.17</u>	<u>0.36</u>	<u>-0.57</u>
Any inorganic constituent with SMCL benchmarks	0.16	<u>-0.24</u>	0.24	<u>0.34</u>	<u>0.25</u>	<u>-0.45</u>	<u>-0.63</u>	<u>-0.20</u>	<u>-0.08</u>	<u>-0.15</u>	<u>0.34</u>	<u>-0.65</u>

Table 10B. Results of Spearman's rho tests for correlations between selected potential explanatory factors and selected water-quality constituents, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[ρ (rho), Spearman's correlation statistic. Significance defined as p-value less than threshold value (α) of 0.05. Tests in which the variables were determined to be significantly correlated on the basis of p-values (not shown) have p-values underlined and in bold font. Black values, positive correlation; red values, negative correlation. Abbreviations: LUFT, leaking or formerly leaking underground fuel tank; SMCL, secondary maximum contaminant level; VOC, volatile organic compound]

ρ	Land-use factors				Geography factors				Primary aquifer system factors			
	Percentage agricultural land use	Percentage natural land use	Percentage urban land use	Density of septic tanks	Density of LUFTs	Aridity Index	Elevation	Latitude	Depth to top of open or screen ¹	Depth to bottom of open or screen ¹	pH	Dissolved oxygen concentration
Classes of organic constituents ²												
Trihalomethanes (chloroform)	-0.09	-0.14	<u>0.23</u>	<u>0.28</u>	0.18	0.00	0.17	0.09	0.04	0.15	-0.14	-0.10
Gasoline oxygenates (methyl <i>tert</i> -butyl ether)	-0.07	<u>-0.26</u>	<u>0.28</u>	0.05	0.17	0.06	0.09	0.10	-0.09	0.03	-0.09	-0.07
Solvents	-0.02	<u>-0.28</u>	<u>0.22</u>	0.19	0.15	-0.07	-0.10	0.18	-0.06	0.12	-0.06	-0.15
Any VOC	-0.03	<u>-0.37</u>	<u>0.37</u>	<u>0.27</u>	<u>0.32</u>	-0.03	-0.15	0.09	-0.21	0.06	-0.12	-0.13
Pesticides	0.18	<u>-0.33</u>	<u>0.31</u>	<u>0.26</u>	0.19	<u>-0.23</u>	<u>-0.30</u>	-0.18	<u>-0.32</u>	-0.11	0.03	-0.15
Any organic constituent	0.07	<u>-0.43</u>	<u>0.40</u>	<u>0.31</u>	<u>0.34</u>	-0.13	<u>-0.27</u>	0.02	<u>-0.28</u>	0.02	-0.04	-0.17
Special-interest constituent												
Perchlorate	0.17	<u>-0.22</u>	0.20	<u>0.27</u>	0.19	<u>-0.41</u>	<u>-0.37</u>	<u>-0.39</u>	-0.26	-0.24	-0.14	-0.01

¹The rho values corresponding to p-values less than 0.05 are higher for tests involving radon-222, chloroform, depth to top of screened or open interval, and depth to bottom of screened or open interval because not all samples had data for those parameters; tests not involving those parameters used 83 samples. Twenty-eight samples were analyzed for radon-222, 74 samples had accepted data for chloroform (see text for discussion), 63 sites were wells, and of those, 61 had data for bottom of interval and 49 had data for top of interval.

²For classes of constituents, statistical test performed with the maximum relative-concentration for any constituent in the class for each sample.

may increase because of evaporative concentration of groundwater in dry climates (low aridity index), or because of longer residence times in contact with aquifer materials containing boron-bearing minerals or fluids (Fram and Belitz, 2012).

Fluoride

Fluoride is the anionic form of the element fluorine. Natural sources of fluoride in groundwater include dissolution of fluoride-bearing minerals, such as fluorite (CaF_2) and fluorapatite [$\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{OH})$] (Hem, 1992). The main anthropogenic source of fluoride to water is addition of sodium fluoride or hexafluorosilicic acid during drinking-water treatment as a public health measure to reduce dental caries (National Research Council, 2006). Hexafluorosilicic acid is a byproduct of the production of phosphate fertilizers and hydrofluoric acid and the processing of aluminum. The MCL-CA for fluoride, 2 mg/L (table 4A), is lower than the MCL-US for fluoride, 4 mg/L. Chronic exposure to fluoride concentrations in drinking water above the MCL-US may result in bone disease and tooth discoloration (National Research Council, 2006).

Fluoride was present at high RCs in 1.8 percent and moderate RCs in 0.5 percent of the aggregated primary aquifer system (table 7B; fig. 11A). It was detected at high RCs in the granitic, metamorphic, and sedimentary primary aquifer systems, but not in the volcanic system (table 7A; figs. 11A, 12C). The proportion of the sedimentary primary aquifer system with high or moderate RCs of fluoride was significantly greater than the proportions with high or moderate RCs in the granitic, metamorphic, or volcanic systems (table 9).

The cells contributing most to the high-RC and moderate-RC aquifer-scale proportions of fluoride in the primary aquifer system as a whole were cells 24, 26, and 27 in the southern end of the SNR study unit and cells 2 and 5 in the northern part (fig. 12C). Fluoride has nearly the same set of significant correlations with potential explanatory factors as does boron (tables 10A,B), and fluoride and boron were strongly correlated with one another (table 11).

Other Trace Elements

Eight other trace elements had high-RC aquifer-scale proportions of 1 percent or less in the aggregated primary aquifer system: antimony, beryllium, cadmium, copper, lead, molybdenum, selenium, and strontium (table 7B). Of these eight trace elements, molybdenum was the only one that also had a moderate-RC aquifer-scale proportion of greater than 1 percent. Molybdenum has a non-regulatory HAL-US benchmark (table 4A), and all data used in the status assessment were from USGS-GAMA because constituents with only HAL-US benchmarks commonly are not analyzed in regulatory sampling for CDPH. Molybdenum was present at high RCs in the granitic and sedimentary primary aquifer systems and at moderate RCs in the granitic, sedimentary, and volcanic systems (table 7A).

Nutrients

Nutrients in groundwater have natural and anthropogenic sources. Natural sources include precipitation, 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 (which emits nitrogen oxides to the atmosphere). Nitrate and nitrite have MCL-US benchmarks, and high levels of either constituent in drinking water can cause “blue baby” syndrome. Nitrate is the more oxidized form, and thus, is the most common form in oxic groundwater systems. Although evapotranspiration from shallow groundwater can increase concentrations of nutrients in groundwater, concentrations of nitrate greater than about 1 mg/L (corresponding to an RC of 0.1) generally are the result of anthropogenic inputs (Nolan and Hitt, 2003; Dubrovsky and others, 2010). For this study, nitrate was classified as an inorganic constituent, and the boundary between low RC and moderate RC for inorganic constituents was defined as an RC of 0.5 (see section “Groundwater Quality Defined as Relative-Concentrations”).

Nutrients were detected at high RCs in 1.4 percent of the aggregated primary aquifer system and at moderate RCs in 3.1 percent (table 8A), and the only nutrient reported at high or moderate RCs was nitrate (table 7B; fig. 11B). The proportions of the granitic and sedimentary primary aquifer systems with high or moderate RCs of nitrate were significantly greater than the proportions of the metamorphic system with high or moderate RCs of nitrate, and the proportion with high or moderate RCs of nitrate in the sedimentary system was greater than that in the volcanic system (table 9). Median nitrate concentrations in samples from the four aquifer lithologies were not significantly different (table 10A).

The cells contributing most to the high-RC and moderate-RC aquifer-scale proportions of nitrate in both granitic and sedimentary primary aquifer systems were all in the southern part of the SNR study unit: cells 22, 23, 24, 25, and 26 (fig. 12D). Nitrate concentrations were significantly negatively correlated with aridity index, elevation, and latitude (table 10B), which is consistent with location of groundwater with higher nitrate concentrations in the southern part of the study unit. Nitrate concentrations were significantly greater in shallow wells than in springs (table 10A). Because values of aridity index and elevation were significantly higher for springs than for shallow wells (table 6A), the relation between nitrate concentration and site type may reflect location rather than an inherent difference in susceptibility to nitrate contamination between shallow wells and springs.

Nitrate concentrations were positively correlated with percentage of urban land use and negatively correlated with percentage of natural land use (table 10B). Nitrate concentrations also showed positive correlations with chloroform, total herbicide, and perchlorate concentrations (table 11). There were no significant relations between nitrate concentrations and groundwater age class, percentage of agricultural land use, density of septic tanks or LUTs, or depth to the top or bottom

of the screened or open interval in wells (tables 10A,B). The lack of correlation between nitrate concentrations and groundwater age class likely reflects the dominance of samples with modern groundwater.

Uranium and Radioactive Constituents

Most of the radioactivity in groundwater comes from decay of naturally occurring uranium and thorium in the rocks or sediments of the aquifers. Radioactive decay of uranium and thorium isotopes produces long series of radioactive daughter products, including isotopes of radium, uranium, and radon. These elements have different chemical properties, and their solubility in groundwater varies with geochemical conditions, water chemistry, and aquifer mineralogy (for example, Hem, 1992). This study included data for the individual radioactive constituents uranium, radium, and radon-222 and for gross alpha and 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. Uranium was compared to the MCL-CA of 20 picocuries per liter (pCi/L), rather than to the MCL-US of 30 µg/L, and gross alpha particle activities were not adjusted for uranium activity (see appendix D).

Radioactive constituents with health-based benchmarks were present at high RCs in 8.2 percent of the aggregated primary aquifer system and at moderate RCs in 20 percent (table 8A). Granitic and sedimentary primary aquifer systems had significantly greater proportions with high or moderate RCs of uranium and radioactive constituents than did metamorphic and volcanic primary aquifer systems (tables 8A, 9).

Uranium

Sources of uranium to groundwater include dissolution of uranium-bearing minerals, such as uraninite (UO₂), zircon, and titanite, and desorption of uranium from mineral surfaces in the presence of bicarbonate (Hem, 1992; Jurgens and others, 2010). Chronic exposure to uranium in drinking water at concentrations greater than the MCL-US or activities greater than the MCL-CA may result in toxic effects to the kidneys or increased cancer risks (U.S. Environmental Protection Agency, 2009).

Uranium was present at high RCs in 2.9 percent of the aggregated primary aquifer system and at moderate RCs in 7.7 percent (table 7B; fig. 11A). There were no significant differences in aquifer-scale proportions among the four lithologic primary aquifer systems (fig. 11A), largely because of the relatively small number of wells in volcanic and metamorphic aquifer lithologies that had data for uranium (tables 7A, 9).

The cells contributing most to the high-RC aquifer-scale proportions of uranium were not the same for the granitic and sedimentary primary aquifer systems. Cells 23, 24, and

14, located along the western side of the southern portion of the study unit, contributed the most to the high aquifer-scale proportion for uranium in granitic rocks (fig. 12E). This area is part of a band within the Sierra Nevada batholith that has previously been identified as having high RCs of uranium in groundwater (for example, California Department of Water Resources, 1990; Fram and Belitz, 2012). The only significant relations between uranium and potential explanatory factors in the SNR study unit dataset were the negative correlations of uranium concentrations with aridity index and latitude, which are consistent with location in this part of the study unit.

Cells 26 and 23 in the southern portion of the study unit and cell 18 around Lake Tahoe contributed the most to the high-RC aquifer-scale proportion for uranium in sedimentary deposits (fig. 12E).

Gross Alpha Particle Activity

Gross alpha particle activity was present at high RCs in 7.8 percent of the aggregated primary aquifer system and at moderate RCs in 14.5 percent (table 7B). The proportions of the granitic and sedimentary systems having high or moderate RCs of gross alpha particle activity were significantly greater than the proportions of the metamorphic systems having high or moderate RCs of uranium, and proportions in the granitic system were greater than the proportions in the volcanic system (tables 7A, 9). Of the 88 wells having high or moderate RCs of gross alpha particle activity and data for uranium, 55 (63 percent) also had high or moderate RCs of uranium. Adjusted gross alpha particle activity was present at high RCs in 0.9 percent of the aggregated primary aquifer system and at moderate RCs in 1.7 percent, indicating that most of the unadjusted gross alpha particle activity was due to uranium activity. Gross alpha particle activity and uranium were positively correlated (table 11). Radium may also contribute to gross alpha particle activity and was present at high RCs in 0.2 percent of the aggregated primary aquifer system and at moderate RCs in 2.2 percent (table 7B).

Radon-222

The source of radon-222 in groundwater is the decay of naturally occurring radium-226 (a member of the uranium-238 decay series) in aquifer materials. Radon-222 was present at high RCs in 14.1 percent of the aggregated primary aquifer system and at moderate RCs in 28.8 percent (table 7B). The proportion of the granitic primary aquifer system with high or moderate RCs of radon-222 was significantly greater than the proportions of the metamorphic, sedimentary, or volcanic systems with high or moderate RCs (table 9). Results for the proportion of the aggregated primary aquifer system as a whole with high or moderate RCs of radon-222 likely were biased towards greater values because of the unequal distribution of the data: 60 percent of the granitic sub-cells

had at least one well with radon-222 data, and 20 percent of the metamorphic, sedimentary, and volcanic sub-cells had at least one well with radon-222 data. Granitic sub-cells having radon-222 data composed 68 percent of the total area of sub-cells having radon-222 data, whereas granitic sub-cells constitute 51 percent of the total area of the study unit. Therefore, data from wells in granitic rocks—the lithology with the highest RCs of radon-222—were over-represented in the calculation of high-RC and moderate-RC aquifer-scale proportions in the study unit as a whole (eq. 4).

Radon-222 activity showed significant negative correlations with the depth to top of open or screened interval (table 10B). This relation likely reflects the occurrence of radon-222's parent isotope, radium-226, in aquifer materials, and the high degree of mobility of radon-222 in groundwater. In oxic, low salinity groundwater, radium is strongly sorbed to the surfaces of iron and manganese oxyhydroxides and to clays formed during weathering of feldspars (Krishnaswami and others, 1982; Szabo and Zapecza, 1991; Thomas and others, 1993). Of the 28 USGS-GAMA SNR study unit samples having radon-222 data, 25 are from fractured-rock aquifers (granitic, metamorphic, or volcanic aquifer lithologies). The amount of weathering of primary minerals in fractured rocks is likely to be greatest near the surface, decreasing with depth. Increased weathering results in the dissolution of more uranium-bearing minerals, the formation of more secondary iron and manganese oxyhydroxide coatings on mineral grains and fracture surfaces, and the alteration of more feldspar to clays. Thus, the greater amount of weathering that occurs at shallower depths in the aquifer system could result in the presence of greater amounts of radium-226 on aquifer fracture surfaces and grain boundaries and, therefore, greater amounts of radon-222 in the groundwater (Focazio and others, 2001).

Constituents with SMCL Benchmarks

The class of constituents with SMCL benchmarks includes salinity indicators and several trace metals 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. SMCL benchmarks are based on these aesthetic and technical concerns and are not health-based benchmarks. SMCL constituents that are salinity indicators include total dissolved solids (TDS), specific conductance, chloride, and sulfate. SMCL constituents that are trace metals include iron, manganese, and zinc. Constituents with SMCL benchmarks were present at high RCs in 18 percent of the aggregated primary aquifer system and at moderate RCs in 6.8 percent (table 8B).

Natural sources of salinity to groundwater include weathering and dissolution of minerals in soils, sediments, and rocks; mixing with saline or brackish waters from the ocean, estuaries,

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 salinity to groundwater include recharge of water used for irrigation, wastewater discharge, and increased evaporation caused by changes in land use (Hem, 1985). All samples with high RCs of chloride or sulfate also had high RCs of TDS, and all samples with moderate RCs of chloride or sulfate also had moderate RCs of TDS; thus, the aquifer-scale proportions for salinity indicators as a group are the same as those for TDS. Salinity indicators were present at high RCs in 1.3 percent of the aggregated primary aquifer system and at moderate RCs in 2.8 percent (table 8B; fig. 11B). No significant differences were observed in aquifer-scale proportions among the four aquifer lithologies (table 9; fig. 11B).

Trace metals with SMCL benchmarks were present at high RCs in 18 percent of the aggregated primary aquifer system and at moderate RCs in 5.5 percent (table 8B). The proportion of the metamorphic primary aquifer system with trace metals with SMCL benchmarks present at high or moderate RCs was significantly greater than the proportions of the granitic, sedimentary, and volcanic systems with high or moderate RCs of trace metals with SMCL benchmarks (tables 8B, 9). Manganese and iron were the trace metals with SMCL benchmarks most commonly present at high and moderate RCs (table 7B). Zinc was present at high or moderate RCs in less than 1 percent of the primary aquifer system.

Manganese and Iron

Manganese and iron were present at high RCs in 15.1 percent and 15.8 percent, respectively, of the aggregated primary aquifer system, and at moderate RCs in 3.3 percent and 4.4 percent, respectively (table 7B; fig. 11B). The proportions of the metamorphic primary aquifer system with high RCs of manganese and iron were significantly greater than the proportions of the granitic, sedimentary, and volcanic systems with high RCs of manganese and iron (tables 7A, 9; fig. 11B). Groundwater with high or moderate RCs of manganese was found in most parts of the SNR study unit (fig. 12F).

Natural sources of manganese and iron to groundwater include weathering and dissolution of minerals in soils, sediments, and rocks. Iron-bearing silicate, sulfide, and (or) oxide minerals occur in most rocks and sediments, and manganese commonly substitutes for iron in silicate minerals. Iron and manganese oxyhydroxide minerals commonly occur as coatings on mineral and sediment grains. The solubilities of manganese and iron are strongly dependent on oxidation-reduction conditions; the more reduced species are much more soluble. As expected, the concentrations of manganese and iron both showed significant, negative correlations with DO, and manganese and iron concentrations were strongly correlated with each other (tables 10B, 11).

Organic and Special-Interest Constituents

The organic constituents include two constituent classes: volatile organic compounds (VOCs) and pesticides. VOCs are characterized by their tendency to evaporate and are present in paints, solvents, fuels, fuel additives, refrigerants, fumigants, and disinfected water. VOCs typically 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. The special-interest group includes two chemically unrelated constituents, perchlorate and *N*-nitrosodimethylamine (NDMA) that are of interest in California because they recently have been detected in groundwater at concentrations that may affect human health.

The GAMA Priority Basin Project included analysis of a large number of organic constituents, many of which are not currently (as of 2013) subject to regulation in California drinking water. USGS-GAMA analytical methods for organic constituents had lower reporting levels than those required for sampling for compliance with CDPH regulations. In the SNR study unit, the majority of organic constituents detected were ones that are already subject to regulation in California drinking water. Of the 85 VOCs analyzed, 12 were detected at least once, and of these, 11 have MCL-US or MCL-CA benchmarks (tables 4A,B). Of the 63 pesticides and pesticide degradates analyzed, 8 were detected at least once, and of these, 2 were parent compounds with MCL-US or MCL-CA benchmarks. In all, of the 70 organic constituents analyzed that had no health-based benchmarks, 5 were detected in groundwater (table 4B; Shelton and others, 2010).

Figure 13 summarizes the maximum RCs of all organic and special-interest constituents detected in USGS-GAMA SNR study unit samples and the area-weighted detection frequencies for these constituents in the study unit as a whole (eq. 5). Figure 14 shows RCs for detections and area-weighted detection frequencies in the four aquifer lithologies for the six organic and special-interest constituents either detected at moderate RCs in the USGS-GAMA SNR study unit wells (tetrachloroethene [PCE], 1,2-dichloroethane [1,2-DCA], and perchlorate) or having an area-weighted detection frequency greater than 10 percent in at least one of the four aquifer lithologies (methyl *tert*-butyl ether [MTBE], chloroform, and simazine). The CDPH database reported detections of high RCs of PCE, 1,2-DCA, and perchlorate in samples collected between May 1, 2006, and October 31, 2008, and benzene and carbon tetrachloride were detected at moderate RCs in USGS-GAMA Tahoe-Martis, Central Sierra, or Southern Sierra study units (Fram and Belitz, 2012).

Aquifer-scale proportions for the eight individual constituents either detected at moderate or high RCs or with area-weighted detection frequencies greater than 10 percent are listed in table 12, and by constituent classes in table 13. Organic constituents with health-based benchmarks were present at high RCs in <1 percent of the aggregated primary aquifer system, at moderate RCs in 3.0 percent, at low RCs in

about 25 percent, and were not detected in about 72 percent of the aggregated primary aquifer system (table 13; fig. 11B).

Relations between water quality and potential explanatory factors were investigated for chloroform, MTBE, maximum RC for solvents, maximum RC for herbicides, maximum RC for any VOC, maximum RC for any organic constituent, and perchlorate (tables 10A,B). The proportions of the sedimentary and metamorphic primary aquifer systems having detections of organic constituents at any concentration were significantly greater than the proportion of the volcanic system having detection of organic constituents at any concentration (tables 13, 14; fig. 11B).

Herbicides

All of the pesticides detected in the SNR study unit that had health-based benchmarks were herbicides (Shelton and others, 2010). Herbicides were not detected at high or moderate RCs in the SNR study unit (table 13). No detections of any of the herbicides analyzed by USGS-GAMA were reported in the CDPH database. The absence of detections in the CDPH database was expected because the maximum RC of an herbicide detected by USGS-GAMA in the SNR study unit was 0.015 (atrazine; Shelton and others, 2010), and the reporting levels for all of the herbicides in the CDPH database had values with RCs greater than or equal to 0.25 (tables 4A,B). The only herbicide with a detection frequency greater than or equal to 10 percent in a primary aquifer system was simazine (table 12; fig. 14). The USGS NAWQA Program found simazine to be one of the most frequently detected pesticide compounds in groundwater across the United States (Gilliom and others, 2006). In California, simazine is most commonly used on orchards and vineyards and on rights-of-way for weed control (Kegley and others, 2010).

The area-weighted detection frequencies of herbicides did not differ significantly among the four primary aquifer system lithologies (table 14). The detection frequencies were calculated using all herbicides with health-based benchmarks that were detected in the SNR study unit: simazine, atrazine, and hexazinone (Shelton and others, 2010). Most detections of herbicides occurred in the southern two-thirds of the western side of the SNR study unit (fig. 15A).

Most of the correlations between herbicide concentrations and potential explanatory factors reflected the importance of location. Herbicide concentrations showed significant negative correlations with aridity index, elevation, and percentage of natural land (table 10B), which is consistent with the observation that most of the herbicide detections occurred in the southern two-thirds of the western side of the SNR study unit (fig. 15A). Herbicide concentrations were not significantly correlated with agricultural land use (table 10B); however, the detection frequency of herbicides in samples from wells with greater than 5 percent agricultural land use in the 500-m buffer around the well (30 percent) was significantly greater than the detection frequency in samples from wells with less than 5 percent agricultural land use (5.5 percent) (contingency table test, $p = 0.009$). Herbicide concentrations were positively correlated

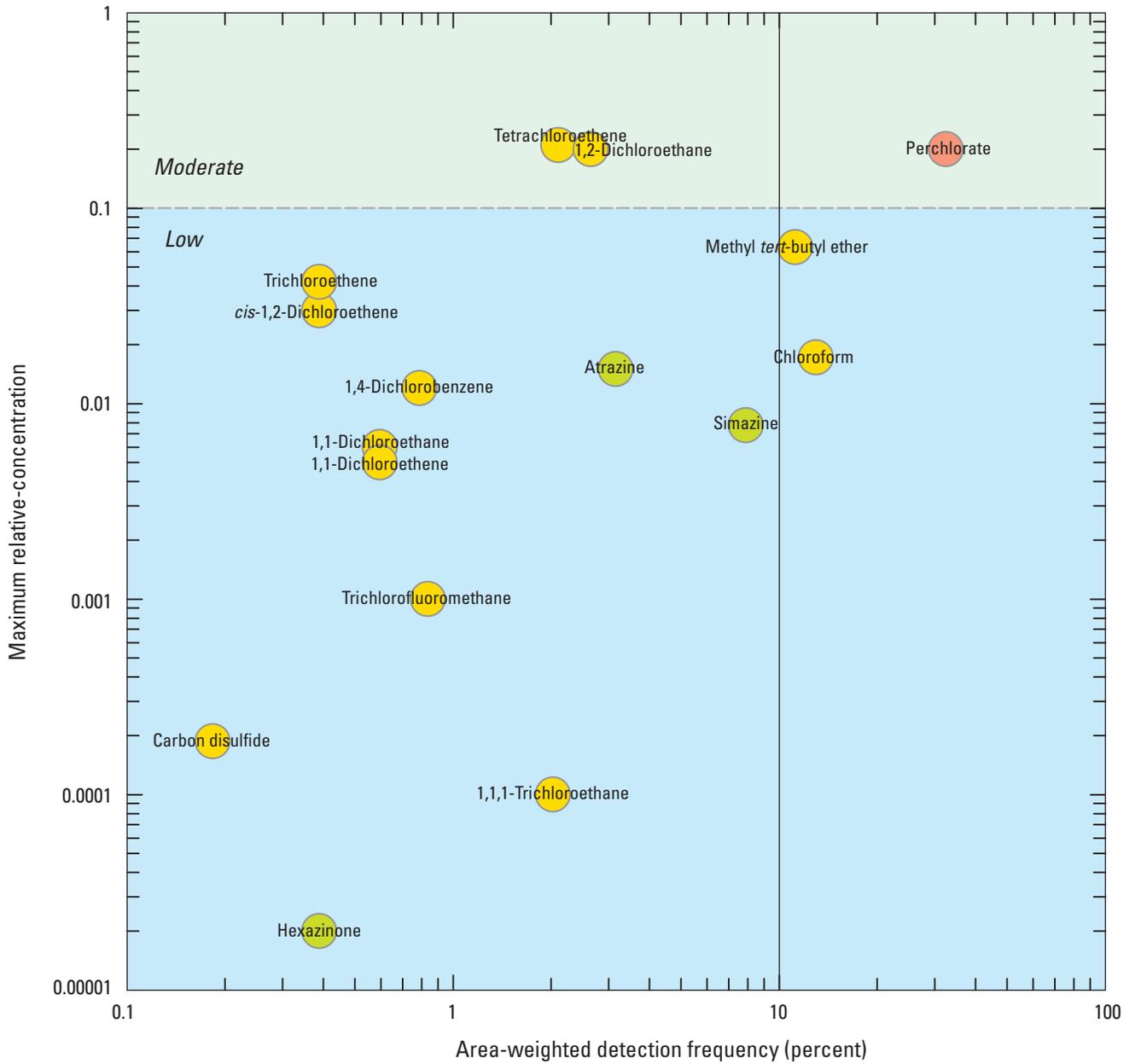


Figure 13. Area-weighted detection frequency and maximum relative-concentration of organic and special-interest constituents detected by the U.S. Geological Survey in samples collected for the Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

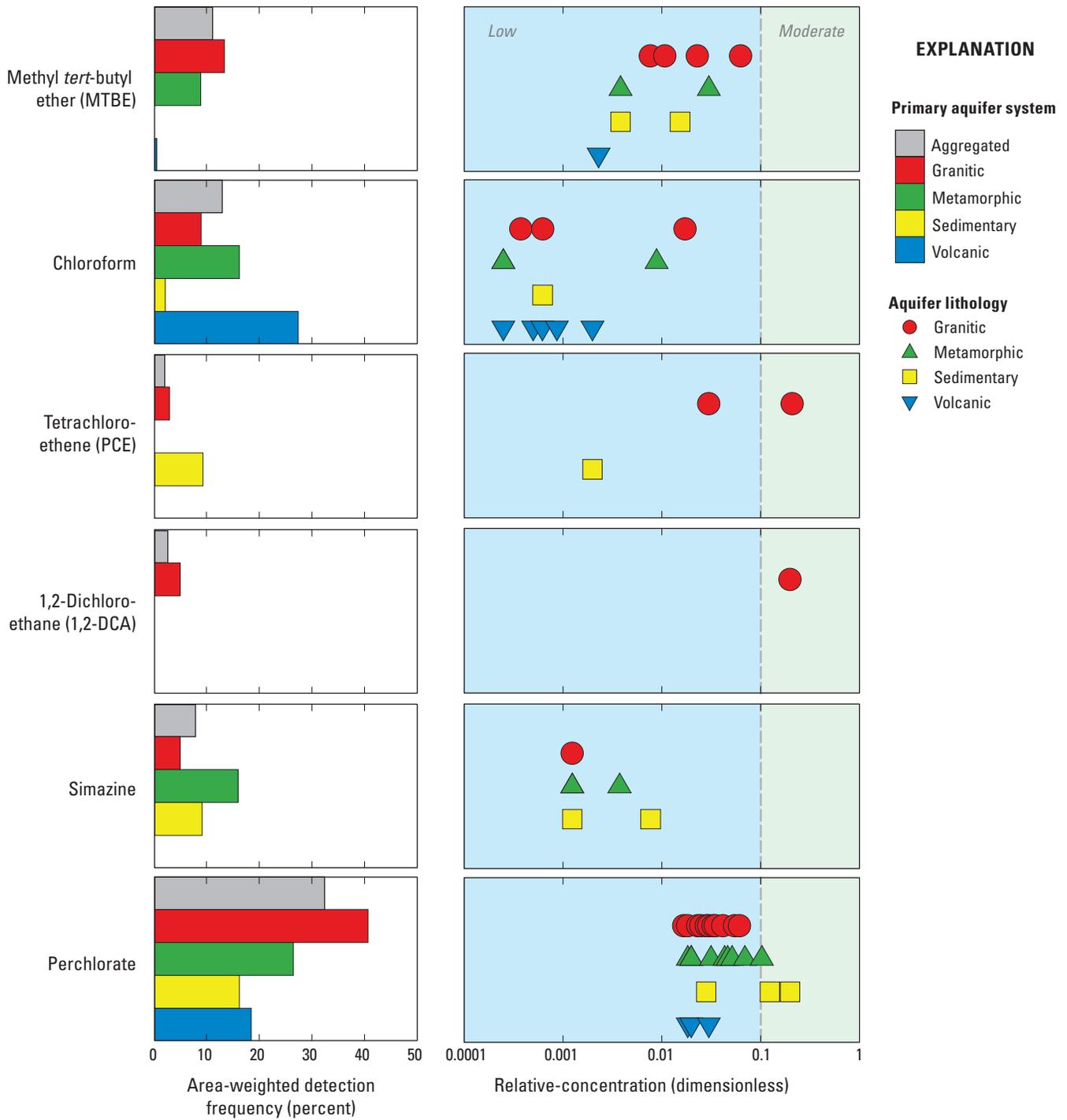


Figure 14. Area-weighted detection frequencies and relative-concentrations of selected organic and special-interest constituents, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

Table 12. Aquifer-scale proportions of organic and special-interest constituents for the granitic, metamorphic, sedimentary, volcanic, and aggregated primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[**Relative-concentration (RC) categories:** high, $RC > 1.0$; moderate, $RC > 0.1$ and $RC \leq 1.0$; low, $RC \leq 0.1$. RC defined as measured value divided by benchmark value. Organic and special-interest 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](#)]

Constituent and primary aquifer system	Grid-based				Spatially weighted		
	Proportion not detected (in percent)	Proportion detected (in percent)			Number of wells	Proportion detected (in percent)	
		Low RC	Moderate RC	High RC		Moderate RC	High RC
Granitic primary aquifer system							
Simazine	95.0	5.0	0	0	111	0	0
Tetrachloroethene (PCE)	97.0	2.2	0.7	0	145	0.3	0
Carbon tetrachloride	100	0	0	0	145	0	0
1,2-Dichloroethane	95.0	0	5.0	0	145	0.8	0
Methyl <i>tert</i> -butyl ether (MTBE)	86.6	13.4	0	0	145	0.1	0
Benzene	100	0	0	0	145	0	0
Chloroform	90.5	9.5	0	0	145	0.2	0
Perchlorate	59.4	40.6	0	0	349	0.7	0
Metamorphic primary aquifer system							
Simazine	84.0	16.0	0	0	39	0	0
Tetrachloroethene (PCE)	100	0	0	0	46	0	0
Carbon tetrachloride	100	0	0	0	46	0	0
1,2-Dichloroethane	100	0	0	0	46	0	0
Methyl <i>tert</i> -butyl ether (MTBE)	91.1	8.9	0	0	46	0	0
Benzene	100	0	0	0	46	0.6	0
Chloroform	83.2	16.8	0	0	46	0	0
Perchlorate	73.5	24.7	1.8	0	154	1.8	0
Sedimentary primary aquifer system							
Simazine	90.9	9.1	0	0	61	0	0
Tetrachloroethene (PCE)	90.7	9.3	0	0	82	0.8	0.6
Carbon tetrachloride	100	0	0	0	82	0.9	0
1,2-Dichloroethane	100	0	0	0	82	0	0.6
Methyl <i>tert</i> -butyl ether (MTBE)	74.6	25.4	0	0	82	0	0
Benzene	100	0	0	0	82	0	0
Chloroform	97.4	2.6	0	0	82	0	0
Perchlorate	83.8	7.1	9.1	0	185	1.6	0.1
Volcanic primary aquifer system							
Simazine	100	0	0	0	37	0	0
Tetrachloroethene (PCE)	100	0	0	0	38	0	0
Carbon tetrachloride	100	0	0	0	38	0	0
1,2-Dichloroethane	100	0	0	0	38	0	0
Methyl <i>tert</i> -butyl ether (MTBE)	99.4	0.6	0	0	38	0	0
Benzene	100	0	0	0	38	0	0
Chloroform	85.7	14.3	0	0	38	0	0
Perchlorate	81.5	18.5	0	0	69	0	0

Table 12. Aquifer-scale proportions of organic and special-interest constituents for the granitic, metamorphic, sedimentary, volcanic, and aggregated primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Relative-concentration (RC) categories: high, $RC > 1.0$; moderate, $RC > 0.1$ and $RC \leq 1.0$; low, $RC \leq 0.1$. RC defined as measured value divided by benchmark value. Organic and special-interest 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](#)]

Constituent and primary aquifer system	Proportion not detected (in percent)	Grid-based			Number of wells	Spatially weighted	
		Proportion detected (in percent)				Proportion detected (in percent)	
		Low RC	Moderate RC	High RC		Moderate RC	High RC
Aggregated lithologic primary aquifer system							
Simazine	92.1	7.9	0	0	248	0	0
Tetrachloroethene (PCE)	97.9	1.7	0.4	0	311	0.2	0.03
Carbon tetrachloride	100	0	0	0	311	0.05	0
1,2-Dichloroethane	97.4	0	2.6	0	311	0.4	0.03
Methyl <i>tert</i> -butyl ether (MTBE)	88.8	11.2	0	0	311	0.1	0
Benzene	100	0	0	0	311	0.2	0
Chloroform	88.1	11.9	0	0	311	0.1	0
Perchlorate	67.6	31.4	1.0	0	757	1.0	0.01

with percentage of urban land use; however, the detection frequencies in samples from wells with greater than 10 percent urban land use (21 percent) and in samples from wells with less than 10 percent urban land use (6.0 percent) were not significantly different (contingency table test, $p = 0.061$). The thresholds of 5 percent agricultural land use and 10 percent urban land use were selected because they were empirically found to have explanatory power by Fram and Belitz (2012).

Solvents

Solvents were detected at high RCs in 0.1 percent of the aggregated primary aquifer system and at moderate RCs in 3.0 percent ([table 13](#)). PCE and 1,2-DCA each were detected at high RCs in 0.03 percent of the aggregated primary aquifer system ([table 12](#)). PCE, 1,2-DCA, and carbon tetrachloride were the solvents detected at moderate RCs. The detection frequencies of solvents as a class were significantly greater in granitic and sedimentary primary aquifer systems than in metamorphic and volcanic systems ([tables 13, 14](#)). No individual solvents had detection frequencies greater than 10 percent ([figs. 13, 14](#)). Solvent concentrations were significantly positively correlated with percentage of urban land use and negatively correlated with percentage of natural land use; there were no significant relations with any other potential explanatory factors ([tables 10A,B](#); [fig. 15B](#)).

Gasoline Oxygenates

Gasoline oxygenates are added to gasoline to increase the efficiency of combustion, thereby enhancing the octane rating of gasoline and reducing pollutant emissions. In 1990, the Clean

Air Act mandated the use of oxygenated gasoline in areas out of compliance with air-quality standards for carbon monoxide or ozone (Clean Air Act Amendments of 1990, 1990). Oxygenated gasoline is used throughout California, and until 2004, the most commonly used oxygenate was MTBE. Use of MTBE was phased out starting December 31, 2003, because of concerns over the degradation of groundwater quality caused by the leakage of MTBE from LUFTs and other point sources (California Air Resources Board, 2003). The only gasoline oxygenate detected in the SNR study unit was MTBE ([tables 4A,B](#)); three other gasoline oxygenates without benchmarks were analyzed, but not detected (Shelton and others, 2010).

MTBE was not detected at high RCs in the SNR study unit, but was detected at moderate RCs in 0.1 percent of the aggregated primary aquifer system ([table 12](#)). The area-weighted detection frequency of MTBE was 11 percent for the study unit as a whole ([table 13](#); [figs. 13, 14](#)), and the area-weighted detection frequencies of MTBE in the sedimentary and granitic primary aquifer systems were significantly greater than the frequency in the volcanic system ([table 14](#); [fig. 14](#)). Detections of MTBE occurred in all geographic areas of the SNR study unit ([fig. 15C](#)). Concentrations of MTBE showed significant positive correlation with percentage of urban land and negative correlation with percentage of natural land. No significant relations were observed with any other potential explanatory factors ([tables 10A,B](#)).

The data suggest that the MTBE detected in the groundwater sampled for this study could have been derived from the atmosphere, although contributions from LUFTs or other point sources cannot be ruled out. Compared to most other VOCs that are commonly detected in groundwater, MTBE has a relatively low Henry's Law constant (Baehr

Table 13. Summary of aquifer-scale proportions for organic constituent classes for the granitic, metamorphic, sedimentary, volcanic, and aggregated primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Relative-concentration (RC) categories for organic constituents: high, $RC > 1.0$; moderate, $RC > 0.1$ and $RC \leq 1.0$; low, $RC \leq 0.5$. RC defined as measured value divided by benchmark value]

Constituent class and primary aquifer system	Proportion not detected (in percent)	Proportion detected (in percent)		
		Low RC	Moderate RC	High RC
Pesticides				
Granitic	92.8	7.2	0	0
Metamorphic	84.0	16.0	0	0
Sedimentary	90.9	9.1	0	0
Volcanic	100	0	0	0
Aggregated	90.9	9.1	0	0
Solvents				
Granitic	89.3	5.0	5.7	0
Metamorphic	100	0	0	0
Sedimentary	90.7	6.5	¹ 1.7	¹ 1.1
Volcanic	100	0	0	0
Aggregated	93.8	3.1	3.0	¹ 0.1
Gas oxygenates				
Granitic	86.6	13.3	¹ 0.1	0
Metamorphic	91.1	8.9	0	0
Sedimentary	74.6	25.4	0	0
Volcanic	99.4	0.6	0	0
Aggregated	88.8	11.1	¹ 0.1	0
Trihalomethanes				
Granitic	91.0	8.8	¹ 0.2	0
Metamorphic	83.8	16.2	0	0
Sedimentary	97.8	2.2	0	0
Volcanic	72.6	27.4	0	0
Aggregated	87.0	12.9	¹ 0.1	0
Volatile organic compounds				
Granitic	77.9	16.3	5.7	0
Metamorphic	82.0	17.4	^{1,2} 0.6	0
Sedimentary	72.5	24.7	¹ 1.7	¹ 1.1
Volcanic	72.6	27.4	0	0
Aggregated	78.2	18.7	3.0	¹ 0.1
Organic constituents				
Granitic	76.4	17.8	5.7	0
Metamorphic	66.0	33.4	^{1,2} 0.6	0
Sedimentary	65.5	31.7	¹ 1.7	¹ 1.1
Volcanic	72.6	27.4	0	0
Aggregated	72.3	24.7	3.0	¹ 0.1

¹A spatially weighted value of aquifer-scale proportion was used because the grid-based value was zero and the spatially weighted value was non-zero.

²Includes one detection of benzene at moderate RC.

Table 14. Results of contingency table tests for differences in aquifer-scale proportions of selected organic constituents and constituent classes between granitic, metamorphic, sedimentary, and volcanic primary aquifer systems, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Significance defined as p-value less than threshold value (α) of 0.05. **Aquifer lithology class:** G, granitic; M, metamorphic; S, sedimentary; V, volcanic. **Abbreviations:** ns, no significant differences; >, greater than]

Constituent class or individual constituent	Proportion detected compared to proportion not detected	
	p-value	Significant differences
Chloroform	0.092	ns
Methyl <i>tert</i> -butyl ether	0.007	G > V, S > V
Solvents	0.034	G > M, G > V S > M, S > V
Any volatile organic compound	0.129	ns
Herbicides	0.073	ns
Any organic constituent	0.020	M > V, S > V
Perchlorate	0.260	ns

and others, 1999). The Henry's Law constant quantifies the partitioning of a compound between air and water; the lower its value, the more the compound is partitioned into water. Studies of shallow groundwater during the 1990s concluded that the concentrations of MTBE measured in groundwater were similar to the concentrations that were expected to have resulted from Henry's Law partitioning of MTBE between urban air and falling precipitation (Squillace and others, 1996, 1997; Baehr and others, 1999; Belitz and others, 2004).

During the period that MTBE was used as a gasoline oxygenate (1992–2003), maximum annual average MTBE concentrations in the air of Central Valley cities monitored by the California Air Resources Board ranged from 2.8 to 5.2 parts per billion by volume (ppbv) (California Air Resources Board, 2004). Prevailing weather patterns move air from the Central Valley to the Sierra Nevada, and local use of oxygenated gasoline in the Sierra Nevada would also have contributed MTBE to the atmosphere. The Henry's Law constant for MTBE is temperature dependent, increasing from about 0.062 atmosphere-liters per mol (atm-L/mol) at 0 degrees Celsius (°C) to about 0.425 (atm-L/mol) at 20 °C (Robbins and others, 1993; Squillace and others, 1996). This range of Henry's Law constant predicts that air containing 2.8 to 5.2 ppbv of MTBE would be in equilibrium with raindrops containing approximately 0.6 to 7 µg/L of MTBE. The maximum concentration of MTBE measured in USGS-GAMA samples from the SNR study unit was 0.8 µg/L (Shelton and others, 2010). If the samples having MTBE detections contained a large proportion of groundwater

recharged during the period when MTBE was added to California gasoline, then the source of the MTBE could have been atmospheric deposition, rather than LUFTs or other point sources.

The lack of statistically significant correlation between MTBE concentration and groundwater age (table 10A) likely reflects the predominance of modern groundwater in the SNR study unit. Of the 42 USGS-GAMA SNR study unit samples classified as modern groundwater, 7 had detections of MTBE. Two of the 31 mixed-age groundwater samples had detections of MTBE, and none of the 7 pre-modern groundwater samples had detections of MTBE. Samples classified as modern and as mixed both contain modern groundwater and therefore could have been exposed to sources of MTBE. However, the detection frequencies of MTBE in groundwater classified as pre-modern (0 percent) and groundwater classified as modern or mixed (13 percent) were not significantly different (contingency table test, $p = 0.33$) perhaps because of the small number of samples classified as pre-modern groundwater.

Trihalomethanes

Water used for drinking water and other household uses in domestic and public (municipal and community) systems may be disinfected by using chlorine in a variety of chemical forms (such as sodium hypochlorite [bleach], hypochlorous acid, chlorine gas, chloramines, or chlorine dioxide). In addition to disinfecting the water, the chlorine compounds react with organic matter to produce trihalomethanes and other chlorinated and (or) brominated disinfection byproducts (for example, Ivahnenko and Barbash, 2004). Chloroform was the only trihalomethane detected in the SNR study unit (Shelton and others, 2010). The area-weighted detection frequency of chloroform in the aggregated primary aquifer system was 12 percent, and chloroform was detected at moderate RCs in 0.1 percent of the system (tables 12, 13). Chloroform was the most frequently detected VOC in groundwater across the United States (Zogorski and others, 2006).

The detection frequencies for chloroform were calculated by using 73 of the lithologic-grid wells because chloroform detections in the other 9 wells may have been the result of contamination from well-head chlorination systems. Of the 16 sites with well-head chlorination systems, 9 had chloroform detections even though chlorinated water was not used for irrigation near any of the sites. For six of the nine sites, chloroform was the only organic constituent detected, and for two sites, chloroform and MTBE were the only organic constituents detected. The well-head chlorination systems generally were located within a few feet of the well head, and in most cases, were downstream of the point where the samples were collected. Some backflow of chlorinated water was possible. The presence of chloroform in wells sampled for this study could also have been a consequence of intentional introduction of chlorine solutions into wells. Shock chlorination (often carried out by pouring bleach down a well) is a recommended procedure for treating

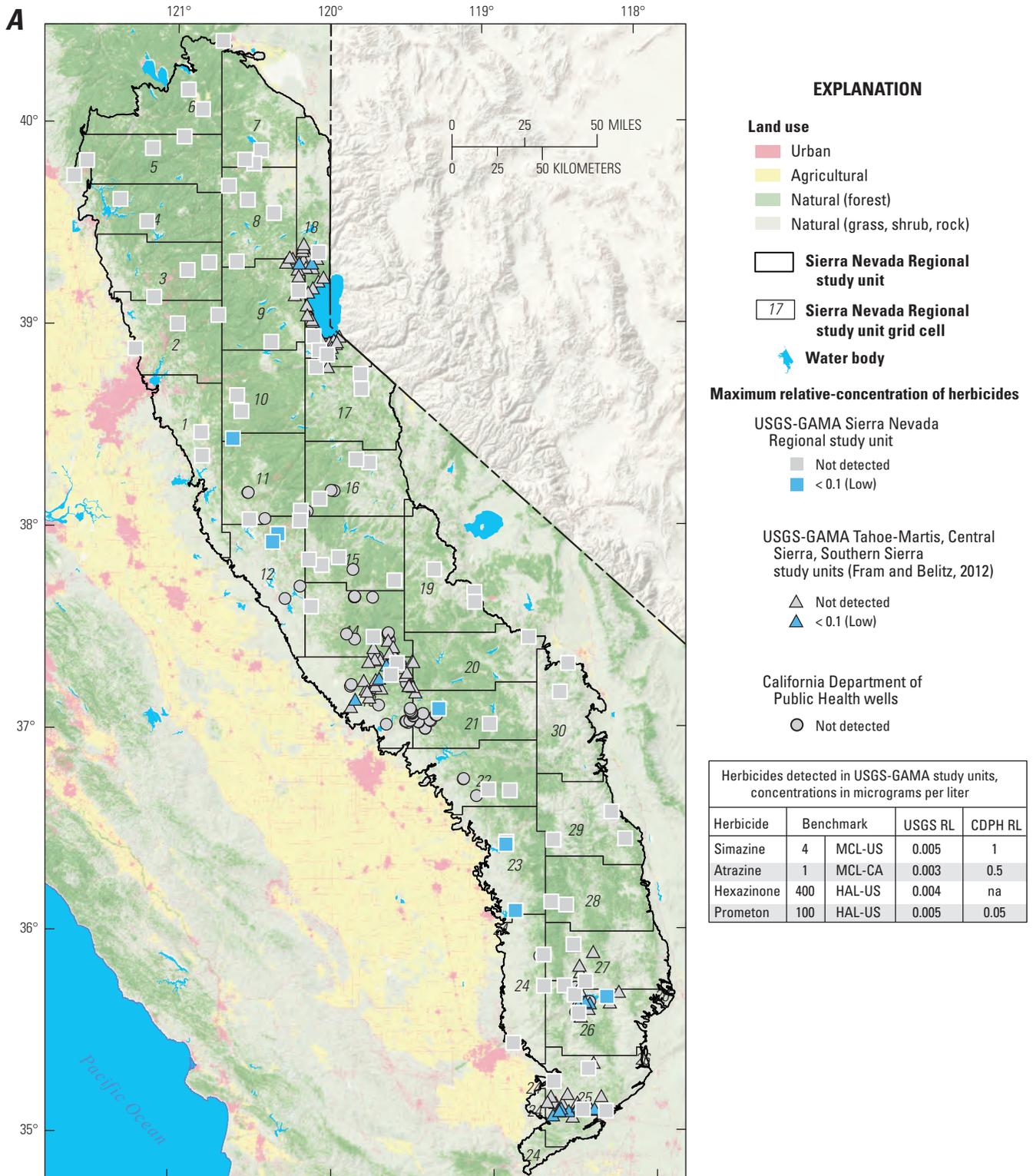


Figure 15. Maximum relative-concentrations of (A) herbicides, (B) solvents, (C) the gasoline oxygenate methyl *tert*-butyl ether (MTBE), (D) the trihalomethane chloroform, and (E) perchlorate for USGS-GAMA wells, and all wells in the California Department of Public Health (CDPH) database with data during the period May 2006 through October 2008, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project. [Abbreviations: HAL-US, U.S. Environmental Protection Agency (USEPA) lifetime health advisory level; MCL-CA, CDPH maximum contaminant level; MCL-US, USEPA maximum contaminant level; na, not available; RL, reporting level; µg/L, micrograms per liter]

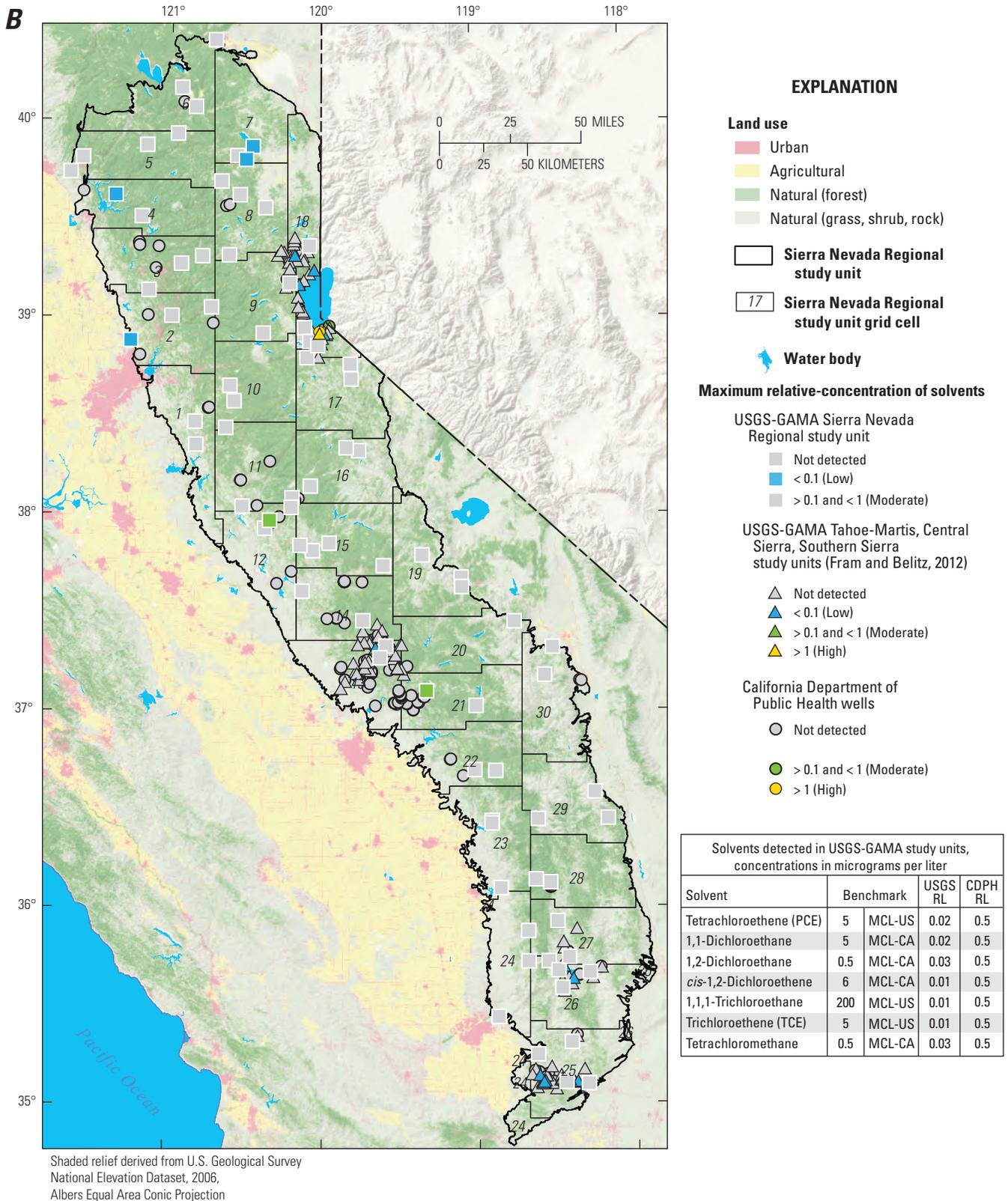


Figure 15. —Continued

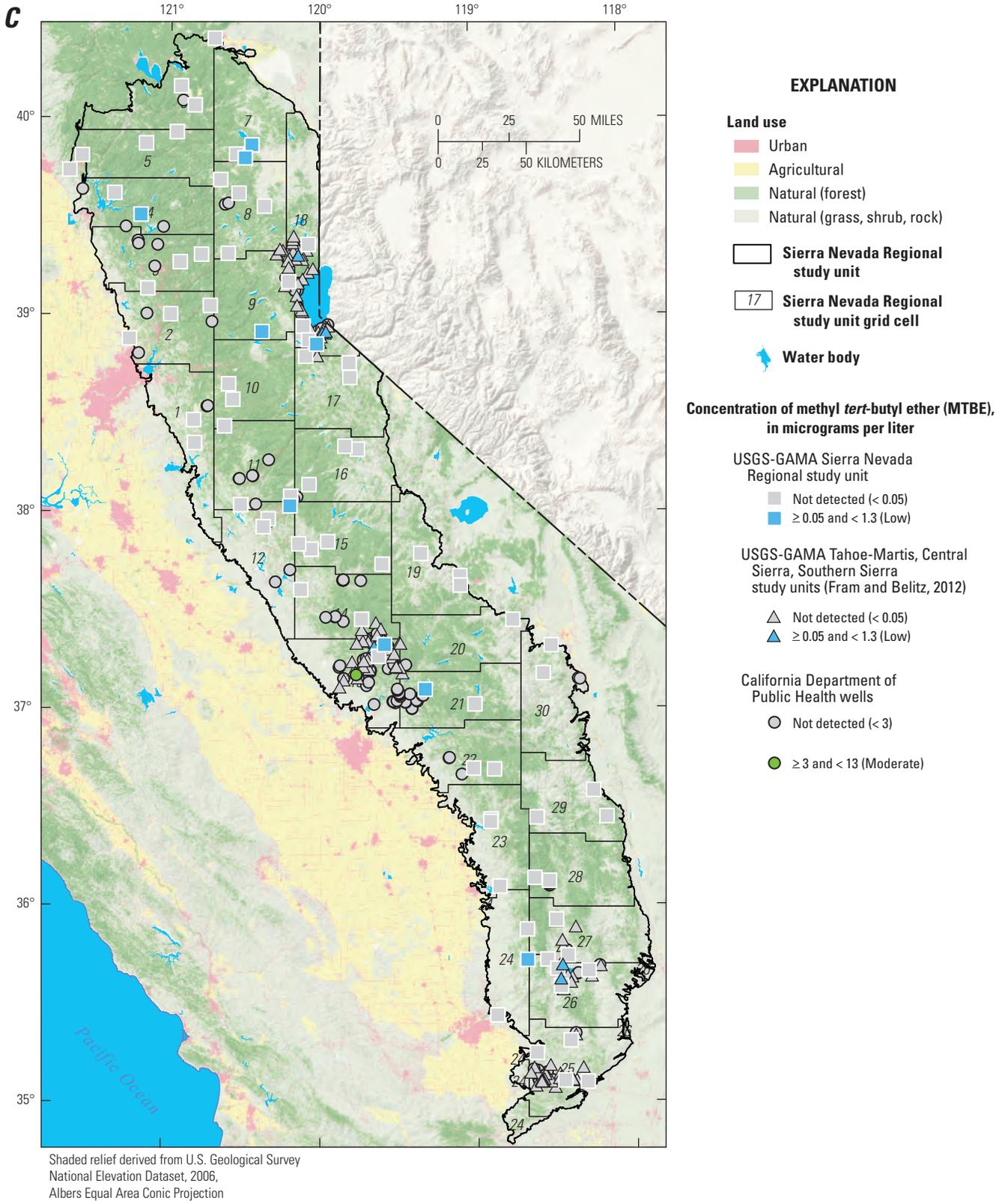


Figure 15. —Continued

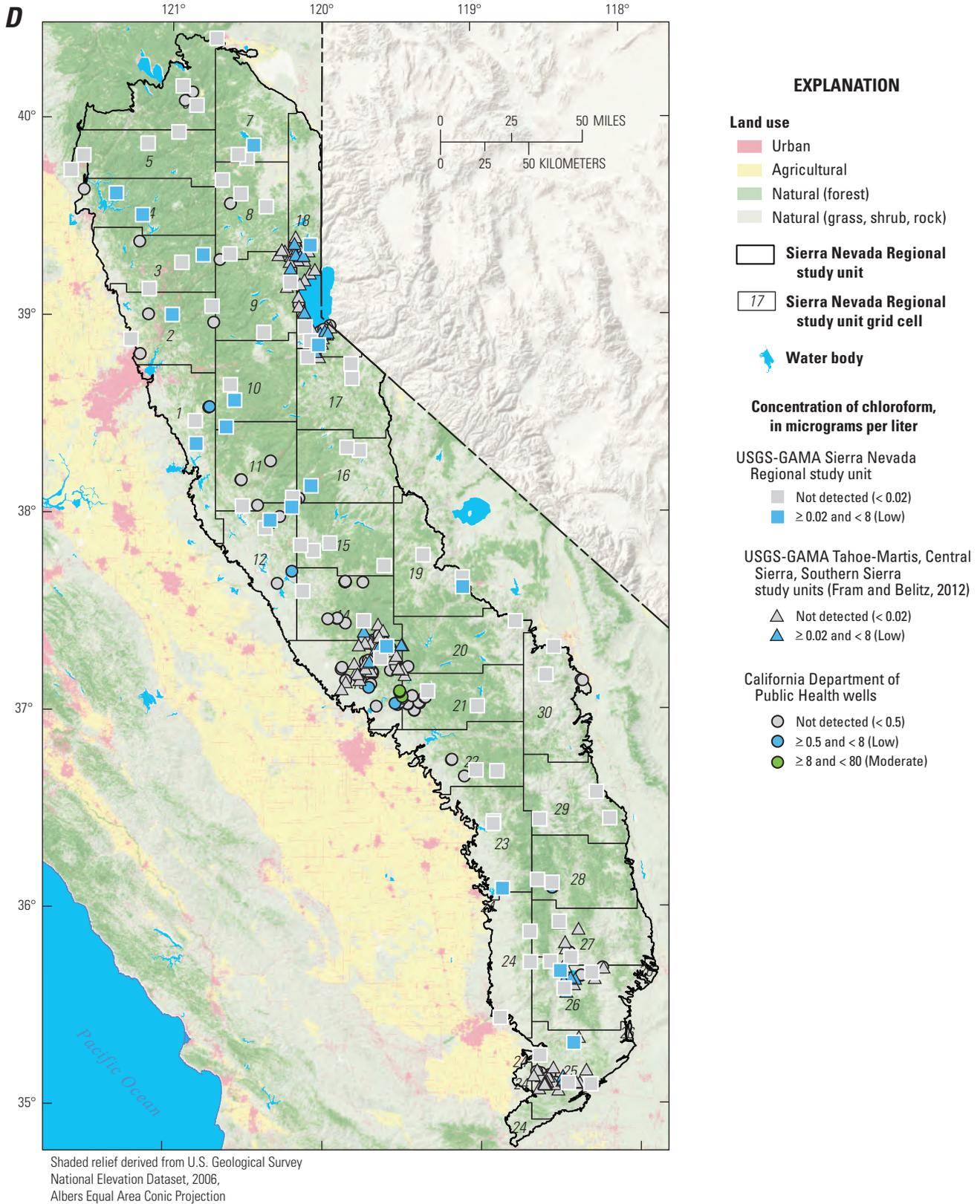


Figure 15. —Continued

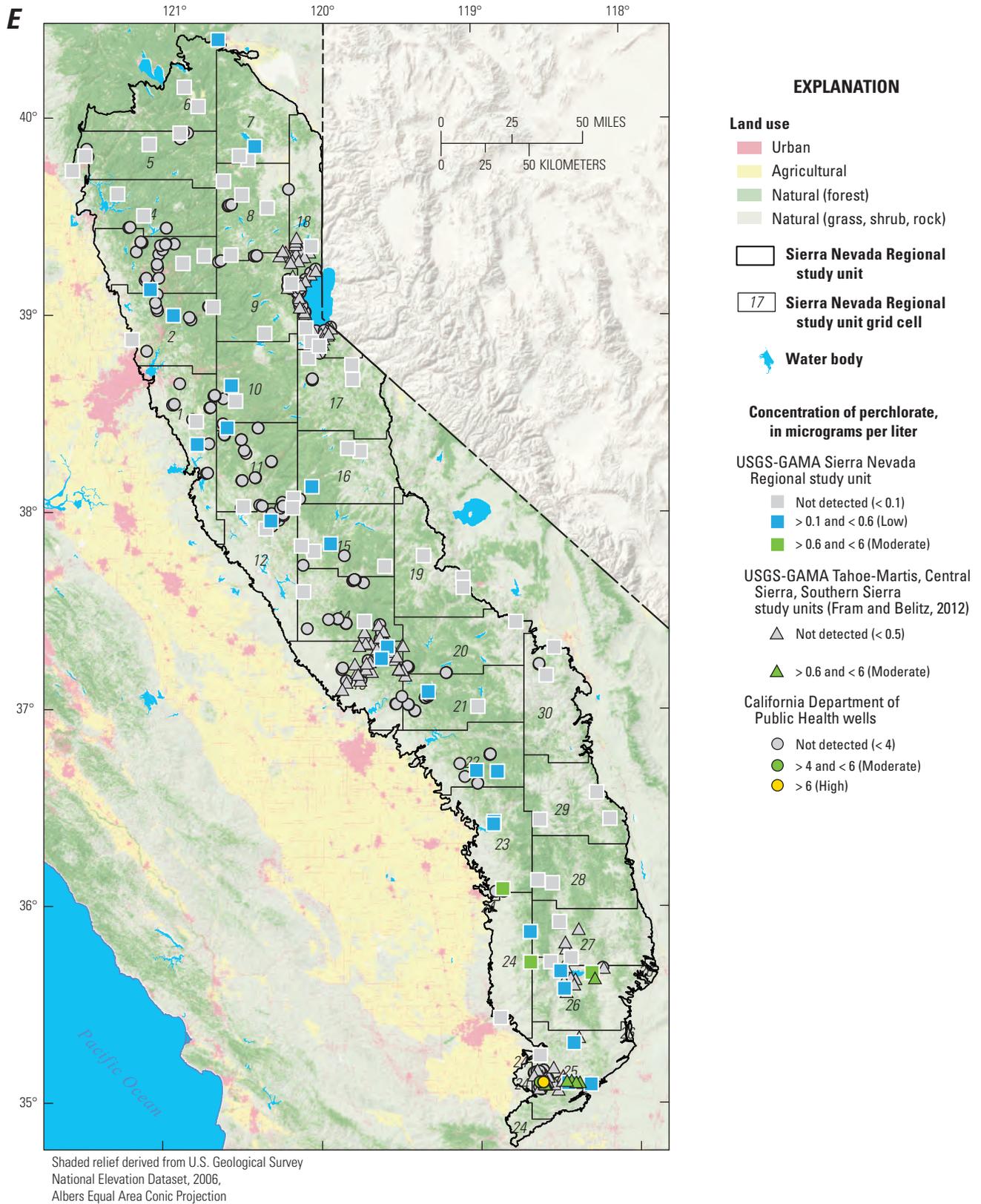


Figure 15. —Continued

bacterial contamination and odor problems in domestic drinking-water supply wells (Centers for Disease Control and Prevention, 2006) and could result in formation of a reservoir of chlorinated water in the well bore and surrounding aquifer material. Small public systems, such as those for schools, campgrounds, restaurants, and community associations, could be more likely to maintain their wells following guidelines for domestic wells than guidelines for larger systems, such as those for municipalities. Of the 18 samples with detections of chloroform, 12 were from wells in schools, camps, meeting halls, and other types of systems serving between 30 and 220 people.

The area-weighted frequencies of chloroform detection did not differ significantly among the four aquifer lithologies (table 14; fig. 14). Detections of chloroform were distributed across the SNR study unit (fig. 15D). Chloroform concentrations showed significant positive correlations with the percentage of urban land use and the density of septic tanks, and there were no significant relations with any other potential explanatory factors (tables 10A,B). The correlations with the percentage of urban land and the density of septic tanks are likely to be consequences of the use of chlorination to disinfect water, as well as the widespread use of bleach for domestic purposes (such as laundry and cleaning).

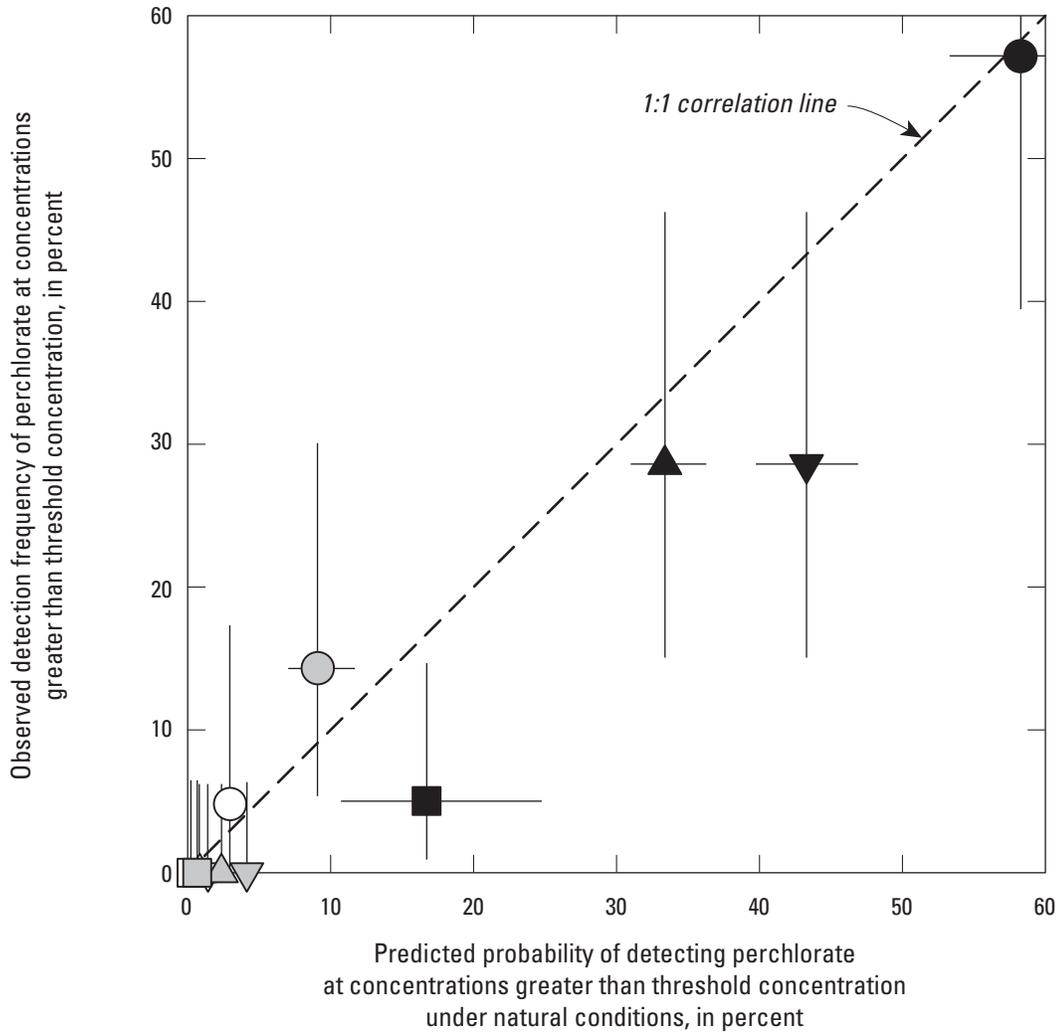
Perchlorate

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 established in 2007. Perchlorate has natural and anthropogenic sources to groundwater. It forms naturally in the atmosphere and is present at very low concentrations in precipitation (Dasgupta and others, 2005; Parker and others, 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, 2011a). Perchlorate is a component of solid rocket fuel and is used in explosives, fireworks, safety flares, and other products

(U.S. Environmental Protection Agency, 2005; 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).

Less than 0.1 percent of the aggregated primary aquifer system had high RCs of perchlorate, and about 1.0 percent had moderate RCs (table 11). The area-weighted detection frequency for perchlorate in the primary aquifer system was 32 percent, and there were no significant differences in detection frequencies among the four aquifer lithologies (table 14; fig. 14). Nearly all detections of perchlorate occurred along the western margin of the study unit, and most were in the southern two-thirds of the study unit (fig. 15E). As expected from this spatial pattern of detections, concentrations of perchlorate showed significant negative correlations with aridity index, elevation, latitude, and percentage of natural land and positive correlation with septic tank density (table 10B).

Perchlorate occurrence frequencies were consistent with those expected from the distribution of perchlorate in groundwater under natural conditions (Fram and Belitz, 2011a). The occurrence frequencies of perchlorate at concentrations greater than threshold concentrations of 0.1, 0.5, and 1.0 µg/L were compared to the predicted probability of perchlorate occurring under natural conditions as a function of aridity index (Fram and Belitz, 2011a). The 83 USGS-GAMA wells were divided into 4 groups of 20 or 21 samples by aridity index. The average aridity index and the observed occurrence frequencies of perchlorate at concentrations greater than 0.1, 0.5, and 1.0 µg/L were calculated for each group. The average aridity indices corresponded to climates ranging from semi-arid (0.32) to wet (1.38). The observed detection frequencies were compared to the predicted probabilities of perchlorate occurring under natural conditions at those aridity indices (Fram and Belitz, 2011a). The observed occurrence frequencies were close to the predicted probabilities (fig. 16), indicating that the occurrence of perchlorate over this wide range of climate conditions in the SNR study unit can be accounted for by natural processes. Anthropogenic sources of perchlorate are not required to explain the occurrence pattern of perchlorate, although contribution from anthropogenic sources cannot be ruled out.



Average aridity index	Threshold perchlorate concentration, in micrograms per liter		
	0.1	0.5	1.0
0.32	●	●	○
0.65	▼	▼	▽
0.88	▲	▲	△
1.38	■	■	□

x-error bars are predicted probabilities for plus/minus one standard deviation of average aridity index.
y-error bars are the 90% confidence interval for observed frequencies.

Figure 16. Predicted probability of detecting perchlorate at concentrations above three threshold concentrations in groundwater under natural conditions at four aridity indices to observed detection frequencies of perchlorate at concentrations above the four threshold concentrations and average aridity indices for sets of 21 or 20 groundwater samples, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

Summary

Groundwater quality in the Sierra Nevada Regional (SNR) 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 SNR study unit covers an area of approximately 25,000 square miles (mi²) (66,000 square kilometers [km²]) and includes all or parts of 20 California counties: Lassen, Plumas, Butte, Sierra, Yuba, Nevada, Placer, El Dorado, Sacramento, Amador, Alpine, Calaveras, Tuolumne, Mono, Mariposa, Madera, Fresno, Inyo, Tulare, and Kern Counties.

The GAMA Priority Basin Project is designed to provide a statistically unbiased assessment of untreated groundwater quality in the primary aquifer system that is used for public drinking-water supplies statewide. The primary aquifer system is defined by the range of depths of the screened or open intervals of wells listed in the State of California's database of wells used for public drinking-water supply. Two types of assessments were made for the SNR study unit: (1) a status assessment yielding quantitative estimates of the current status of groundwater quality in the primary aquifer system and (2) an 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 USGS for the GAMA Priority Basin Project (USGS-GAMA) and data compiled in the State's database. (The California Department of Public Health [CDPH] Drinking Water Program 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.) Water-quality and ancillary data were collected by USGS-GAMA from 83 wells in the SNR study unit during 2008. The organizing feature for examining these data was aquifer lithology. Drinking-water supply wells in the SNR study unit are located in fractured hard-rock aquifers and alluvial basins. The fractured hard-rock aquifers were classified as granitic, metamorphic, or volcanic rocks, and the alluvial basins and other accumulations of sediment were classified as sedimentary deposits. The study unit was divided into 30 equal-area grid cells, and in each cell, 1 well was randomly selected from each of the 4 aquifer lithologies that contained wells. USGS-GAMA sampled wells in 82 of the 91 possible lithologic-grid sub-cells. Samples from the 82 USGS-grid wells and 1 additional well were analyzed for organic constituents (volatile organic compounds and pesticides), inorganic constituents (major ions, trace elements, and radioactive constituents), special-interest constituents (perchlorate and *N*-nitrosodimethylamine [NDMA]) and geochemical and age-dating tracers. Additional water-quality data were obtained from 117 wells sampled by USGS-GAMA in 2006–07 for

3 small study units inside the SNR study unit and from 1,066 wells in the CDPH database having data for samples collected between May 1, 2006, and October 31, 2008.

Relative-concentrations (defined as sample concentration divided by benchmark concentration for the constituent) were used for evaluating groundwater quality for those constituents having Federal and (or) California regulatory or non-regulatory benchmarks for drinking-water quality. A relative-concentration (RC) of > 1.0 indicates a concentration above a benchmark. Organic and special-interest constituent RCs were classified as "high" ($RC > 1.0$), "moderate" ($1.0 \geq RC > 0.1$), or "low" ($RC \leq 0.1$). 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 for evaluating regional-scale groundwater quality. High-RC aquifer-scale proportion is defined as the areal percentage of the primary aquifer system having $RC > 1.0$ 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 with moderate and low RCs, respectively. Aquifer-scale proportions were calculated on an area-weighted basis for the primary aquifer systems, corresponding to the four aquifer lithologies (granitic rocks, metamorphic rocks, sedimentary deposits, and volcanic rocks), and the aggregated system, corresponding to the study unit as a whole. Both grid-based, which used one value per grid cell per lithology, and spatially weighted, which used multiple values per cell per lithology, approaches were used.

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 between the four aquifer lithologies. In the SNR study unit as a whole, one or more inorganic constituents with health-based benchmarks had high RCs in 16 percent of the primary aquifer system and moderate RCs in 21 percent. As classes, trace elements, radioactive constituents, and nutrients were present at high RCs in 11 percent, 8.2 percent, and 1.4 percent of the aggregated primary aquifer system, respectively. The proportions of the granitic and sedimentary systems having high or moderate RCs of any inorganic constituent with health-based benchmarks were significantly greater than the proportions of the metamorphic system.

Among inorganic constituents with health-based benchmarks, arsenic had the greatest high-RC (9.7 percent) and moderate-RC (10 percent) aquifer-scale proportions in the study unit as a whole. The high-RC aquifer-scale proportion for arsenic in the volcanic primary aquifer system was significantly greater than in the other three systems. Boron was present at high RCs in 2.0 percent and at moderate RCs in 2.2 percent of the aggregated primary aquifer system. Fluoride was present at high RCs in 1.8 percent and moderate RCs in 0.5 percent of the aggregated primary aquifer system, and the sedimentary primary aquifer system had a greater combined high and moderate aquifer-scale proportion

than the other systems. Nitrate was present at high RCs in 1.4 percent and moderate RCs in 3.1 percent of the aggregated primary aquifer system, and the granitic and sedimentary systems had significantly greater combined high and moderate aquifer-scale proportions than the metamorphic and volcanic systems (2.3 percent and 1.7 percent, respectively). Uranium was present at high RCs in 2.9 percent and moderate RCs in 7.7 percent of the aggregated primary aquifer system.

For inorganic constituents with aesthetic-based benchmarks (secondary maximum contaminant levels, SMCLs), 18 percent of the aggregated primary aquifer system had high RCs of one or more constituents, and 6.8 percent had moderate RCs. Trace elements (primarily iron and manganese) and salinity indicators with SMCL benchmarks were present at high RCs in 18 percent and 1.3 percent of the aggregated primary aquifer system, respectively. The metamorphic primary aquifer system had significantly greater combined high and moderate aquifer-scale proportions of manganese and iron than the other systems.

One or more organic constituents with health-based benchmarks had high RCs in 0.1 percent of the aggregated primary aquifer system, moderate RCs in 3.0 percent, and low RCs in 23 percent. Organic constituents were not detected in 74 percent of the aggregated primary aquifer system. The metamorphic and sedimentary systems had significantly greater frequencies of occurrence of organic constituents than the granitic and volcanic systems. Solvents were present at high RCs in 0.1 percent of the aggregated primary aquifer system and at moderate RCs in 3.0 percent. Chloroform and gasoline oxygenates (methyl *tert*-butyl ether, MTBE) were not detected at high RCs, and each was present at moderate RCs in 0.1 percent of the aggregated primary aquifer system. Pesticides were not detected at high or moderate RCs. Three organic constituents (MTBE, chloroform, and simazine) had area-weighted detection frequencies greater than 10 percent in the aggregated primary aquifer system or at least one of the four lithologic primary aquifer systems. The special-interest constituent perchlorate was detected at high RCs in 0.01 percent of the aggregated primary aquifer system and at moderate RCs in 1.0 percent.

Statistical tests were used to evaluate relations between concentrations of constituents and potential explanatory factors descriptive of land use, geography, depth, geochemical conditions, and groundwater age. For inorganic constituents, the potential explanatory factors most commonly having significant relations were factors describing geochemical conditions and geographic location. Higher concentrations of trace elements, radioactive constituents, and constituents with SMCL benchmarks generally were associated with anoxic conditions, higher pH, and location within a particular compositional band in the Sierra Nevada batholith corresponding to the southwestern part of the study unit. Patterns of significant relations were somewhat different from those obtained previously for the three study units contained within the SNR study unit, largely because of differences in characteristics of sites with granitic aquifer lithology. For organic constituents, higher concentrations of organic

constituents generally were associated with greater percentage of urban land use. The high proportions of springs and modern groundwater in the dataset likely account for the absence of significant relations between concentrations of organic constituents and measures of well depth or groundwater age.

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Appendix A. Lithologic-Grid Wells

The status assessments for other GAMA Priority Basin Project study units calculated aquifer-scale proportions for inorganic constituents by using both the grid-based and spatially weighted methods (for example, Landon and others, 2010; Burton and others, 2012; Fram and Belitz, 2012). The grid-based calculations required supplementing the data collected by the USGS with data from the CDPH database because the USGS generally did not have a grid well in every grid cell and data for inorganic constituents were not collected at every well sampled by the USGS. Data to complete the grid dataset were obtained from selected wells in the CDPH database (hereinafter referred to as CDPH-grid wells). Although grid-based calculations of aquifer-scale proportions for inorganic constituents were not used for the SNR study unit status assessment presented in this report, a set of CDPH-grid wells was selected to complete the grid dataset for potential use in multi-study-unit synthesis reports.

The SNR study unit was divided into 30 equal-area grid cells (2,200 km² each; [fig. A1](#)) (Scott, 1990), and each cell was subdivided into 1 to 4 sub-cells, 1 for each of the 4 aquifer lithologies (granitic rock, metamorphic rock, sedimentary deposits, and volcanic rock) present in the cell. All of the CDPH wells in a cell were assigned random ranks, and the highest-ranked well in each sub-cell for which permission to sample could be obtained and which met basic sampling criteria was selected as the lithologic-grid well to represent that sub-cell. Not all cells contained areas of all four aquifer lithologies, and not all aquifer lithologies present in a cell contained wells. The 30 grid cells each had 2 to 4 aquifer lithologies containing CDPH wells, resulting in total of 91 possible lithologic-grid sub-cells. USGS-GAMA sampled wells in 82 of the 91 possible lithologic-grid sub-cells ([table A1](#)). One additional well was sampled in sub-cell 1M.

All 82 USGS-grid wells were part of the lithologic-grid network. Thirty of the USGS-grid wells also composed the fundamental-grid network, which was used for data analysis by Shelton and others (2010), but was not used in this study. The fundamental-grid network consisted of 30 wells, 1 from each cell. The highest-ranked grid well from among the 2 to 4 lithologic sub-cells present in the cell was defined as the fundamental-grid well. Fundamental-grid wells were named with an alphanumeric GAMA_ID consisting of an initial prefix identifying the study unit (SIERRA), a second prefix indicating aquifer lithology (G, M, S, and V for granitic, metamorphic, sedimentary, and volcanic aquifer lithologies, respectively), and a number indicating the order of sample collection ([figs. A1A,B](#); [table A1](#)). The other 52 USGS-grid wells (and the 1 extra well) were named in the same way, except that the second prefix included an “L” for lithologic grid (GL, ML, SL, and VL for granitic, metamorphic, sedimentary, and volcanic aquifer lithologies, respectively).

The CDPH database was queried to provide data for inorganic constituents to represent the nine sub-cells that did not have a USGS-grid well. The CDPH database also was queried to provide data for the two inorganic constituents not analyzed for every USGS-grid well: radon-222 and radium activities. Only CDPH wells with data during the period May 1, 2006, through October 31, 2008, were considered. If the well had more than one analysis for a constituent in that interval, then the most recent data were selected.

CDPH-grid wells were selected for the nine sub-cells without USGS-grid wells (sub-cells 1G, 1S, 3S, 9M, 9S, 10S, 11V, 13S, 20S; [table A1](#)) as follows:

1. For four of the nine sub-cells (sub-cells 9M, 10S, 11V, 13S), there was only one CDPH well with any of the needed data; those wells were selected as the CDPH-grid well to represent their respective sub-cells.
2. For 3 of the 9 sub-cells (sub-cells 1G, 9S, 20S), there were 7 to 13 wells with data; however, in each sub-cell, 1 well had data for many inorganic constituents, and the others had data for few inorganic constituents (usually only nutrients). The wells with data for the largest number of constituents were selected as the CDPH grid wells to represent these sub-cells.
3. For the remaining two of the nine sub-cells, the wells in the sub-cell had data for the same number of constituents (sub-cell 3S had three wells with data for nutrients only, and sub-cell 1S had two wells with data for nitrate and arsenic only). For each sub-cell, the well with the highest random rank was selected as the CDPH-grid well to represent the sub-cell.

The CDPH wells were given names consisting of the same prefix used by the USGS wells in the study area or study unit, the second prefix “DPH,” and the next number in the series after the USGS-grid well numbers ([table A1](#)). The “DPH” prefix indicates that the CDPH-grid well is not also a USGS-grid well. The data from these nine CDPH-grid wells are listed in [tables A2](#) and [A3](#). Of the nine CDPH-grid wells, four had data only for nutrients, and five had data for nutrients and some trace elements and (or) constituents with SMCL benchmarks ([tables A2, A3](#)).

The CDPH database also was queried to provide data for the two inorganic constituents not analyzed at every lithologic-grid well (radon-222 and radium activities). USGS-GAMA sampled for radon-222 at 28 of the 82 sites on the lithologic-grid network, and none of the remaining 54 wells had data for radon-222 in the CDPH database. USGS-GAMA sampled for radium in 30 wells, and 6 of the remaining 52 wells had data for radium in the CDPH database (sub-cells 1M, 5M, 7V, 8S, 18V, 26M; [table A1](#)). The CDPH radium data for these six wells were used to supplement the USGS-GAMA data for those wells ([table A2](#)).

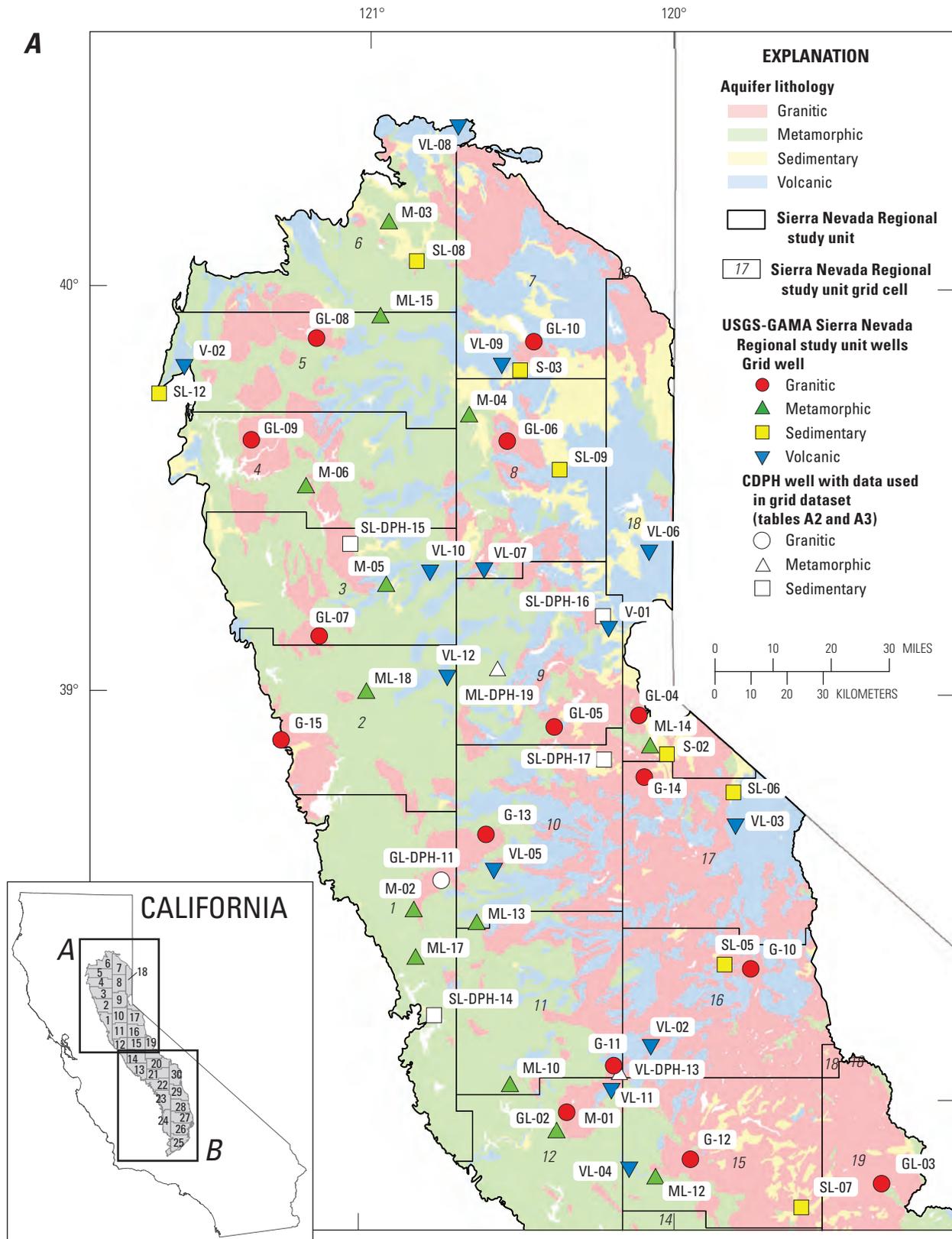


Figure A1. Locations of grid cells (USGS) Public Health (CDPH) lithologic-grid wells in the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

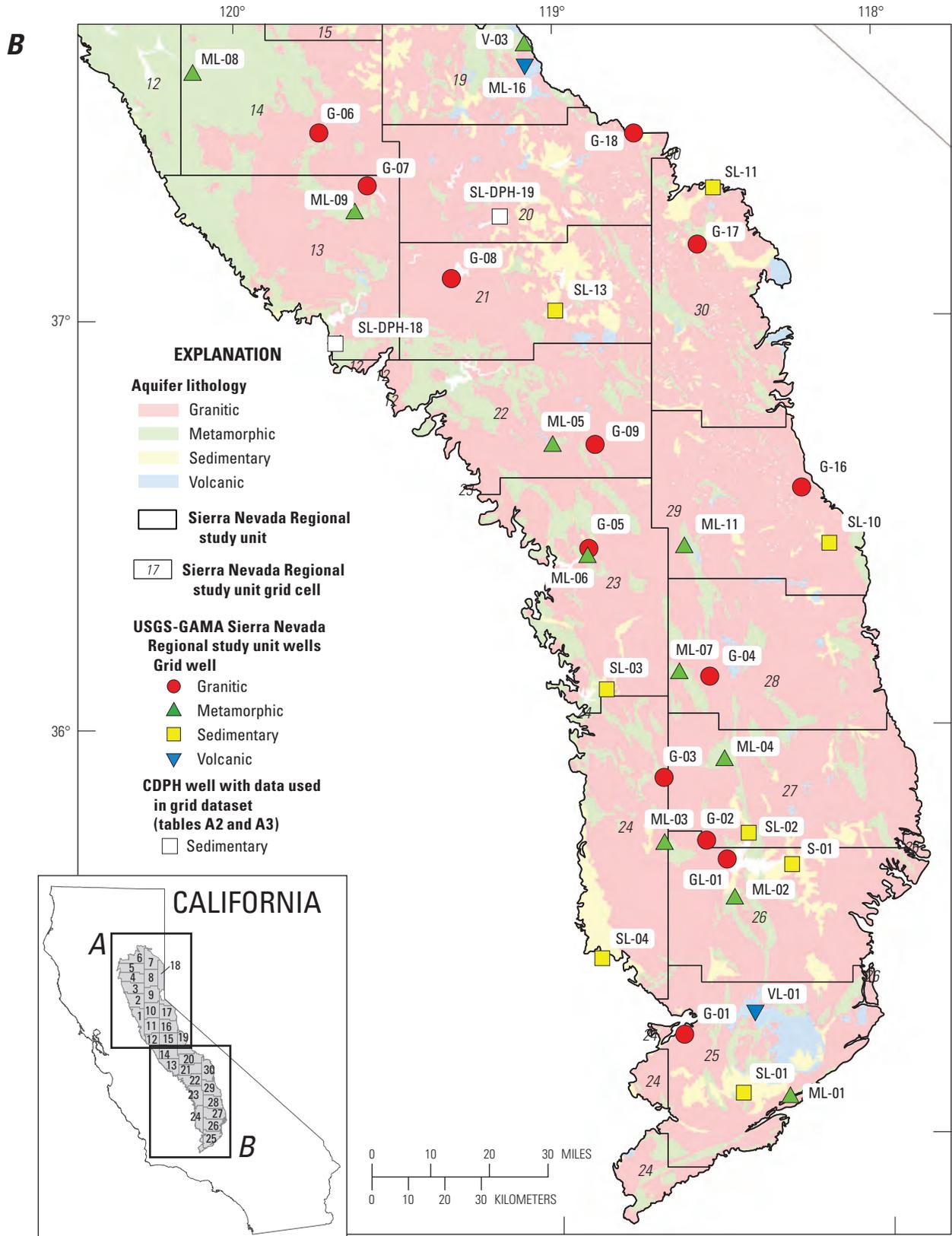


Figure A1. —Continued

Table A1. Nomenclature for lithologic grid wells, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[California Department of Public Health (CDPH) data refers to the number of constituents for which the CDPH database was the source of data for the well. Fifteen wells had CDPH data for 1 or more constituents. The nine wells that are not also U.S. Geological Survey (USGS) wells have “DPH” in the identification number prefix. **Identification number prefixes:** SIERRA, Sierra Nevada Regional study unit; G, granitic aquifer lithology in fundamental and lithologic grids; GL, granitic aquifer lithology in lithologic grid; M, metamorphic aquifer lithology in fundamental and lithologic grids; ML, metamorphic aquifer lithology in lithologic grid; S, sedimentary aquifer lithology in fundamental and lithologic grids; SL, sedimentary aquifer lithology in lithologic grid; V, volcanic aquifer lithology in fundamental and lithologic grids; VL, volcanic aquifer lithology in lithologic grid. **Abbreviations:** –, no CDPH data selected]

Cell	Granitic aquifer lithology		Metamorphic aquifer lithology		Sedimentary aquifer lithology		Volcanic aquifer lithology	
	GAMA well identification number	CDPH data	GAMA well identification number	CDPH data	GAMA well identification number	CDPH data	GAMA well identification number	CDPH data
1	SIERRA-GL-DPH-11	25	SIERRA-M-02 ¹ SIERRA-ML-17 ¹	1	SIERRA-SL-DPH-14	2	no wells	–
2	SIERRA-G-15	–	SIERRA-ML-18	–	no wells	–	SIERRA-VL-12	–
3	SIERRA-GL-07	–	SIERRA-M-05	–	SIERRA-SL-DPH-15	1	SIERRA-VL-10	–
4	SIERRA-GL-09	–	SIERRA-M-06	–	no wells	–	no wells	–
5	SIERRA-GL-08	–	SIERRA-ML-15	1	SIERRA-SL-12	–	SIERRA-V-02	–
6	no wells	–	SIERRA-M-03	–	SIERRA-SL-08	–	SIERRA-VL-08	–
7	SIERRA-GL-10	–	no wells	–	SIERRA-S-03	–	SIERRA-VL-09	1
8	SIERRA-GL-06	–	SIERRA-M-04	–	SIERRA-SL-09	1	SIERRA-VL-07	–
9	SIERRA-GL-05	–	SIERRA-ML-DPH-19	1	SIERRA-SL-DPH-16	23	SIERRA-V-01	–
10	SIERRA-G-13	–	SIERRA-ML-13	–	SIERRA-SL-DPH-17	2	SIERRA-VL-05	–
11	SIERRA-G-11	–	SIERRA-ML-10	–	no wells	–	SIERRA-VL-DPH-13	26
12	SIERRA-GL-02	–	SIERRA-M-01	–	no wells	–	SIERRA-VL-11	–
13	SIERRA-G-07	–	SIERRA-ML-09	–	SIERRA-SL-DPH-18	1	no wells	–
14	SIERRA-G-06	–	SIERRA-ML-08	–	no wells	–	no wells	–
15	SIERRA-G-12	–	SIERRA-ML-12	–	SIERRA-SL-07	–	SIERRA-VL-04	–
16	SIERRA-G-10	–	no wells	–	SIERRA-SL-05	–	SIERRA-VL-02	–
17	SIERRA-G-14	–	no wells	–	SIERRA-SL-06	–	SIERRA-VL-03	–
18	SIERRA-GL-04	–	SIERRA-ML-14	–	SIERRA-S-02	–	SIERRA-VL-06	1
19	SIERRA-GL-03	–	SIERRA-ML-16	–	no wells	–	SIERRA-V-03	–
20	SIERRA-G-18	–	no wells	–	SIERRA-SL-DPH-19	11	no wells	–
21	SIERRA-G-08	–	no wells	–	SIERRA-SL-13	–	no wells	–
22	SIERRA-G-09	–	SIERRA-ML-05	–	no wells	–	no wells	–
23	SIERRA-G-05	–	SIERRA-ML-06	–	SIERRA-SL-03	–	no wells	–
24	SIERRA-G-03	–	SIERRA-ML-03	–	SIERRA-SL-04	–	no wells	–
25	SIERRA-G-01	–	SIERRA-ML-01	–	SIERRA-SL-01	–	SIERRA-VL-01	–
26	SIERRA-GL-01	–	SIERRA-ML-02	1	SIERRA-S-01	–	no wells	–
27	SIERRA-G-02	–	SIERRA-ML-04	–	SIERRA-SL-02	–	no wells	–
28	SIERRA-G-04	–	SIERRA-ML-07	–	no wells	–	no wells	–
29	SIERRA-G-16	–	SIERRA-ML-11	–	SIERRA-SL-10	–	no wells	–
30	SIERRA-G-17	–	no wells	–	SIERRA-SL-11	–	no wells	–

¹SIERRA-M-02 is used for the grid-based calculation of aquifer-scale proportion; both wells are used for the spatially weighted calculation.

Table A2. California Department of Public Health (CDPH) data for nutrients and radioactive constituents used for the grid-based calculations of aquifer-scale proportions on the fundamental-grid and lithologic-grid networks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Wells having “DPH” in the GAMA well identification number were not sampled by U.S. Geological Survey (USGS); the other wells were sampled by USGS. CDPH data are the most recent analysis for each constituent during the period May 1, 2006, through October 31, 2008. In the CDPH database, non-detections are reported as 0 for some samples and as less than the reporting limit for other samples. **Units:** mg/L, milligrams per liter; pCi/L, picocuries per liter.

Abbreviations: USGS, data provided by U.S. Geological Survey (Shelton and others, 2010); na, not available; <, less than]

GAMA well identification number	Cell	Nitrate, as nitrogen (mg/L)	Nitrite, as nitrogen (mg/L)	Radium (pCi/L)	Uranium (pCi/L)	Gross alpha (pCi/L)
Granitic aquifer lithology						
SIERRA-GL-DPH-11	1	0.8	<0.05	na	5.6	na
Metamorphic aquifer lithology						
SIERRA-M-02	1	USGS	USGS	2.2	USGS	USGS
SIERRA-ML-15	5	USGS	USGS	0	USGS	USGS
SIERRA-ML-DPH-19	9	0	na	na	na	na
SIERRA-ML-02	26	USGS	USGS	0.03	USGS	USGS
Sedimentary aquifer lithology						
SIERRA-SL-DPH-14	1	0.6	<0.05	na	na	na
SIERRA-SL-DPH-15	3	0.6	na	na	na	na
SIERRA-SL-09	8	USGS	USGS	0.1	USGS	USGS
SIERRA-SL-DPH-16	9	0.4	0	na	na	na
SIERRA-SL-DPH-17	10	0	0	na	na	na
SIERRA-SL-DPH-18	13	13.2	na	na	na	na
SIERRA-SL-DPH-19	20	3.9	na	na	na	na
Volcanic aquifer lithology						
SIERRA-VL-09	7	USGS	USGS	0.25	USGS	USGS
SIERRA-VL-DPH-13	11	0	0	na	11.5	13.8
SIERRA-VL-06	18	USGS	USGS	<1	USGS	USGS

Table A3. California Department of Public Health (CDPH) data for trace elements with health-based benchmarks and inorganic constituents with secondary maximum contaminant level (SMCL) benchmarks used for the grid-based calculations of aquifer-scale proportions on the fundamental-grid and lithologic-grid networks, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Wells having “DPH” in the GAMA well identification number were not sampled by the U.S. Geological Survey (USGS). CDPH data are the most recent analysis for each constituent during the period May 1, 2006, through October 31, 2008. In the CDPH database, non-detections are reported as 0 for some samples and as less than the reporting limit for other samples. **Units:** µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter. **Abbreviations:** na, not available; <, less than]

Constituent	Units	GAMA well identification number				
		SIERRA-GL-DPH-11 (cell 1)	SIERRA-SL-DPH-15 (cell 3)	SIERRA-SL-DPH-16 (cell 9)	SIERRA-SL-DPH-19 (cell 20)	SIERRA-VL-DPH-13 (cell 11)
Trace elements with health-based benchmarks						
Aluminum	µg/L	<50	na	0	na	0
Antimony	µg/L	<5	na	0	na	0
Arsenic	µg/L	2.4	na	0	na	3.3
Barium	µg/L	<50	na	34	na	0
Beryllium	µg/L	<1	na	0	na	0
Boron	µg/L	na	na	na	na	na
Cadmium	µg/L	<1	na	0	na	0
Chromium	µg/L	<2	na	7.3	na	19
Copper	µg/L	<3	na	0	1,400	0
Fluoride	mg/L	0.11	na	0	0	0
Lead	µg/L	<3	na	na	na	0
Mercury	µg/L	<1	na	0	na	0
Molybdenum	µg/L	na	na	na	na	na
Nickel	µg/L	<5	na	0	na	0
Selenium	µg/L	<2	na	0	na	0
Strontium	µg/L	na	na	na	na	na
Thallium	µg/L	<1	na	0	na	0
Vanadium	µg/L	na	na	na	na	na
Inorganic constituents with SMCL benchmarks						
Iron	µg/L	<20	na	0	0	0
Manganese	µg/L	<5	na	0	0	0
Silver	µg/L	<2	na	0	0	0
Zinc	µg/L	23	na	0	400	0
Chloride	mg/L	4.9	na	9.6	6.3	1.6
Specific conductance	µS/cm	437	140	138	45	366
Sulfate	mg/L	4.8	na	12.7	5.1	5.1
Total dissolved solids	mg/L	324	na	79	120	75

Appendix B. Attribution of Ancillary Data

Land Use

Land use was classified using an enhanced version of the satellite-derived (30-m 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. 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. Land-use statistics for the study unit, study areas, and areas within a 500-m radius around each study well (500-m buffers) were calculated for classified datasets using ArcGIS. A 500-m radius centered on the well has been shown to be effective for correlating land use with contaminant occurrence (for example, Rupert, 2003; Johnson and Belitz, 2009). Land-use data for wells are listed in [table B1](#).

Land-cover classes are 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 Bureau of Land Management lands in the Sierra Nevada, is classified as natural land, not agricultural land. In the seven national forests entirely within the Sierra Nevada hydrogeologic province (Plumas, Tahoe, Lake Tahoe Basin Management Unit, El Dorado, Stanislaus, Sierra, and Sequoia), there were approximately 3,640,000 acres of grazing allotments and approximately 165,000 billed animal-unit months in 2004 (U.S. Government Accounting Office, 2005). This corresponds to a density of approximately 0.05 cattle per acre per month. For comparison, cattle density on irrigated pasture in the San Joaquin Valley averages 8 cattle per acre per month (Gildersleeve, 2006).

Septic Systems and LUFTs

Septic tank density was determined using 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 (Tyler Johnson, U.S. Geological Survey, written commun., 2009) ([table B1](#)).

The density of leaking or formerly leaking underground fuel tanks (LUFTs) was determined from the locations of tanks in the SWRCB's GeoTracker database of environmental

cleanup sites (California State Water Resources Control Board, 2007). The density of LUFTs was calculated using Theissen polygons (Tyler Johnson, U.S. Geological Survey, written commun., 2007). The boundaries of the Theissen polygon around a particular LUFT were created by bisecting the linear distances between the LUFT and all the surrounding LUFTs. The density of LUFTs 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 LUFT density of the Theissen polygon in which it is located ([table B1](#)).

Aquifer Lithology

Aquifer lithology was classified into four categories on the basis of lithologic information from driller's logs and 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. In those cases where the lithologic category estimated from the geologic map disagreed with the lithology described in the driller's log, the category from the driller's log was used. In addition, several sites located near lakes plotted in the lake on the map; the lithologic category for each of these sites was estimated from the geologic units mapped surrounding the lake. The 83 wells sampled by USGS-GAMA were located in areas classified into 16 of the 66 geologic units defined on the California State geologic map (Jennings, 1977; Saucedo and others, 2000). These 16 geologic units were grouped into 4 lithologic categories on the basis of rock type and age:

- Granitic rocks: Mesozoic granitic rocks (California State geologic map unit: grMz).
- Metamorphic rocks: Paleozoic and Mesozoic metavolcanic, metasedimentary, ultramafic, and mafic rocks (California State geologic map units: mv, Mzv, Pzv, m, J, Pz).
- Sedimentary deposits: Cenozoic sedimentary deposits, including alluvial, fluvial, lacustrine, and glacial sediments (California State geologic map units: Q, Qg, Tc, Ec, Mc). The Quaternary age non-marine sedimentary deposits (Q, Qg) are Pleistocene and Holocene in age. The Tertiary age non-marine sedimentary deposits (Ec, Mc, Tc) are Eocene, Miocene, and unspecified Tertiary in age, respectively.
- Volcanic rocks: Cenozoic volcanic rocks, including lava flows and pyroclastic deposits (California State geologic map units: Ti, Tv, Tvp, Qv). The Tertiary age volcanic rocks (Ti, Tv, Tvp) are primarily Miocene and Pliocene in age, and the Quaternary age volcanic rocks (Qv) are Pleistocene and Holocene in age.

Table B1. Land-use percentages, septic tank density, leaking or formerly leaking underground fuel tank (LUFT) density, and geologic unit for wells sampled by the USGS Geologic Survey (USGS) for the Sierra Nevada Regional Study Unit, 2008, California Groundwater Assessment and Monitoring Basin Assessment (GAMA) Priority Basin Project. Continued

[Geologic unit: Granitic aquifer lithology: grMz, Mesozoic granitic rocks. Metamorphic aquifer lithology: J, Jurassic marine metasedimentary rocks; m, Mesozoic/Paleozoic metavolcanic/metasedimentary rocks; mv, Mesozoic/Paleozoic metavolcanic rocks; Mzv, Mesozoic metavolcanic rocks; Pz, Paleozoic marine metasedimentary rocks; Pzv, Paleozoic metavolcanic rocks; um, ultramafic rocks. Sedimentary aquifer lithology: Q, Holocene alluvial sediment; Qg, Holocene/Quaternary glacial sediment; Tc, Tertiary non-marine sediment; Mc, Miocene non-marine sediment; Ec, Eocene non-marine sediment. Volcanic aquifer lithology: Q, Quaternary volcanic rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Ti, Tertiary volcanic dikes. **Abbreviations:** tanks/km², number of tanks per square kilometer; –, not available]

GAMA well identification number	Land-use percentages ¹			Septic density ² (tanks/km ²)	LUFT density ³ (tanks/km ²)	Geologic unit ⁴
	Agricultural	Natural	Urban			
Granitic aquifer lithology						
SIERRA-G-01	0	100	0	4.0	0.004	grMz
SIERRA-G-02	0	98	2	1.1	0.008	grMz
SIERRA-G-03	0	100	0	5.5	0.001	grMz
SIERRA-G-04	0	100	0	1.1	0.001	grMz
SIERRA-G-05	0	100	0	3.6	0.193	grMz
SIERRA-G-06	0	87	13	3.2	0.003	grMz
SIERRA-G-07	0	95	5	9.3	0.056	grMz
SIERRA-G-08	0	18	82	8.4	0.040	grMz
SIERRA-G-09	0	100	0	0.8	0.001	grMz
SIERRA-G-10	0	100	0	0.0	0.002	grMz
SIERRA-G-11	0	100	0	0.9	0.055	grMz ⁵
SIERRA-G-12	0	100	0	0.2	0.004	grMz
SIERRA-G-13	0	100	0	0.9	0.007	grMz
SIERRA-G-14	0	100	0	7.4	0.023	grMz
SIERRA-G-15	53	47	0	3.6	0.036	grMz
SIERRA-G-16	1	99	0	0.3	0.004	grMz
SIERRA-G-17	0	100	0	0.5	0.001	grMz
SIERRA-G-18	0	100	0	0.3	0.001	grMz
SIERRA-GL-01	0	100	0	4.5	0.008	grMz
SIERRA-GL-02	0	31	69	17.8	0.349	grMz
SIERRA-GL-03	0	100	0	0.1	0.004	grMz
SIERRA-GL-04	0	100	0	0.0	0.008	grMz
SIERRA-GL-05	0	100	0	0.4	0.004	grMz
SIERRA-GL-06	0	100	0	0.7	0.010	grMz
SIERRA-GL-07	0	100	0	2.8	0.038	grMz
SIERRA-GL-08	0	100	0	0.7	0.001	grMz
SIERRA-GL-09	0	91	9	5.6	0.010	grMz
SIERRA-GL-10	0	100	0	0.3	0.002	grMz
Metamorphic aquifer lithology						
SIERRA-M-01	0	100	0	4.2	0.070	mv
SIERRA-M-02	0	100	0	2.7	0.005	Mzv
SIERRA-M-03	0	100	0	1.5	0.011	Pzv ⁶
SIERRA-M-04	0	100	0	5.4	0.010	Pzv
SIERRA-M-05	0	100	0	6.0	0.011	J ⁷
SIERRA-M-06	0	90	10	1.9	0.011	Mzv ⁸

Table B1. Land-use percentages, septic tank density, leaking or formerly leaking underground fuel tank (LUFT) density, and geologic unit for wells sampled by the USGS for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[**Geologic unit:** Granitic aquifer lithology: grMz, Mesozoic granitic rocks. Metamorphic aquifer lithology: J, Jurassic marine metasedimentary rocks; m, Mesozoic/Paleozoic metavolcanic/metasedimentary rocks; mv, Mesozoic/Paleozoic metavolcanic rocks; Mzv, Mesozoic metavolcanic rocks; Pz, Paleozoic marine metasedimentary rocks; Pzv, Paleozoic metavolcanic rocks; um, ultramafic rocks. Sedimentary aquifer lithology: Q, Holocene alluvial sediment; Qg, Holocene/Quaternary glacial sediment; Tc, Tertiary non-marine sediment; Mc, Miocene non-marine sediment; Ec, Eocene non-marine sediment. Volcanic aquifer lithology: Q, Quaternary volcanic rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Ti, Tertiary volcanic dikes. **Abbreviations:** tanks/km², number of tanks per square kilometer; –, not available]

GAMA well identification number	Land-use percentages ¹			Septic density ² (tanks/km ²)	LUFT density ³ (tanks/km ²)	Geologic unit ⁴
	Agricultural	Natural	Urban			
Metamorphic aquifer lithology—Continued						
SIERRA-ML-01	0	94	6	0.3	0.002	m
SIERRA-ML-02	0	87	13	28.7	0.003	m
SIERRA-ML-03	16	84	0	1.1	0.007	m
SIERRA-ML-04	0	100	0	0.0	0.001	m
SIERRA-ML-05	0	100	0	0.5	0.013	m
SIERRA-ML-06	9	91	0	3.9	0.006	m
SIERRA-ML-07	0	100	0	1.1	0.001	m
SIERRA-ML-08	0	100	0	1.5	0.005	J
SIERRA-ML-09	0	100	0	3.5	0.029	m
SIERRA-ML-10	0	100	0	3.1	0.016	mv
SIERRA-ML-11	0	100	0	0.2	0.002	mv
SIERRA-ML-12	0	86	14	0.9	0.004	Pz
SIERRA-ML-13	0	92	8	11.0	0.032	Pz
SIERRA-ML-14	0	100	0	0.0	0.019	Mzv
SIERRA-ML-15	47	30	22	0.5	0.004	Pz
SIERRA-ML-16	0	100	0	0.0	0.001	Mzv
SIERRA-ML-17	0	99	1	1.6	0.117	Mzv
SIERRA-ML-18	0	96	4	29.6	0.213	J
Sedimentary aquifer lithology						
SIERRA-S-01	89	9	2	0.5	0.004	Q
SIERRA-S-02	0	61	39	0.0	0.398	Q
SIERRA-S-03	0	87	13	1.6	0.005	Q
SIERRA-SL-01	28	71	1	2.0	0.098	Q
SIERRA-SL-02	1	93	6	26.3	0.080	Q ⁹
SIERRA-SL-03	11	56	32	3.3	0.006	Q
SIERRA-SL-04	0	100	0	0.6	0.008	Q ¹⁰
SIERRA-SL-05	0	100	0	0.0	0.002	Qg
SIERRA-SL-06	0	100	0	0.3	0.002	Q
SIERRA-SL-07	0	91	9	0.1	0.009	Q
SIERRA-SL-08	30	38	32	1.6	0.002	Q
SIERRA-SL-09	13	87	0	0.5	0.004	Q
SIERRA-SL-10	1	99	0	0.1	0.000	Qg
SIERRA-SL-11	0	89	11	0.5	0.003	Qg
SIERRA-SL-12	0	94	6	4.0	0.042	Tc
SIERRA-SL-13	0	100	0	0.1	0.001	Qg

Table B1. Land-use percentages, septic tank density, leaking or formerly leaking underground fuel tank (LUFT) density, and geologic unit for wells sampled by the USGS for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[**Geologic unit:** Granitic aquifer lithology: grMz, Mesozoic granitic rocks. Metamorphic aquifer lithology: J, Jurassic marine metasedimentary rocks; m, Mesozoic/Paleozoic metavolcanic/metasedimentary rocks; mv, Mesozoic/Paleozoic metavolcanic rocks; Mzv, Mesozoic metavolcanic rocks; Pz, Paleozoic marine metasedimentary rocks; Pzv, Paleozoic metavolcanic rocks; um, ultramafic rocks. Sedimentary aquifer lithology: Q, Holocene alluvial sediment; Qg, Holocene/Quaternary glacial sediment; Tc, Tertiary non-marine sediment; Mc, Miocene non-marine sediment; Ec, Eocene non-marine sediment. Volcanic aquifer lithology: Q, Quaternary volcanic rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Ti, Tertiary volcanic dikes. **Abbreviations:** tanks/km², number of tanks per square kilometer; –, not available]

GAMA well identification number	Land-use percentages ¹			Septic density ² (tanks/km ²)	LUFT density ³ (tanks/km ²)	Geologic unit ⁴
	Agricultural	Natural	Urban			
Volcanic aquifer lithology						
SIERRA-V-01	0	96	4	1.2	0.695	Tvp
SIERRA-V-02	0	39	61	117.3	0.018	Tvp
SIERRA-V-03	0	100	0	0.0	0.001	Qv
SIERRA-VL-01	7	93	0	0.3	0.002	Ti
SIERRA-VL-02	0	100	0	16.3	0.006	Tvp
SIERRA-VL-03	0	100	0	0.3	0.002	Tvp
SIERRA-VL-04	0	99	1	14.8	0.015	Tvp
SIERRA-VL-05	0	100	0	1.4	0.007	Tvp
SIERRA-VL-06	0	100	0	1.3	0.007	Tv
SIERRA-VL-07	0	100	0	0.2	0.006	Tvp
SIERRA-VL-08	0	97	3	1.9	0.004	Qv
SIERRA-VL-09	0	100	0	1.2	0.005	Tvp
SIERRA-VL-10	0	100	0	5.8	0.018	Tvp
SIERRA-VL-11	0	84	16	30.7	0.075	Tvp
SIERRA-VL-12	0	100	0	0.3	0.004	Tvp

¹Land-use percentages within 500-meter radius of well site (Johnson and Belitz, 2009).

²Septic tank density within 500-meter radius of well site, based on data from U.S. Census Bureau (1990).

³LUFT density with 500-meter radius of well site, based on locations from California State Water Resources Control Board (2007).

⁴Geologic units from geologic map of California (Saucedo and others, 2000).

⁵Geologic unit based on geologic map was Tvp (volcanic aquifer lithology); geologic unit changed to grMz (granitic aquifer lithology) based on driller's log.

⁶Geologic unit based on geologic map was Q (sedimentary aquifer lithology); geologic unit changed to Pzv (metamorphic aquifer lithology) based on driller's log and geologic map.

⁷Geologic unit based on geologic map was Ec (sedimentary aquifer lithology); geologic unit changed to J (metamorphic aquifer lithology) based on driller's log and geologic map.

⁸Geologic unit based on geologic map was um (metamorphic aquifer lithology); geologic unit changed to Mzv (metamorphic aquifer lithology) based on driller's log and geologic map.

⁹Geologic unit based on geologic map was water; geologic unit changed to Q (sedimentary aquifer lithology) based on driller's log.

¹⁰Geologic unit based on geologic map was M (metamorphic aquifer lithology); changed to Q (sedimentary aquifer lithology) based on driller's log.

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.

Table B1 lists the geologic units for wells in the four aquifer lithologic classes (granitic, metamorphic, sedimentary, and volcanic). The percentage of each grid cell assigned to each of the four aquifer lithologies is listed in table B2.

Site Information and Hydrologic Conditions

Well construction data were obtained primarily from driller’s logs. In locations where driller’s logs were not available, well construction data were obtained from ancillary records from well owners or the USGS National Water Information System database. The procedures used to verify well identifications were described by Shelton and others (2010). Well depths and the depths to the top and bottom of the screened or open interval for the USGS-grid wells are listed in table B3. 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.

Sites were classified as either production wells or springs. Production wells pump the groundwater from the aquifer into a distribution system. Sites 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. Driller’s logs for springs reported installation of horizontal boreholes.

The climate at each well site was represented by an aridity index (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997) (table B3):

$$\text{aridity index} = \frac{\text{average annual precipitation}}{\text{average annual evapotranspiration}}$$

Higher values of the index correspond to wetter conditions. Average annual precipitation for each well site was quantified using the PRISM average annual precipitation for 1971–2000 geographic information system (GIS) coverage (PRISM Climate 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, U.S. Geological Survey California Water Science Center, oral commun., 2009).

Table B2. Percentage of area of grid cells assigned to the four aquifer lithologic classes, Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Average cell area is 2,160 square kilometers (km²) (standard deviation 20 km²)]

Cell	Aquifer lithology (percent of cell area)			
	Granitic rocks	Metamorphic rocks	Sedimentary deposits	Volcanic rocks
1	10	87	2	1
2	17	76	1	5
3	18	64	4	14
4	24	61	3	12
5	22	58	0	20
6	12	59	10	19
7	33	3	15	49
8	22	16	27	34
9	25	37	8	30
10	36	28	3	33
11	25	60	0	16
12	11	86	1	2
13	66	32	1	1
14	50	49	2	0
15	63	24	10	3
16	65	2	2	31
17	56	1	2	41
18	27	7	26	40
19	72	16	8	3
20	82	4	13	1
21	75	12	12	1
22	75	24	0	0
23	75	22	3	0
24	74	15	11	0
25	63	14	11	12
26	78	11	11	0
27	83	11	5	1
28	82	15	1	2
29	90	5	4	1
30	75	12	10	3

Hydrologic conditions in the Sierra Nevada hydrogeologic province vary with elevation and latitude, among other factors. The elevation of the well head or spring at the land surface was used as a proxy for relative position in the groundwater flow system. Elevations were obtained from U.S. Geological Survey digital elevation GIS coverage and are reported in feet relative to the North American Vertical Datum of 1988 (NAVD 88) (table B3). Latitude was reported in degrees relative to the North American Datum of 1983 (NAD 83) and used as a proxy for position in the north-to-south gradient of precipitation and temperature in California.

Table B3. Hydrologic conditions and well construction information for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[**Depth classification:** spring, no vertically drilled hole and groundwater emerges at the land surface without a pump; shallow well, bottom of screened or open interval < 170 feet below land surface datum (ft bls); overlapping well, top of screened or open interval < 170 ft bls and bottom of screened or open interval > 170 ft bls; deep well, top of screened or open interval > 170 ft bls; unknown well, no construction information available for the well. **Abbreviations:** NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; –, no data available; na, not applicable; <, less than; >, greater than]

GAMA well identification number	Well construction information			Hydrologic conditions			
	Well depth (ft bls)	Top of screened or open interval (ft bls)	Bottom of screened or open interval (ft bls)	Depth classification [spring (SP), shallow well (SH), overlapping well (OL), deep well (DP)]	Elevation of land-surface datum (ft above NAVD 88)	Aridity index (dimensionless)	Latitude (degrees in NAD 83)
Granitic aquifer lithology							
SIERRA-G-01	600	300	600	DP	3,248	0.28	35.25
SIERRA-G-02	na	na	na	SP	5,964	0.76	35.72
SIERRA-G-03	300	30	300	OL	2,985	0.50	35.88
SIERRA-G-04	na	na	na	SP	7,600	0.93	36.13
SIERRA-G-05	120	120	120	SH	823	0.38	36.44
SIERRA-G-06	900	100	900	OL	3,105	0.75	37.46
SIERRA-G-07	700	52	700	OL	3,401	0.76	37.33
SIERRA-G-08	120	57	120	SH	5,606	0.78	37.11
SIERRA-G-09	na	na	na	SP	7,460	0.99	36.70
SIERRA-G-10	105	105	105	SH	6,248	1.73	38.33
SIERRA-G-11	650	–	–	OL or DP	3,777	0.88	38.09
SIERRA-G-12	675	57	675	OL	3,870	0.76	37.86
SIERRA-G-13	400	60	400	OL	2,763	1.00	38.66
SIERRA-G-14	400	50	400	OL	6,755	1.29	38.80
SIERRA-G-15	480	60	480	OL	200	0.47	38.89
SIERRA-G-16	na	na	na	SP	8,596	0.55	36.58
SIERRA-G-17	na	na	na	SP	9,800	0.66	37.18
SIERRA-G-18	na	na	na	SP	10,110	0.75	37.46
SIERRA-GL-01	280	160	280	OL	3,646	0.27	35.68
SIERRA-GL-02	400	52	400	OL	2,079	0.69	37.97
SIERRA-GL-03	na	na	na	SP	10,280	1.18	37.80
SIERRA-GL-04	na	na	na	SP	6,584	1.13	38.95
SIERRA-GL-05	150	50	150	SH	5,637	1.37	38.92
SIERRA-GL-06	na	na	na	SP	6,019	1.69	39.63
SIERRA-GL-07	100	65	100	SH	1,687	0.84	39.14
SIERRA-GL-08	100	–	–	SH	5,267	1.99	39.88
SIERRA-GL-09	205	50	205	OL	2,320	1.28	39.63
SIERRA-GL-10	610	470	610	DP	5,647	0.58	39.87
Metamorphic aquifer lithology							
SIERRA-M-01	400	–	–	OL or DP	1,521	0.59	37.93
SIERRA-M-02	440	–	–	OL or DP	1,103	0.59	38.47
SIERRA-M-03	na	na	na	SP	3,903	0.98	40.17
SIERRA-M-04	na	na	na	SP	6,424	1.60	39.70
SIERRA-M-05	–	–	–	Unknown well	3,075	1.29	39.28

Table B3. Hydrologic conditions and well construction information for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[**Depth classification:** spring, no vertically drilled hole and groundwater emerges at the land surface without a pump; shallow well, bottom of screened or open interval < 170 feet below land surface datum (ft bls); overlapping well, top of screened or open interval < 170 ft bls and bottom of screened or open interval > 170 ft bls; deep well, top of screened or open interval > 170 ft bls; unknown well, no construction information available for the well. **Abbreviations:** NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; –, no data available; na, not applicable; <, less than; >, greater than]

GAMA well identification number	Well construction information			Hydrologic conditions			
	Well depth (ft bls)	Top of screened or open interval (ft bls)	Bottom of screened or open interval (ft bls)	Depth classification [spring (SP), shallow well (SH), overlapping well (OL), deep well (DP)]	Elevation of land-surface datum (ft above NAVD 88)	Aridity index (dimensionless)	Latitude (degrees in NAD 83)
Metamorphic aquifer lithology—Continued							
SIERRA-M-06	190	150	190	OL	3,361	1.56	39.52
SIERRA-ML-01	130	70	130	SH	3,848	0.26	35.10
SIERRA-ML-02	165	140	165	SH	2,967	0.24	35.59
SIERRA-ML-03	190	50	190	OL	3,522	0.41	35.72
SIERRA-ML-04	–	–	–	Unknown well	3,554	0.37	35.93
SIERRA-ML-05	300	60	300	OL	4,203	0.71	36.70
SIERRA-ML-06	75	30	75	SH	962	0.35	36.43
SIERRA-ML-07	300	–	–	OL or DP	4,813	0.74	36.14
SIERRA-ML-08	122	–	–	SH	872	0.44	37.61
SIERRA-ML-09	250	124	250	OL	3,699	0.74	37.27
SIERRA-ML-10	275	–	–	OL or DP	1,546	0.61	38.04
SIERRA-ML-11	na	na	na	SP	8,120	1.07	36.45
SIERRA-ML-12	360	100	360	OL	3,094	0.83	37.82
SIERRA-ML-13	1000	60	890	OL	2,080	0.75	38.44
SIERRA-ML-14	na	na	na	SP	6,780	1.18	38.88
SIERRA-ML-15	171	–	–	SH	3,443	0.88	39.94
SIERRA-ML-16	70	–	–	SH	8,309	0.87	37.68
SIERRA-ML-17	245	100	245	OL	1,343	0.58	38.36
SIERRA-ML-18	225	55	225	OL	1,920	0.88	39.01
Sedimentary aquifer lithology							
SIERRA-S-01	120	78	120	SH	2,653	0.20	35.67
SIERRA-S-02	600	130	310	OL	6,304	0.89	38.86
SIERRA-S-03	520	110	520	OL	4,845	0.51	39.81
SIERRA-SL-01	400	200	400	DP	4,183	0.25	35.11
SIERRA-SL-02	55	10	55	SH	2,643	0.19	35.74
SIERRA-SL-03	155	20	155	SH	783	0.24	36.10
SIERRA-SL-04	360	259	360	DP	563	0.14	35.44
SIERRA-SL-05	na	na	na	SP	5,920	1.11	38.34
SIERRA-SL-06	490	260	490	DP	5,633	0.49	38.77
SIERRA-SL-07	800	360	780	DP	3,944	0.91	37.74
SIERRA-SL-08	200	110	196	OL	3,550	0.94	40.08
SIERRA-SL-09	na	na	na	SP	5,174	0.65	39.56
SIERRA-SL-10	163	–	–	SH	9,918	0.41	36.45
SIERRA-SL-11	300	50	280	OL	5,212	0.20	37.32

Table B3. Hydrologic conditions and well construction information for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[**Depth classification:** spring, no vertically drilled hole and groundwater emerges at the land surface without a pump; shallow well, bottom of screened or open interval < 170 feet below land surface datum (ft bls); overlapping well, top of screened or open interval < 170 ft bls and bottom of screened or open interval > 170 ft bls; deep well, top of screened or open interval > 170 ft bls; unknown well, no construction information available for the well. **Abbreviations:** NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; –, no data available; na, not applicable; <, less than; >, greater than]

GAMA well identification number	Well construction information			Hydrologic conditions			
	Well depth (ft bls)	Top of screened or open interval (ft bls)	Bottom of screened or open interval (ft bls)	Depth classification [spring (SP), shallow well (SH), overlapping well (OL), deep well (DP)]	Elevation of land-surface datum (ft above NAVD 88)	Aridity index (dimensionless)	Latitude (degrees in NAD 83)
Sedimentary aquifer lithology—Continued							
SIERRA-SL-12	77	77	77	SH	505	0.87	39.74
SIERRA-SL-13	na	na	na	SP	7,980	0.86	37.03
Volcanic aquifer lithology							
SIERRA-V-01	na	na	na	SP	6,758	1.34	39.18
SIERRA-V-02	702	280	702	DP	2,364	1.34	39.82
SIERRA-V-03	220	60	220	OL	7,654	0.60	37.63
SIERRA-VL-01	93	–	–	SH	2,801	0.21	35.31
SIERRA-VL-02	580	–	–	OL or DP	5,570	0.90	38.15
SIERRA-VL-03	280	131	280	OL	5,677	0.57	38.69
SIERRA-VL-04	307	57	307	OL	3,072	0.81	37.85
SIERRA-VL-05	500	445	500	DP	3,591	0.95	38.58
SIERRA-VL-06	383	363	383	DP	5,596	0.59	39.37
SIERRA-VL-07	380	51	380	OL	5,391	1.79	39.32
SIERRA-VL-08	na	na	na	SP	4,551	0.39	40.42
SIERRA-VL-09	na	na	na	SP	5,340	0.71	39.83
SIERRA-VL-10	na	na	na	SP	4,564	1.59	39.32
SIERRA-VL-11	400	50	400	OL	4,015	0.89	38.04
SIERRA-VL-12	930	235	930	DP	3,991	1.17	39.06

Groundwater Age Classification

As noted earlier, groundwater dating techniques provide estimates of the time elapsed since a given parcel of groundwater entered the saturated zone. The techniques used in this report to estimate groundwater residence times or “age” were those based on tritium (for example: Tolstikhin and Kamenskiy, 1969; Torgersen and others, 1979) and ¹⁴C activities (for example: Vogel and Ehhalt, 1963; Plummer and others, 1993).

Tritium is a short-lived radioactive isotope of hydrogen with a half-life of 12.32 years (Lucas and Unterweger, 2000). Produced naturally in the atmosphere from the interaction of cosmogenic radiation with nitrogen (Craig and Lal, 1961), or anthropogenically through above-ground nuclear explosions and the operation of nuclear reactors, tritium enters the hydrologic cycle following exchange with protium (¹H) in water to form “tritiated water.” Above-ground nuclear

explosions resulted in a large increase in tritium values in precipitation, beginning in about 1952 and peaking in 1963 at values over 1,000 tritium units (TU) in the northern hemisphere (Michel, 1989).

A range of tritium values from 0.2 to 1.0 TU have been used in previous investigations 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 SNR study unit in 2008, two groundwater age thresholds were defined on the basis of tritium values: tritium values greater than 0.25 TU were deemed to indicate the presence of some groundwater recharged since 1952, and tritium values greater than 1.5 were considered to indicate a predominance of groundwater recharged since 1952. The lower threshold of 0.25 TU was selected because background tritium values in California precipitation under natural conditions are expected to range

from 2 to 6 TU (Robert Michel, U.S. Geological Survey, written commun., 2013), and values in precipitation at the latitudes and longitudes corresponding to the SNR study unit are approximately 5 to 6 TU (Michel, 1989). Radioactive decay of tritium in water with a tritium value of 6 TU in 1950 would have a tritium value of 0.25 TU in 2008. The upper threshold of 1.5 TU was selected because all samples with tritium less than 1.5 TU had ¹⁴C activities of less than 100 percent modern carbon (pmC), as determined using the approach described below.

¹⁴C is a widely used chronometer that is based on the radiocarbon content of organic and inorganic carbon. ¹⁴C is formed in the atmosphere by the interaction of cosmic-ray neutrons with nitrogen and, to a lesser degree, with oxygen and carbon. ¹⁴C is incorporated into carbon dioxide and mixed throughout the atmosphere. The carbon dioxide enters the hydrologic cycle because it dissolves in precipitation and surface water in contact with the atmosphere. As a result, dissolved inorganic carbon species (primarily carbonic acid, bicarbonate, and carbonate) are commonly used for ¹⁴C dating of groundwater. ¹⁴C activity in groundwater, expressed as pmC, reflects the time elapsed since groundwater was last exposed to the atmospheric ¹⁴C. ¹⁴C has a half-life of 5,730 years and, as such, can be used to estimate groundwater ages ranging from 1,000 to approximately 30,000 years before present (Clark and Fritz, 1997).

¹⁴C data may be reported in units of percent modern (pM) or in units of pmC. ¹⁴C data for the SNR study unit in Shelton and others (2010) are given in pM units as reported by the analyzing laboratory. ¹⁴C data in pM units have been normalized for carbon isotopic fractionation based on a δ¹³C value of -25 per mil (‰). The un-normalized ¹⁴C data in pmC units are used in this report. Data were converted from pM to pmC using following equation derived from Plummer and others (2004):

$$pmC = \frac{pM \left(1 + \frac{\delta^{13}C}{1,000} \right)^2}{0.975^2}, \quad (B1)$$

where

pM is the ¹⁴C value in units of pM, and
 δ¹³C is the measured ¹³C composition in units of per mil.

The ¹⁴C age (residence time, presented in years) is calculated based on the decrease in ¹⁴C content as a result of radioactive decay since groundwater recharge, relative to an assumed initial ¹⁴C content (Clark and Fritz, 1997). Groundwater ages are reported as radiocarbon ages, in years before 1950:

$$\text{radiocarbon age} = \frac{5,568}{\ln(2)} \times \ln \left(\frac{A_0}{A} \right) - \frac{D_{\text{samp}} - 1950}{1.029}, \quad (B2)$$

where

5,568 is the Libby half-life for ¹⁴C, in years,
*A*₀ is the initial ¹⁴C content, assumed to be 99 pmC,
A is the measured ¹⁴C content, in pmC, and
*D*_{samp} is the date of sample collection in decimal years.

Calculated radiocarbon ages in this study are referred to as “uncorrected” because they have not been adjusted to consider water-rock interactions, such as exchanges with sedimentary sources of carbon (Fontes and Garnier, 1979). Estimated errors in radiocarbon ages are up to ±20 percent. Groundwater with a ¹⁴C content of >88 pmC is reported as having an age of <1,000 years; no attempt is made to refine ¹⁴C ages <1,000 years. Measured values of percent modern carbon can be >100 pmC because the definition of the ¹⁴C content in “modern” carbon does not include the excess ¹⁴C produced in the atmosphere by above-ground nuclear weapons testing (Clark and Fritz, 1997). For samples collected for the SNR study unit in 2008, ¹⁴C 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 all samples with tritium values less than 0.25 TU also had ¹⁴C values less than 90 pmC.

The age distributions in groundwater samples were classified as pre-modern, modern, and mixed using the thresholds for tritium and ¹⁴C values as shown in [table B4](#). Samples with tritium ≥1.5 TU and ¹⁴C ≥ 90 pmC were classified as modern; samples with tritium <0.25 TU and ¹⁴C < 90 pmC were classified as pre-modern; all other samples were classified as mixed. Tritium concentrations, uncorrected ¹⁴C age, and age classifications for the samples are listed in [table B5](#).

Although more sophisticated lumped parameter models have been introduced for analyzing age distributions that incorporate mixing (for example, Cook and Böhlke, 2000), use of these alternative models to characterize age mixtures was beyond the scope of this report. Rather, classification into modern (recharged after 1952), mixed, and pre-modern (recharged before 1952) categories was sufficient to provide an appropriate and useful characterization for examining groundwater quality.

Table B4. Tritium and carbon-14 threshold values used for groundwater age classification for the Sierra Nevada Regional study (SNR) unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Abbreviations: TU, tritium units; pmC, percent modern carbon; >, greater than; <, less than; ≥, greater than or equal to]

Age class	Number of samples	Threshold values	
		Tritium (TU)	¹⁴ C (pmC)
Pre-modern	7	<0.25	<90
Mixed	14	>0.25 and <1.5	any
Mixed	17	≥1.5	<90
Modern	42	≥1.5	≥90
Modern or mixed	3	≥1.5	No data

Table B5. Tritium and carbon-14 data and groundwater age classifications for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Groundwater age classification based on tritium and carbon-14 data (see [table B4](#)). **Abbreviations:** $\delta^{13}\text{C}$, delta carbon-13 ; ^{14}C , carbon-14; TU, tritium units; –, not available; <, less than]

GAMA well identification number	Tritium (TU)	Percent modern carbon	Uncorrected ^{14}C age (years)	$\delta^{13}\text{C}$	Groundwater age classification
Granitic aquifer lithology					
SIERRA-G-01	0.25	60	4,110	-14.5	Pre-modern
SIERRA-G-02	4.16	90	<1,000	-16.7	Modern
SIERRA-G-03	0.34	72	2,540	-14.4	Mixed
SIERRA-G-04	2.85	110	<1,000	-20.7	Modern
SIERRA-G-05	2.13	111	<1,000	-17.9	Modern
SIERRA-G-06	0.68	82	1,520	-19.1	Mixed
SIERRA-G-07	3.63	107	<1,000	-20.9	Modern
SIERRA-G-08	2.44	106	<1,000	-20.9	Modern
SIERRA-G-09	2.88	111	<1,000	-20.7	Modern
SIERRA-G-10	2.94	103	<1,000	-16.3	Modern
SIERRA-G-11	3.04	105	<1,000	-19.5	Modern
SIERRA-G-12	2.50	107	<1,000	-17.4	Modern
SIERRA-G-13	2.60	110	<1,000	-19.6	Modern
SIERRA-G-14	2.69	108	<1,000	-20.8	Modern
SIERRA-G-15	1.50	66	3,270	-17.7	Mixed
SIERRA-G-16	4.51	80	1,700	-18.3	Mixed
SIERRA-G-17	3.54	101	<1,000	-16.4	Modern
SIERRA-G-18	4.76	88	<1,000	-15.3	Mixed
SIERRA-GL-01	1.53	106	<1,000	-15.5	Modern
SIERRA-GL-02	2.69	107	<1,000	-19.7	Modern
SIERRA-GL-03	4.89	76	2,180	-13.2	Mixed
SIERRA-GL-04	3.85	106	<1,000	-17.0	Modern
SIERRA-GL-05	5.42	106	<1,000	-21.1	Modern
SIERRA-GL-06	2.47	115	<1,000	-21.1	Modern
SIERRA-GL-07	3.22	117	<1,000	-19.0	Modern
SIERRA-GL-08	2.53	110	<1,000	-19.8	Modern
SIERRA-GL-09	2.69	116	<1,000	-22.2	Modern
SIERRA-GL-10	4.04	81	1,590	-15.4	Mixed
Metamorphic aquifer lithology					
SIERRA-M-01	1.37	74	2,380	-15.3	Mixed
SIERRA-M-02	1.47	62	3,730	-16.2	Mixed
SIERRA-M-03	0.56	–	–	–	Mixed
SIERRA-M-04	3.22	66	3,290	-14.1	Mixed
SIERRA-M-05	1.34	71	2,720	-20.5	Mixed
SIERRA-M-06	3.10	96	<1,000	-20.4	Modern
SIERRA-ML-01	1.56	73	2,520	-11.5	Mixed
SIERRA-ML-02	2.47	110	<1,000	-15.3	Modern
SIERRA-ML-03	2.10	98	<1,000	-16.1	Modern
SIERRA-ML-04	2.53	44	6,470	-6.6	Modern or Mixed ¹
SIERRA-ML-05	3.47	119	<1,000	-18.9	Modern

Table B5. Tritium and carbon-14 data and groundwater age classifications for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Groundwater age classification based on tritium and carbon-14 data (see [table B4](#)). **Abbreviations:** $\delta^{13}\text{C}$, delta carbon-13 ; ^{14}C , carbon-14; TU, tritium units; –, not available; <, less than]

GAMA well identification number	Tritium (TU)	Percent modern carbon	Uncorrected ^{14}C age (years)	$\delta^{13}\text{C}$	Groundwater age classification
Metamorphic aquifer lithology—Continued					
SIERRA-ML-06	2.85	111	<1,000	-16.1	Modern
SIERRA-ML-07	0.21	51	5,310	-10.4	Pre-modern
SIERRA-ML-08	3.00	65	3,430	-14.1	Mixed
SIERRA-ML-09	1.59	91	<1,000	-19.7	Modern
SIERRA-ML-10	2.75	79	1,880	-16.5	Mixed
SIERRA-ML-11	3.73	89	<1,000	-15.6	Mixed
SIERRA-ML-12	2.88	–	–	-17.8	Modern or Mixed
SIERRA-ML-13	2.31	93	<1,000	-14.9	Modern
SIERRA-ML-14	4.07	94	<1,000	-18.5	Modern
SIERRA-ML-15	2.94	83	1,470	-15.3	Mixed
SIERRA-ML-16	1.84	96	<1,000	-15.7	Modern
SIERRA-ML-17	2.10	92	<1,000	-17.5	Modern
SIERRA-ML-18	2.94	82	1,580	-18.2	Mixed
Sedimentary aquifer lithology					
SIERRA-S-01	2.50	123	<1,000	-13.1	Modern
SIERRA-S-02	2.50	101	<1,000	-19.9	Modern
SIERRA-S-03	1.37	93	<1,000	-17.1	Mixed
SIERRA-SL-01	0.18	88	1,000	-12.4	Pre-modern
SIERRA-SL-02	3.82	24	11,340	-5.1	Modern or Mixed ¹
SIERRA-SL-03	2.66	106	<1,000	-12.5	Modern
SIERRA-SL-04	-0.09	1	38,860	-14.3	Pre-modern
SIERRA-SL-05	2.82	99	<1,000	-17.5	Modern
SIERRA-SL-06	0.34	92	<1,000	-16.3	Mixed
SIERRA-SL-07	2.75	105	<1,000	-17.6	Modern
SIERRA-SL-08	1.97	96	<1,000	-19.5	Modern
SIERRA-SL-09	0.28	89	<1,000	-17.8	Mixed
SIERRA-SL-10	5.26	85	1,230	-17.3	Mixed
SIERRA-SL-11	2.19	98	<1,000	-15.2	Modern
SIERRA-SL-12	0.62	98	<1,000	-18.0	Mixed
SIERRA-SL-13	2.75	109	<1,000	-19.8	Modern
Volcanic aquifer lithology					
SIERRA-V-01	1.66	99	<1,000	-18.2	Modern
SIERRA-V-02	0.90	92	<1,000	-20.5	Mixed
SIERRA-V-03	3.73	61	3,910	-11.8	Mixed
SIERRA-VL-01	2.10	86	1,140	-11.5	Mixed
SIERRA-VL-02	1.69	91	<1,000	-17.9	Modern
SIERRA-VL-03	2.31	62	3,840	-12.6	Mixed
SIERRA-VL-04	-0.12	86	1,170	-19.4	Pre-modern
SIERRA-VL-05	0.84	60	4,070	-19.9	Mixed
SIERRA-VL-06	0.06	27	10,390	-15.8	Pre-modern

Table B5. Tritium and carbon-14 data and groundwater age classifications for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Groundwater age classification based on tritium and carbon-14 data (see [table B4](#)). Abbreviations: $\delta^{13}\text{C}$, delta carbon-13 ; ^{14}C , carbon-14; TU, tritium units; –, not available; <, less than]

GAMA well identification number	Tritium (TU)	Percent modern carbon	Uncorrected ^{14}C age (years)	$\delta^{13}\text{C}$	Groundwater age classification
Volcanic aquifer lithology—Continued					
SIERRA-VL-07	2.28	65	3,370	-14.1	Mixed
SIERRA-VL-08	1.22	97	<1,000	-16.1	Mixed
SIERRA-VL-09	0.34	98	<1,000	-18.3	Mixed
SIERRA-VL-10	2.35	111	<1,000	-23.4	Modern
SIERRA-VL-11	3.60	102	<1,000	-18.8	Modern
SIERRA-VL-12	0.25	54	4,910	-17.1	Pre-modern

¹Samples are classified as modern or mixed because the $\delta^{13}\text{C}$ value suggests the dissolved carbonate system has been strongly affected by interaction with sedimentary carbon, which likely also altered the ^{14}C percent modern carbon value (for example, Clark and Fritz, 1997).

Geochemical Conditions

Oxidation-reduction (redox) conditions may 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 (TEAPs), 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. The microbes couple reduction of each of these electron acceptors with the oxidation of organic matter to produce energy needed for metabolism or growth. Groundwater samples may contain redox-active chemical species that suggest that 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 may not be consistent with one another, indicating the presence of electrochemical disequilibrium and complicating the assessment of redox conditions (Lindberg and Runnels, 1984; Appelo and Postma, 2005).

Oxidation-reduction conditions were classified on the basis of 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) ([table B6](#)). The 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 (66 of the 83 sites [80 percent]), the groundwater was classified as oxic ($\text{DO} \geq 1$ mg/L). Anoxic conditions ($\text{DO} < 1$ mg/L), present in 17 of the 83 wells (20 percent), were further classified as either suboxic, nitrate-reducing, manganese-reducing, or manganese- and iron-reducing ([table B7](#)).

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 may provide information about the progress of the TEAP involving the constituent. The following ratios are reported in [table B7](#):

- $\text{As}^{+5}/\text{As}^{+3}$, 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);
- $\text{Fe}^{+3}/\text{Fe}^{+2}$, 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 (2010). The concentrations of As^{+5} and Fe^{+3} were calculated from these data by difference. $\text{As}^{+5}/\text{As}^{+3}$ was reported as greater than 10 if the total arsenic concentration was above the reporting limit and As^{+3} was not detected. $\text{As}^{+5}/\text{As}^{+3}$ was reported as less than 0.01 if the total arsenic concentration equaled the As^{+3} concentration. Similarly, $\text{Fe}^{+3}/\text{Fe}^{+2}$ was reported as greater than 10 if the total iron 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.

Table B6. Dissolved oxygen, nitrate, manganese, and iron concentration threshold values used for oxidation-reduction classification for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Anoxic sub-classes: NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing. Units: mg/L, milligrams per liter; µg/L, micrograms per liter. Abbreviations: <, less than; ≥, greater than or equal to]

Class	Number of samples	Threshold values			
		Dissolved oxygen (mg/L)	Nitrate-N (mg/L)	Manganese (µg/L)	Iron (µg/L)
Oxic	66	≥1	Any	<50	<100
Anoxic—suboxic	6	<1	<0.5	<50	<100
Anoxic—NO ₃ -red	3	<1	≥0.5	<50	<100
Anoxic—Mn-red	1	<1	<0.5	≥50	<100
Anoxic—MnFe-red	7	<1	<0.5	≥50	≥100

Table B7. Oxidation-reduction classification, dissolved oxygen concentrations, pH, and oxidation-reduction species ratios for arsenic and iron for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

[Oxidation-reduction classification: NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese- and iron-reducing. See table B6 for definitions of classes. Ratios of oxidized to reduced species of metals: As⁺⁵/As⁺³, ratio of the amount of arsenic in the +5 oxidation state (arsenate) to the amount in the +3 oxidation state (arsenite); Fe⁺³/Fe⁺², ratio of the amount of iron in the +3 oxidation state (ferric iron) to the amount in the +2 oxidation state (ferrous iron). Abbreviations: µg/L, micrograms per liter; mg/L, milligrams per liter; >, greater than; <, less than; ≤, less than or equal to; na, not available; –, concentration too low to measure ratio; x, not anoxic]

GAMA well identification number	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification	Sub-class for anoxic samples	Ratios of oxidized and reduced species of metals	
					As ⁺⁵ /As ⁺³	Fe ⁺³ /Fe ⁺²
Granitic aquifer lithology						
SIERRA-G-01	7.7	0.3	Anoxic	Suboxic	–	–
SIERRA-G-02	5.9	7.3	Oxic	x	–	–
SIERRA-G-03	6.6	≤0.2	Anoxic	NO ₃ -red	–	–
SIERRA-G-04	7.5	na ¹	Oxic	x	–	–
SIERRA-G-05	6.5	5.8	Oxic	x	–	–
SIERRA-G-06	7.5	≤0.2	Anoxic	Suboxic	–	–
SIERRA-G-07	6.2	2.1	Oxic	x	–	0.18
SIERRA-G-08	5.8	5.2	Oxic	x	–	–
SIERRA-G-09	5.4	7.6	Oxic	x	–	–
SIERRA-G-10	6.4	4.7	Oxic	x	–	–
SIERRA-G-11	6.3	9.4	Oxic	x	–	–
SIERRA-G-12	6.6	7.5	Oxic	x	–	–
SIERRA-G-13	6.2	9.8	Oxic	x	–	–
SIERRA-G-14	6.3	4.8	Oxic	x	–	–
SIERRA-G-15	9.1	≤0.2	Anoxic	Suboxic	–	–
SIERRA-G-16	6.4	8.4	Oxic	x	–	–
SIERRA-G-17	8.6	9.9	Oxic	x	² >10	–
SIERRA-G-18	6.3	8.1	Oxic	x	–	–
SIERRA-GL-01	6.9	6.6	Oxic	x	³ >10	–
SIERRA-GL-02	6.3	2.6	Oxic	x	–	–
SIERRA-GL-03	7.3	9.2	Oxic	x	–	–

Table B7. Oxidation-reduction classification, dissolved oxygen concentrations, pH, and oxidation-reduction species ratios for arsenic and iron for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Oxidation-reduction classification: NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese- and iron-reducing. See table B6 for definitions of classes. Ratios of oxidized to reduced species of metals: As⁺⁵/As⁺³, ratio of the amount of arsenic in the +5 oxidation state (arsenate) to the amount in the +3 oxidation state (arsenite); Fe⁺³/Fe⁺², ratio of the amount of iron in the +3 oxidation state (ferric iron) to the amount in the +2 oxidation state (ferrous iron). Abbreviations: µg/L, micrograms per liter; mg/L, milligrams per liter; >, greater than; <, less than; ≤, less than or equal to; na, not available; –, concentration too low to measure ratio; x, not anoxic]

GAMA well identification number	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification	Sub-class for anoxic samples	Ratios of oxidized and reduced species of metals	
					As ⁺⁵ /As ⁺³	Fe ⁺³ /Fe ⁺²
Granitic aquifer lithology—Continued						
SIERRA-GL-04	6.0	3.4	Oxic	x	–	–
SIERRA-GL-05	6.9	7.9	Oxic	x	–	–
SIERRA-GL-06	5.8	8.8	Oxic	x	–	–
SIERRA-GL-07	6.8	7.6	Oxic	x	–	–
SIERRA-GL-08	6.0	9.5	Oxic	x	–	–
SIERRA-GL-09	5.5	7.3	Oxic	x	–	–
SIERRA-GL-10	7.5	2.4	Oxic	x	–	2.00
Metamorphic aquifer lithology						
SIERRA-M-01	7.7	≤0.2	Anoxic	Suboxic	–	–
SIERRA-M-02	7.2	≤0.2	Anoxic	MnFe-red	–	³ 0.23
SIERRA-M-03	7.4	3.9	Oxic	x	–	–
SIERRA-M-04	7.4	6.5	Oxic	x	–	–
SIERRA-M-05	7.0	0.3	Anoxic	MnFe-red	–	³ 0.01
SIERRA-M-06	6.0	9.6	Oxic	x	–	–
SIERRA-ML-01	7.3	3.1	Oxic	x	² –	–
SIERRA-ML-02	7.1	6.3	Oxic	x	² >10	–
SIERRA-ML-03	7.0	0.3	Anoxic	NO ₃ -red	² –	–
SIERRA-ML-04	6.3	3.3	Oxic	x	–	–
SIERRA-ML-05	5.9	10.0	Oxic	x	–	–
SIERRA-ML-06	7.0	5.6	Oxic	x	–	–
SIERRA-ML-07	7.6	1.9	Oxic	x	–	–
SIERRA-ML-08	6.9	0.3	Anoxic	NO ₃ -red	–	–
SIERRA-ML-09	6.7	4.5	Oxic	x	–	–
SIERRA-ML-10	7.1	7.3	Oxic	x	² >10	–
SIERRA-ML-11	7.5	11.6	Oxic	x	–	–
SIERRA-ML-12	6.8	≤0.2	Anoxic	MnFe-red	–	³ <0.01
SIERRA-ML-13	7.0	2.7	Oxic	x	–	0.29
SIERRA-ML-14	6.9	10.8	Oxic	x	–	–
SIERRA-ML-15	6.5	6.5	Oxic	x	–	–
SIERRA-ML-16	7.3	≤0.2	Anoxic	MnFe-red	² 0.26	³ 0.04
SIERRA-ML-17	6.6	7.1	Oxic	x	–	3.33
SIERRA-ML-18	6.6	2.1	Oxic	x	–	–
Sedimentary aquifer lithology						
SIERRA-S-01	7.3	6.6	Oxic	x	–	–
SIERRA-S-02	8.7	3.6	Oxic	x	² >10	–
SIERRA-S-03	6.9	2.7	Oxic	x	–	–

Table B7. Oxidation-reduction classification, dissolved oxygen concentrations, pH, and oxidation-reduction species ratios for arsenic and iron for wells sampled by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[**Oxidation-reduction classification:** NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese- and iron-reducing. See table B6 for definitions of classes. **Ratios of oxidized to reduced species of metals:** As⁺⁵/As⁺³, ratio of the amount of arsenic in the +5 oxidation state (arsenate) to the amount in the +3 oxidation state (arsenite); Fe⁺³/Fe⁺², ratio of the amount of iron in the +3 oxidation state (ferric iron) to the amount in the +2 oxidation state (ferrous iron). **Abbreviations:** µg/L, micrograms per liter; mg/L, milligrams per liter; >, greater than; <, less than; ≤, less than or equal to; na, not available; –, concentration too low to measure ratio; x, not anoxic]

GAMA well identification number	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification	Sub-class for anoxic samples	Ratios of oxidized and reduced species of metals	
					As ⁺⁵ /As ⁺³	Fe ⁺³ /Fe ⁺²
Sedimentary aquifer lithology—Continued						
SIERRA-SL-01	7.5	6.1	Oxic	x	–	–
SIERRA-SL-02	6.3	0.5	Anoxic	MnFe-red	³ 0.12	³ <0.01
SIERRA-SL-03	7.3	1.7	Oxic	x	² >10	–
SIERRA-SL-04	8.9	≤0.2	Anoxic	Suboxic	–	–
SIERRA-SL-05	6.4	9.2	Oxic	x	–	–
SIERRA-SL-06	6.8	4.8	Oxic	x	–	–
SIERRA-SL-07	7.1	7.7	Oxic	x	–	–
SIERRA-SL-08	6.7	2.5	Oxic	x	–	–
SIERRA-SL-09	7.5	9.7	Oxic	x	–	–
SIERRA-SL-10	7.0	7.5	Oxic	x	–	–
SIERRA-SL-11	7.2	4.5	Oxic	x	–	–
SIERRA-SL-12	7.3	0.3	Anoxic	MnFe-red	² 0.05	³ 0.15
SIERRA-SL-13	5.7	5.8	Oxic	x	–	–
Volcanic aquifer lithology						
SIERRA-V-01	7.4	9.3	Oxic	x	–	–
SIERRA-V-02	7.0	6.2	Oxic	x	–	–
SIERRA-V-03	6.5	⁴ >1	Oxic	x	³ >10	–
SIERRA-VL-01	7.1	4.4	Oxic	x	–	–
SIERRA-VL-02	6.6	6.2	Oxic	x	–	–
SIERRA-VL-03	7.9	≤0.2	Anoxic	Suboxic	0.18	0.33
SIERRA-VL-04	6.4	4.2	Oxic	x	–	–
SIERRA-VL-05	7.2	6.4	Oxic	x	–	–
SIERRA-VL-06	7.9	≤0.2	Anoxic	Mn-red	³ 2.91	3.84
SIERRA-VL-07	7.5	0.3	Anoxic	MnFe-red	–	³ 0.07
SIERRA-VL-08	7.1	8.6	Oxic	x	–	–
SIERRA-VL-09	7.2	8.8	Oxic	x	–	–
SIERRA-VL-10	5.2	8.8	Oxic	x	–	–
SIERRA-VL-11	6.2	5.6	Oxic	x	–	² 0.16
SIERRA-VL-12	7.5	4.0	Oxic	x	–	0.67

¹The median dissolved oxygen concentration of USGS-GAMA samples from springs with granitic aquifer lithology and oxic conditions was assigned to SIERRA-G-04 for the statistical tests of relations between dissolved oxygen concentrations and potential explanatory factors and water-quality constituents.

²Moderate relative-concentration (5–10 µg/L arsenic or 150–300 µg/L iron).

³High relative-concentration (>10 µg/L arsenic or >300 µg/L iron).

⁴The median dissolved oxygen concentration of USGS-GAMA samples from wells with volcanic aquifer lithology and oxic conditions was assigned to SIERRA-V-03 for the statistical tests of relations between dissolved oxygen concentrations and potential explanatory factors and water-quality constituents.

Appendix C. Effect of Data Gaps on Aquifer-Scale Proportions for Inorganic Constituents

Of the 1,266 wells used in this study, 1,224 had data for at least 1 inorganic constituent with a health-based benchmark during the period May 2006 through October 2008. For 176 of these wells, the source of the nutrient and trace element data used in this study was samples collected by the USGS for the SNR study unit (83 samples; Shelton and others, 2010) or the Tahoe-Martis, Central Sierra, and Southern Sierra study units (83 samples; Fram and Belitz, 2012). Seventy-two of the Tahoe-Martis, Central Sierra, and Southern Sierra study unit wells were in just 4 SNR study unit sub-cells (13G, 18S, 18V, 25S). Samples collected by the USGS were analyzed for 21 to 26 inorganic constituents with health-based benchmarks. Of the 1,048 wells for which the source of the nutrient and trace element data was the CDPH database, only 224 wells had data for 10 or more inorganic constituents with health-based benchmarks. Wells with data for inorganic constituents with health-based benchmarks were unevenly distributed among the SNR study unit sub-cells ([table C1](#)).

The reason that so many of the CDPH wells do not have data for the full suite of inorganic constituents is that the CDPH has different reporting requirements for different types of public-supply wells. All public water systems using groundwater are required to monitor annually for nitrate concentrations, and all community and non-transient, non-community water systems also are required to monitor once during each 3-year period for other inorganic constituents (California Department of Public Health, 2013c). Approximately 45 percent of the public-supply wells listed in the CDPH database for the SNR study unit are classified as transient, non-community, and are therefore not required to monitor for concentrations of other inorganic constituents. In addition, water systems may apply for a waiver to reduce the frequency of monitoring for inorganic constituents other than nitrate to once during every 9-year period if there have been no past exceedences of MCLs. As a result, the CDPH database contains nitrate data for samples collected from 1,040 wells during the period May 2006 through October 2008, but trace element, major ion, and radioactive constituent data for samples from only 225 to 275 wells during the same period.

The uneven distribution of data may affect the results of calculations of aquifer-scale proportions for classes of constituents if the aquifer-scale proportions of the constituents within the class are not similar. In the SNR study unit, this situation occurred most notably in the calculation of aquifer-scale proportions for the class of any inorganic constituent with health-based benchmarks. The high-RC aquifer-scale proportion for nitrate, 1.4 percent, was calculated using 1,131 wells, whereas the high-RC proportions for trace elements (11 percent) and radioactive constituents (8.2 percent) were calculated using 530 and 502 wells, respectively ([table 7B](#)). The high-RC aquifer-scale proportion for any inorganic constituent is 9.5 percent if it is calculated using all 1,224 wells with data for any inorganic constituent and is

16 percent if it is calculated using only the 671 wells with data for at least 1 trace element or radioactive constituent.

[Figure C1](#) illustrates a simple example of the problem. Out of 20 wells, 10 have data for both nitrate and arsenic, and 10 only have data for nitrate. Of the 20 wells with nitrate data, 2 have a high RC for nitrate, resulting in a high-RC proportion of 10 percent for nitrate. Of the 10 wells with arsenic data, 5 have a high RC for arsenic, giving a high-RC proportion for arsenic. There are two ways to calculate the high-RC proportion for any inorganic constituent—and they make different assumptions about the water-quality characteristics of the wells lacking arsenic data.

The first method is to calculate the high-RC proportion using only the wells that have data for both nitrate and arsenic, which yields a result of 50 percent for the high-RC proportion for any inorganic constituent. This method assumes that wells 1–10 are a representative subset of wells 1–20 and that the water-quality characteristics of wells 11–20 are the same as those of wells 1–10.

The second method is to calculate the high-RC proportion using all of the wells, which yields a result of 30 percent for the high-RC proportion for any inorganic constituent. This method assumes that the distribution of high RCs for nitrate in wells 11–20 is representative of the distribution of high RCs for other constituents in wells 11–20 and that the addition of arsenic data for wells 11–20 would not change the proportion of wells with high RCs for any inorganic constituent. In wells 1–10, however, the distribution of high RCs of nitrate is not representative of the distribution of high RCs of arsenic. In other words, this method assumes that the water-quality characteristics of wells 11–20 are not the same as those of wells 1–10.

Returning to the SNR study unit, assessment of major-ion data suggested that the subset of CDPH wells having data for major ions (and other inorganic constituents) may be biased towards wells at lower elevations ([appendix E](#)). In particular, wells from the western part of the central and southern Sierra Nevada may be over-represented in the dataset of wells with data for inorganic constituents. Concentrations of nitrate, arsenic, boron, and fluoride all showed significant negative correlations with elevation ([table 10B](#)). These relations suggest that the dataset as a whole may contain a higher proportion of wells with high RCs of these constituents than it would if all wells in the dataset had data for all constituents. However, the structure of the spatially weighted calculations mitigates the effect of having more data in one part of the study unit compared to another.

For this study, nothing indicates that within a given sub-cell, the water-quality characteristics of wells with more data should be different from those of wells with less data. Therefore, aquifer-scale proportions for the class of inorganic constituents with health-based benchmarks was calculated using only the 671 wells having data for at least 1 trace element or radioactive constituent (and generally for nitrate as well), rather than using the 1,224 wells having data for at least 1 inorganic constituent (only nitrate for nearly half of the wells).

Table C1. Sources of data for inorganic constituents with health-based benchmarks for Sierra Nevada Regional (SNR) study unit sub-cells, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Sources of data for inorganic constituents with health-based benchmarks: USGS SNR, samples collected and analyzed by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit (24 or 26 constituents); USGS TCS, samples collected and analyzed by USGS for the Tahoe-Martis, Central Sierra, and Southern Sierra study units (21 to 26 constituents); CDPH many, wells with data reported for 10 to 21 constituents in the California Department of Public Health (CDPH) database; CDPH few, wells with data reported for 1 to 7 constituents in the CDPH database. Inorganic constituents with health-based benchmarks include trace elements, nutrients, and radioactive constituents. —, no wells in that aquifer lithology sub-cell]

Cell	Granitic aquifer lithology (number of wells with data)						Metamorphic aquifer lithology (number of wells with data)						Sedimentary aquifer lithology (number of wells with data)						Volcanic aquifer lithology (number of wells with data)					
	USGS SNR	USGS	CDPH	CDPH	few	many	USGS SNR	USGS	CDPH	CDPH	few	many	USGS SNR	USGS	CDPH	CDPH	few	many	USGS SNR	USGS	CDPH	CDPH	few	many
Number of inorganic constituents	24 or 26	21 to 26	10 to 21	1 to 7	1 to 7		24 or 26	21 to 26	10 to 21	1 to 7	1 to 7		24 or 26	21 to 26	10 to 21	1 to 7	1 to 7	1 to 7	24 or 26	21 to 26	10 to 21	10 to 21	1 to 7	1 to 7
24	1	0	2	3	0		1	0	0	0	0		1	0	0	1	1	1	—	—	—	—	—	—
25	1	0	5	17	0		1	1	3	0	0		1	15	12	21	21	0	1	0	0	—	—	2
26	1	0	2	5	1		1	1	3	5	5		1	1	6	31	31	—	—	—	—	—	—	—
27	1	1	1	17	1		1	0	2	9	18		1	1	3	18	18	—	—	—	—	—	—	—
28	1	0	4	7	1		1	0	0	1	—		—	—	—	—	—	—	—	—	—	—	—	—
29	1	0	1	0	0		1	0	0	0	0		1	0	0	0	0	—	—	—	—	—	—	—
30	1	0	0	0	—		—	—	—	—	—		1	0	2	0	0	—	—	—	—	—	—	—

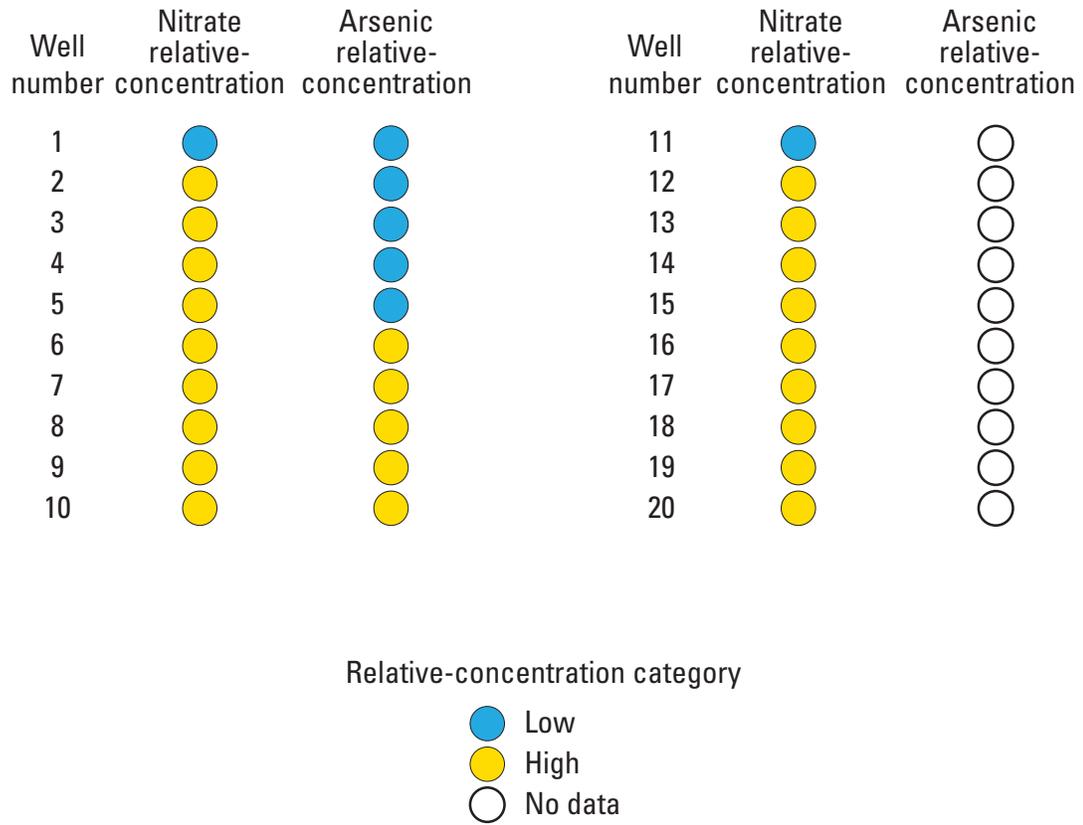


Figure C1. Hypothetical case of 20 wells used to illustrate the effect of uneven distribution of data on calculation of aquifer-scale proportions.

Appendix D. Radioactivity

The class of radioactive constituents includes constituents whose abundances commonly are measured as activities rather than concentrations. Activity is measured in units of picocuries per liter, and 1 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 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, 2009). Data collected by USGS-GAMA and data compiled in the CDPH database are reported as gross alpha particle activity without correction for uranium activity (“unadjusted”). Gross alpha 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, calculation of adjusted gross alpha particle activity is not always possible. For this reason, results for unadjusted gross alpha particle activity (that is, without correction for uranium) are the primary data used in the status assessments made by USGS-GAMA for Priority Basin Project study units. Results for adjusted gross alpha particle activity also are given in this report for comparison.

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 may 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 may change with time after sample collection due to radioactive decay of parent isotopes and ingrowth and subsequent decay of radioactive daughter isotopes (activity may 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 MCL-CA for uranium is 20 pCi/L. For samples having only uranium data in units of micrograms per liter, a conversion factor of 0.74 picocurie per microgram (pCi/μg) was used to convert the data to uranium activities. This conversion factor was obtained from the relation between uranium activities and concentrations in USGS-GAMA SNR study unit samples (Shelton and others, 2010):

$$U_{act} = 0.74 \times U_{mass} (R^2 = 0.988), \quad (D1)$$

where

- U_{mass} is the concentration of uranium in micrograms per liter, and
- U_{act} is the activity of uranium in picocuries per liter. Total uranium activity is assumed to equal the sum of the activities of the three uranium isotopes, uranium-234, -235, and -238.

Appendix E. Comparison of Major-Ion Data

Major-ion data for the 83 wells sampled by USGS-GAMA were compared with major-ion data from all wells in the CDPH database within the SNR study unit to determine whether the two datasets were representative of the same population of public-supply wells in the SNR study unit. The CDPH well dataset consisted of all wells within the study unit with a complete major-ion analysis between May 2006 and October 2008. If multiple analyses were available, the most recent one with an acceptable cation-anion balance was selected. The datasets were compared using Piper diagrams (Piper, 1944; Hem, 1992). Groundwater types are defined on a Piper diagram according to the cations and anions present in the greatest proportions (fig. E1).

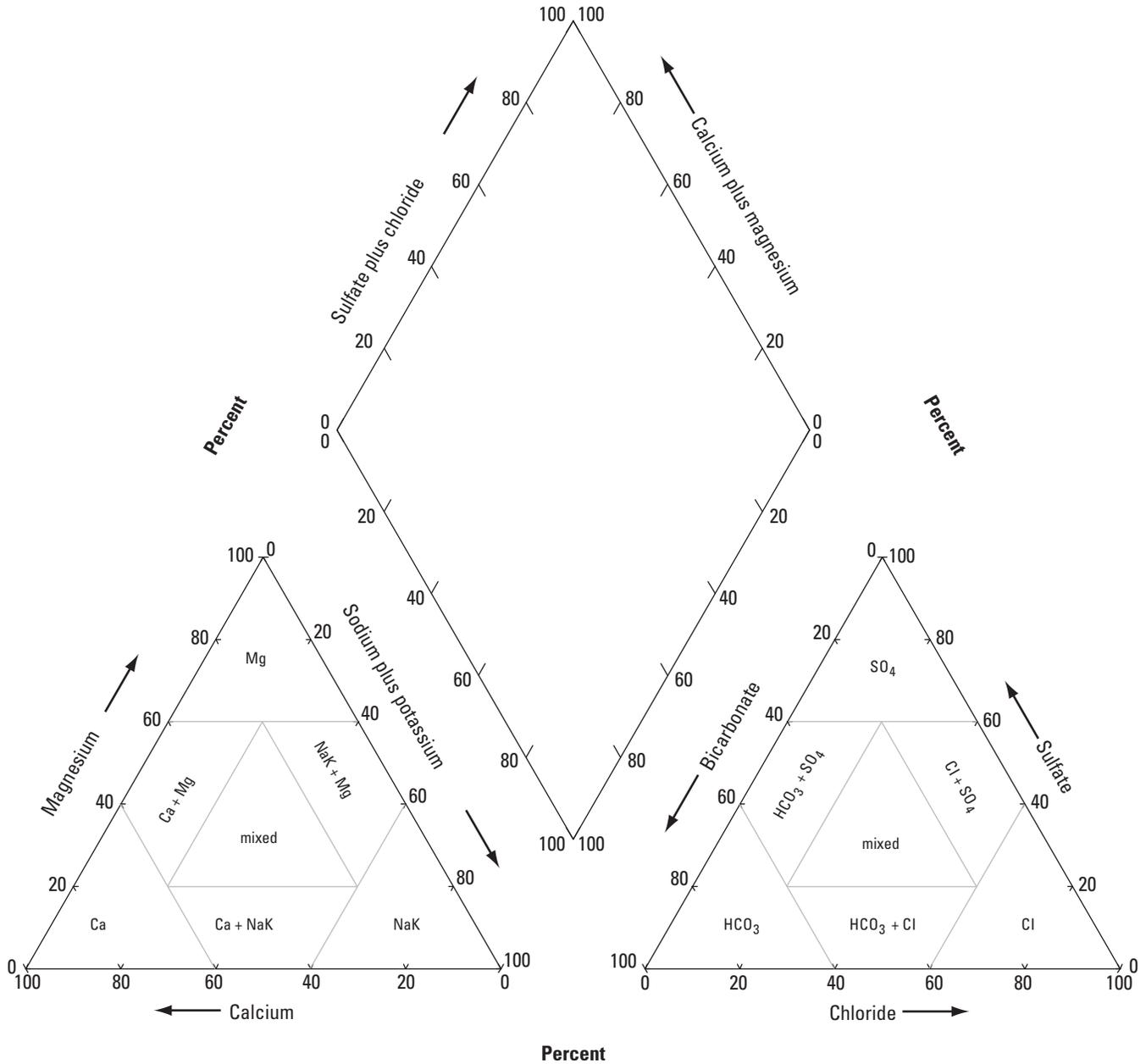
To minimize the use of poor-quality data, only major-ion analyses with acceptable cation-anion balances were plotted on the Piper diagrams. For electroneutrality, the total concentrations of positive charges in a water sample, expressed as milliequivalents of cations per liter, must equal the total concentration 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, 1992). 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.

Major-ion analyses from the CDPH database occasionally required adjustment of the reported alkalinity value to achieve acceptable cation-anion balance. The CDPH database has fields for bicarbonate alkalinity and total alkalinity, but the data in these fields were not always populated correctly. Total alkalinity is a measured value, and bicarbonate alkalinity is a calculated value that is typically 1.22 times the total alkalinity (in units of milligrams per liter as CaCO_3) for water with pH values in the range of pH values for most groundwater. This relation was not consistently observed in the CDPH database for the SNR study unit. In particular, total alkalinity and bicarbonate alkalinity were commonly reported as the same value. The second type of inconsistency was a total alkalinity value that was greater than the bicarbonate alkalinity, without the presence of sufficient sources of non-carbonate alkalinity to account for the difference. The third type of inconsistency was the presence of values for total alkalinity or bicarbonate alkalinity, but not both. For major-ion analyses with unacceptable cation-anion balances, cation-anion balance was recalculated by substituting trial values of total alkalinity. These trial values were calculated by assuming that the reported total alkalinity and bicarbonate alkalinity values were reversed or were incorrectly calculated from one another. Calculations were done assuming $\text{pK}_{a1} = 6.35$ and $\text{pK}_{a2} = 10.33$ for the carbonate equilibria and measured pH values. If no pH value was available, a pH of 7 was assumed.

If any substitution resulted in an acceptable cation-anion balance, the major-ion analysis with the substituted value was used for plotting the data on the Piper diagram. Of the 2,239 wells listed in the CDPH database for the SNR study unit, 1,236 wells have water-quality data for one or more constituents for samples collected between May 1, 2006, and October 31, 2008. Of these 1,236 wells, 234 have data for at least 1 complete major-ion analysis, and of those, 226 wells had a major-ion analysis with acceptable cation-anion balance.

The distribution of groundwater types represented by the USGS-GAMA wells was different from the distribution of groundwater types with major-ion data in the CDPH database (fig. E2). The anion composition of the water sampled from most of the wells in both datasets was classified as bicarbonate-type (HCO_3^-); however, the percentage of HCO_3^- -type wells in the USGS-GAMA dataset (93 percent) was significantly greater than the percentage of HCO_3^- -type wells in the CDPH dataset (82 percent) (fig. E3; contingency table test, $p = 0.020$). The cation compositions of wells in the USGS-GAMA and CDPH datasets also were significantly different (fig. E2; contingency table test, $p = 0.043$). Most of the difference between the datasets was due to the USGS-GAMA dataset having a significantly higher proportion of wells with calcium+magnesium (Ca+Mg) cation composition and a significantly lower proportion of wells with calcium+sodium+potassium (Ca+NaK) cation composition than the CDPH dataset (fig. E3).

The differences in anion and cation compositions between the USGS-GAMA and CDPH wells may be related to differences in the geographic distribution of wells in the two datasets. The USGS-GAMA wells are spatially distributed across the study unit. In contrast, the 226 CDPH wells predominantly are located on the western side of the central and southern parts of the study unit (fig. E4). Median elevation and latitude of the 83 USGS-GAMA wells were significantly greater than the median elevation and latitude of the 224 CDPH wells (Wilcoxon rank-sum test; $p < 0.001$). In the USGS-GAMA dataset, the fraction of HCO_3^- in the anions showed positive correlations with elevation and with latitude (Spearman's rho test, $p < 0.001$, $\rho = 0.43$ and 0.47 , respectively). The 226 CDPH wells with complete major-ion analyses included a significantly lower percentage of wells located at elevations greater than 7,000 ft than did the 1,010 CDPH wells with data for at least 1 constituent, but not a complete major-ion analysis (contingency table test, $p = 0.047$). The under-representation of wells located at elevations greater than 7,000 ft among the CDPH wells with major-ion analyses could therefore account for smaller proportion of wells having HCO_3^- as the dominant anion class in the CDPH wells compared to the USGS-GAMA dataset.



EXPLANATION

Cations		Anions	
Ca	Calcium	HCO ₃	Bicarbonate
Mg	Magnesium	Cl	Chloride
NaK	Sodium plus potassium	SO ₄	Sulfate

Figure E1. Definitions of groundwater types.

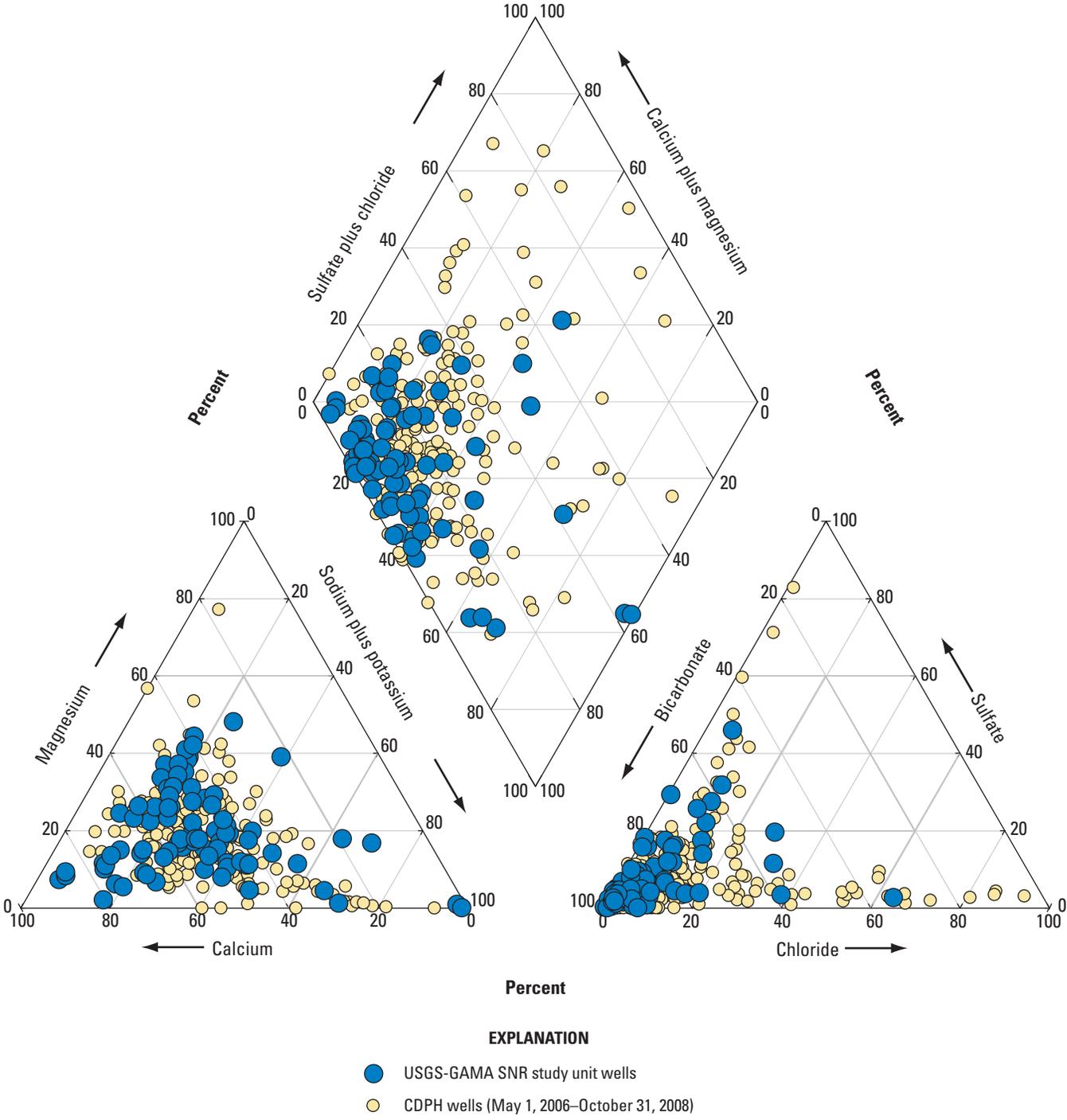


Figure E2. Groundwater types for samples collected by USGS-GAMA for the study unit and samples in the California Department of Public Health (CDPH) database having major-ion chemical analyses with acceptable cation-anion balance during May 2006 through October 2008, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

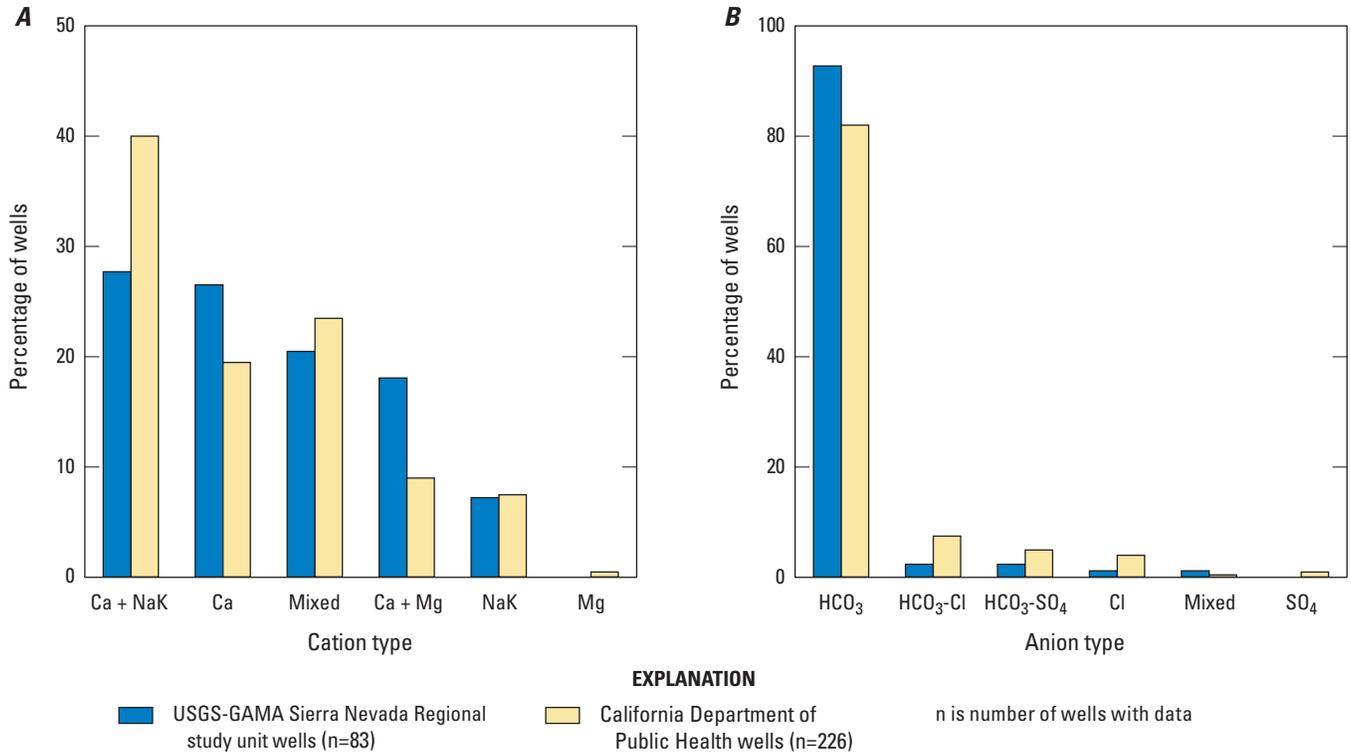


Figure E3. Percentages of USGS-GAMA and California Department of Public Health (CDPH) wells classified by groundwater type on the basis of (A) cation composition and (B) anion composition for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

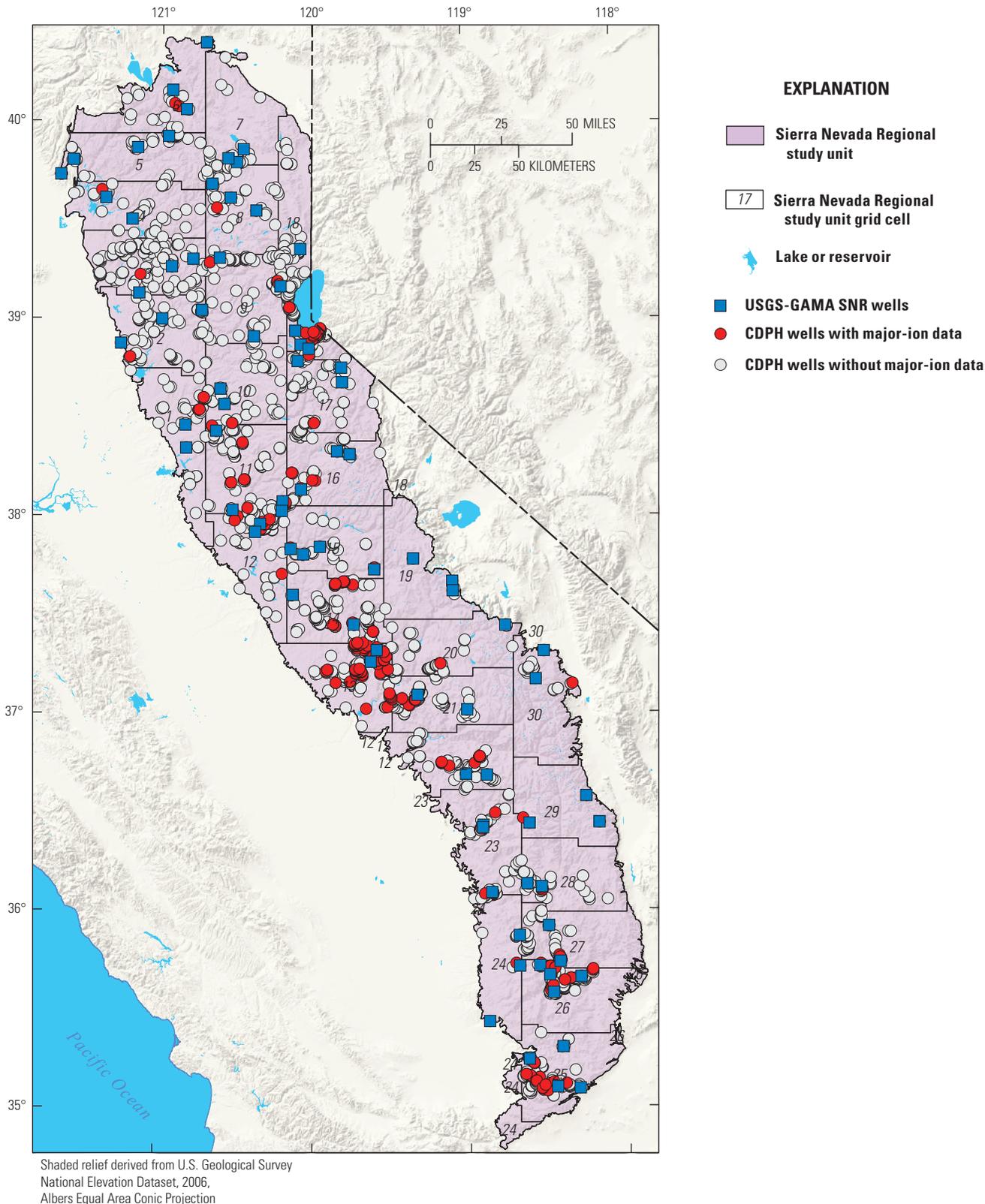


Figure E4. Locations of USGS-GAMA wells sampled for the Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project and wells in the California Department of Public Health (CDPH) database having major-ion chemical analyses with acceptable cation-anion balance during May 2006 through October 2008.

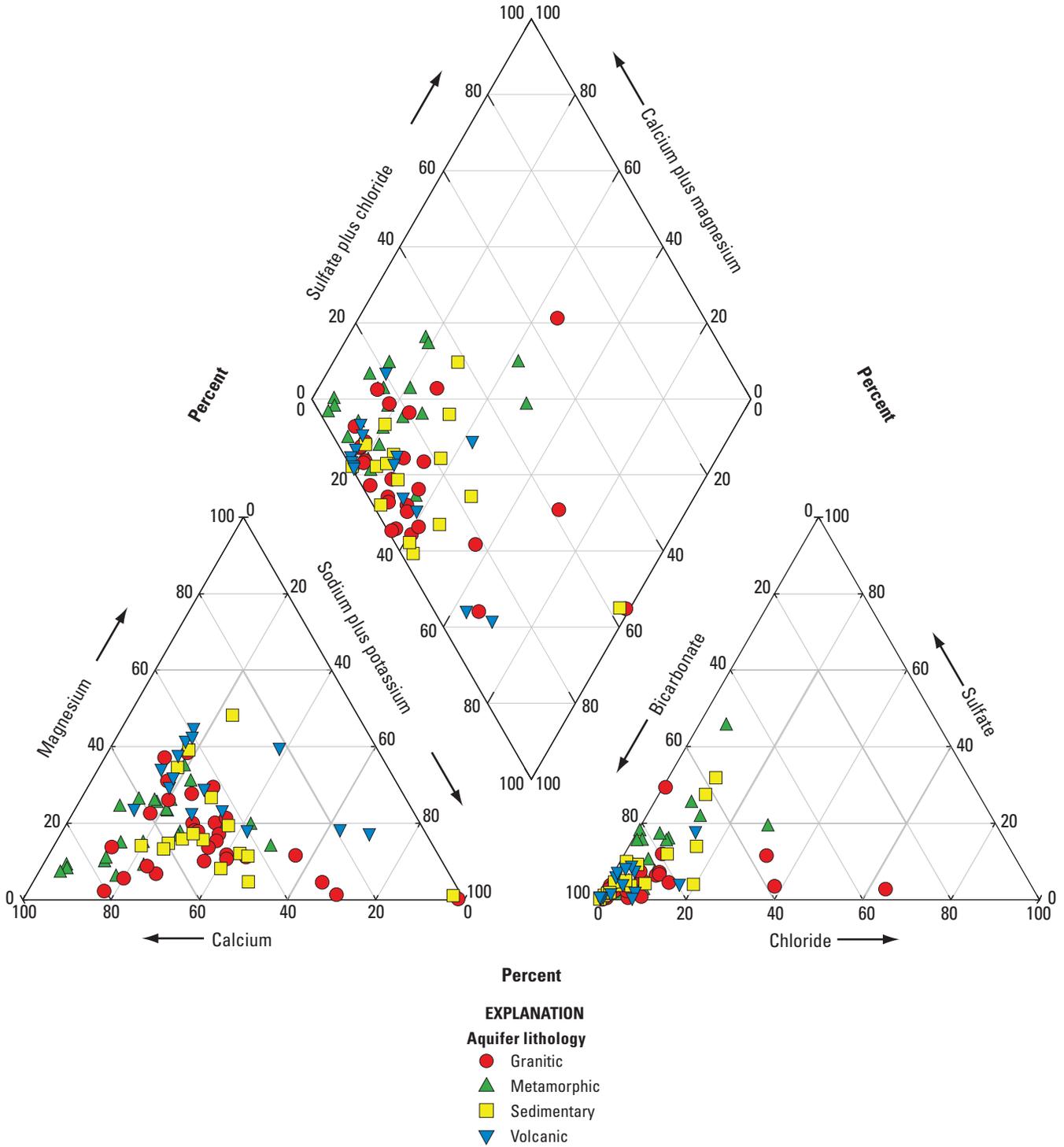


Figure E5. Groundwater types for samples collected by USGS-GAMA for the study unit from wells in the four aquifer lithologies, Sierra Nevada Regional study unit, 2008, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.

Appendix F. Additional Water-Quality Data

Noble gas data provided by Lawrence Livermore National Laboratory that were not available at the time of publication of the Data Series Report (Shelton and others, 2010) are tabulated in this appendix (table F1). These data were not used in this report; they are provided herein to complete the publication of all of the data collected for the study.

Table F1. Results for analyses of noble gases by Lawrence Livermore National Laboratory for samples collected by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (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. **Abbreviations:** cm³ STP/g H₂O, cubic centimeters at standard temperature and pressure per gram of water; na, not available]

GAMA well identification number	Helium-3/ Helium-4 (atom ratio) (61040)	Helium-4 (cm ³ STP/g H ₂ O) (85561)	Neon (cm ³ STP/g H ₂ O) (61046)	Argon (cm ³ STP/g H ₂ O) (85563)	Krypton (cm ³ STP/g H ₂ O) (85565)	Xenon (cm ³ STP/g H ₂ O) (85567)
	x 10 ⁻⁷	x 10 ⁻⁷	x 10 ⁻⁷	x 10 ⁻⁴	x 10 ⁻⁸	x 10 ⁻⁸
Granitic aquifer lithology						
SIERRA-G-01	12.72	1.04	4.00	4.86	9.93	1.25
SIERRA-G-02	13.89	0.41	1.82	3.41	8.12	1.18
SIERRA-G-03	1.12	39.42	2.53	3.39	7.27	0.94
SIERRA-G-04	na	na	na	na	na	na
SIERRA-G-05	13.26	0.53	3.46	3.81	7.76	1.02
SIERRA-G-06	5.71	40.53	2.75	3.81	8.47	1.15
SIERRA-G-07	14.22	0.43	1.65	3.26	7.69	1.06
SIERRA-G-08	13.71	0.59	2.60	4.04	9.15	1.26
SIERRA-G-09	14.00	0.44	2.07	3.46	7.10	1.14
SIERRA-G-10	11.81	0.76	1.95	3.43	8.06	1.16
SIERRA-G-11	12.88	0.40	1.77	3.09	7.42	1.04
SIERRA-G-12	13.15	0.39	1.75	2.89	6.53	0.91
SIERRA-G-13	na	na	na	na	na	na
SIERRA-G-14	2.87	3.16	2.13	3.77	8.69	1.27
SIERRA-G-15	1.68	108.04	2.39	3.59	7.68	1.06
SIERRA-G-16	10.76	0.38	1.35	2.67	6.83	1.05
SIERRA-G-17	13.81	0.67	2.77	3.52	7.78	1.08
SIERRA-G-18	13.74	0.73	2.92	4.06	8.82	1.11
SIERRA-GL-01	13.61	0.43	1.89	2.90	6.67	0.99
SIERRA-GL-02	8.51	1.03	2.73	3.92	8.51	1.15
SIERRA-GL-03	13.90	0.31	1.52	3.05	7.61	1.09
SIERRA-GL-04	13.71	0.38	1.75	3.22	7.53	1.11
SIERRA-GL-05	18.55	0.54	2.18	3.66	8.84	1.27
SIERRA-GL-06	13.95	0.39	1.80	3.46	8.34	1.22
SIERRA-GL-07	14.41	1.80	6.72	6.64	11.56	1.72
SIERRA-GL-08	13.90	0.40	1.78	3.40	8.23	1.23
SIERRA-GL-09	15.85	0.51	2.22	3.63	7.96	1.15
SIERRA-GL-10	18.36	0.78	2.96	4.28	9.03	1.25

Table F1. Results for analyses of noble gases by Lawrence Livermore National Laboratory for samples collected by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (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. **Abbreviations:** cm³ STP/g H₂O, cubic centimeters at standard temperature and pressure per gram of water; na, not available]

GAMA well identification number	Helium-3/ Helium-4 (atom ratio) (61040)	Helium-4 (cm ³ STP/g H ₂ O) (85561)	Neon (cm ³ STP/g H ₂ O) (61046)	Argon (cm ³ STP/g H ₂ O) (85563)	Krypton (cm ³ STP/g H ₂ O) (85565)	Xenon (cm ³ STP/g H ₂ O) (85567)
	x 10 ⁻⁷	x 10 ⁻⁷	x 10 ⁻⁷	x 10 ⁻⁴	x 10 ⁻⁸	x 10 ⁻⁸
Metamorphic aquifer lithology						
SIERRA-M-01	0.55	116.31	3.13	3.99	8.16	1.14
SIERRA-M-02	0.67	70.00	3.39	4.37	9.00	1.10
SIERRA-M-03	na	na	na	na	na	na
SIERRA-M-04	16.56	0.50	2.19	3.92	8.89	1.39
SIERRA-M-05	8.91	1.00	2.73	3.89	8.52	1.24
SIERRA-M-06	16.66	0.51	2.42	3.69	8.44	1.19
SIERRA-ML-01	8.71	1.78	3.70	4.30	8.42	1.04
SIERRA-ML-02	15.52	0.65	2.76	3.78	8.17	1.12
SIERRA-ML-03	13.18	0.79	3.11	3.87	7.84	1.01
SIERRA-ML-04	10.24	0.83	2.04	3.02	6.64	0.94
SIERRA-ML-05	13.78	0.37	2.53	3.12	6.72	0.94
SIERRA-ML-06	na	na	na	na	na	na
SIERRA-ML-07	5.04	3.25	2.22	3.49	7.69	1.14
SIERRA-ML-08	2.17	8.25	2.94	3.94	8.06	1.13
SIERRA-ML-09	14.60	1.00	4.06	4.62	9.52	1.16
SIERRA-ML-10	10.06	3.08	6.71	5.43	9.96	1.20
SIERRA-ML-11	14.01	1.68	6.33	6.39	12.30	1.48
SIERRA-ML-12	12.09	0.74	2.29	3.42	7.53	0.98
SIERRA-ML-13	1.64	21.93	2.03	3.42	7.74	1.10
SIERRA-ML-14	13.86	0.39	9.88	3.68	7.38	1.00
SIERRA-ML-15	3.73	10.14	2.64	3.78	8.06	1.06
SIERRA-ML-16	5.57	6.11	2.33	3.70	8.24	1.20
SIERRA-ML-17	14.57	3.60	9.54	8.67	14.03	1.59
SIERRA-ML-18	6.59	1.41	2.57	3.80	8.25	1.13
Sedimentary aquifer lithology						
SIERRA-S-01	12.45	1.22	3.29	4.10	8.14	1.08
SIERRA-S-02	5.82	2.43	2.13	3.66	8.23	1.20
SIERRA-S-03	4.63	7.07	2.37	3.76	8.42	1.21
SIERRA-SL-01	13.41	0.65	2.62	3.58	7.70	1.04
SIERRA-SL-02	3.40	38.56	2.02	3.31	7.36	1.04
SIERRA-SL-03	2.28	6.81	2.30	3.29	7.06	0.97
SIERRA-SL-04	3.75	12.22	2.25	3.65	8.41	1.21
SIERRA-SL-05	na	na	na	na	na	na
SIERRA-SL-06	15.11	0.59	2.15	3.59	8.27	1.12
SIERRA-SL-07	4.73	2.58	2.21	3.77	8.75	1.23
SIERRA-SL-08	17.84	0.54	2.17	3.68	8.49	1.19
SIERRA-SL-09	13.56	0.39	1.72	3.39	8.01	1.13

Table F1. Results for analyses of noble gases by Lawrence Livermore National Laboratory for samples collected by the U.S. Geological Survey (USGS) for the Sierra Nevada Regional (SNR) study unit, 2008, California Groundwater Ambient Monitoring and Assessment (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. **Abbreviations:** cm³ STP/g H₂O, cubic centimeters at standard temperature and pressure per gram of water; na, not available]

GAMA well identification number	Helium-3/ Helium-4 (atom ratio) (61040)	Helium-4 (cm ³ STP/g H ₂ O) (85561)	Neon (cm ³ STP/g H ₂ O) (61046)	Argon (cm ³ STP/g H ₂ O) (85563)	Krypton (cm ³ STP/g H ₂ O) (85565)	Xenon (cm ³ STP/g H ₂ O) (85567)
	x 10 ⁻⁷	x 10 ⁻⁷	x 10 ⁻⁷	x 10 ⁻⁴	x 10 ⁻⁸	x 10 ⁻⁸
Sedimentary aquifer lithology—Continued						
SIERRA-SL-10	23.83	0.55	1.93	3.20	7.45	1.07
SIERRA-SL-11	11.28	0.58	1.69	3.03	7.09	0.98
SIERRA-SL-12	13.92	0.59	3.45	3.77	7.70	1.02
SIERRA-SL-13	na	na	na	na	na	na
Volcanic aquifer lithology						
SIERRA-V-01	17.67	0.44	2.02	3.60	8.51	1.24
SIERRA-V-02	2.74	7.02	2.17	3.52	8.19	1.11
SIERRA-V-03	7.34	4.96	1.89	3.33	7.55	1.32
SIERRA-VL-01	3.47	5.27	1.92	2.95	6.62	0.90
SIERRA-VL-02	14.00	0.42	1.87	3.19	7.46	1.12
SIERRA-VL-03	8.30	1.27	2.54	3.64	8.32	1.09
SIERRA-VL-04	10.57	0.66	2.04	3.40	7.78	1.14
SIERRA-VL-05	10.92	0.53	1.88	3.19	7.73	1.08
SIERRA-VL-06	33.66	4.92	1.98	3.40	7.74	1.11
SIERRA-VL-07	9.77	1.21	2.55	4.11	9.32	1.31
SIERRA-VL-08	13.25	0.39	1.69	3.06	7.13	1.04
SIERRA-VL-09	13.83	0.37	1.70	3.28	7.92	1.12
SIERRA-VL-10	na	na	na	na	na	na
SIERRA-VL-11	14.98	0.39	1.73	3.36	7.69	1.10
SIERRA-VL-12	7.71	1.01	2.42	3.68	8.14	1.13

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