

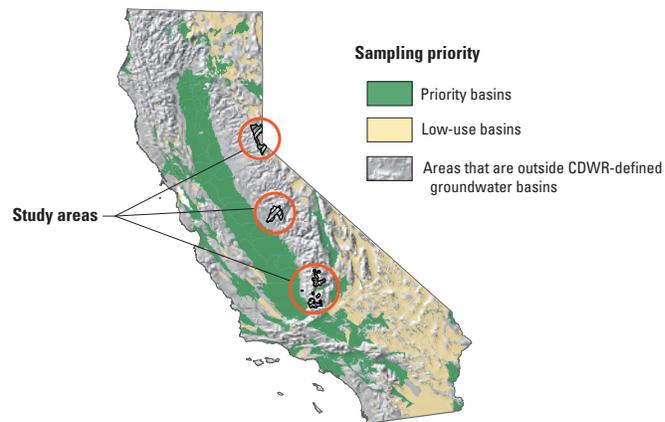
Prepared in cooperation with the California State Water Resources Control Board
A product of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program

Status and Understanding of Groundwater Quality in the Tahoe-Martis, Central Sierra, and Southern Sierra Study Units, 2006–2007: California GAMA Priority Basin Project



Scientific Investigations Report 2011–5216

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: Lake Tahoe shoreline, El Dorado County, California. (Photograph taken by Cathy Munday, U.S. Geological Survey.)

Back cover: Supply well in the Tehachapi-Cummings Valley, Kern County, California. (Photograph taken by Justin Kulongoski, U.S. Geological Survey.)

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By Miranda S. Fram and Kenneth Belitz

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Scientific Investigations Report 2011–5216

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Suggested citation:

Fram, M.S., and Belitz, Kenneth, 2012, Status and Understanding of Groundwater Quality in the Tahoe-Martis, Central Sierra, and Southern Sierra Study Units, 2006–2007—California GAMA Priority Basin Project: U.S. Geological Survey Scientific Investigations Report 2011-5216, 222 p.

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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		
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)

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32.$$

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

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8.$$

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 ($\mu\text{g}/\text{L}$). One milligram per liter is equivalent to 1 part per million (ppm); 1 microgram per liter is equivalent to 1 part per billion (ppb).

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).

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Abbreviations and Acronyms

AB	Assembly Bill (through the California State Assembly)
AL-US	U.S. Environmental Protection Agency action level
BQ	benchmark quotient
GAMA	Groundwater Ambient Monitoring and Assessment Program
HAL-US	U.S. Environmental Protection Agency lifetime health advisory level
HBSL	health-based screening level
LRL	laboratory reporting level
LSD	land-surface datum
LT-MDL	long-term method detection level
MCL	maximum contaminant level
MCL-CA	California Department of Public Health maximum contaminant level
MCL-US	U.S. Environmental Protection Agency maximum contaminant level
MDL	method detection limit
MRL	minimum reporting level
NL-CA	California Department of Public Health notification level
pe	electron activity
RC	relative-concentration
RSD5-US	U.S. Environmental Protection Agency risk-specific dose at a risk factor of 10 ⁻⁵
SI	saturation index
SMCL	secondary maximum contaminant level
SMCL-CA	California Department of Public Health secondary maximum contaminant level
SMCL-US	U.S. Environmental Protection Agency secondary maximum contaminant level
SWP	State Water Project
TEAP	terminal electron-acceptor processes

Organizations

BLM	U.S. Bureau of Land Management
CDPH	California Department of Public Health (Department of Health Services prior to July 1, 2007)
CDPR	California Department of Pesticide Regulation
CDWR	California Department of Water Resources
LLNL	Lawrence Livermore National Laboratory
NAWQA	National Water-Quality Assessment Program (USGS)
SWRCB	State Water Resources Control Board (California)
TCCWD	Tehachapi-Cummings County Water District
US	United States
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Selected Chemical Names

Ammonia-N	ammonia as nitrogen
BDCM	bromodichloromethane
CaWO ₄	scheelite
CCl ₄	carbon tetrachloride (tetrachloromethane)
CFC-11	trichlorofluoromethane
CFC-113	1,1,2-trichloro-1,2,2-trifluoroethane
CS ₂	carbon disulfide
DBCP	1,2-dibromo-3-chloropropane
EDB	1,2-dibromoethane (ethylene dibromide)
H ₂ CO ₃	carbonic acid
HCO ₃ ⁻	bicarbonate
MTBE	methyl <i>tert</i> -butyl ether
NDMA	<i>N</i> -nitrosodimethylamine
Nitrate-N	nitrate as nitrogen
Nitrite-N	nitrite as nitrogen
PCE	perchloroethene (tetrachloroethene)
1,1,1-TCA	1,1,1-trichloroethane
TCE	trichloroethene
1,2,3-TCP	1,2,3-trichloropropane
TDS	total dissolved solids
THM	trihalomethane
VOC	volatile organic compound

Units of Measure

cm ³ STP g ⁻¹	cubic centimeters at standard temperature and pressure per gram
δd	delta notation; the ratio of a heavier isotope to the more common lighter isotope of an element, relative to a standard reference material, expressed as per mil
ft	foot (feet)
ka	kilo annum (thousand years ago)
Ma	mega annum (million years ago)
meq/L	milliequivalents per liter
mg/L	milligram per liter (parts per million)
mi	mile
μg/L	microgram per liter (parts per billion)
μS/cm	micro Siemen per centimeter
pCi/L	picocurie per liter
per mil	parts per thousand
pmc	percent modern carbon
tanks/km ²	septic tanks per square kilometer
TU	tritium unit

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Status and Understanding of Groundwater Quality in the Tahoe-Martis, Central Sierra, and Southern Sierra Study Units, 2006–2007: California GAMA Priority Basin Project

By Miranda S. Fram and Kenneth Belitz

Abstract

Groundwater quality in the Tahoe-Martis, Central Sierra, and Southern Sierra study units was investigated as part of the Priority Basin Project of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program. The three study units are located in the Sierra Nevada region of California in parts of Nevada, Placer, El Dorado, Madera, Tulare, and Kern Counties. The GAMA Priority Basin Project is being conducted by the California State Water Resources Control Board, in collaboration with the U.S. Geological Survey (USGS) and the Lawrence Livermore National Laboratory. The project was designed to provide statistically robust assessments of untreated groundwater quality within the primary aquifer systems used for drinking water. The primary aquifer systems (hereinafter, primary aquifers) for each study unit are defined by the depth of the screened or open intervals of the wells listed in the California Department of Public Health (CDPH) database of wells used for municipal and community drinking-water supply. The quality of groundwater in shallower or deeper water-bearing zones may differ from that in the primary aquifers; shallower groundwater may be more vulnerable to contamination from the surface.

The assessments for the Tahoe-Martis, Central Sierra, and Southern Sierra study units were based on water-quality and ancillary data collected by the USGS from 132 wells in the three study units during 2006 and 2007 and water-quality data reported in the CDPH database. Two types of assessments were made: (1) status, assessment of the current quality of the groundwater resource, and (2) understanding, identification of the natural and human factors affecting groundwater quality. The assessments characterize untreated groundwater quality, not the quality of treated drinking water delivered to consumers by water purveyors.

Relative-concentrations (sample concentrations divided by benchmark concentrations) were used for evaluating groundwater quality for those constituents that have Federal or California regulatory or non-regulatory benchmarks for drinking-water quality. A relative-concentration (RC) greater than ($>$) 1.0 indicates a concentration above a benchmark.

RCs for organic constituents (volatile organic compounds and pesticides) and special-interest constituents were classified as “high” ($RC > 1.0$), “moderate” ($1.0 \geq RC > 0.1$), or “low” ($RC \leq 0.1$). For inorganic constituents (major ions, trace elements, nutrients, and radioactive constituents), the boundary between low and moderate RCs was set at 0.5.

A new metric, aquifer-scale proportion, was used in the *status assessment* as the primary metric for evaluating regional-scale groundwater quality. High aquifer-scale proportion is defined as the percentage of the area of the primary aquifers with $RC > 1.0$ for a particular constituent or class of constituents; moderate and low aquifer-scale proportions are defined as the percentages of the area of the primary aquifer with moderate and low RCs, respectively. Percentages are based on an areal rather than a volumetric basis. Two statistical approaches—grid-based, which used one value per grid cell, and spatially weighted, which used multiple values per grid cell—were used to calculate aquifer-scale proportions for individual constituents and classes of constituents. The spatially weighted estimates of high aquifer-scale proportions were within the 90-percent (%) confidence intervals of the grid-based estimates in all cases.

The *status assessment* showed that inorganic constituents had greater high and moderate aquifer-scale proportions than did organic constituents in all three study units. In the Tahoe-Martis study unit, RCs for inorganic constituents with health-based benchmarks (primarily arsenic) were high in 20% of the primary aquifer, moderate in 13%, and low in 67%. In the Central Sierra study unit, aquifer-scale proportions for inorganic constituents with health-based benchmarks (primarily arsenic, uranium, fluoride, and molybdenum) were 41% high, 36% moderate, and 23% low. In the Southern Sierra study unit, 32, 34, and 34% of the primary aquifer had high, moderate, and low RCs of inorganic constituents with health-based benchmarks (primarily arsenic, uranium, fluoride, boron, and nitrate). The high aquifer-scale proportions for inorganic constituents with non-health-based benchmarks were 14, 34, and 24% for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively, and the primary constituent was manganese for all three study units.

Organic constituents with health-based benchmarks were not present at high RCs in the primary aquifers of the Central Sierra and Southern Sierra study units, and were present at high RCs in only 1% of the Tahoe-Martis study unit. Moderate aquifer-scale proportions for organic constituents were <5% in all three study units. Of the 173 organic constituents analyzed, 22 were detected, and of those 22, 17 have health-based benchmarks. Organic constituents were detected in 20, 27, and 40% of the primary aquifers in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively. Four organic constituents had study-unit detection frequencies of >10%: the trihalomethane chloroform in the Tahoe-Martis study unit; chloroform and the herbicide simazine in the Central Sierra study unit; and chloroform, simazine, the herbicide atrazine, and the solvent perchloroethene in the Southern Sierra study unit.

The second component of this study, the *understanding assessment*, identified the natural and human factors that may have affected groundwater quality in the three study units by evaluating statistical correlations between water-quality constituents and potential explanatory factors. The potential explanatory factors evaluated were land use, septic tank density, climate, relative position in the regional flow system, aquifer lithology, geographic location, well depth and depth to the top of the screened or open interval in the well, groundwater age distribution, pH, and dissolved oxygen concentration. Results of the statistical evaluations were used to explain the occurrence and distribution of constituents in the study units.

Aquifer lithology (granitic, metamorphic, sedimentary, or volcanic rocks), groundwater age distribution [modern (recharged since 1952), pre-modern (recharged before 1952), or mixed (containing both modern and pre-modern recharge)], geographic location, pH, and dissolved oxygen were the most significant factors explaining the occurrence patterns of most inorganic constituents. High and moderate RCs of arsenic were associated with pre-modern and mixed-age groundwater and two distinct sets of geochemical conditions: (1) oxic, high-pH conditions, particularly in volcanic rocks, and (2) low-oxygen to anoxic conditions and low- to neutral-pH conditions, particularly in granitic rocks. In granitic and metamorphic rocks, high and moderate RCs of uranium were associated with pre-modern and mixed-age groundwater, low-oxygen to anoxic conditions, and location within parts of the Central Sierra and Southern Sierra study units known to have rocks with anomalously high uranium content compared to other parts of the Sierra Nevada. High and moderate RCs of uranium in sedimentary rocks were associated with pre-modern-age groundwater, oxic and high-pH conditions, and location in the Tahoe Valley South subbasin within the Tahoe-Martis study unit.

Land use within 500 meters of the well and groundwater age were the most significant factors explaining occurrence patterns of organic constituents. Herbicide detections were most strongly associated with modern- and mixed-age groundwater from wells with agricultural land use.

Trihalomethane detections were most strongly associated with modern- and mixed-age groundwater from wells with >10% urban land use and (or) septic tank density >7 tanks per square kilometer. Solvent detections were not significantly related to groundwater age. Eighty-three percent of the wells with modern- or mixed-age groundwater, and 86% of wells with detections of herbicides and (or) THMs had depths to the top of the screened or open interval of <170 feet. These observations suggest that modern groundwater has infiltrated to depths of approximately 170 feet below land surface.

Land use and occurrence of herbicides and solvents were the most significant factors explaining the occurrence of nitrate. Wells with >5% agricultural land use and detection of a herbicide or solvent had the highest nitrate concentrations. Comparison between observed and predicted detection frequencies of perchlorate suggests that the perchlorate detected at concentrations <1 microgram per liter likely reflects the distribution of perchlorate under natural conditions, and that the perchlorate detected at higher concentrations may reflect redistribution of originally natural perchlorate salts by irrigation in the agricultural areas of the Southern Sierra study unit.

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 (California State Water Resources Control Board, 2010, website at <http://www.waterboards.ca.gov/gama/>). The statewide GAMA Program currently consists of three projects: (1) the GAMA Priority Basin Project, conducted by the USGS (U.S. Geological Survey, 2010, website at <http://ca.water.usgs.gov/gama/>); (2) the GAMA Domestic Well Project, conducted by the SWRCB; and (3) the GAMA Special Studies, conducted by LLNL. On a statewide basis, the GAMA Priority Basin Project focused primarily 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, Supplemental Report of the 1999 Budget Act 1999–00 Fiscal Year). 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, Sections 10780–10782.3 of the California Water Code, Assembly Bill 599).

The GAMA Priority Basin Project 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 (CDPR), California Department of Water Resources (CDWR), and local water agencies and well owners (Kulongoski and Belitz, 2004).

The range of hydrologic, geologic, and climatic conditions that exists in California must be considered in a statewide assessment of groundwater quality. Belitz and others (2003) partitioned the state into 10 hydrogeologic provinces, each with distinctive hydrologic, geologic, and climatic characteristics (fig. 1A). All of these hydrogeologic provinces include groundwater basins and subbasins designated by the CDWR (California Department of Water Resources, 2003). Groundwater basins generally consist of relatively permeable, unconsolidated deposits of alluvial or volcanic origin. Eighty percent of the approximately 16,000 active and standby drinking-water wells listed in the statewide database maintained by the CDPH (hereinafter referred to as CDPH wells) are located in CDWR-designated groundwater basins within these hydrologic provinces. Groundwater basins and subbasins 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 registered pesticide applications (Belitz and others, 2003). Of the 472 basins and subbasins designated by the CDWR, 116 priority basins, representing approximately 95 percent (%) of the CDPH wells located in basins, were selected for the project.

In addition, some areas outside of the designated groundwater basins were included to represent the 20% of CDPH wells not located in groundwater basins. Of the 10 hydrogeologic provinces, the Sierra Nevada contains the largest number of CDPH wells outside of designated groundwater basins. About 97% of the total area and approximately 85% of the CDPH wells in the Sierra Nevada are outside of designated groundwater basins. The Tahoe-Martis, Central Sierra, and Southern Sierra study units are located in the Sierra Nevada hydrogeologic province (fig. 1A). All three study units include areas outside of the designated groundwater basins; the Tahoe-Martis and Southern Sierra study units also include several small CDWR-designated groundwater basins.

The goal of the GAMA Priority Basin Project is 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 and selected explanatory factors, and (3) *Trends*: detection of changes in groundwater quality (Kulongoski and Belitz, 2004). The assessments are intended to characterize the quality of groundwater within the primary aquifer systems of the study unit, not the treated drinking water delivered to consumers by water purveyors. The primary aquifer systems (hereinafter, primary aquifers) for the study units are defined by the depths of the screened or open intervals of the wells listed in the CDPH database for the study units. The CDPH database lists wells used for municipal and community drinking-water supplies, and includes wells from systems classified as non-transient (such as cities, towns, and mobile-home parks) and transient (such as schools, campgrounds, and restaurants). Groundwater quality in shallower or deeper parts of the aquifer systems may differ from that in the primary aquifers. In particular, shallower groundwater may be more vulnerable to surface contamination. As a result, samples from shallow wells (such as many private domestic wells and environmental monitoring wells) typically have higher concentrations of constituents from anthropogenic sources [such as volatile organic compounds (VOCs) and nitrate] than samples from wells screened in the deeper primary aquifer.

Purpose and Scope

The purposes of this report are to provide (1) *study unit description*: descriptions of the hydrogeologic settings of the Tahoe-Martis, Central Sierra, and Southern Sierra study units, (2) *status assessment*: assessments of the status of the current quality of groundwater in the primary aquifers in the three study units, and (3) *understanding assessment*: identification of the natural and human factors affecting groundwater quality and explanation of the relations between water quality and selected explanatory factors. Water-quality data for samples collected by the USGS for the GAMA Program in the three study units and details of sample collection, analysis, and quality-assurance procedures are reported by Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009). Untreated groundwater samples were collected from the three study units between May 2006 and October 2007. Utilizing those same data, this report describes methods used in designing the sampling network, identifying CDPH data for use in the *status assessment*, estimating aquifer-scale proportions for constituents, analyzing ancillary datasets, and assessing the status and understanding of groundwater quality by statistical and graphical approaches.



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

Provinces from Belitz and others (2003)

Figure 1. (A) Locations of the Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project, and the California hydrogeologic provinces, and (B) selected major geologic features in California.

B



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

- | | |
|---|---|
| <ul style="list-style-type: none"> Mesozoic granitic rocks Paleozoic and Mesozoic metamorphic and sedimentary rocks and non-granitic plutonic rocks | <ul style="list-style-type: none"> Cenozoic sedimentary deposits Cenozoic volcanic and volcanoclastic rocks |
|---|---|

Figure 1.—Continued

The *status assessment* uses two methods for calculating the areal proportion of the primary aquifer with groundwater of defined quality (aquifer-scale proportion). Both methods are based on equal-area grid cells covering the study unit: one uses one well to represent each cell, and the other uses multiple wells to represent each cell. The first method is based on water-quality data from 103 wells selected by the USGS for spatial coverage of one well per grid cell across the three study units (USGS-grid wells). Samples were collected by the USGS for analysis of anthropogenic organic constituents, naturally occurring inorganic constituents, and geochemical and age-dating tracers (Fram and Belitz, 2007; Ferrari and others, 2008; Fram and others, 2009). Water-quality data from the CDPH database also were used to supplement data collected by the USGS for the GAMA Program. The resulting set of water-quality data from USGS-grid wells and selected CDPH wells was considered to be representative of the primary aquifer systems in the three study units. The second method uses the USGS-grid wells, data from 29 additional wells sampled by the USGS for the GAMA Program, and data from many wells in the CDPH database. GAMA status assessments are designed to provide a statistically robust characterization of groundwater quality in the primary aquifers at the study-unit scale (Belitz and others, 2003). The statistically robust design also allows study units to be compared and results to be synthesized at regional and statewide scales.

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, the ratio of the concentration of a constituent in groundwater to the concentration of the benchmark for that constituent. The assessments in this report characterize the quality of untreated groundwater resources in the primary aquifers in the study units, not the treated drinking water delivered to consumers by water purveyors. After withdrawal from the ground, water typically is treated, disinfected, and (or) blended with other waters to maintain acceptable water quality. Regulatory benchmarks apply to treated water that is served to the consumer, not to untreated groundwater.

The *understanding assessment* is based on water-quality data from the 103 USGS-grid wells and the 29 additional wells sampled by the USGS for the GAMA Program. The potential explanatory factors evaluated are land use, septic-tank density, climate, relative position in the regional flow system, aquifer lithology, well depth and depth to the top of the screened or open interval in the well, groundwater age distribution, pH, and dissolved oxygen concentration. Connections between potential explanatory factors and water quality are evaluated using statistical tests for correlations and by analysis of graphical relations.

Definitions and Locations of Study Units

The Tahoe-Martis study unit covers an area of approximately 460 square miles (mi²) [1,200 square kilometers (km²)] in El Dorado, Placer, Nevada, and Alpine Counties, California, in the northeast part of the Sierra Nevada hydrogeologic province (figs. 1A, 2A). The Tahoe-Martis study unit was divided into three study areas: the Martis study area, the Tahoe study area, and the Hard Rock study area. The boundary of the Martis study area corresponds to the CDWR Martis Valley basin (California Department of Water Resources, 2006a), and the boundaries of the Tahoe study area correspond to the South, West, and North subbasins of the CDWR Tahoe Valley basin (California Department of Water Resources, 2004a,b,c). The Hard Rock study area corresponds to the surface-water watersheds surrounding the Martis and Tahoe Valley basins and Lake Tahoe.

The Central Sierra study unit covers an area of approximately 370 mi² (960 km²) in Madera and Mariposa Counties, California, in the central part of the Sierra Nevada hydrogeologic province (figs. 1A, 2B). The study unit consists of two study areas defined by surface-water watersheds, and it contains no CDWR-designated groundwater basins. The Coarse Gold study area corresponds to the watershed of the Upper Fresno River upstream of Hensley Lake, and the Wishon study area corresponds to the watershed of the North Fork Willow Creek, a tributary of the San Joaquin River.

The Southern Sierra study unit covers an area of approximately 1,800 mi² (4,700 km²) in Kern and Tulare Counties, California, at the southern end of the Sierra Nevada hydrogeologic province (figs. 1A, 2C). The study unit area is defined by the watersheds of Tehachapi and Caliente Creeks, the small creeks at the southern end of the Sierra Nevada that drain towards the Central Valley, the Middle and Upper Kern Rivers, and the East Tehachapi closed drainage basin. The study unit includes six small groundwater basins, as defined by the CDWR (California Department of Water Resources, 2003). Wells sampled in the southern part of the study unit were in or near the Cummings Valley, Brite Valley, Tehachapi Valley West, and Tehachapi Valley East groundwater basins, and wells sampled in the northern part of the study unit were in or nearby the Kern River Valley groundwater basin (fig. 2C). No wells were sampled in the Walker Creek Valley basin. The Southern Sierra study unit was not divided into study areas.

As part of the GAMA Priority Basin Project, untreated-groundwater samples were collected from 52 sites in the Tahoe-Martis study unit during the period June–September 2007 (Fram and others, 2009), 30 sites in the Central Sierra study unit during May 2006 (Ferrari and others, 2008), and 50 sites in the Southern Sierra study unit during June 2006 (Fram and Belitz, 2007). Of the 132 sites, 7 were springs, and 125 were wells. For ease of discussion, all sites are referred to as wells unless the difference between well and spring is important to the discussion.

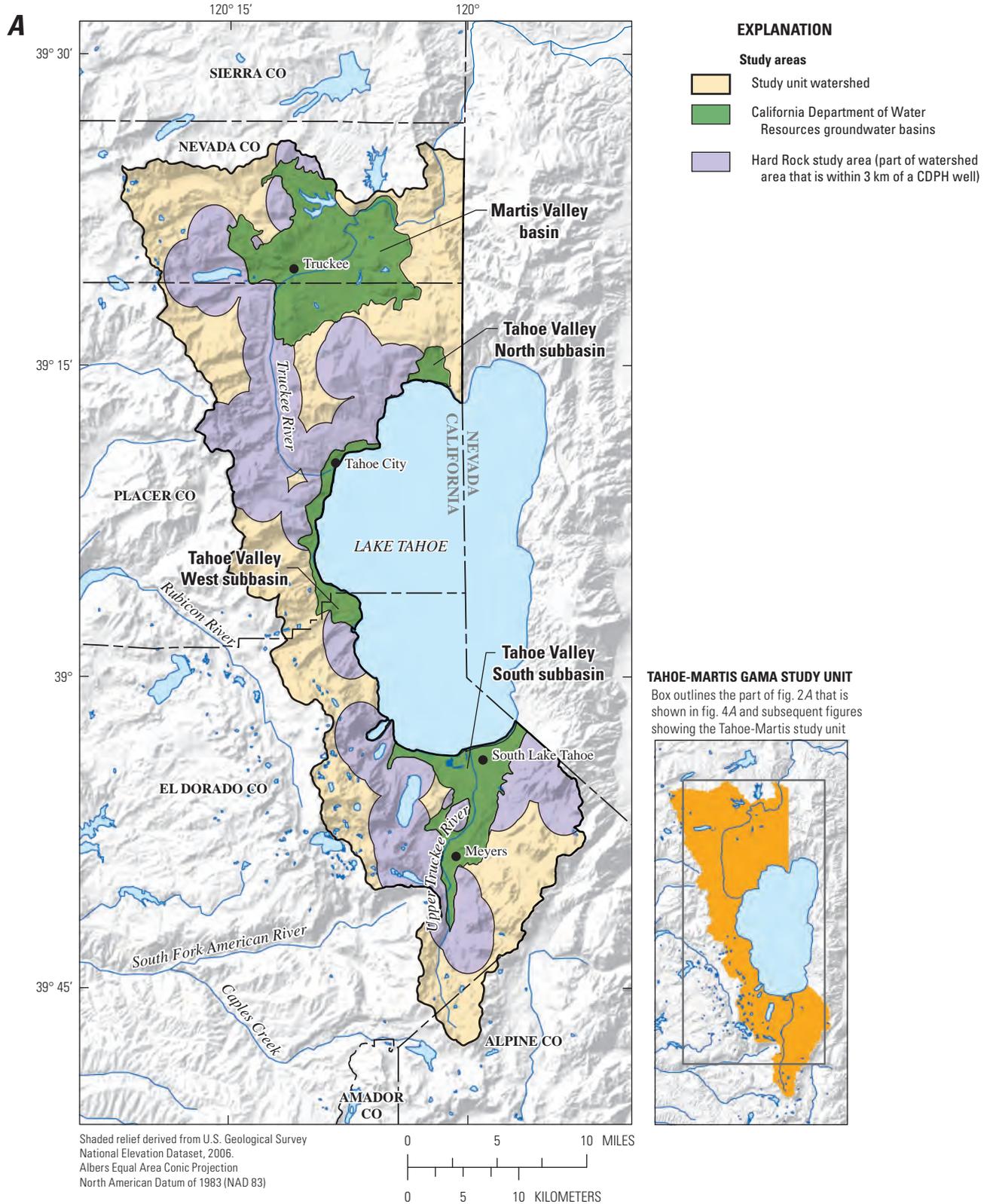


Figure 2. Geographic features of the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

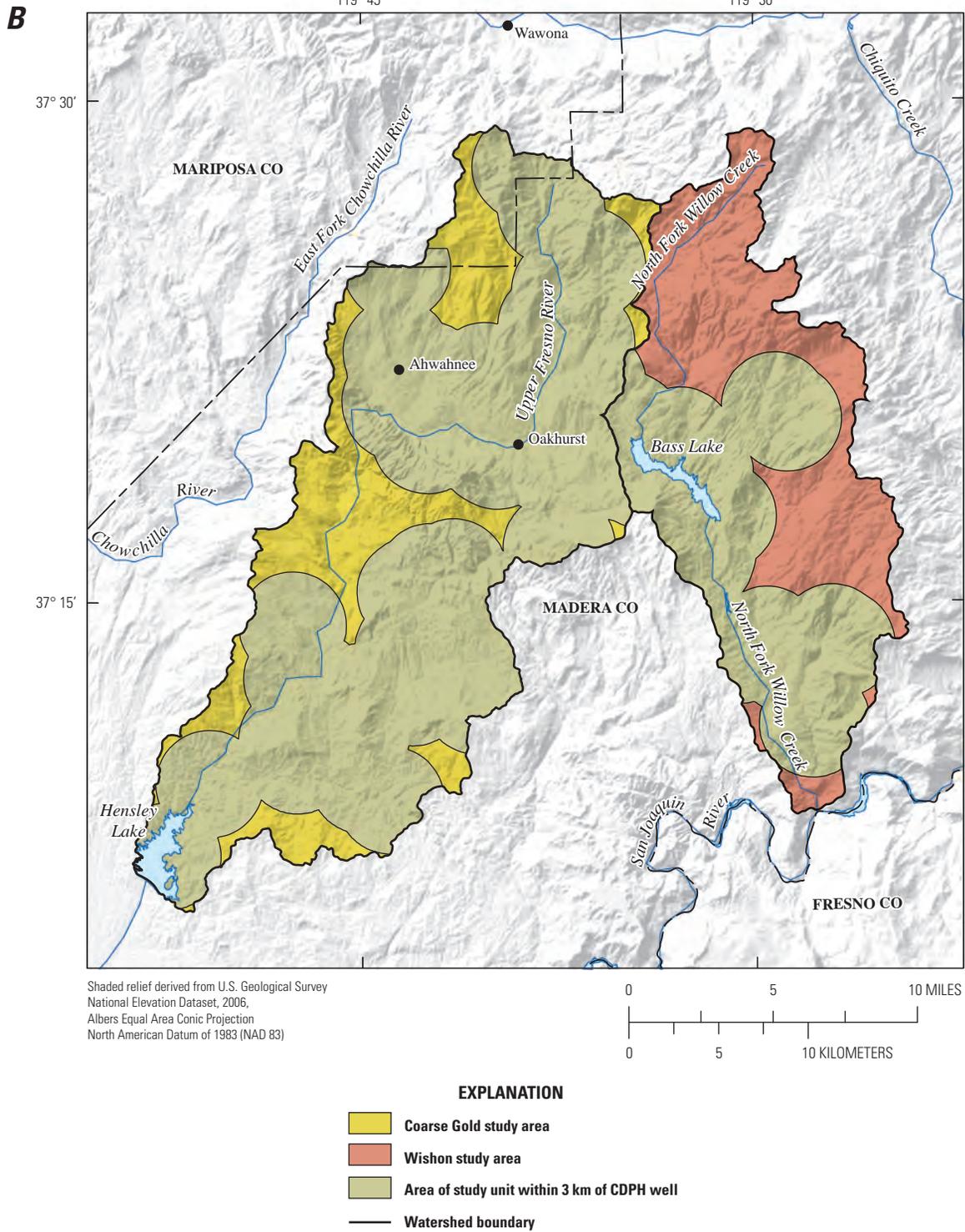


Figure 2.—Continued

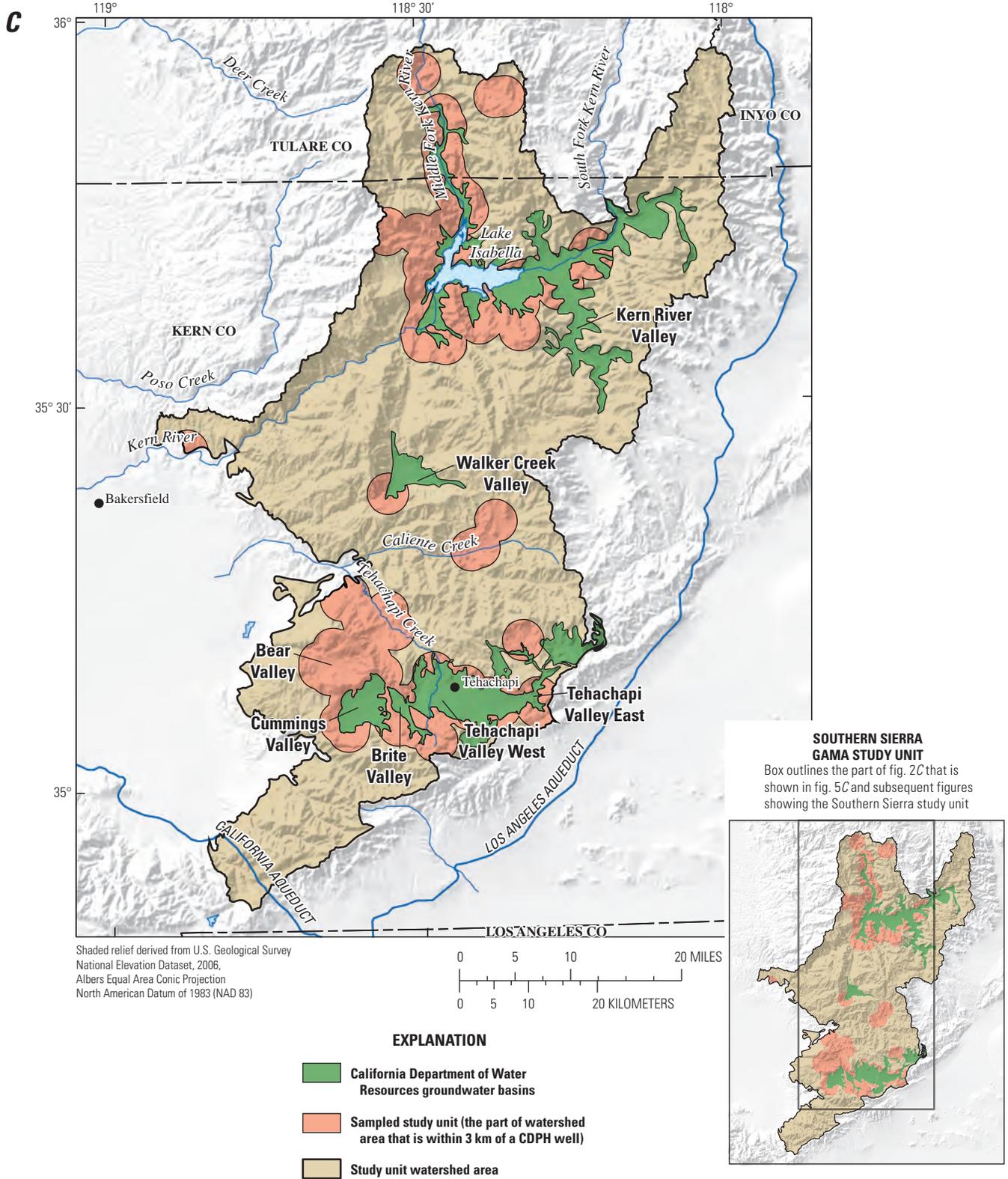


Figure 2.—Continued

Hydrogeologic Setting

The Sierra Nevada hydrogeologic province encompasses a broad range of geologic, hydrologic, and land-use settings. The Sierra Nevada is an asymmetric mountain range that extends for 400 miles (mi) approximately parallel to the long axis of the State of California (fig. 1A). The western side 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 high (2,440 m). The western boundary of the Sierra Nevada province is defined by the limit of Quaternary sediments of the Central Valley. The eastern boundary is defined by the limits of 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 province is terminated by the Garlock Fault at the southern end (fig. 1B) and by the Cascades and Modoc Plateau in the north (fig. 1A).

The dominant geologic feature of the province 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). 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). The Western Metamorphic Belt occupies the foothills in the northern half of the province 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. Late Cenozoic (approximately 35 Ma to 1 Ma) volcanism blanketed areas of the Sierra Nevada, particularly in the northern part of the province. By the Late Miocene (16 Ma to 12 Ma), the Sierra Nevada existed as a 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). Portions of the Sierra Nevada were glaciated in the multiple major glacial advances during the Pleistocene (Birkeland, 1964; Raub and others, 2006).

The Sierra Nevada is dominated by natural land use. Approximately 40% of the area is managed by the U.S. Forest Service (USFS), and approximately 20% is under

the jurisdiction of the National Park Service or the Bureau of Land Management (BLM) (Sierra Nevada Ecosystem Project, 1996). Most of the remaining 40% is privately owned. Agricultural land use constitutes a small percentage 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. Free-range stock grazing on leased USFS and BLM lands as well as on private land is common in many parts of the Sierra Nevada province, but is not counted as agricultural land use by the land-use classification system used in this report (see appendix C). Urban land use also constitutes a small percentage of the 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, 1996a; 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. 1A)). As of 1990, 80% of the permanent population lived on 3% of the land area. Recreation and tourism are the primary industries in the Sierra Nevada, and the resulting transient population is much larger than the permanent population. For example, recreational use of public lands was estimated at 50 to 60 million visitor days in 1993 (Duane, 1996b), and was predicted to be 122 million visitor days in 2010 for USFS lands alone (U.S. Forest Service, 2001).

Like much of California, the Sierra Nevada has a Mediterranean climate pattern: 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 varies with elevation and latitude (PRISM Group, Oregon State University, 2007). Most of the precipitation falls in the winter season, between October and April. Precipitation is typically greater at higher elevations and more northerly locations. Above about 6,500 ft (1,980 m), most of the precipitation falls as snow. Runoff from Sierra Nevada watersheds, primarily in the form of snow melt, provides approximately 50% of California's developed water (Carle, 2004).

Groundwater is used extensively for municipal, community, and domestic drinking-water supplies in the Sierra Nevada, and much of this groundwater comes from hard-rock aquifers rather than from groundwater basins. Approximately 3% of the Sierra Nevada hydrogeologic province consists of CDWR-defined groundwater basins; the other 97% consists primarily of granitic and metamorphic rocks, with lower amounts of volcanic rocks and sediment deposits not in groundwater basins. Granitic and metamorphic rocks of the Sierra Nevada have low permeability except where fractured. Fractures and joints typically are more extensive in size and number in the upper few hundred feet of bedrock and typically decrease with depth (Page and others, 1984; Borchers, 1996)

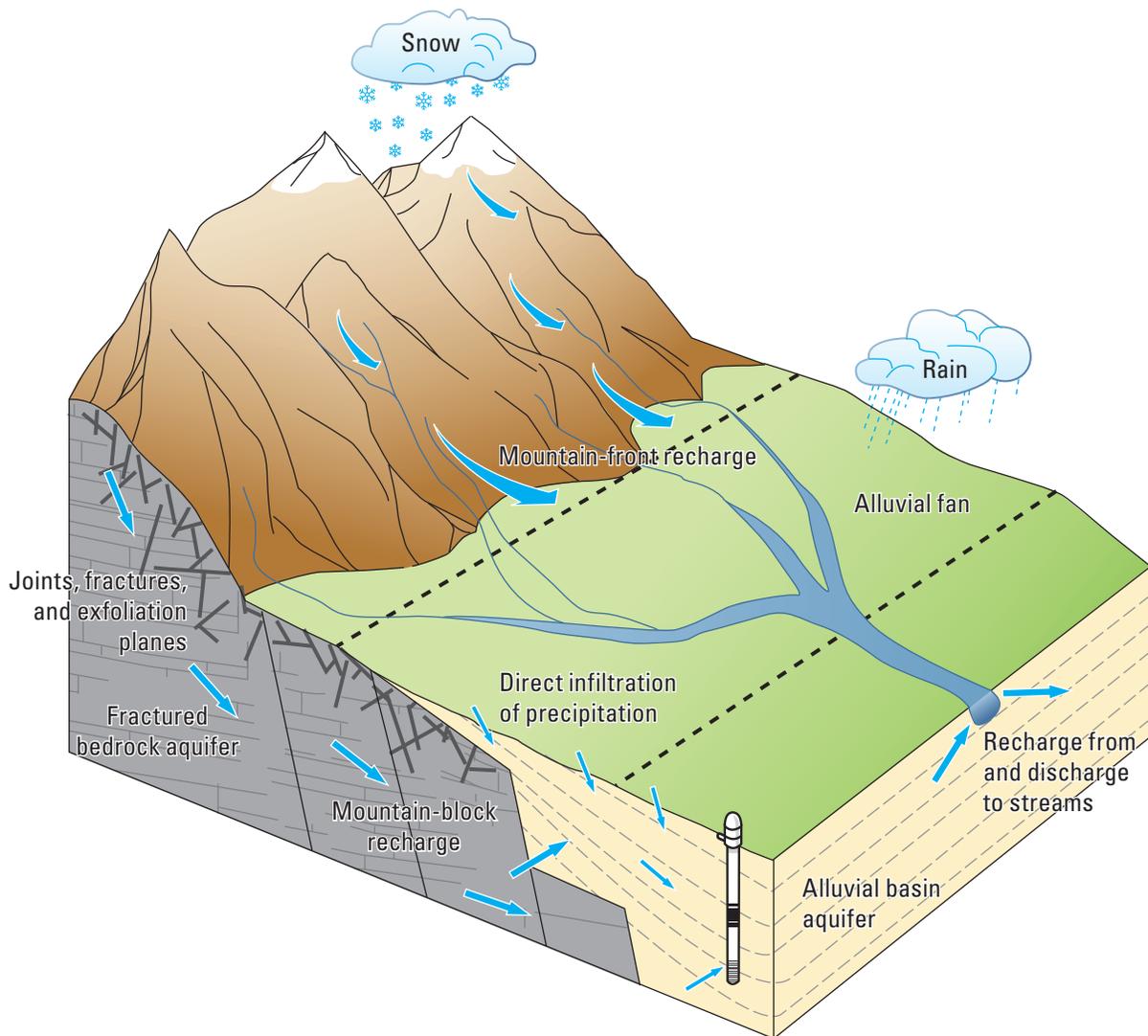


Figure 3. Conceptual model of groundwater flow in a fractured-bedrock aquifer, and recharge of a small alluvial basin adjacent to mountains consisting of fractured rock.

(fig. 3). 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.

Although groundwater basins compose a small part of the province area, they typically have a high density of groundwater use because they commonly contain population centers and have wells with much greater yields than those in the surrounding fractured-rock aquifers. Recharge to

groundwater basins of the Sierra Nevada has two primary modes (fig. 3): (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 subsurface. Precipitation falling directly on the basin percolates vertically downward through the sediments of the basin or enters stream channels.

The Tahoe-Martis, Central Sierra, and Southern Sierra study units represent three areas of the province with distinct geologic, hydrologic, and land-use characteristics.

Tahoe-Martis Study Unit

Lake Tahoe and the Tahoe Valley and Martis Valley groundwater basins lie in a structural valley between the Sierra Nevada crest to the west and the Carson Range to the east (fig. 4A). The average surface elevation of Lake Tahoe is 6,225 ft (1,897 m), and the lowest area in the Martis Valley basin lies at 5,700 ft (1,740 m). The mountains bounding the valleys rise to over 9,500 ft (2,900 m). The valley was formed by extensional faulting that resulted in approximately 5,000 ft (1,525 m) of vertical displacement of the Sierra Nevada crest and Carson Range relative to the valley floor that occupies the graben between the two mountain ranges. Uplift of the Sierra Nevada crest occurred during the Miocene (Crowley and others, 2008; Mulch and others, 2008) and Pliocene (1.8 to 5 Ma; Birkeland, 1963), although displacement along faults around Lake Tahoe has continued through the Pleistocene and Holocene to the present (Kent and others, 2005).

The bedrock in the Lake Tahoe area is primarily composed of Mesozoic (80 to 120 Ma) granitic rocks, mostly granodiorite plutons within the Sierra Nevada batholith (fig. 4A). Included within the granitic rocks are scattered remnants of the older metamorphic rocks into which the granitic plutons intruded. Uplift of the Sierra Nevada and Carson Range was accompanied by volcanic activity. Thick sequences of Miocene to Pleistocene (10 to 1 Ma) volcanic rocks cover the granitic bedrock in the Martis Valley basin and watershed area, and in the Lake Tahoe watershed approximately north of the Placer–El Dorado county line (Birkeland, 1963; Cousens and others, 2008). The older volcanic rocks are dominated by andesite tuffs, breccias, and lavas, and the younger rocks by basalt and latite lavas and cinder cones. Lake Tahoe is impounded by a dam of lava flows.

The Lake Tahoe and Truckee areas preserve evidence of four major glacial advances during the Pleistocene (fig. 2A; Birkeland, 1964). The topography of the Tahoe Valley subbasins and Martis Valley basin is dominated by glacial moraines and outwash plains, primarily from the Tahoe (70 to 150 kilo annum (ka; thousand years ago) and Tioga (14 to 26 ka) glaciations. The glaciers also formed ice dams that episodically raised the level of the lake as much as 600 ft above the current lake level, as evidenced by wave-cut terraces high on the mountains around the lake.

Average annual precipitation at stations in Truckee and on the California shores of Lake Tahoe is 30–35 in/yr (76–89 cm/yr). (Note that snowfall has been converted to equivalent depth of water.) Precipitation increases to an average of more than 80 in/yr (200 cm/yr) at the highest elevations on the western side of the Lake Tahoe watershed (Crippen and Pavelka, 1970; California Department of Water

Resources, 2008; Western Regional Climate Center, 2008). At Lake Tahoe approximately half of the precipitation falls as snow, and at the highest elevations, nearly all of the precipitation falls as snow. Ninety percent of the precipitation falls between October and April (California Department of Water Resources, 2008; Western Regional Climate Center, 2008).

The groundwater-bearing units in the South, West, and North subbasins of the Tahoe Valley basin consist of Pliocene to Holocene glacial, lacustrine, and fluvial deposits, referred to as basin-fill deposits (Burnett, 1971; California Department of Water Resources, 2004a,b,c). The predominant sediments in the basins are glacial outwash sediments that were deposited on prograding deltas as the glaciers retreated. The outwash sediments are composed of sorted, stratified material; the grain size ranges from boulders to fine silt. Glacial tills also were deposited in lateral and terminal moraines. In the Tahoe Valley South subbasin, the sediments were derived primarily from the granitic rocks in the surrounding Sierra Nevada and Carson Ranges. Fluctuations in the level of Lake Tahoe during the glacial periods resulted in interbedding of lacustrine and glacial deposits. The lacustrine deposits range from coarse sand to silt and clay layers. The fine-grained lacustrine deposits constitute discontinuous confining layers within the basin fill. The relatively thin Holocene fluvial deposits in the modern stream channels do not contribute much to groundwater storage in the basins (California Department of Water Resources, 2004a).

The basin-fill deposits typically range from 50 to 150 ft (15 to 45 m) thick in the Tahoe Valley South subbasin, but thicknesses up to 1,600 ft (490 m) have been measured near the city of South Lake Tahoe (California Department of Water Resources, 2004a). Sediment thicknesses in the Tahoe Valley North and West subbasins are less well known, but are thought to range from 20 ft (6 m) to as much as 200 ft (60 m) (California Department of Water Resources, 2004b,c). Groundwater conditions range from unconfined to semi-confined to confined.

Groundwater is recharged primarily by infiltration of rain and snow melt. Recharge occurs through the surface of the basin-fill deposits, and from high elevations through the fractures and faults in the bedrock and surface soils (Thodal, 1997). Temperature profiles in wells in the South Tahoe subbasin and surrounding bedrock suggest that mountain-block and mountain-front recharge (fig. 3) contribute to recharge of the basin (Fogg and Trask, 2007). Streamflow characteristics of the Upper Truckee River and creeks in the Tahoe Valley South subbasin suggest that these streams are net “gaining” streams, receiving groundwater discharge as they traverse the subbasin (Rowe and Allander, 2000).

A

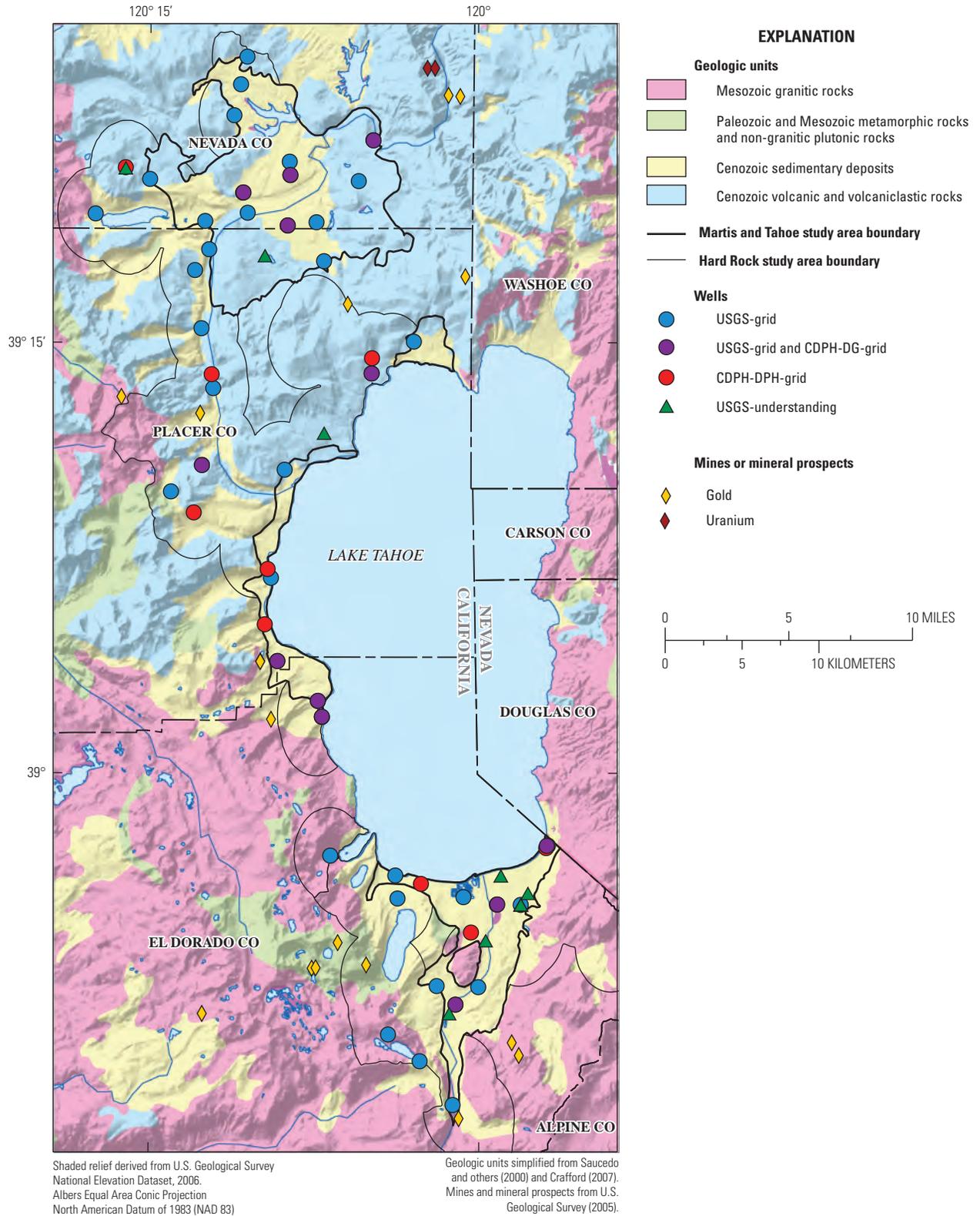


Figure 4. Geologic features and areal distribution of USGS-grid, CDPH-grid, and USGS-understanding wells sampled in the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

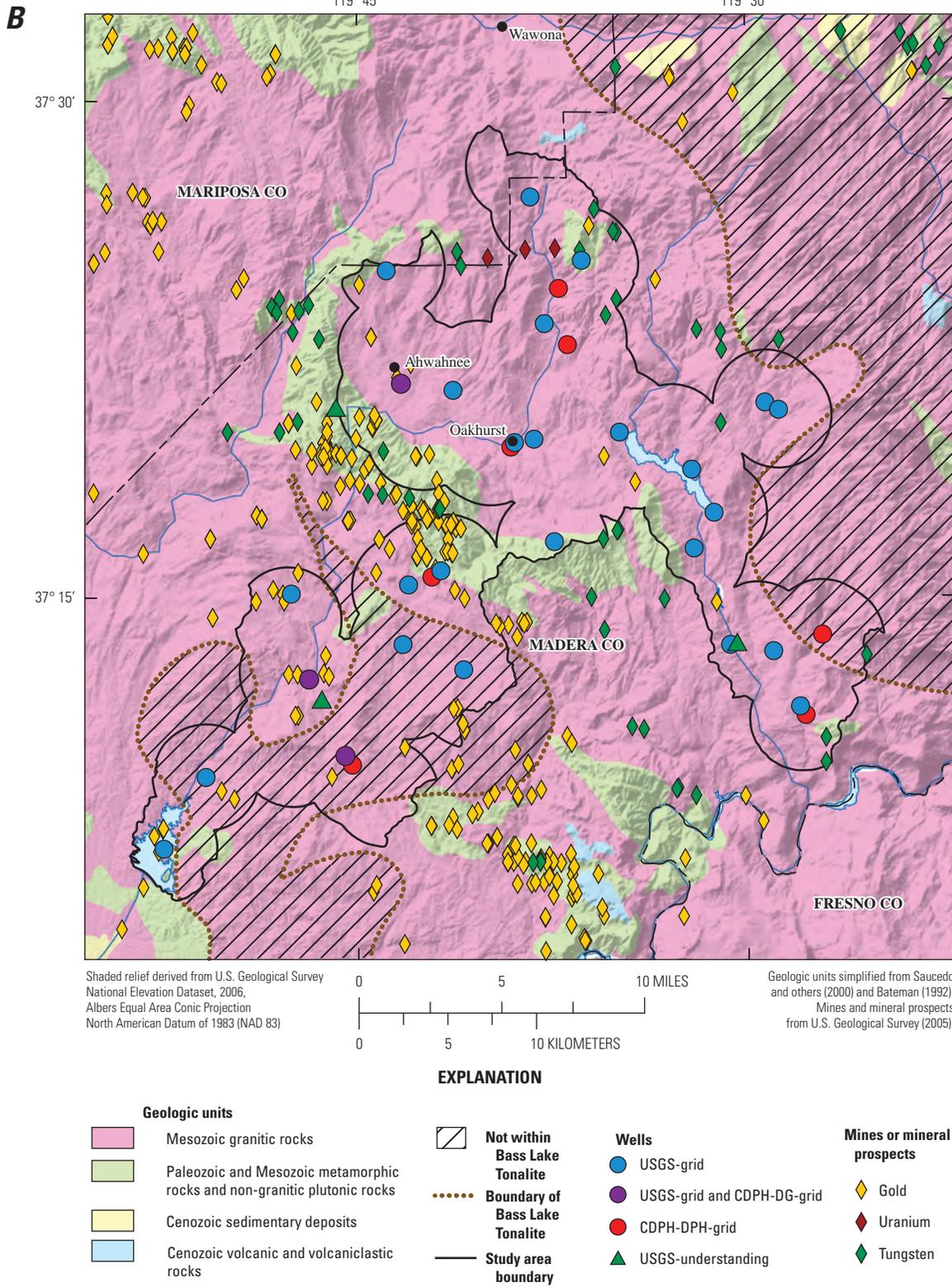


Figure 4.—Continued

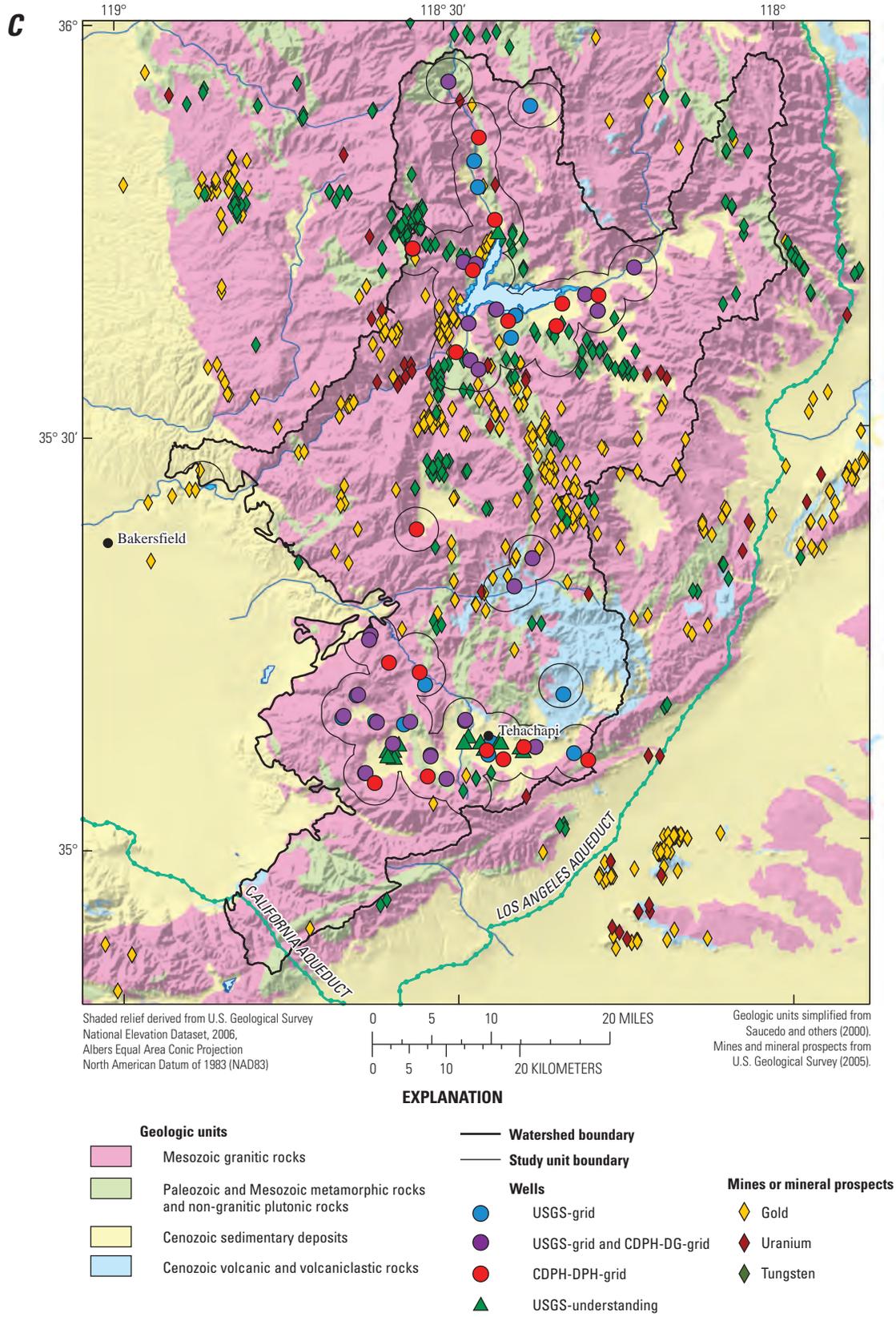


Figure 4.—Continued

The groundwater-bearing units in the Martis Valley basin consist of interlayered volcanic and sedimentary deposits of late Miocene to late Pleistocene age (7 to <1 Ma) (Nimbus Engineers, 2001; California Department of Water Resources, 2006a). The sedimentary deposits are composed of glacial, lacustrine, and fluvial deposits with depositional characteristics similar to those of the basin-fill sedimentary deposits in the Tahoe Valley subbasins. The primary source of sediment deposited in the Martis Valley basin is the andesitic volcanic and volcanoclastic units located in and around the basin. The glacial outwash sediments that cover approximately half of the surface of the Martis Valley basin are up to 150 ft (45 m) thick (Birkeland, 1964). The volcanic units include andesitic lavas, tuffs, breccias, and volcanoclastic deposits.

The water-bearing sedimentary and volcanic units in the Martis Valley are up to 1,200 ft (365 m) thick and are underlain by low-permeability Miocene volcanic rocks. The stratigraphy of the basin is complex, but it is typically separated into upper and lower aquifer systems that appear to have limited interconnection (Nimbus Engineers, 2001). Groundwater recharge occurs primarily by infiltration of rain and snow melt in the basin and in the mountains surrounding the basin (fig. 3).

The groundwater-bearing units in the Hard Rock study area are the Mesozoic granitic rocks in the southern part and the Miocene to Pleistocene volcanic rocks in the northern part (fig. 4A). Extensive faulting on the margins of the structural valley containing Lake Tahoe and the Tahoe Valley and Martis Valley groundwater basins likely contributes to the permeability of the granitic and volcanic rocks. In addition, most of the volcanic rocks are stratified, and some have zones of high permeability between lava flow units and within some of the volcanoclastic deposits.

Land use in 88% of the Tahoe-Martis study unit is classified as undeveloped (figs. 5A, 6A). Most of the undeveloped areas are forested. At the highest elevations, which occur on the western side of the Hard Rock study area, the forests give way to alpine scrub vegetation and bare rock. The center of the Martis Valley has open grassland and shrubland. No cultivated agriculture occurs within the study unit, although some undeveloped lands are used for open-range cattle grazing (appendix C). Urban land use composes 12% of the study unit area and is concentrated in the Tahoe Valley South subbasin, along the shoreline of Lake Tahoe, and in the western half of the Martis Valley basin.

Central Sierra Study Unit

The Central Sierra study unit area is defined by the surface-water watersheds of the Upper Fresno River and North Fork Willow Creek, a tributary of the San Joaquin River (fig. 2B). The Upper Fresno River watershed (Coarse Gold study area) ranges in elevation from about 6,000 ft (1,800 m) at the headwaters to about 500 ft (150 m) near Hensley Lake. The Willow Creek watershed (Wishon study area) ranges in elevation from about 8,500 ft (2,600 m) at the headwaters to about 1,500 ft (460 m) where the creek joins the San Joaquin River. Willow Creek flows through Bass Lake, a reservoir created for hydroelectric power generation.

Most of the Central Sierra study unit is underlain by granitic rocks, with a few areas underlain by metamorphic rocks (fig. 4B). Most of the granitic rocks are part of the Bass Lake Tonalite, a 114-Ma pluton that outcrops across over 800 mi² (2,000 km²) in the central part of the Sierra Nevada batholith (Bateman, 1988). The Bass Lake Tonalite is primarily composed of hornblende-biotite tonalite, and includes facies ranging from granite to quartz diorite in composition. The study unit also includes smaller trondhjemite and granodiorite plutons related to the Bass Lake Tonalite. The arcuate band of metamorphic rocks in the center of the study unit is the Coarsegold roof pendant, which consists of metasedimentary and metavolcanic rocks (Bateman, 1992). The metasedimentary rocks are primarily slates and schists with lesser amounts of chert, marble, and metagreywacke, and the metavolcanic rocks are primarily pillow lavas with lesser amounts of tuff and breccia. The slates and schists contain masses of metagabbro that are likely coeval with the metavolcanic rocks.

The Central Sierra study unit is located southeast of the southeastern end of the Sierra Nevada's Mother Lode Gold Belt. Placer and lode gold mining in the study unit began in 1849, with most prospects located in a belt near the center of the study unit (fig. 4B; U.S. Geological Survey, 2005). The mines in the study unit were small compared to mines in the Mother Lode; between 1848 and 1965, gold mines in Madera County produced <2% of the amount of gold produced in Nevada County, the richest county in the Mother Lode (Clark, 1970). Most of the gold was found in quartz veins located near the contacts between granodiorite plutons and pendants of schist.

A

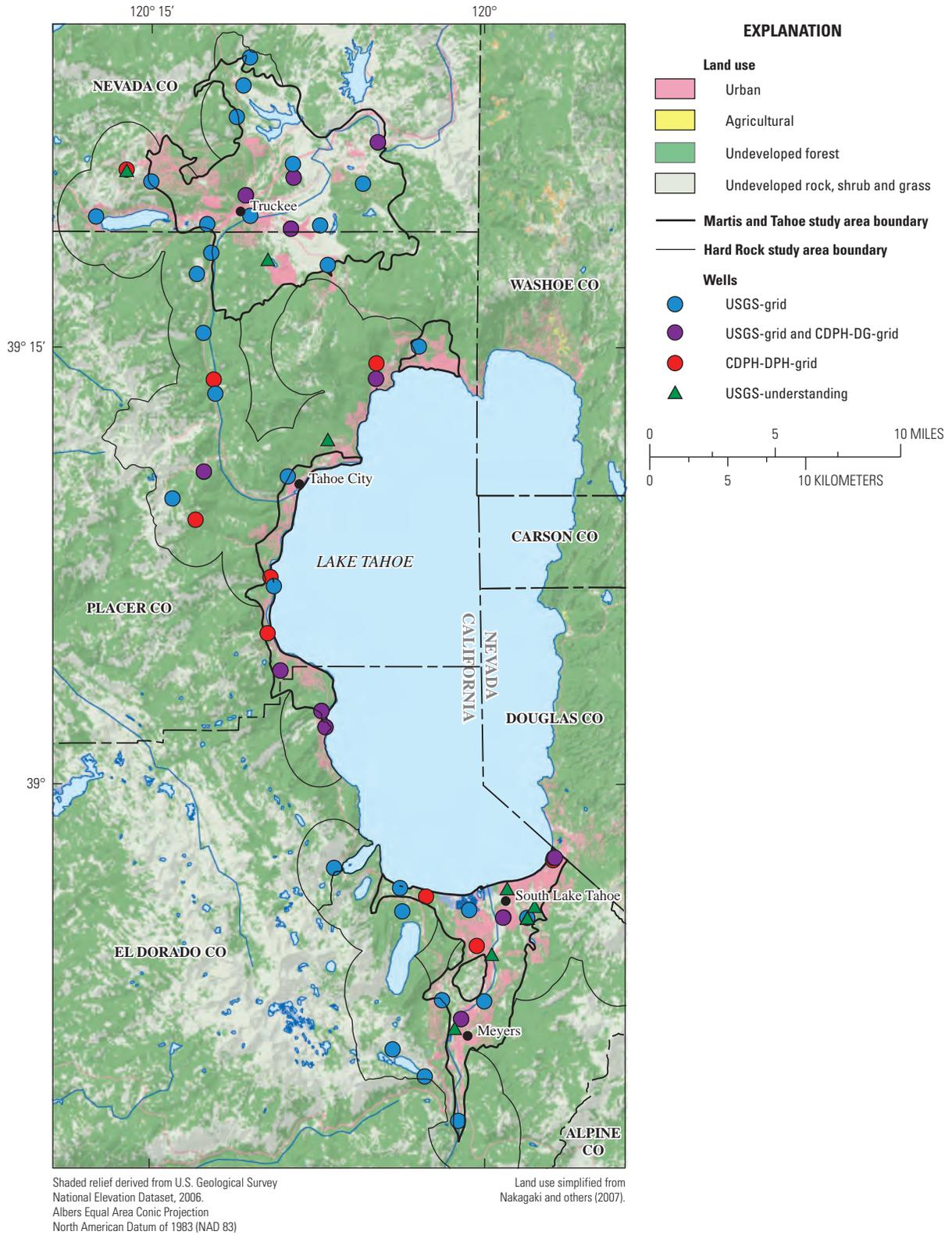


Figure 5. Land use and areal distribution of USGS-grid, CDPH-grid, and USGS-understanding wells sampled in the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

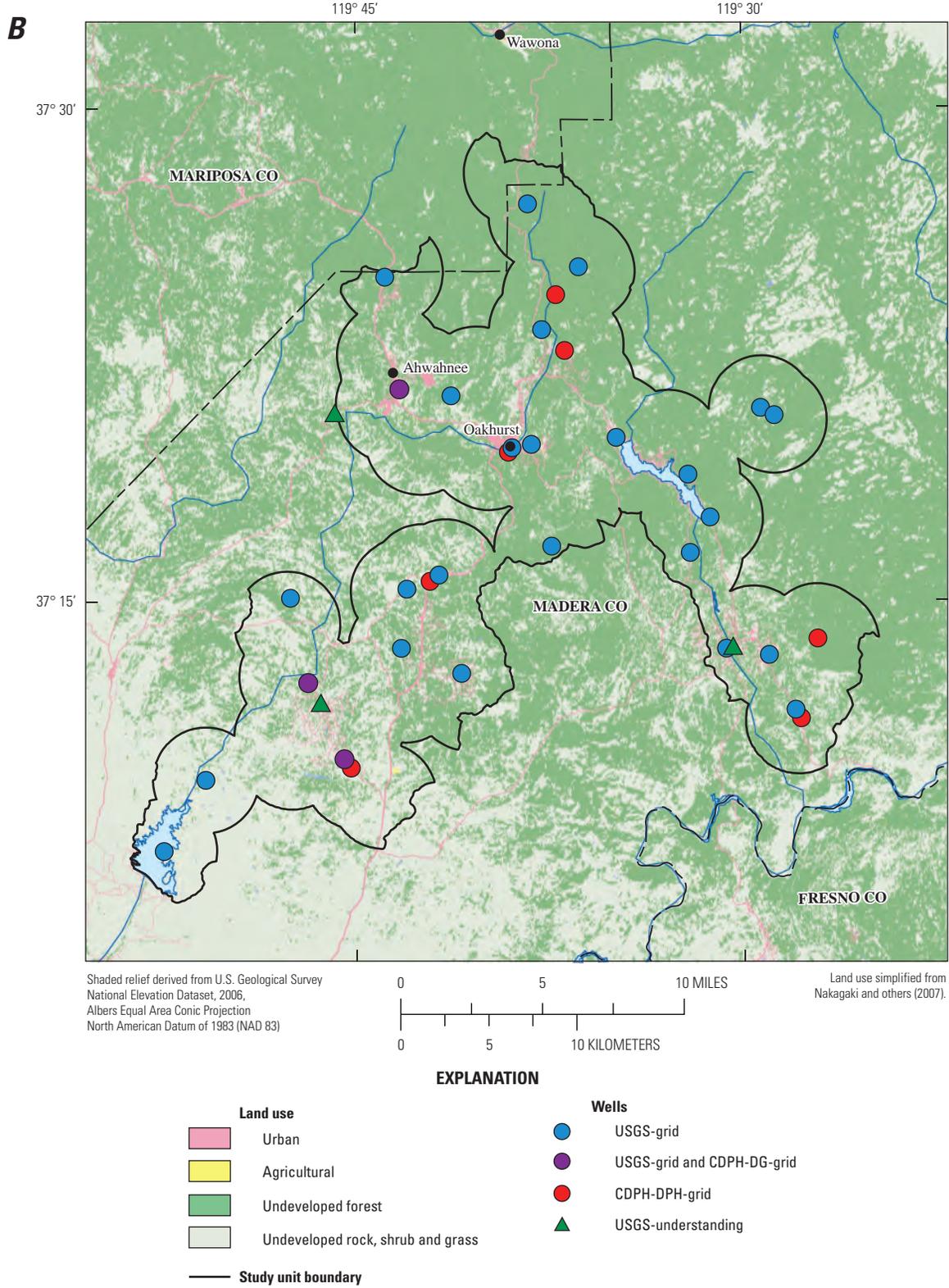


Figure 5.—Continued

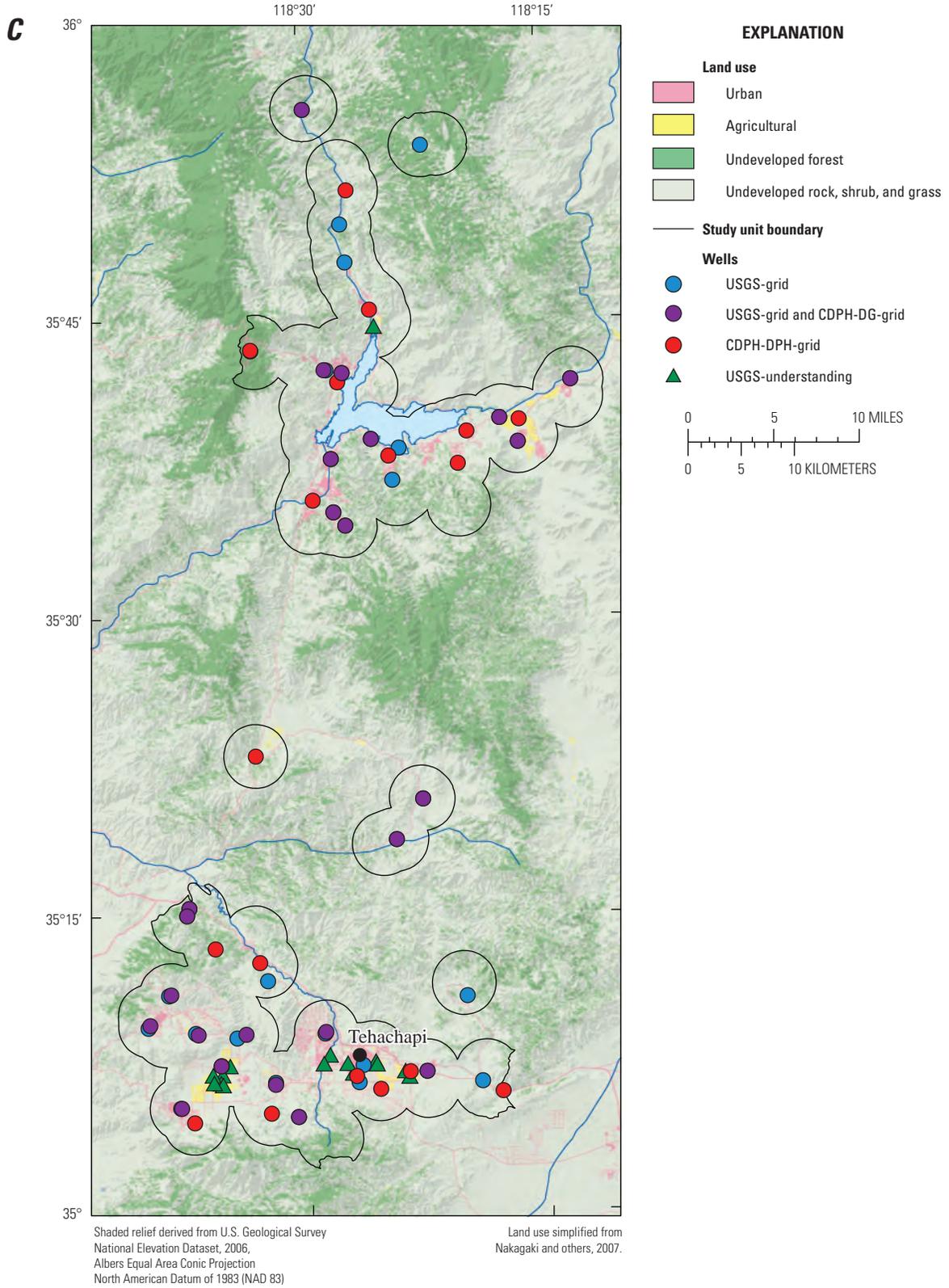


Figure 5.—Continued

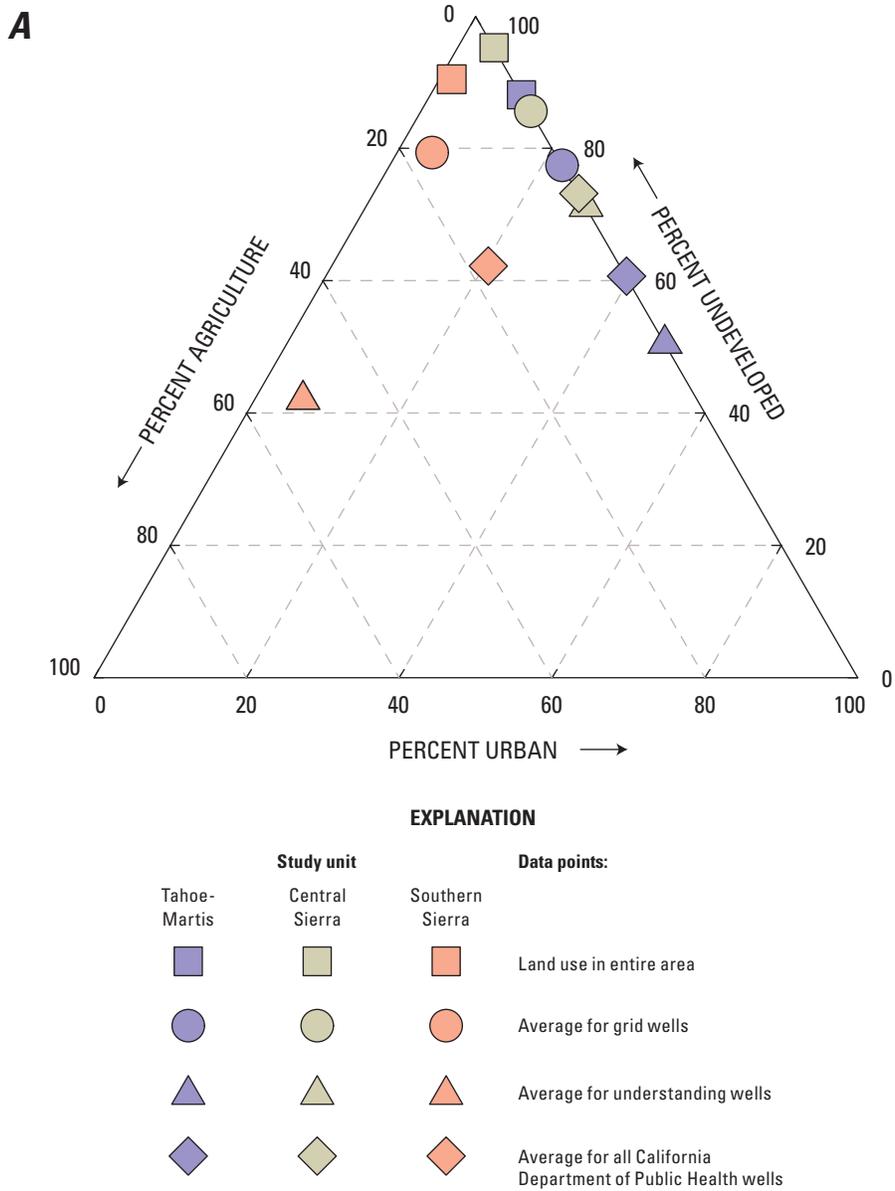
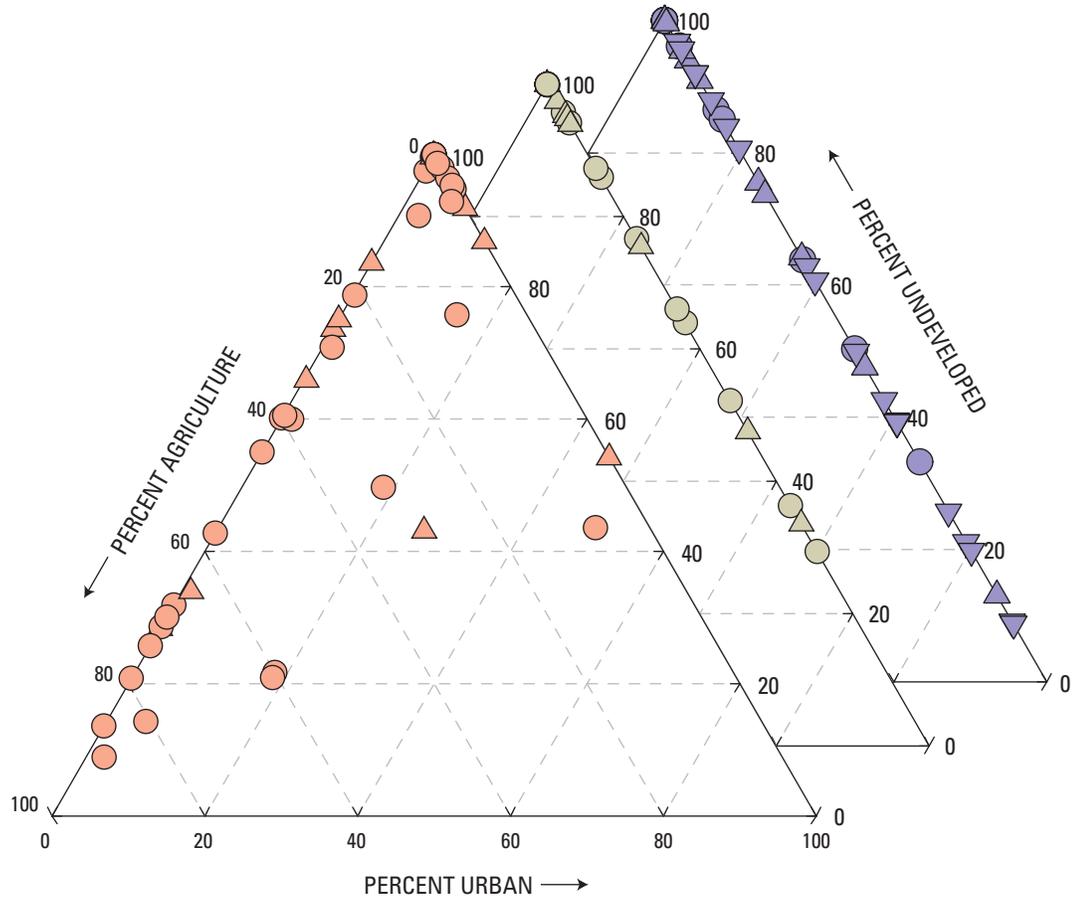


Figure 6. Percentage of urban, agricultural, and undeveloped land use in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project in (A) the study units, and (B) the areas surrounding each USGS-grid and USGS-understanding well.

B



EXPLANATION

- | | | | | | |
|--------------------------------------|----------------------------------|--|------------------------------------|---|---------------|
| Tahoe-Martis study unit wells | | Central Sierra study unit wells | | Southern Sierra study unit wells | |
| ● | Hard Rock grid and understanding | ● | Coarse Gold grid and understanding | ▲ | grid |
| ▲ | Martis grid and understanding | ▲ | Wishon grid and understanding | ● | understanding |
| ▼ | Tahoe grid and understanding | | | | |

Figure 6.—Continued

The other commodity mined in Madera County was tungsten. The largest tungsten mine was northeast of the study unit, but there were numerous tungsten prospects within the study unit, particularly around Bass Lake (fig. 4B; U.S. Geological Survey, 2005). Mining activity peaked during World Wars I and II because tungsten is a component of high-strength steel alloy (Partridge, 1941). The tungsten occurs in the mineral scheelite (CaWO_4) and is found in tactite masses along and near the contacts between granodiorite plutons and calcareous schists and marbles in xenoliths and pendants of metamorphic rocks (Krauskopf, 1953). Tactite is a skarn deposit, a rock type composed primarily of calcium-rich, silica-poor silicate minerals that forms in contact metamorphic aureoles in calcareous rocks.

The dominant source of groundwater in the study unit is the granitic rock. The granitic rocks are mantled by 0–100 ft (0–30 m) of grus (decomposed granitic rocks) and thin, discontinuous soils; however, these units typically are less permeable than the granitic bedrock (California Department of Water Resources, 1966). Groundwater moves through open joints, fractures, and exfoliation planes in the granitic bedrock (fig. 3). These fracture systems may be interconnected or isolated, resulting in variability in water levels, well yields, and water quality on local and regional scales. Groundwater recharge occurs primarily by infiltration of precipitation and snowmelt runoff, and seepage from surface-water bodies. Average annual precipitation ranges from <20 in/yr (50 cm/yr) near Hensley Lake in the foothills to >70 in/yr (180 cm/yr) in the highest elevations within the study unit (Todd Engineers, 2002). More than half of the average annual precipitation falls during the months of December, January, and February (California Department of Water Resources, 2006b).

Land use in 95% of the Central Sierra study unit is classified as undeveloped (figs. 5B, 6A). The area is mainly forested in the higher elevations and is shrubland or grassland in the lower elevations. No cultivated agriculture occurs within the study unit, although some undeveloped lands are used for open-range cattle grazing (appendix C). Residential and commercial development composes 5% of the land use and is focused along major transportation routes. Population in eastern Madera County has increased from 5,853 in 1970 to 36,376 in 1997, which has increased demand on the groundwater resources (Oakhurst Area Chamber of Commerce, 2006).

Southern Sierra Study Unit

The Southern Sierra study unit can be divided into three general hydrogeologic settings: the southern groundwater basins, the northern groundwater basin, and areas outside of the basins.

The southern part of the Southern Sierra study unit is a seismically active area near the intersection of the San Andreas and Garlock Faults, two of California's most prominent structural features (fig. 1B). Strain caused by motion on the San Andreas, Garlock, and White Wolf Faults appears to be partially accommodated by motion along many small faults in the region, which may have contributed to the formation of fault-bounded basins. The Bear Valley, Cummings Valley, Brite Valley, Tehachapi Valley East and West (hereinafter called the Tehachapi Valley) basins (fig. 2C) are all at least partially bounded by mapped faults (fig. 4C; Dibblee and Louke, 1970; Dibblee and Warne, 1970; Jennings, 1977). The basins contain alluvial fan and fluvial deposits derived from the erosion of the surrounding mountains. The oldest sedimentary deposits are Miocene in age (approximately 20 Ma) and roughly concurrent with the initiation of strike-slip motion on the San Andreas fault. Recent earthquakes in the area, such as the magnitude 7.3 Kern County earthquake on the White Wolf fault in 1952, indicate that the basins are continuing to develop.

The primary groundwater-bearing units in the basins are alluvial sediments of Pleistocene to Holocene age (2 Ma to present). Creeks draining the Tehachapi Mountains and Sierra Nevada have deposited alluvial fans around the margins of the basins and floodplain deposits in the centers of the basins (Michael and McCann, 1962; Dibblee and Louke, 1970; Dibblee and Warne, 1970; California Department of Water Resources, 2006c,d,e,f). Lithologically, the sediments are arkosic cobbles, gravels, sands, silts, and clays, with the coarser materials in the alluvial fans and the finer sediments in the floodplains. Maximum thicknesses of these alluvial deposits are approximately 500 ft (150 m) in the Cummings Valley and Brite Valley basins (Fugro-West Inc., ETIC Engineering, 2004; California Department of Water Resources, 2006c,d) and >600 ft (180 m) in the Tehachapi Valley basin. The Tehachapi basins have longer depositional histories than the Cummings Valley and Brite Valley basins, and have Miocene-Pliocene alluvial, fluvial, and pyroclastic deposits that are also water-bearing (Michael and McCann, 1962; Dibblee and Louke, 1970; California Department of Water Resources, 2006e,f). The eastern portion of the Tehachapi Valley basin has extensive Miocene-age volcanic rocks, primarily andesite lavas and flow breccias (fig. 4C; Dibblee and Louke, 1970).

Natural recharge occurs by infiltration of precipitation in the basins and by infiltration from the perennial and ephemeral creeks that drain the surrounding mountains (California Department of Water Resources, 2006c,d,e,f); however, the relative importance of natural recharge is decreasing as artificial recharge from irrigation and intentional recharge programs increases. Agricultural lands and urban/suburban landscapes in the basins are extensively irrigated.

The basins are managed collectively by the Tehachapi-Cummings County Water District (TCCWD). Since 1973, TCCWD has imported water from the State Water Project (SWP), and the Cummings Valley, Brite Valley, Tehachapi Valley, and Bear Valley (hereinafter referred to collectively as the Tehachapi-Cummings Valley) are all now supplied with imported water. The availability of imported water has changed the water-use patterns in the TCCWD region. The SWP water typically has relatively high concentrations of organic carbon, and disinfection of this water by municipalities in the basin produces unacceptable levels of disinfection byproducts. To avoid this problem, TCCWD manages an extensive conjunctive-use program in which SWP water allocated to municipal users in the TCCWD service area is used for artificial recharge and the municipal users pump an equivalent amount of groundwater (Tehachapi-Cummings County Water District, 2004a,b). SWP water is primarily recharged in spreading basins on the alluvial fans in the northeast corner of the Cummings Valley and the southern side of the Tehachapi Valley and in Lake Jacobsen on the southern side of Brite Valley. Since the arrival of imported water in 1973, groundwater levels in the TCCWD area have increased from 55 to 100 ft (from 17 to 30 m) and typically have returned approximately to the levels measured in 1950, prior to extensive groundwater pumping in the area (Tehachapi-Cummings County Water District, 2004a,b).

The Kern River Valley groundwater basin in the northern part of the Southern Sierra study unit has an irregular shape that follows the drainage pattern of the main stem and south fork of the upper Kern River (figs. 2C, 4C). The main stem lies in the trace of the Kern Canyon Fault from the river's headwaters on the western slopes of Mt. Whitney (the highest peak in the conterminous 48 states) approximately 80 miles north of the study unit to Lake Isabella. The Kern Canyon Fault originally formed concurrently with the surrounding plutons and is still a major topographic and geologic discontinuity in the southern Sierra Nevada (Saleeby and others, 2008). Lake Isabella is impounded by Isabella Dam, which was constructed in 1953 by the U.S. Army Corps of Engineers, and is operated as part of the Federal Central Valley Project.

The primary water-bearing units are the Pleistocene to Holocene fluvial deposits in the channel of the Kern River and around Lake Isabella (California Department of Water Resources, 2006g). Natural recharge occurs by infiltration of precipitation falling in the basin and surrounding watershed,

and infiltration of water from the Kern River. Landscape and agricultural irrigation are additional sources of recharge.

In areas of the Southern Sierra study unit outside of the defined groundwater basins, groundwater is pumped from local aquifers in fractured hard rock (fig. 3). The Mesozoic granitic rocks, Paleozoic to Mesozoic metamorphic rocks, and the Miocene volcanic units are all locally water bearing. Most of the metamorphic rocks are part of the Kings Sequence, which is primarily composed of high metamorphic grade quartzites, marbles, and pelitic schists (Ross, 1989; Saleeby and others, 2008). Metamorphic grade increases sharply at the southern end of the Sierra Nevada, and metamorphic rocks around Brite Valley are primarily hypersthene granulites. The Mesozoic granitic rocks in the Southern Sierra study unit consist of numerous plutons ranging in age from 94 to 105 Ma (Saleeby and others, 2008). Most of the plutons are tonalites or granodiorites, but plutons ranging in composition from granite to gabbro are present locally. As in the Tahoe-Martis and Central Sierra study units, groundwater in the granitic and metamorphic rocks of the Southern Sierra study unit moves through joints and fractures. The Kern River Valley region of the Southern Sierra study unit has numerous sites of lode gold and lode tungsten mining and prospecting, primarily associated with quartz veins and fracture systems at the boundaries between the granitic rocks and metamorphic roof pendants and within nearby granitic rocks (Troxel and Morton, 1962).

The study unit has approximately 8,000 ft (2,400 m) of topographic relief. The Cummings Valley and Tehachapi Valley basins are relatively flat with an elevation of approximately 4,000 ft (1,200 m), and the Tehachapi Mountains to the south rise over 8,000 ft (2,400 m). Average water level in Lake Isabella is 2,600 ft (790 m), and the peaks of the Sierra Nevada rise up to 10,000 ft (3,000 m) 40 mi (64 km) north of the lake. Precipitation at Lake Isabella Dam (elevation 2,635 ft; 803 m) and in the city of Tehachapi (4,017 ft; 1,224 m) averages 11 in/yr (28 cm/yr), with 80 to 90% falling between November and April (California Department of Water Resources, 2007). Winter precipitation falls mostly as snow at elevations above 5,000 ft (1,500 m).

Land use in the Southern Sierra study unit is 90% undeveloped and is mostly shrublands and grasslands (figs. 5C, 6A). Some undeveloped lands are used for open-range cattle grazing (appendix C). Cultivated agricultural land use composes 8% of the area and is concentrated in the centers of the Tehachapi Valley and Cummings Valley and at the eastern end of the Kern River Valley basin. The dominant agricultural crops are sod, oats and alfalfa for fodder, carrots, and apples (Kern County Department of Agriculture and Measurement Standards, 2000). Urban land use, mostly residential, composes 2% of the area and occurs primarily in the Tehachapi Valley and Cummings Valley and the Kern River Valley basins.

Methods

This section describes the methods used in the *status* and *understanding assessments*. Methods used to collect and analyze groundwater samples and results for quality-control assessment for the analytes listed in [table 1](#) are described by Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009). Methods used for compilation of data on potential explanatory factors are described in [appendix C](#).

Status Assessment

The *status assessment* was designed to quantify groundwater quality in areal proportions of the primary aquifer. This section describes the methods used for: (1) defining groundwater quality, (2) assembling the datasets used for the assessment, (3) determining which constituents warrant additional evaluation, and (4) calculating aquifer-scale proportions.

Groundwater quality was defined in terms of relative-concentration (RC), which references the concentrations of constituents in groundwater to the concentrations of regulatory and non-regulatory benchmarks used to evaluate drinking-water quality. Constituents were selected for additional evaluation in the *status assessment* on the basis of objective criteria by using these RCs. 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*. Two statistical methods were used to calculate the areal proportions of the primary aquifer occupied by groundwater with high, moderate, or low RCs for a constituent or constituent class (aquifer-scale proportions): (1) the “grid-based” method, which uses one value per cell to represent groundwater quality (Belitz and others, 2010), and (2) the “spatially weighted” method, which uses many values per cell.

The CDPH database contains records from more than 25,000 wells, necessitating targeted retrievals to access water-quality data effectively. For example, for the areas representing the Tahoe-Martis, Central Sierra, and Southern Sierra study units, the CDPH database contains more than 260,000 analyses from 755 wells over a period of 25 years. The CDPH data were used in three ways in the *status assessment*: (1) to fill in gaps in USGS-GAMA data for the grid-based calculations of aquifer-scale proportions, (2) to help identify constituents for additional evaluation in the assessment, and (3) to provide the majority of the data used in the spatially weighted calculations of aquifer-scale proportions.

Relative-Concentrations and Water-Quality Benchmarks

To provide context for water-quality data, measured concentrations of constituents may be compared to water-quality benchmarks that are typically applied to finished drinking water. Toccalino and others (2004), Toccalino and Norman (2006), and Rowe and others (2007) converted measured concentration to a Benchmark Quotient (BQ), which is the ratio of measured concentration to a water-quality benchmark. BQs are relative-concentrations. BQs that are <1.0 indicate sample concentrations less than the benchmark, and values >1.0 indicate sample concentrations greater than the benchmark. The use of BQs also permits comparison of constituents present at a wide range of concentrations on a single scale.

The BQ concept is used in this study; however, the ratio of measured concentration to a water-quality benchmark is called a relative-concentration (RC) rather than a BQ because the benchmarks used to calculate RCs are not the same as the benchmarks used to calculate BQs for all constituents. BQs are calculated using U.S. Environmental Protection Agency (USEPA) maximum contaminant levels (MCL-US) or USGS-USEPA Health-Based Screening Levels (HBSLs). HBSLs are determined using USEPA methodologies for establishing drinking-water guidelines, and the most recent USEPA peer-reviewed, publically-available human-health toxicity information (Toccalino, 2007). RCs are calculated using benchmarks established by the USEPA and CDPH (U.S. Environmental Protection Agency, 1999, 2009a,b; California Department of Public Health, 2006, 2008, 2010). HBSLs were not used in this study because they are not recognized by California drinking-water regulatory agencies, and the GAMA Program was created to specifically focus on groundwater quality in California.

The benchmarks used for each constituent for calculating RCs were selected in the following order of priority:

1. Regulatory, health-based CDPH and USEPA maximum contaminant levels (MCL-CA and MCL-US, respectively) and action levels (AL-US).
2. Non-regulatory CDPH and USEPA secondary maximum contaminant levels (SMCL-CA and SMCL-US, respectively). For constituents with both recommended and upper SMCL-CA levels, the values for the upper levels were used.
3. Non-regulatory, health-based CDPH notification levels (NL-CA), USEPA lifetime health advisory levels (HAL-US) and USEPA risk-specific doses. Risk-specific doses for risks of 1 in 10^5 (RSD5-US) were calculated by dividing by 10 the USEPA values for the concentration of a constituent in drinking water corresponding to an estimated excess lifetime cancer risk of 1 in 10^4 .

Note that for constituents with multiple types of benchmarks, this hierarchy may not result in selection of the benchmark with the lowest concentration. For example, zinc has an SMCL-CA of 5,000 micrograms per liter ($\mu\text{g/L}$) and a HAL-US of 2,000 $\mu\text{g/L}$; the comparison benchmark selected using this hierarchy is the SMCL-CA. Additional information on the types of benchmarks and listings of the benchmarks for all constituents analyzed are provided by Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009).

Fifty-eight constituents detected in the Tahoe-Martis, Central Sierra, or Southern Sierra study units have MCL-US, MCL-CA, SMCL-CA, NL-CA, HAL-US, or RSD5-US benchmarks, and therefore can have RCs calculated. For 30 of the 58 constituents, the benchmarks used in this study have the same concentrations as the benchmarks used by Toccalino (2007), thus, RCs and BQs for these constituents would have the same values. For 13 constituents, the MCL-CA or NL-CA benchmark used in this study has a lower concentration than the HBSL used by Toccalino (2007), thus, RCs would have higher values than BQs. For two constituents, the benchmarks used in this study have higher concentrations than the HBSLs, thus, RCs would have lower values than BQs. Another 13 constituents have MCL-CA or NL-CA values, but no MCL-US or HBSL values, and therefore, would have RCs but no BQs.

For ease of discussion, RCs of constituents were classified into low, moderate, and high categories:

Category	Organic and special-interest constituents	Inorganic constituents
High	$\text{RC} > 1.0$	$\text{RC} > 1.0$
Moderate	$1.0 \geq \text{RC} > 0.1$	$1.0 \geq \text{RC} > 0.5$
Low	$0.1 \geq \text{RC}$	$0.5 \geq \text{RC}$

The boundary between “moderate” and “low” RCs was set at 0.1 for organic and special-interest constituents for consistency with other studies and reporting requirements (U.S. Environmental Protection Agency, 1998; Toccalino, 2007). For organic constituents, detection at concentrations greater than one-tenth of a health-based benchmark value ($\text{RC} > 0.1$) commonly is used to identify constituents that may warrant additional monitoring to evaluate trends in their occurrences. Organic constituents typically are human-made and are infrequently detected at $\text{RCs} > 0.1$. Of the three special-interest constituents, two are organic compounds (1,2,3-trichloropropane and *N*-nitrosodimethylamine). The third, perchlorate, is an inorganic compound and is in the special-interest group, rather than the inorganic constituent group, because at the inception of the GAMA Priority Basin Project, the State of California was assessing potential regulation of perchlorate concentrations in drinking water and therefore had a “special interest” in perchlorate occurrence. An MCL-CA was promulgated in October 2007.

For inorganic constituents, the boundary between “moderate” and “low” RCs was set at 0.5. The primary reason for using a higher boundary value was to focus attention on the inorganic constituents of most immediate concern. In a national survey of water quality in aquifers used for public drinking-water supply, Toccalino and others (2010) found that organic constituents (pesticides and VOCs) were present at BQs > 0.1 in approximately 10% of the samples and that inorganic constituents (trace elements and radioactive constituents) were present at BQs > 0.1 in approximately 80% 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. Concentrations of the human-made organic constituents may change rapidly in groundwater; therefore, such early warning is vital for planning and implementing measures to protect aquifer systems from further contamination and to mitigate existing contamination. Resources may be focused on the 10% of wells that have BQs > 0.1 of organic constituents; however, a similar focusing of resources would not be possible for the inorganic constituents because most of the wells (80%) have inorganic constituents present at BQs > 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. Thus, early warning of potential groundwater contamination by inorganic constituents may be less critical for management of potential water-quality problems. Having a boundary between low and moderate RC (or BQ) that is 0.5 allows identification of inorganic constituents—from among the many that may be present at concentrations approaching benchmarks—that may warrant more immediate attention from water-resource managers.

Setting the boundary between “moderate” and “low” RCs at 0.5 for inorganic constituents, rather than 0.1, also permitted use of water-quality data from the CDPH database in the assessments. For example, in the Tahoe-Martis study unit, 23 inorganic constituents had health-based benchmarks for which there were data from both the CDPH database and USGS-GAMA. RCs of reporting limits used by USGS-GAMA were < 0.1 for all 23 constituents (fig. 7). 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 limits used in the CDPH database was 0.1 (fig. 7). The RCs of the most prevalent reporting limits for 11 constituents were > 0.1 . These 11 are the trace elements antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, and thallium; the nutrient nitrite; and the radioactive constituents gross alpha particle activity and radium. If the boundary were set at 0.1, then data from the CDPH database would yield only minimum

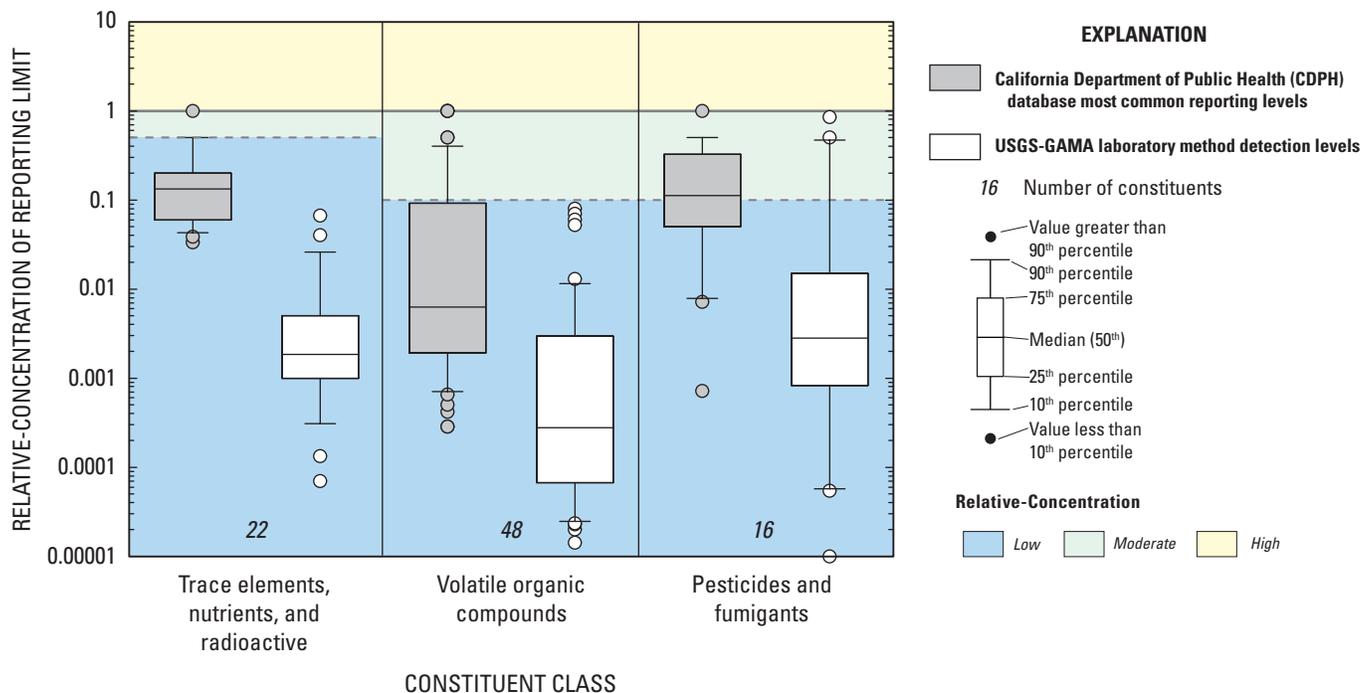


Figure 7. Method-detection levels used for analysis of constituents by USGS-GAMA in the time period during which samples were collected for the Tahoe-Martis study unit, and the most common reporting levels for the same constituents used in the CDPH database for wells in the area corresponding to the Tahoe-Martis study during the 3-year interval used in the status assessment.

estimates of the prevalence of groundwater with moderate RCs of these 11 constituents. Elevated concentrations of arsenic and activities of gross alpha particles, in particular, are commonly detected in groundwater from the Tahoe-Martis, Central Sierra, and Southern Sierra study units. Setting both upper and lower bounds on the proportion of the primary aquifers with high and moderate RCs of these constituents is an important component of the *status assessment* portion of this study; thus, the boundary between low and moderate had to be set at an RC >0.1.

The decision to set the boundary at 0.5 (rather than 0.2, 0.25, 0.675, or some other value >0.1) is somewhat arbitrary, and represents a balance between the desire to be most protective of human health (lower boundary value), the desire to focus attention on those constituents of greatest potential concern (higher boundary value), and the limitations of the data in the CDPH database. For the Tahoe-Martis study unit, a boundary of 0.5 permits use of data from the CDPH database to identify moderate RCs for all inorganic constituents except for antimony.

In this study, nutrients are grouped with trace elements and radioactive constituents rather than with organic constituents because nitrate concentrations, like the concentrations of many trace elements, may be affected by both natural and anthropogenic sources, whereas the VOCs and pesticides have only anthropogenic sources. However, the concentrations of nutrients in groundwater may be more

affected by human activities than the concentrations of other inorganic constituents, and therefore, may be more likely to change rapidly. On that basis, one could choose to group the nutrients with organic constituents and use the boundary of RC=0.1 between low and moderate categories. The MCL-US for nitrate, as nitrogen (nitrate-N) is 10 milligrams per liter (mg/L); if RC=0.1 were used as the boundary, concentrations above 1 mg/L would be classified as moderate; if RC=0.5 were used as the boundary, concentrations above 5 mg/L would be classified as moderate. Nitrate has both natural and anthropogenic sources. Mueller and Helsel (1996) define a nitrate concentration of 2 mg/L as the threshold above which nitrate is likely to be anthropogenic in origin, based on a national study of nitrate concentrations in groundwater. If elevated nitrate concentrations (moderate or high) are considered anthropogenic in origin (Toccalino and others, 2010), then a boundary of 0.1 may overestimate the prevalence of groundwater contaminated by anthropogenic sources of nitrate, and a boundary of 0.5 may underestimate it.

Complex classifications could be devised based upon the properties and sources of individual constituents; however, use of a single moderate/low boundary value for each of the two major groups of constituents, organic and inorganic, provides a consistent criteria for distinguishing constituents occurring at moderate rather than low concentrations.

Datasets for Status Assessment

Three datasets were used in the *status assessment*: USGS-grid wells, CDPH-grid wells, and additional, non-grid wells from USGS and CDPH. This section describes how each dataset was constructed. Comparisons of USGS-GAMA and CDPH data are presented in [appendix D](#).

USGS-Grid Wells

The primary data used for the grid-based calculations of aquifer-scale proportions are from wells sampled by USGS-GAMA. Detailed descriptions of the methods used to identify wells for sampling are given in Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009). Briefly, each study unit or study area was divided into equal-area grid cells, and in each cell, one well was randomly selected to represent the cell (Scott, 1990). Wells primarily were selected from the population of wells in the statewide database maintained by CDPH. The three study units contained a total of 115 grid cells, and USGS-GAMA sampled wells in 103 of those cells (USGS-grid wells) ([figs. 8A–C](#)). Of the 103 USGS-grid wells, 92 were listed in the CDPH database, 3 were unlisted public-supply wells, and the other 8 were irrigation, domestic, industrial, or monitoring wells screened or open at depths similar to the depths of CDPH wells in the cell or neighboring cells. USGS-grid wells were named with an alphanumeric GAMA_ID consisting of a prefix identifying the study unit or study area (TTAHO, TROCK, and TMART for the Tahoe, Hard Rock, and Martis study areas, respectively, in the Tahoe-Martis study unit; CGOLD and CWISH for the Coarse Gold and Wishon study areas, respectively, in the Central Sierra study unit; and SOSA for the Southern Sierra study unit) and a number indicating the order of sample collection ([appendix A](#); [fig. A1](#); [table A1](#)).

Samples were collected in accordance with protocols established by the USGS National Water-Quality Assessment (NAWQA) Program (Koterba and others, 1995) and the USGS National Field Manual (U.S. Geological Survey, variously dated). Detailed descriptions of the methods used to collect and analyze samples, and quality-control results are given in Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009).

Samples collected from USGS-grid wells were analyzed for 166 to 243 constituents ([table 1](#)). Samples for analysis of field water-quality parameters, VOCs, pesticides, perchlorate, noble gases, tritium, and stable isotopes of water were collected from all wells. Samples for analysis of major and minor ions, trace elements, nutrients, carbon isotopes, and redox species were collected from most wells, and samples for analysis of radioactive constituents were collected from some wells.

CDPH-Grid Wells

Of the 115 grid cells in the three study units, 12 cells did not have a USGS-grid well, 28 cells had a USGS-grid well but no USGS data for major ions, trace elements, nutrients, and radioactive constituents, and 49 cells had a USGS-grid well but incomplete USGS data for radioactive constituents. The CDPH database was queried to identify wells to provide these missing inorganic data. CDPH wells with data during the most recent 3 years available at the time of sampling were considered. If the well had more than one analysis for a constituent in the 3-year interval, the most recent data were selected. The 3-year intervals were as follows:

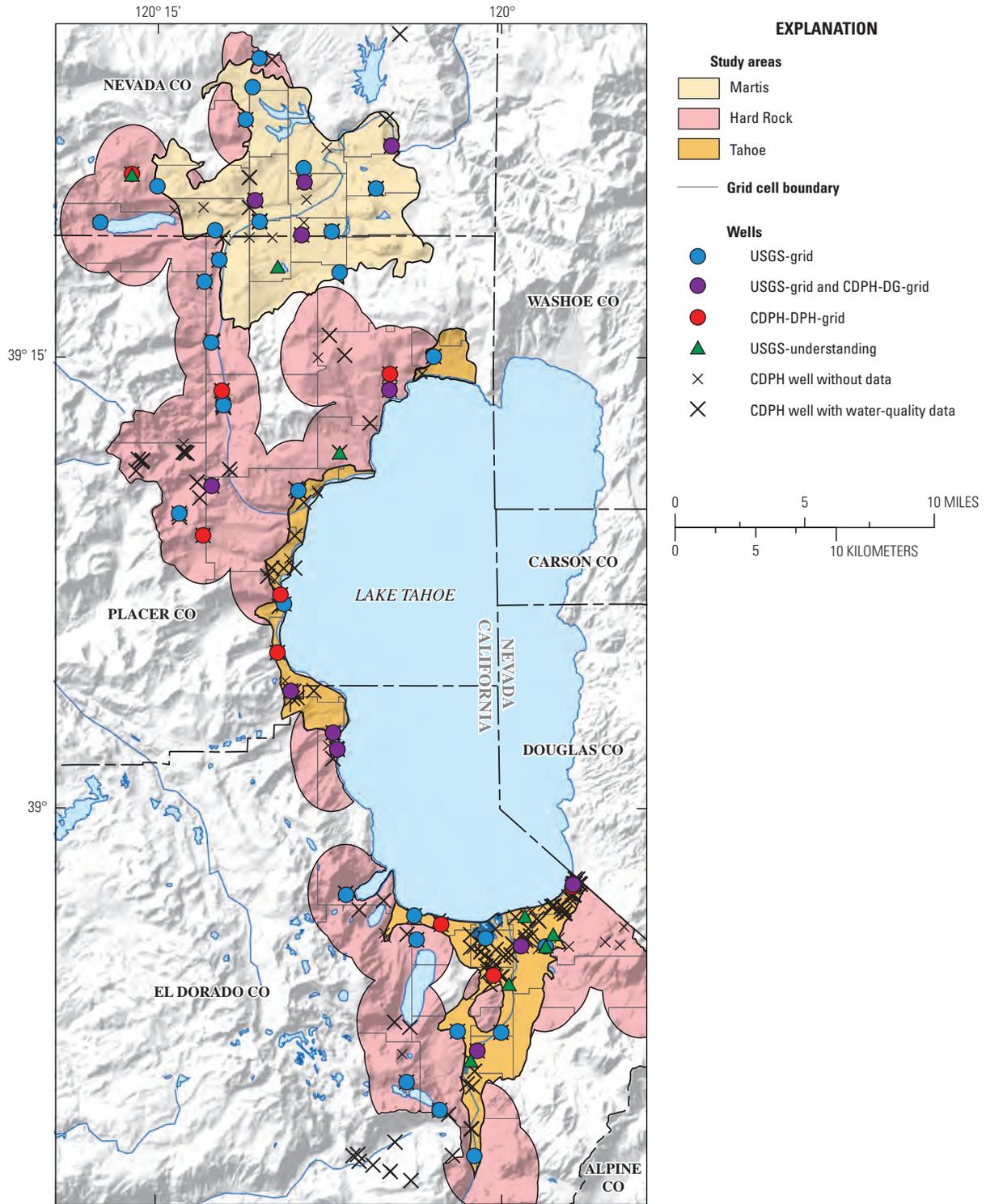
Study unit	3-year interval	Number of wells with data
Tahoe-Martis	May 1, 2004–April 30, 2007	157
Central Sierra	June 1, 2003–May 31, 2006	169
Southern Sierra	February 1, 2003–January 31, 2006	205

The decision tree used to identify suitable CDPH wells is described in [appendix A](#). Briefly, the first choice was to use CDPH data from the same well as the USGS-grid well (“DG” CDPH-grid wells, where DG refers to CDPH and USGS; [fig. A1](#); [table A1](#)). If the DG well did not have all of the needed data, a second well was randomly selected from the subset of CDPH wells with data (“DPH” CDPH-grid wells, where DPH refers to CDPH; [fig. A1](#); [table A1](#)). No more than one DPH CDPH-grid well was selected in a cell. The combination of the USGS-grid wells and the DG and DPH CDPH-grid wells produced a grid-well network covering 108 of the 115 grid cells in the three study units ([figs. 8A,B,C](#)). The remaining seven cells had no wells accessible for sampling and no wells with water-quality data in the CDPH database.

The CDPH database generally did not contain data for all of the missing inorganic constituents at every CDPH-grid well; therefore, the number of wells used for the grid-based assessment differed for various inorganic constituents ([table 2](#)). Although other organizations also collect water-quality data, the CDPH data are the only data available from a statewide database of groundwater chemistry that is suitable for comprehensive analysis.

CDPH data were not used to supplement USGS-grid well data for VOCs, pesticides, or perchlorate for the *status assessment*. A larger number of VOCs and pesticide compounds are analyzed for the USGS-GAMA Program than are available from the CDPH database. USGS-GAMA collected data for 88 VOCs and 63 pesticides and pesticide degradates at every well ([table 1](#)); the CDPH database for the three study units contains data for up to 61 VOCs and 27 pesticides at a subset of the wells in the database. In addition, method detection limits for USGS-GAMA analyses of organic constituents were typically one to two orders of magnitude lower than the reporting limits for analyses compiled by the CDPH ([fig. 7](#)).

A



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

Figure 8. Locations of grid cells and USGS-grid wells, CDPH-grid wells, USGS-understanding wells, and other CDPH wells in the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

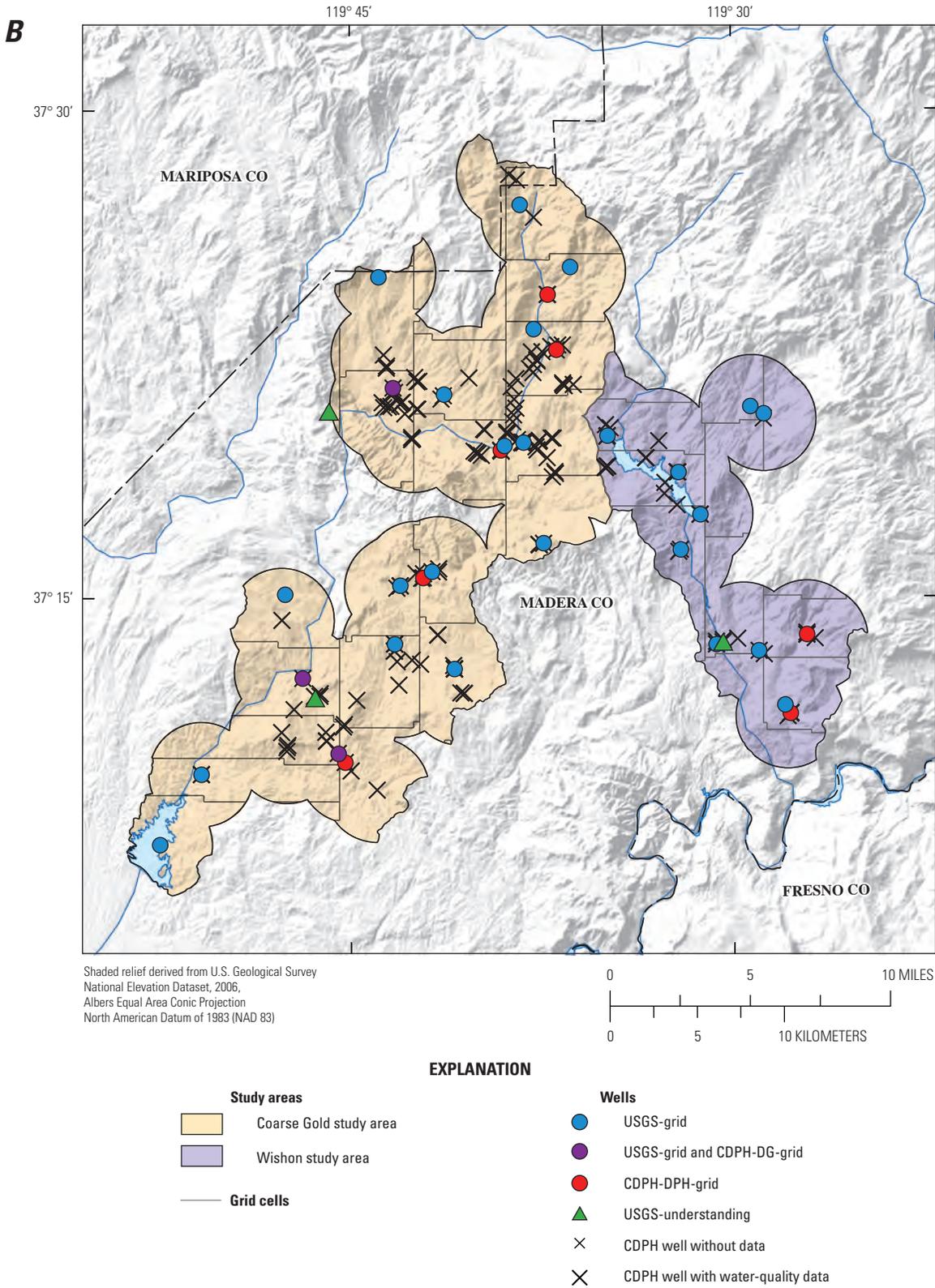


Figure 8.—Continued

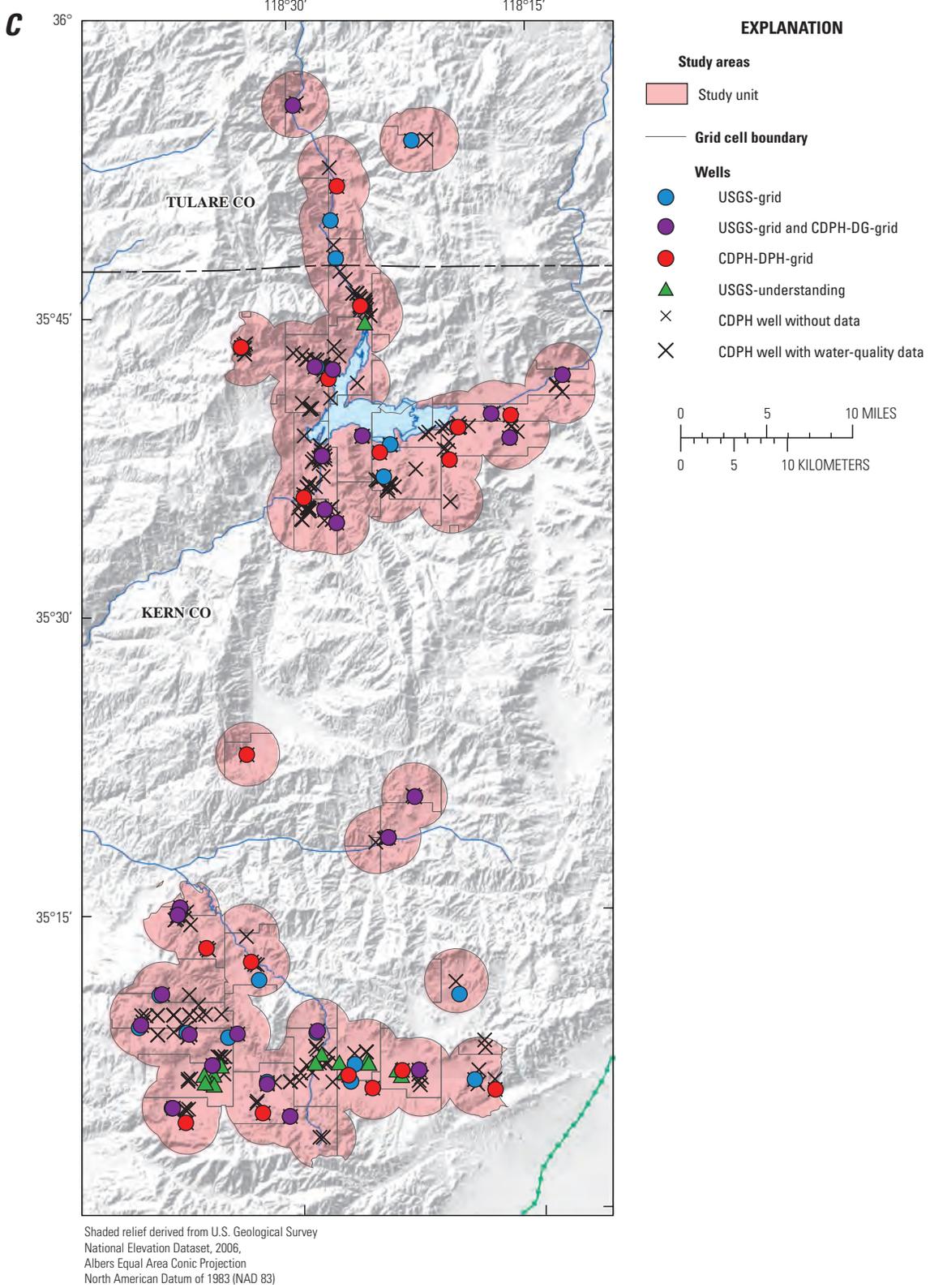


Figure 8.—Continued

Table 1. Summary of constituent groups and number of wells sampled by the U.S. Geological Survey for different analytical schedules for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.[Constituent names: NDMA, *N*-nitrosodimethylamine; TDS, total dissolved solids; 1,2,3-TCP, 1,2,3-trichloropropane. Other abbreviations: na, not analyzed]

	Tahoe-Martis study unit schedule ¹		Central Sierra study unit schedule ¹		Southern Sierra study unit schedule ¹		
	Intermediate	Slow	Intermediate	Slow	Fast	Intermediate	Slow
Total number of wells	42	10	16	14	27	16	7
Number of grid wells sampled	33	8	13	14	27	4	4
Number of understanding wells sampled	9	2	3	0	0	12	3
Number of constituents analyzed							
Inorganic constituents							
Specific conductance	1	1	1	1	1	1	1
Nutrients	5	5	5	5	na	5	5
Dissolved organic carbon	na	na	1	1	na	1	1
Major ions, alkalinity, and TDS	12	12	12	12	na	12	12
Trace elements	25	25	26	26	na	26	26
Radioactive constituents							
Uranium isotopes ⁶	1	1	1	1	na	na	na
Radon-222	1	1	na	1	na	na	1
Radium isotopes ⁷	na	1	na	1	na	na	1
Gross alpha and beta particle activity ⁸	na	2	na	2	na	na	2
Organic constituents²							
Volatile organic compounds (VOCs) ³	85	85	85	85	85	85	85
Gasoline oxygenates ⁴	3	3	3	3	3	3	3
Pesticides and degradates	63	63	83	83	63	63	63
Special-interest constituents							
Perchlorate	1	1	1	1	1	1	1
NDMA and low-level 1,2,3-TCP ⁵	na	1	2	2	na	2	2
Geochemical and age-dating tracers							
Dissolved oxygen, pH, and temperature	3	3	3	3	3	3	3
Arsenic and iron redox species ratios	2	2	2	2	na	2	2
Chromium redox species ratio	na	na	1	1	1	1	1
Carbon-14 and $\delta^{13}\text{C}$ of dissolved carbonates	2	2	2	2	na	2	2
Tritium ⁹	1	1	1	1	na	1	1
Noble gases (helium, neon, argon, krypton, xenon), $^3\text{He}/^4\text{He}$ of helium, and tritium ¹⁰	7	7	7	7	7	7	7
$\delta^2\text{H}$ and $\delta^{18}\text{O}$ stable isotopes of water	2	2	2	2	2	2	2
$^{87}\text{Sr}/^{86}\text{Sr}$ of dissolved strontium	1	1	1	1	na	na	na
Sum:	215	219	239	243	166	217	221

¹ “Fast,” “intermediate,” and “slow” schedules refer to the amount of time required for a field crew to complete all work at a well.² All schedules except the Intermediate schedule in the Tahoe-Martis study unit also had 14 pharmaceutical compounds analyzed. These results are not discussed in this report; thus, the compounds are not included in the count of constituents analyzed.³ Includes 10 constituents classified as fumigants or fumigant synthesis byproducts.⁴ In the Tahoe-Martis study unit, gasoline oxygenates were analyzed only in the Tahoe study area.⁵ Includes one analyte, 1,2,3-TCP, in common with VOC analyses. However, the laboratory reporting limit for the low-level analysis is 0.005 microgram per liter ($\mu\text{g}/\text{L}$) compared to 0.18 $\mu\text{g}/\text{L}$ for the VOC analysis. Therefore, the low-level analysis is counted as a separate analysis. 1,2,3-TCP was not analyzed in the Tahoe-Martis study unit.⁶ Uranium activity equals the sum of the three isotopes measured: uranium-234, uranium-235, and uranium-238.⁷ Radium activity equals the sum of the two isotopes measured: radium-226 and radium-228.⁸ Both 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.⁹ Analyzed at U.S. Geological Survey Stable Isotope and Tritium Laboratory, Menlo Park, California.¹⁰ Analyzed at Lawrence Livermore National Laboratory, Livermore, California.

Table 2. Number of USGS-grid and CDPH-grid wells used in the status assessments for inorganic constituents in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[CDPH, California Department of Public Health; GAMA, Groundwater Ambient Monitoring and Assessment Program; USGS, U.S. Geological Survey]

Constituent	Tahoe-Martis study unit (45 cells)		Central Sierra study unit (30 cells)		Southern Sierra study unit (40 cells)	
	Number of grid wells sampled by USGS-GAMA	Number of grid wells selected from CDPH database	Number of grid wells sampled by USGS-GAMA	Number of grid wells selected from CDPH database	Number of grid wells sampled by USGS-GAMA	Number of grid wells selected from CDPH database
Inorganic constituents with health-based benchmarks						
Trace elements						
Aluminum	41	0	27	2	7	24
Antimony	41	0	27	2	7	24
Arsenic	41	0	27	2	7	25
Barium	41	0	27	2	7	24
Beryllium	41	0	27	2	7	24
Boron	41	0	27	0	7	8
Cadmium	41	0	27	2	7	24
Chromium	41	0	27	2	7	23
Copper	41	0	27	2	7	23
Fluoride	41	0	27	2	7	24
Lead	41	0	27	2	7	24
Mercury	41	0	27	2	7	24
Molybdenum	41	0	27	0	7	0
Nickel	41	0	27	2	7	24
Selenium	41	0	27	2	7	24
Strontium	41	0	27	0	7	0
Thallium	41	0	27	2	7	24
Uranium	41	0	27	0	7	1
Vanadium	41	0	27	0	7	7
Nutrients						
Ammonia	41	0	27	0	7	0
Nitrate ¹	41	0	27	2	7	30
Nitrite	41	0	27	2	7	26
Radioactive constituents						
Gross alpha particle activity	8	15	14	10	4	24
Gross beta particle activity	8	9	14	0	4	0
Radium activity	8	9	14	1	4	8
Radon-222 activity	40	0	14	0	4	2
Uranium activity	41	0	27	1	0	19
Inorganic constituents with secondary maximum contaminant level benchmarks						
Iron	41	0	27	2	7	23
Manganese	41	0	27	2	7	23
Silver	41	0	27	1	7	23
Zinc	41	0	27	2	7	23
Chloride	41	0	27	2	7	23
Specific conductance	41	0	27	2	33	1
Sulfate	41	0	27	2	7	23
Total dissolved solids	41	0	27	2	7	23

¹ USGS-GAMA analyses were for nitrate plus nitrite; however, nitrite concentrations were negligible compared to nitrate in all cases.

Additional Data Used for Spatially Weighted Calculation

The spatially weighted calculations of aquifer-scale proportions used data from the USGS-grid wells, additional wells sampled by USGS-GAMA, and all wells in the CDPH database having water-quality data during the 3-year intervals prior to the USGS-GAMA sampling periods. For wells with both USGS-GAMA and CDPH data, only the USGS-GAMA data were used.

In addition to the 103 USGS-grid wells, a total of 29 other wells were sampled in the three study units by USGS-GAMA. These additional wells were selected to increase sampling density in certain areas to help understand specific water-quality issues in those areas (figs. 8A,B,C; Fram and Belitz, 2007; Ferrari and others, 2008; Fram and others, 2009). These 29 wells are referred to as “USGS-understanding” wells and were numbered in the order of collection with prefixes modified from those used for the USGS-grid wells (TMARTU, TROCKU, TTAHOU, CGOLDU, CWISHU, and SOSAFP,) (fig. A1; table C1). With the exception of four TTAHOU monitoring wells, all of the USGS-understanding wells were screened or open at similar depths to the grid wells and were included in the dataset for the spatially weighted calculations.

Selection of Constituents for Additional Evaluation in the Status Assessment

As many as 243 constituents were analyzed in samples from Tahoe-Martis, Central Sierra, and Southern Sierra study unit wells as part of the *status assessment* (table 1); however, only a subset of these constituents was selected for additional evaluation in this report. Three criteria were used to select constituents for additional evaluation in the *status assessment*:

1. Constituents present at high or moderate RCs in the USGS-grid wells or USGS-understanding wells used in the *status assessment*, or
2. Organic constituents having study-unit detection frequencies >10% in the USGS-grid well dataset for a particular study unit, or
3. Constituents present at high or moderate RCs in the CDPH database within the 3-year intervals prior to the USGS-GAMA sampling periods.

These criteria identified 23 inorganic constituents, 12 organic constituents, and 1 constituent of special interest for additional evaluation for at least one of the three study units (table 3). An additional 27 inorganic constituents and 15 organic

constituents were detected by USGS-GAMA, but were not selected for additional evaluation because they either have no established benchmarks or were only detected at low RCs (table 4). All 19 geochemical and age-dating tracers also were detected. The remaining 146 constituents that were not detected by USGS-GAMA in any of the three study units are listed in Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009).

The CDPH database 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 3-year intervals used for the *status assessment*.

Study unit	Historical period	Number of wells with data
Tahoe-Martis	June 26, 1984–April 30, 2004	180
Central Sierra	January 19, 1984–May 31, 2003	184
Southern Sierra	January 12, 1977–January 31, 2003	252

Constituents may be historically high but not currently high because of improvement of groundwater quality with time or abandonment of wells with high concentrations of constituents. Historically high constituents that do not otherwise meet the criteria for additional evaluation in the *status assessment* were not considered representative of potential groundwater-quality concerns in the three study units during the current periods.

The Tahoe-Martis, Central Sierra, and Southern Sierra study units had 9, 6, and 17 historically high constituents, respectively (table 5). Eight of these constituents also were detected at moderate RCs in the 3-year intervals used in the *status assessment*, and were therefore included in the constituents selected for additional evaluation in the *status assessment* (table 3). Of the 32 total historically high constituents for the three study units, 27 were high in only 1 well each.

Forty-five constituents with regulatory, health-based benchmarks that are reported in the CDPH database were not analyzed by USGS-GAMA. Most of these constituents are semi-volatile organic compounds. None of these constituents were reported at high concentrations in the 3-year intervals used for the *status assessment* in the three study units. Two constituents, heptachlor epoxide and di(2-ethylhexyl) phthalate, were each reported at a high concentration once historically in the Southern Sierra study unit (table 5).

Table 3. Benchmark type and value for constituents selected for additional evaluation in the status assessments of groundwater quality in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Inorganic constituents selected if maximum concentration measured in USGS-GAMA samples or reported in CDPH database during the 3-year time period used for the status assessment was greater than 0.5 times benchmark concentration. Organic constituents selected if maximum concentration was greater than 0.1 times benchmark concentration, or if study unit detection frequency at any concentration was greater than 10 percent. **Benchmark type:** Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; Prop MCL-US, proposed USEPA maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark units:** mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; pCi/L, picocurie per liter. **Other Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health; D-eval, detected by USGS-GAMA and selected for additional evaluation in status assessment for study unit; D, detected by USGS-GAMA but not selected for additional evaluation in status assessment for study unit; eval, not detected by USGS-GAMA in the study unit, but selected for additional evaluation in status assessment on the basis of concentrations reported in the CDPH database; –, not detected in study unit]

Constituent	Typical use or source	Benchmarks			Study unit		
		Type ¹	Value	Units	Tahoe-Martis	Central Sierra	Southern Sierra
Inorganic constituents with health-based benchmarks							
Trace elements							
Aluminum	Naturally occurring	MCL-CA	1,000	µg/L	D	D	D-eval ²
Antimony	Naturally occurring	MCL-US	6	µg/L	D	D	D-eval ²
Arsenic	Naturally occurring	MCL-US	10	µg/L	D-eval	D-eval	D-eval
Boron	Naturally occurring	NL-CA	1,000	µg/L	D-eval	D-eval	D-eval
Chromium	Naturally occurring	MCL-CA	50	µg/L	D	D-eval ²	D-eval ²
Fluoride	Naturally occurring	MCL-CA	2	mg/L	D	D-eval	D-eval
Lead	Naturally occurring	AL-US	15	µg/L	D	D-eval	D-eval
Molybdenum	Naturally occurring	HAL-US	40	µg/L	D-eval	D-eval	D-eval
Selenium	Naturally occurring	MCL-US	50	µg/L	D	D-eval ²	D
Strontium	Naturally occurring	HAL-US	4,000	µg/L	D-eval	D	D
Uranium	Naturally occurring	MCL-US	30	µg/L	D-eval	D-eval	D-eval
Nutrients							
Nitrate, as nitrogen ³	Natural, fertilizer, sewage	MCL-US	10	mg/L	D	D-eval	D-eval
Radioactive constituents							
Gross alpha particle activity	Naturally occurring	MCL-US	15	pCi/L	D-eval	D-eval	D-eval
Radium activity	Naturally occurring	MCL-US	5	pCi/L	D-eval	D-eval	D-eval
Radon-222 activity	Naturally occurring	Prop MCL-US	4,000	pCi/L	D-eval	D-eval	D-eval
Uranium activity	Naturally occurring	MCL-CA	20	pCi/L	D-eval	D-eval	D-eval
Inorganic constituents with secondary maximum contaminant level benchmarks							
Chloride	Naturally occurring	SMCL-CA	500	mg/L	D-eval	D-eval	D
Iron	Naturally occurring	SMCL-CA	300	µg/L	D-eval	D-eval	D-eval
Manganese	Naturally occurring	SMCL-CA	50	µg/L	D-eval	D-eval	D-eval
Specific conductance	Naturally occurring	SMCL-CA	1,600	µS/cm	D-eval	D-eval	D-eval
Sulfate	Naturally occurring	SMCL-CA	500	mg/L	D-eval	D	D-eval
Total dissolved solids (TDS)	Naturally occurring	SMCL-CA	1,000	mg/L	D-eval	D-eval	D-eval
Zinc	Naturally occurring	SMCL-CA	5,000	µg/L	D	D-eval	D-eval
Organic and special-interest constituents with health-based benchmarks							
Pesticides							
Atrazine	Herbicide	MCL-CA	1	µg/L	D	D	D-eval
Simazine	Herbicide	MCL-US	4	µg/L	–	D-eval	D-eval
Volatile Organic Compounds							
1,2-Dichloropropane	Fumigant	MCL-US	5	µg/L	Eval	–	D
1,4-Dichlorobenzene	Fumigant	MCL-CA	5	µg/L	–	Eval	–
DBCP	Fumigant	MCL-US	0.2	µg/L	Eval	–	–

Table 3. Benchmark type and value for constituents selected for additional evaluation in the status assessments of groundwater quality in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California Groundwater Ambient Monitoring and Assessment (GAMA) Priority Basin Project.—Continued

[Inorganic constituents selected if maximum concentration measured in USGS-GAMA samples or reported in CDPH database during the 3-year time period used for the status assessment was greater than 0.5 times benchmark concentration. Organic constituents selected if maximum concentration was greater than 0.1 times benchmark concentration, or if study unit detection frequency at any concentration was greater than 10 percent. **Benchmark type:** Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; Prop MCL-US, proposed USEPA maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. **Benchmark units:** mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; pCi/L, picocurie per liter. **Other Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health; D-eval, detected by USGS-GAMA and selected for additional evaluation in status assessment for study unit; D, detected by USGS-GAMA but not selected for additional evaluation in status assessment for study unit; eval, not detected by USGS-GAMA in the study unit, but selected for additional evaluation in status assessment on the basis of concentrations reported in the CDPH database; –, not detected in study unit]

Constituent	Typical use or source	Benchmarks			Study unit		
		Type ¹	Value	Units	Tahoe-Martis	Central Sierra	Southern Sierra
Organic and special-interest constituents with health-based benchmarks—Continued							
Volatile Organic Compounds—Continued							
1,2-Dichloroethane	Solvent, fumigant, plastics	MCL-CA	0.5	µg/L	Eval	–	–
Chloromethane	Refrigerant, industrial	HAL-US	30	µg/L	Eval	–	–
Perchloroethene (PCE)	Dry-cleaning, metal degreasing	MCL-US	5	µg/L	D-eval	D-eval	D-eval
Carbon tetrachloride	Solvent, industrial, dry-cleaning	MCL-CA	0.5	µg/L	D-eval	–	D-eval
Chloroform	Disinfection byproduct	MCL-US ⁴	80	µg/L	D-eval	D-eval	D-eval
Methyl <i>tert</i> -butyl ether (MTBE)	Gasoline oxygenate	MCL-CA	13	µg/L	D	D-eval ²	D
Benzene	Gasoline hydrocarbon	MCL-CA	1	µg/L	–	D-eval	–
Constituents of special interest							
Perchlorate	Natural, rocket fuel, flares	MCL-CA	6	µg/L	–	–	D-eval

¹ Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical, and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks:

MCL-CA: California Department of Public Health (2008),

MCL-US: U.S. Environmental Protection Agency (2009a),

SMCL-CA: California Department of Public Health (2006),

NL-CA: California Department of Public Health (2010),

HAL-US: U.S. Environmental Protection Agency (2009b),

Prop MCL-US: U.S. Environmental Protection Agency (1999).

² Selected on the basis of concentrations reported in CDPH database. Constituent also detected by USGS-GAMA at low relative-concentrations.

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

⁴ MCL-US benchmark for trihalomethanes is the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform.

Table 4. Constituents detected in samples collected by USGS-GAMA, but not selected for additional evaluation in the status assessments for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Detected constituents were not selected for additional evaluation if they had no benchmarks, or for inorganic constituents, if the maximum concentration measured in USGS-GAMA samples or reported in CDPH database during the 3-year time period used for the status assessment was less than or equal to 0.5 times benchmark concentration, or for organic constituents, the maximum concentration was less than or equal to 0.1 times benchmark concentration and study unit detection frequency at any concentration was less than 10 percent. **Benchmark type:** Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. None, no benchmark. **Benchmark units:** mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; pCi/L, picocurie per liter. **Other Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health; D, detection at low relative-concentration; std units, standard units; <, less than; >, greater than; –, not detected; na, not analyzed]

Constituent	Typical use or source	Benchmarks			Study unit		
		Type ¹	Value	Units	Tahoe-Martis	Central Sierra	Southern Sierra
Inorganic constituents with benchmarks							
Ammonia, as nitrogen	Naturally occurring	HAL-US ²	24.7	mg/L	D	D	D
Barium	Naturally occurring	MCL-CA	1,000	µg/L	D	D	D
Beryllium	Naturally occurring	MCL-US	4	µg/L	D	D	D
Cadmium	Naturally occurring	MCL-US	5	µg/L	D	D	D
Copper	Naturally occurring	AL-US	1,300	µg/L	D	D	D
Gross beta particle activity	Naturally occurring	MCL-US	50	pCi/L	D	D	D
Mercury	Naturally occurring	MCL-US	2	µg/L	na	D	–
Nickel	Naturally occurring	MCL-CA	100	µg/L	D	D	D
Nitrite, as nitrogen	Naturally occurring	MCL-US	1	mg/L	D	D	D
Silver	Naturally occurring	SMCL-CA	100	µg/L	–	–	D
Thallium	Naturally occurring	MCL-US	2	µg/L	D	–	D
Vanadium	Naturally occurring	NL-CA	50	µg/L	D	D	D
Inorganic constituents with no benchmarks							
Bicarbonate	Naturally occurring	None	None	None	D	D	D
Bromide	Naturally occurring	None	None	None	D	D	D
Calcium	Naturally occurring	None	None	None	D	D	D
Carbonate	Naturally occurring	None	None	None	D	D	D
Cobalt	Naturally occurring	None	None	None	D	D	D
Dissolved organic carbon	Naturally occurring	None	None	None	na	D	D
Iodide	Naturally occurring	None	None	None	D	D	D
Lithium	Naturally occurring	None	None	None	D	D	D
Magnesium	Naturally occurring	None	None	None	D	D	D
Nitrogen, total	Naturally occurring	None	None	None	D	D	D
Orthophosphate	Naturally occurring	None	None	None	D	D	D
Potassium	Naturally occurring	None	None	None	D	D	D
Silica	Naturally occurring	None	None	None	D	D	D
Sodium	Naturally occurring	None	None	None	D	D	D
Tungsten	Naturally occurring	None	None	None	D	D	D
Organic constituents with benchmarks							
Bromodichloromethane	Disinfection byproduct	MCL-US ³	80	µg/L	D	–	–
Carbon disulfide	Natural, industrial	NL-CA	160	µg/L	D	D	–
1,2-Dichlorobenzene	Solvent, insecticide	MCL-US	600	µg/L	–	–	D
<i>cis</i> -1,2-Dichloroethene	Solvent, PCE breakdown	MCL-CA	6	µg/L	–	–	D
Prometon	Herbicide	HAL-US	100	µg/L	–	–	D
1,1,1-Trichloroethane	Solvent, industrial, fumigant	MCL-US	200	µg/L	D	–	–
Trichloroethene (TCE)	Solvent, PCE breakdown	MCL-US	5	µg/L	D	–	D
Trichlorofluoromethane (CFC-11)	Refrigerant	MCL-CA	150	µg/L	–	–	D
1,2,3-Trichloropropane	Fumigant, solvent	HAL-US	40	µg/L	na	–	D
1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	Refrigerant	MCL-CA	1,200	µg/L	–	–	D

Table 4. Constituents detected in samples collected by USGS-GAMA, but not selected for additional evaluation in the status assessments for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Detected constituents were not selected for additional evaluation if they had no benchmarks, or for inorganic constituents, if the maximum concentration measured in USGS-GAMA samples or reported in CDPH database during the 3-year time period used for the status assessment was less than or equal to 0.5 times benchmark concentration, or for organic constituents, the maximum concentration was less than or equal to 0.1 times benchmark concentration and study unit detection frequency at any concentration was less than 10 percent. **Benchmark type:** Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. None, no benchmark. **Benchmark units:** mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; pCi/L, picocurie per liter. **Other Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health; D, detection at low relative-concentration; std units, standard units; <, less than; >, greater than; –, not detected; na, not analyzed]

Constituent	Typical use or source	Benchmarks			Study unit		
		Type ¹	Value	Units	Tahoe-Martis	Central Sierra	Southern Sierra
Organic constituents with no benchmarks							
Deethylatrazine	Herbicide degradate (atrazine)	None	None	None	D	D	D
3,4-Dichloroaniline	Herbicide degradate (diuron)	None	None	None	–	D	–
Dicrotophos	Insecticide	None	None	None	D	–	–
Diisopropyl ether	Gasoline oxygenate	None	None	None	D	–	–
Fipronil sulfide	Insecticide degradate (fipronil)	None	None	None	–	–	D
Geochemical and age-dating tracers							
Tritium	Naturally occurring	MCL-CA	20,000	pCi/L	D	D	D
pH	Naturally occurring	SMCL-US	<6.5 or >8.5	std units	D	D	D
Dissolved oxygen and temperature	Naturally occurring	None	None	None	D	D	D
Arsenic and iron redox species ratios	Naturally occurring	None	None	None	D	D	D
Chromium redox species ratio	Naturally occurring	None	None	None	na	D	D
Carbon-14 and δ ¹³ C of dissolved carbonates	Naturally occurring	None	None	None	D	D	D
Noble gases (helium, neon, argon, krypton, xenon) and ³ He/ ⁴ He of helium	Naturally occurring	None	None	None	D	D	D
δ ² H and δ ¹⁸ O stable isotopes of water	Naturally occurring	None	None	None	D	D	D
⁸⁷ Sr/ ⁸⁶ Sr of dissolved strontium	Naturally occurring	None	None	None	D	D	na

¹ Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical, and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks:

MCL-CA: California Department of Public Health (2008),
MCL-US, AL-US, and SMCL-US: U.S. Environmental Protection Agency (2009a),
SMCL-CA: California Department of Public Health (2006),
NL-CA: California Department of Public Health (2010),
HAL-US: U.S. Environmental Protection Agency (2009b),
Prop MCL-US: U.S. Environmental Protection Agency (1999).

² HAL-US benchmark is 30 mg/L for ammonia, as ammonia.

³ MCL-US benchmark for trihalomethanes is the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform.

Table 5. Constituents reported at concentrations greater than benchmarks historically in the California Department of Public Health database, but not during the 3-year time periods used in status assessment, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[**Benchmark type:** Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. None, no benchmark. **Benchmark units:** mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; pCi/L, picocurie per liter. **Other Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health]

Constituent	Typical use or source	Benchmark			Date of most recent high value	Number of wells with historical data	Number of wells with a high value
		Type ¹	Value	Units			
Tahoe-Martis study unit							
Methy <i>tert</i> -butyl ether (MTBE)	Gasoline oxygenate	MCL-CA	13	µg/L	07-27-99	85	1
Perchlorate	Natural, rocket fuel, flares	MCL-CA	6	µg/L	10-21-02	37	1
Nitrate, as nitrogen	Naturally occurring	MCL-US	10	mg/L	09-24-87	162	1
Aluminum	Naturally occurring	MCL-CA	1,000	µg/L	01-26-93	90	1
Cadmium	Naturally occurring	MCL-US	5	µg/L	08-05-03	90	1
Lead	Naturally occurring	AL-US	15	µg/L	09-19-96	79	6
Mercury	Naturally occurring	MCL-US	2	µg/L	08-27-96	90	3
Radium activity ²	Naturally occurring	MCL-US	5	pCi/L	08-08-01	6	1
Uranium activity ²	Naturally occurring	MCL-CA	20	pCi/L	08-28-02	36	2
Central Sierra study unit							
Methy <i>tert</i> -butyl ether (MTBE) ²	Gasoline oxygenate	MCL-CA	13	µg/L	05-27-03	135	1
Nitrate, as nitrogen ^{2,3}	Naturally occurring	MCL-US	10	mg/L	03-06-03	110	1
Antimony	Naturally occurring	MCL-US	6	µg/L	06-27-95	58	1
Copper	Naturally occurring	AL-US	1,300	µg/L	07-31-02	69	1
Lead ²	Naturally occurring	AL-US	15	µg/L	05-09-95	65	1
Thallium	Naturally occurring	MCL-US	2	µg/L	06-27-95	58	1
Southern Sierra study unit							
Chloroform ⁴	Disinfection byproduct	MCL-US ⁵	80	µg/L	07-16-96	205	1
1,1-Dichloroethane	Solvent	MCL-CA	5	µg/L	03-17-93	206	1
1,2-Dichloroethane	Solvent, fumigant, plastics	MCL-CA	0.5	µg/L	05-27-99	206	1
Dichloromethane	Paint stripper, solvent	MCL-US	5	µg/L	03-16-01	205	4
Heptachlor epoxide ⁶	Insecticide degradate	MCL-CA	0.01	µg/L	08-22-97	80	1
Di(2-ethylhexyl)phthalate ⁶	Plasticizer	MCL-CA	4	µg/L	04-08-91	104	1
Barium	Naturally occurring	MCL-CA	1,000	µg/L	11-20-96	218	1
Beryllium	Naturally occurring	MCL-US	4	µg/L	06-03-02	180	1
Cadmium	Naturally occurring	MCL-US	5	µg/L	03-10-92	218	1
Lead ²	Naturally occurring	AL-US	15	µg/L	08-13-01	219	13
Mercury	Naturally occurring	MCL-US	2	µg/L	09-16-84	218	1
Nickel	Naturally occurring	MCL-CA	100	µg/L	06-03-02	181	1
Selenium	Naturally occurring	MCL-US	50	µg/L	06-09-99	217	1
Thallium	Naturally occurring	MCL-US	2	µg/L	07-23-02	181	1
Zinc ²	Naturally occurring	SMCL-CA	5,000	µg/L	03-18-97	222	1
Sulfate ²	Naturally occurring	SMCL-CA	500	mg/L	07-21-99	225	1
Chloride	Naturally occurring	SMCL-CA	500	mg/L	07-22-99	225	1

Table 5. Constituents reported at concentrations greater than benchmarks historically in the California Department of Public Health database, but not during the 3-year time periods used in status assessment, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[**Benchmark type:** Regulatory, health-based benchmarks: MCL-US, USEPA maximum contaminant level; AL-US, USEPA action level; MCL-CA, CDPH maximum contaminant level. Non-regulatory, health-based benchmarks: HAL-US, USEPA lifetime health advisory level; NL-CA, CDPH notification level. Non-regulatory, aesthetic-based benchmarks: SMCL-CA, CDPH secondary maximum contaminant level. None, no benchmark. **Benchmark units:** mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; pCi/L, picocurie per liter. **Other Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health]

Footnotes:

¹ Maximum contaminant level benchmarks are listed as MCL-US when the MCL-US and MCL-CA are identical, and as MCL-CA when the MCL-CA is lower than the MCL-US or no MCL-US exists. Sources of benchmarks:

MCL-CA: California Department of Public Health (2008),
MCL-US and AL-US: U.S. Environmental Protection Agency (2009a),
SMCL-CA: California Department of Public Health (2006),
NL-CA: California Department of Public Health (2010),
HAL-US: U.S. Environmental Protection Agency (2009b),
Prop MCL-US: U.S. Environmental Protection Agency (1999).

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

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

⁴ Study unit detection frequency for constituent was greater than 10 percent; therefore, it was selected for additional evaluation in the status assessment for the study unit.

⁵ MCL-US benchmark for trihalomethanes is the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform.

⁶ Constituent 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 aquifers of the Tahoe-Martis, Central Sierra, and Southern Sierra study units. The primary aquifers are defined by the depth intervals over which wells listed in the CDPH database are screened, or open. The use of the term “primary aquifers” does not imply that there exists a discrete aquifer unit. In most groundwater basins, municipal and community supply wells typically are screened or open at greater depths than are domestic wells (Burow and others, 2008). Thus, because domestic wells are not listed in the CDPH database, the primary aquifer generally corresponds to the deeper portion of the aquifer system tapped by municipal and community supply wells; however, this segregation between the depths of municipal and domestic 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). Most of the wells used in the *status assessment* for the Tahoe-Martis, Central Sierra, and Southern Sierra study units are listed in the CDPH databases, and are therefore classified as municipal or community drinking-water supply wells. However, to the extent that domestic wells in the three study units are screened or open over the same depth intervals as the CDPH wells, the assessments presented in this report may also be applicable to the portions of the aquifer systems used for domestic drinking-water supplies.

Two statistical approaches, grid-based and spatially weighted, were used to evaluate the proportions of the primary aquifers in the three study units with high, moderate, and low RCs of constituents. For ease of discussion, these proportions are referred to as “high,” “moderate,” and “low” aquifer-scale proportions. Calculations of aquifer-scale proportions were made for individual constituents meeting the criteria for additional evaluation in the *status assessment*, and for classes of constituents. Detailed descriptions of the calculations are presented in [appendix B](#), and brief summaries are given here.

The grid-based calculation uses the grid-well dataset assembled from the USGS-grid and CDPH-grid wells. For each constituent, the high aquifer-scale proportion was calculated by dividing the number of cells represented by a high RC for that constituent by the total number of grid cells with data for that constituent (Belitz and others, 2010). The moderate aquifer-scale proportion was calculated similarly. Confidence intervals for the high aquifer-scale proportions were computed using the Jeffreys interval for the binomial distribution (Brown and others, 2001). The grid-based approach is spatially unbiased; however, it may not detect constituents that are present at high RCs in small proportions of the aquifer system. For calculation of high aquifer-scale proportion for a class of constituents, cells were considered

high if any of the constituents had a high RC. Cells were considered moderate if any of the constituents had a moderate RC, but none had a high RC.

The spatially weighted calculation uses the dataset assembled from all CDPH and USGS GAMA wells. For each constituent, the high aquifer-scale proportion was calculated by computing the proportion of wells with high values in each cell and then averaging the proportions for all cells (Isaaks and Srivastava, 1989; Belitz and others, 2010). The moderate aquifer-scale proportion was calculated similarly. Confidence intervals for spatially weighted detection frequencies of high concentrations are not described in this report. For calculation of high aquifer-scale proportion for a class of constituents, values for wells were considered high if the values for any of the constituents in that class were high. Values for wells were considered moderate if the values for any of the constituents were moderate, but no values for wells were high.

In addition, for each constituent, the detection frequencies of high and moderate RCs for individual constituents were calculated using the same dataset as used for the spatially weighted calculations. However, these detection frequencies are not spatially unbiased because the wells in the CDPH database are not uniformly distributed ([figs. 8A,B,C](#)). For example, if a constituent was present at high RCs in a small region of the aquifer that had a high density of wells, the detection frequency of high RCs would be greater than the high aquifer-scale proportion. Detection frequencies are provided for reference but were not used to assess aquifer-scale proportions.

The Tahoe-Martis and Central Sierra study units had study areas whose cell sizes were different from one another. To obtain spatially unbiased results for these study units, aquifer-scale proportions were calculated for each study area in the study unit separately, and then combined, weighted by the relative areas of the study units ([appendix B](#)). Aquifer-scale proportions for the study areas are presented in [appendix B](#); aquifer-scale proportions for the study units are discussed in the main body of the report.

The grid-based high aquifer-scale proportions were used to represent proportions in the primary aquifer unless the spatially weighted proportions were significantly different than the grid-based values. Significantly different results were defined as follows:

- If the grid-based high aquifer-scale proportion was zero and the spatially weighted proportion was non-zero, then the spatially weighted result was used. This situation can arise when a constituent is present at high concentrations in a small proportion of the primary aquifers.
- If the grid-based high aquifer-scale proportion was non-zero and the spatially weighted proportion was outside the 90% confidence interval around the grid-based proportion, then the spatially weighted proportion was used.

The grid-based moderate and low proportions were used in most cases because the reporting limits relative to benchmarks for many organic constituents and some inorganic constituents in the CDPH database were higher than the boundary between the moderate and low RC categories (fig. 7). However, if the grid-based moderate proportion was zero and the spatially weighted proportion non-zero, then the spatially weighted value was used as a minimum estimate for the moderate proportion.

Understanding Assessment

The purpose of the *understanding assessment* is to place groundwater quality within a physical and chemical context. A finite set of potential explanatory factors was considered: land use, aquifer lithology, well depth and depth to top of screened or open interval in well, relative position in the regional groundwater flow gradient, aridity index, density of septic systems, groundwater age, oxidation-reduction condition, and pH. Statistical tests were used to identify significant correlations between the constituents of interest and potential explanatory factors.

- Constituents with high aquifer-scale proportions of >2%. These constituents were selected to focus the assessment for understanding on those constituents that have the greatest effect on groundwater quality.
- Classes of organic constituents that included constituents with study-unit detection frequencies of >10%, regardless of concentration.

The *understanding assessment* was based on the 132 wells sampled by USGS-GAMA. Other CDPH wells were not used because data for many of the potential explanatory factors were not available. Samples from almost all USGS-GAMA wells were analyzed for dissolved oxygen, noble gases, and stable isotopes of water; samples from most wells were analyzed for tritium, carbon isotopes, and redox species of iron and arsenic (table 1). Data for these geochemical and age-dating tracers are not maintained in the CDPH database. Well construction data were also not available for most CDPH wells. The three study units were aggregated into one dataset for the *understanding assessment*.

Nonparametric statistical methods were used to test the significance of correlations between water-quality parameters and potential explanatory factors. 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% ($\alpha=0.05$) 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, aquifer lithology, well depth class, and study unit were treated as categorical variables because there were a finite number of values a well could be assigned: for example, groundwater ages were classified as modern, pre-modern, or mixed. Land use, septic tank density, aridity index, elevation, well depth, depth to top of screened or open interval, dissolved oxygen, and pH were treated as continuous variables because there were an infinite number of values a well could be assigned: for example, land use was represented by percentages of land-use types. Well depth was treated as both a continuous (depth in feet below land surface) and categorical (shallow, deep, or mixed) variable. Concentrations of water-quality constituents were treated as continuous variables.

Correlations between potential explanatory factors, and between potential explanatory factors and water-quality constituents were tested for significance.

- 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 between categorical variables and continuous variables were evaluated using the Wilcoxon rank-sum and Kruskal-Wallis tests. The Kruskal-Wallis test is equivalent to the Wilcoxon rank-sum test when the categorical variable has only two possible values. The null hypothesis for both tests is that median values of the continuous variable in each of the independent groups defined by the categorical variable are not significantly different from one another. If the Kruskal-Wallis test yielded a result of significance, then the Wilcoxon rank-sum test was applied pair-wise to the groups to determine which pairs had significantly different median values of the continuous variable.
- Relations between categorical variables were evaluated using contingency tables. For a contingency table analysis, the data are recorded as a matrix of counts. One variable is assigned to the columns and the other to the rows, and the entries in the cells of the matrix are the number of observations, O_{ij} , which fall into the i^{th} row and j^{th} column of the matrix. A test statistic is computed by comparing the observed counts (O_{ij}) to the counts expected if the two variables are independent, and significance is determined by comparing the test statistic to the $(1-\alpha)$ quantile of a chi-squared distribution. If the contingency table test yielded a result of significance, then the location of the most important pairs was determined by comparing magnitudes of the components of the test statistic.

Evaluation of Potential Explanatory Factors

The values assigned to wells for potential explanatory factors (land use, aquifer lithology and hydrologic conditions, well depth and groundwater age distribution, and geochemical conditions) are described in this section. Correlations among these potential explanatory factors that could affect apparent relations between potential explanatory factors and water quality are also described. Methods used for assigning the values are described in [appendix C](#).

Land Use

Briefly, land use was quantified as the percentages of three land-use types: agricultural, urban, and undeveloped. Land-use percentages were calculated for study units, study areas, and within a radius of 500 m (500-m buffers) around wells (Johnson and Belitz, 2009).

Land use based on all of the land within the study unit boundaries ([figs. 5A,B,C](#)) is >88% undeveloped for all three study units ([fig. 6A](#)). In the Tahoe-Martis and Central Sierra study units, the remainder is urban land use. Only the Southern Sierra study unit contains areas of agricultural land use (8%). Compared to the land use in the entire study unit, the average land use around the CDPH wells in all three study units is 20 to 30% more urban, and in the case of the Southern Sierra study unit, also almost 10% more agricultural. In contrast, the average land use around the grid wells in all three study units is only 10% more urban or agricultural than the overall land use in the study unit ([fig. 6A](#)). The difference between overall land use and land use around wells reflects the fact that wells are preferentially located where there are people living and working. 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 more urban areas typically have a higher density of CDPH wells.

For the Tahoe-Martis study unit, overall land use is 12% urban, average land use around the grid wells is 23% urban, and average land use around the CDPH wells is 40% urban ([fig. 6A](#)). Land use around individual grid wells ranges from 0 to 91% urban ([table C1](#); [fig. 6B](#)). The TTAHO study area has a higher proportion of urban land use than do the TMART and TROCK study areas ([fig. 5A](#)), and accordingly, 10 of the 19 USGS-grid wells with $\geq 12\%$ urban land use are from the TTAHO study area ([table C1](#); [fig. 6B](#)). Average land use around the understanding wells is 49% urban in the TTAHO

study area ([fig. 6A](#)) because 8 of the 11 USGS-understanding wells are in that study area ([fig. 8A](#)). The majority of the CDPH wells in the Tahoe-Martis study unit also are in the TTAHO study area ([fig. 8A](#)); thus, the average land use around the CDPH wells is strongly biased towards urban.

For the Central Sierra study unit, overall land use is 5% urban, average land use around the grid wells is 14% urban, and average land use around the CDPH wells is 27% urban ([fig. 6A](#)). Land use around individual grid wells ranges from 0 to 71% urban ([table C1](#); [fig. 6B](#)). Average land use around grid wells in the CGOLD and CWISH study areas is similar (15 and 12% urban, respectively), although the areas of densest urban land use (the towns of Oakhurst and Ahwanee) are both in the CGOLD study area ([fig. 5B](#)).

For the Southern Sierra study unit, overall land use is 2% urban and 8% agricultural, average land use around the grid wells is 5% urban and 16% agricultural, and average land use around the CDPH wells is 21% urban and 17% agricultural. Land use around individual grid wells typically is either a mixture of urban and undeveloped (0 to 49% urban) or a mixture of agricultural and undeveloped (0 to 89% agricultural) ([table C1](#); [fig. 6B](#)). Average land use around the USGS-understanding wells is 6% urban and 52% agricultural ([fig. 6A](#)) because 8 of the 15 understanding wells are located in agricultural fields in the Cummings Valley and Tehachapi Valley basins ([fig. 8C](#)). Average land use around the CDPH wells is more urban and more agricultural than overall land use in the study unit because the majority of the wells are located in the CDWR groundwater basins, where all of the agricultural land use and most of the urban land use are concentrated.

The density of septic tanks in the 500-m buffers around the USGS wells in the three study units ranges from 0 to 138 tanks per square kilometer (tanks/km²) ([table C1](#)). Wells in the Tahoe-Martis study unit have significantly lower septic tank densities (median = 0.5 tank/km²) than do wells in the Central Sierra (median = 4.4 tanks/km²) or Southern Sierra (median = 2.7 tanks/km²) study units ([fig. 9](#); $p < 0.001$). For comparison, the median septic tank density around the 1,810 wells sampled by USGS for the GAMA Priority Basin Project during 2004–2008 was 2.8 tanks/km² (Tyler Johnson, U.S. Geological Survey, California Water Science Center, written commun., 2009). The low density in the Tahoe-Martis study unit reflects regulations that have required development of sewer systems and forbidden installation of septic systems in the Lake Tahoe watershed since 1972 to protect lake water quality (State of California, 1971). Septic-tank density likely is elevated in the Central Sierra study unit because local communities have only recently begun building sewer systems in response to recent population growth.

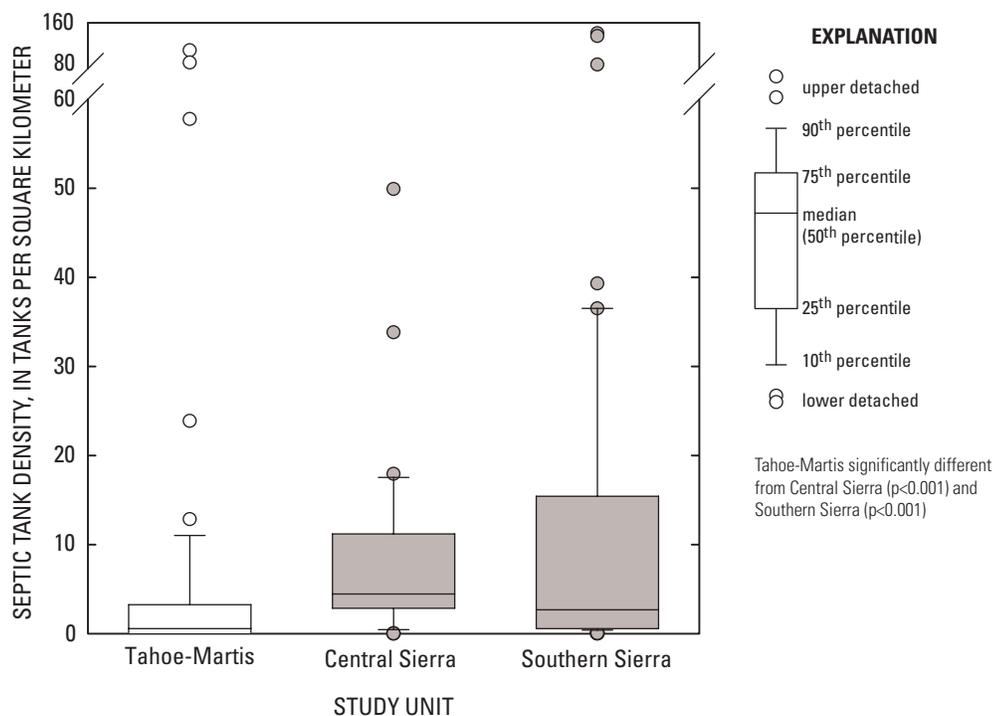


Figure 9. Density of septic tanks in the areas surrounding wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Aquifer Lithology and Hydrologic Conditions

As discussed in the section “[Hydrogeologic Setting](#),” the geologic settings of the Tahoe-Martis, Central Sierra, and Southern Sierra study units are complex, and wells are located in a range of rock types. For the purpose of examining broad relations between aquifer lithology and water quality, the geology of the study units was simplified into four rock types ([appendix C](#)):

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

The Cenozoic volcanic rocks and sedimentary deposits include units that are Tertiary (primarily Miocene and Pliocene in age) and Quaternary (Pleistocene and Holocene epochs) in age. Analysis of groundwater chemistry as a function of geologic variations within each of the four classes is beyond the scope of this report. Chemical and mineralogical data for aquifer materials are not available for the wells used in this study.

Of the 41 cells with grid wells in the Tahoe-Martis study unit, 16 are represented by wells with sedimentary aquifer lithology, 18 by wells with volcanic aquifer lithology, and 7 by wells with granitic aquifer lithology (fig. 10). Wells from the three study areas within the Tahoe-Martis study unit have markedly different aquifer lithologies (table C1). Thirteen of 14 grid cells in the TTAHO study area are represented by wells with sedimentary aquifer lithology. Twelve of 14 grid cells in the TMART study area are represented by wells with volcanic aquifer lithology; 8 of these 12 wells

have sedimentary surficial geology, but are screened or open in volcanic rocks at depth. Grid cells in the TROCK study area were evenly split between representation by wells with volcanic and granitic aquifer lithologies, with one well with sedimentary lithology.

Of the 29 cells with grid wells in the Central Sierra study unit (table A1), 27 are represented by wells with granitic aquifer lithology (fig. 10; table C1), in accordance with the dominance of granitic rocks over metamorphic rocks in the study unit (fig. 4B).

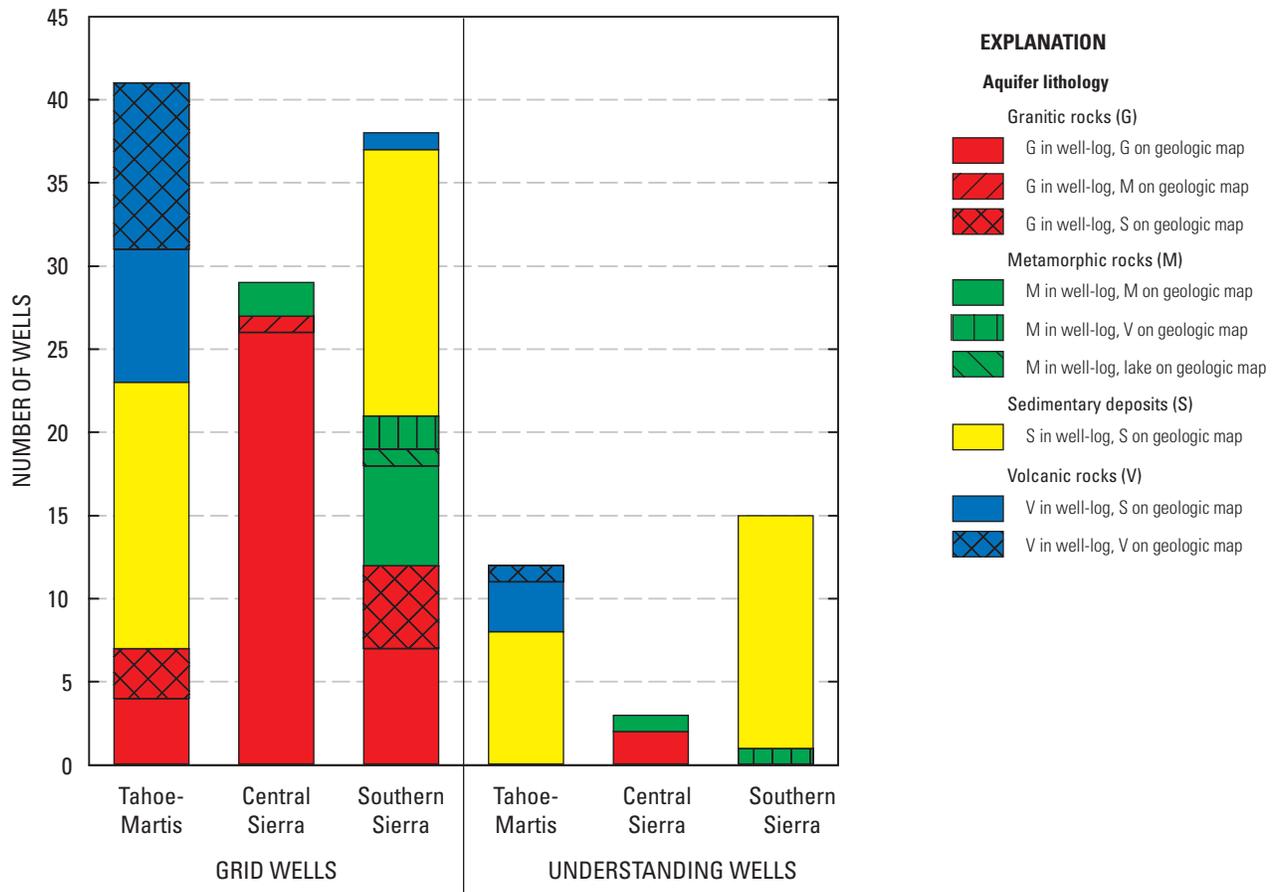


Figure 10. Aquifer lithology classification for grid wells and USGS-understanding wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Of the 38 cells with grid wells in the Southern Sierra study unit (table A1), 21 are represented by wells with granitic or metamorphic aquifer lithology, 16 by wells with sedimentary aquifer lithology, and 1 by a well with volcanic aquifer lithology (fig. 10; table C1). Five wells with granitic aquifer lithology have sedimentary surficial geology but are primarily or solely screened or open in granitic rocks beneath the thin veneer of alluvial or fluvial sediments at the margins of the Tehachapi Valley, Cummings Valley, and Kern River Valley basins (table C1). Fourteen of the 15 USGS understanding wells have sedimentary aquifer lithology, and are located in the central parts of the Tehachapi Valley and Cummings Valley groundwater basins where the thickness of alluvial sediments is much greater.

Hydrologic conditions are represented by elevation and aridity index at the well site (table C2). Elevation was considered a proxy for relative position in a generalized regional groundwater flow system. The aridity index was used as an indicator of climate. The aridity index is defined as average annual precipitation divided by average annual evapotranspiration, and is equal to the UNESCO Aridity Index (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997). The relation between aridity index and elevation is different for the three study units (fig. 11). Climate in the Tahoe-Martis study unit is dry sub-humid to humid at elevations below 6,500 ft, and climate at elevations above 6,500 ft is typically characterized as wet. Climate in the Central Sierra study unit ranges from semi-arid at low elevations to wet at high elevations. Most of the Southern Sierra study unit is characterized by a semi-arid climate.

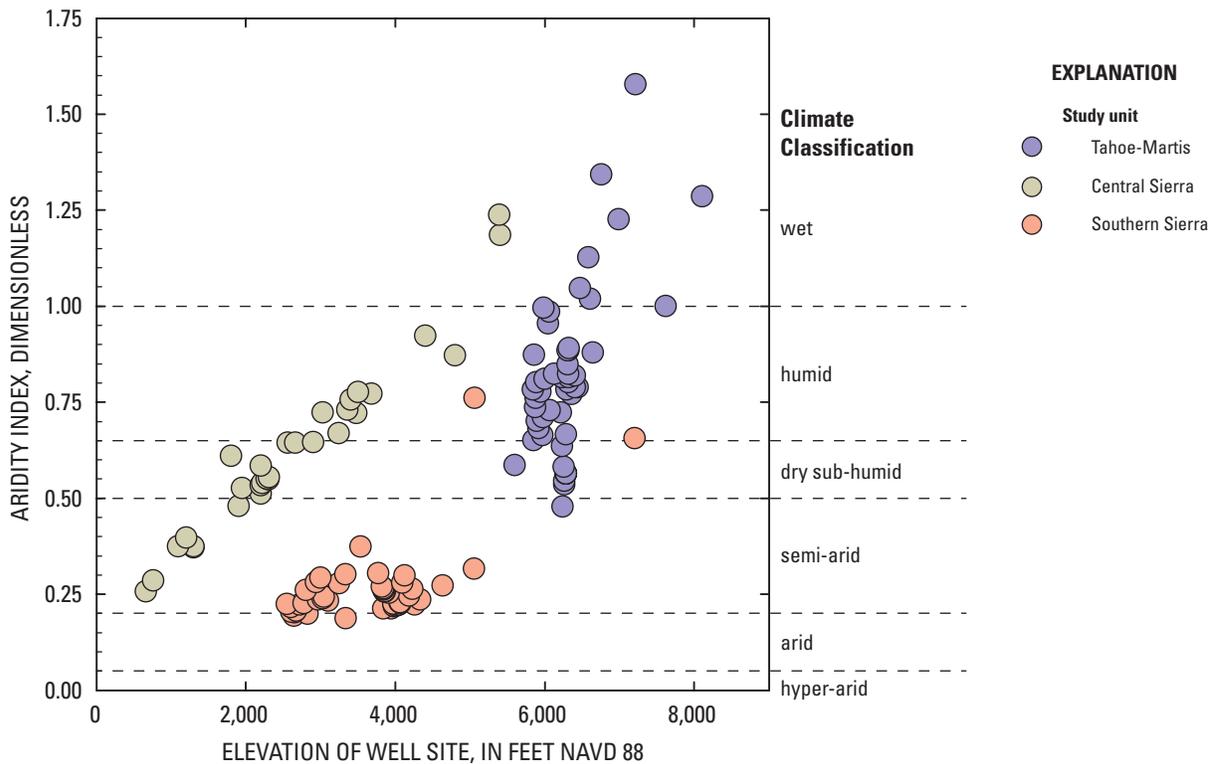


Figure 11. Relation between elevation and aridity index at well sites, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Well Depth and Groundwater Age Distribution

Well construction characteristics differ among the three study units ([table C2](#); [figs. 12A,B](#)). Grid wells from the Tahoe-Martis study unit have the widest ranges of both well depth and depth to top of screened or open interval, largely because of the large differences in geologic setting among the three study areas ([fig. 4A](#)). The median depth of TMART grid wells is 606 feet below land surface (ft bls), which is significantly greater than the median depth of TROCK grid wells (median = 73 ft bls; $p=0.003$) and greater than the depths of most of the TTAHO wells (median = 217 ft bls). Five of the 12 TROCK grid wells are springs emerging at ground surface rather than wells, and are defined as having depth and depth to top screened or open interval of 0 ft bls for the purposes of this report ([table C2](#)). TMART grid wells also had the greatest depth to top of the screened or open interval (median = 175 ft bls) ([fig. 12B](#)). The Truckee River Operating Agreement places restrictions on well locations and depths to the top of the screened or open interval for wells in the Martis Valley to minimize pumping from the shallow aquifer that may reduce flows in the Truckee River (U.S. Bureau of Reclamation, 2008).

The median depth of grid wells from the Central Sierra study unit is 620 ft bls, with half of the wells having depths between 440 and 885 ft bls. Median depth to the top of the screened or open interval is 60 ft bls, with half of the wells having depth to top of screened or open interval in a narrow range of 52 to 92 ft bls. All of the Central Sierra study unit grid wells are drilled in hard rock, and many are open holes (no casing) below 50 ft bls. There were no significant differences in well construction characteristics between CGOLD and CWISH wells nor between grid and understanding wells.

Compared to wells from the Central Sierra study unit, wells from the Southern Sierra study unit have shallower depths (median = 285 ft bls; $p < 0.001$), and greater depths to the top of the screened or open interval ([figs. 12A,B](#)). Within the Southern Sierra study unit, well depths varied with geologic setting (not shown). Grid wells from the Kern River Valley area have a median depth of 150 ft bls and a median depth to the top of the screened interval of 60 ft bls. In contrast, grid wells from the Tehachapi-Cummings Valley area are significantly deeper, with a median depth of

375 ft bls ($p=0.007$) and a median depth to the top of screened interval of 140 ft bls ($p=0.012$). Understanding wells in the Tehachapi-Cummings Valley are typically deeper than the grid wells, but the differences were not significant ($p > 0.3$).

Groundwater samples, particularly samples from wells with long screened or open intervals, typically represent mixtures of groundwaters that have different ages. 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. Data for the age-dating tracers tritium, carbon-14, and helium-4 were used to classify groundwater age distributions into three categories: modern, mixed, and pre-modern ([table C3](#)). Samples with tritium activities indicating presence of a substantial amount of water recharged since approximately 1950 were classified as containing “modern” groundwater. Samples with carbon-14 activities and helium-4 abundances indicating presence of a substantial amount of water recharged more than approximately 100 years ago were classified as containing “pre-modern” groundwater. Samples with characteristics of both modern and pre-modern groundwaters were classified as “mixed”. Groundwater age was treated as both a 2-factor classification and a 3-factor classification for tests of statistical relations between potential explanatory factors and water quality. For the 2-factor classification, the modern and mixed categories were combined into one category, “young” groundwater.

Of the 132 samples collected by USGS-GAMA, 26 were classified as having “modern” groundwater age distributions, 53 as having “mixed” age distributions, and 39 as having “pre-modern” age distributions ([table C4](#)). Fourteen samples were classified as “modern or mixed” because they had insufficient data to confirm the presence or absence of pre-modern groundwater. (See [appendix C](#) for discussion.)

Classified groundwater ages typically increase with well depth and with depth to the top of the screened or open interval. Groundwater with modern age distributions came from wells with significantly shallower depths than groundwater with mixed ($p < 0.001$) or pre-modern age distributions ($p < 0.001$) ([fig. 13B](#)). Groundwater with pre-modern age distributions came from wells with significantly greater depths to the top of the screened or open interval than groundwater with modern ($p=0.001$) or mixed age distributions ($p=0.002$) ([fig. 13A](#)).

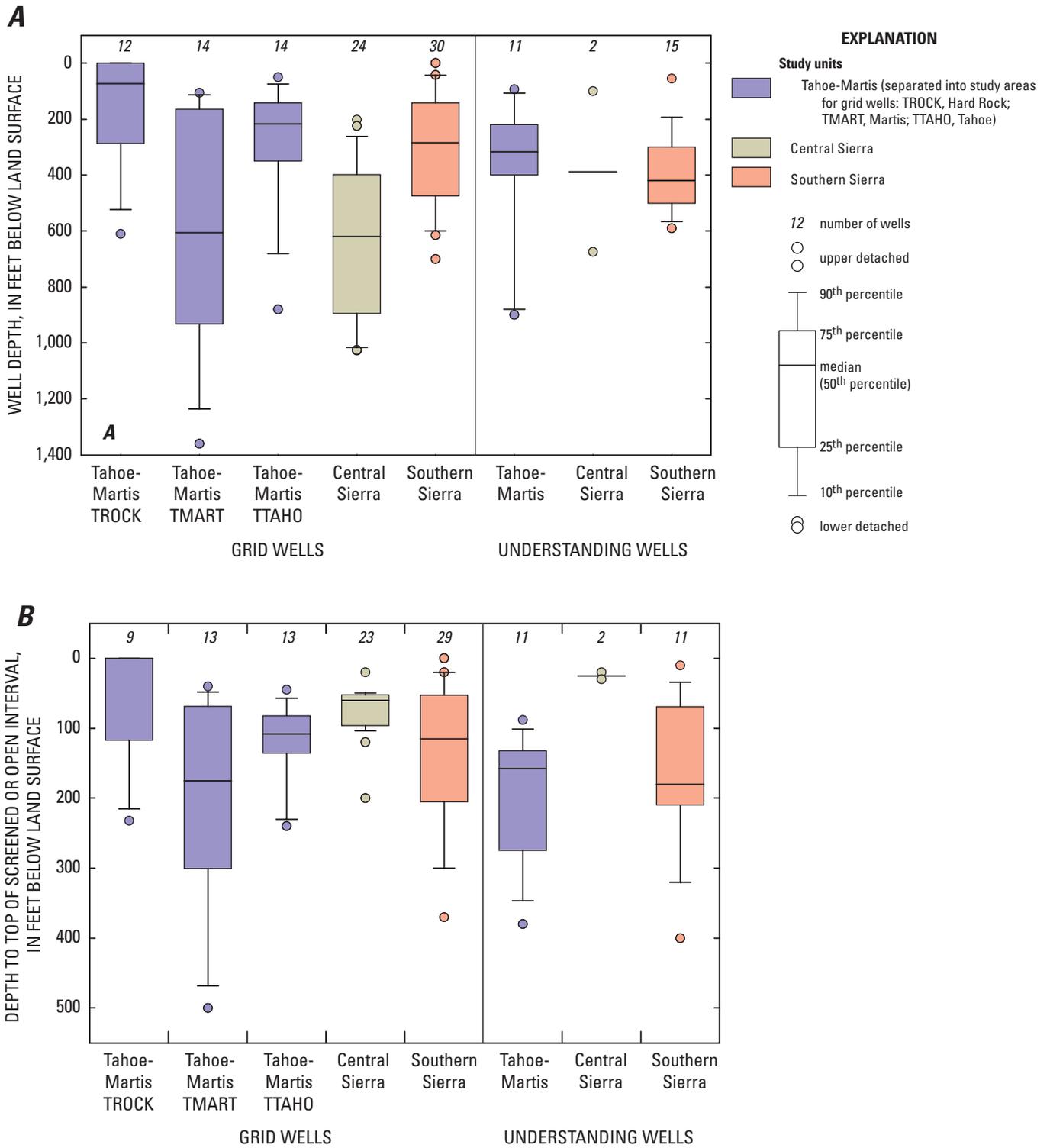


Figure 12. (A) Well depths and (B) depths to top of screened or open interval for grid and understanding wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

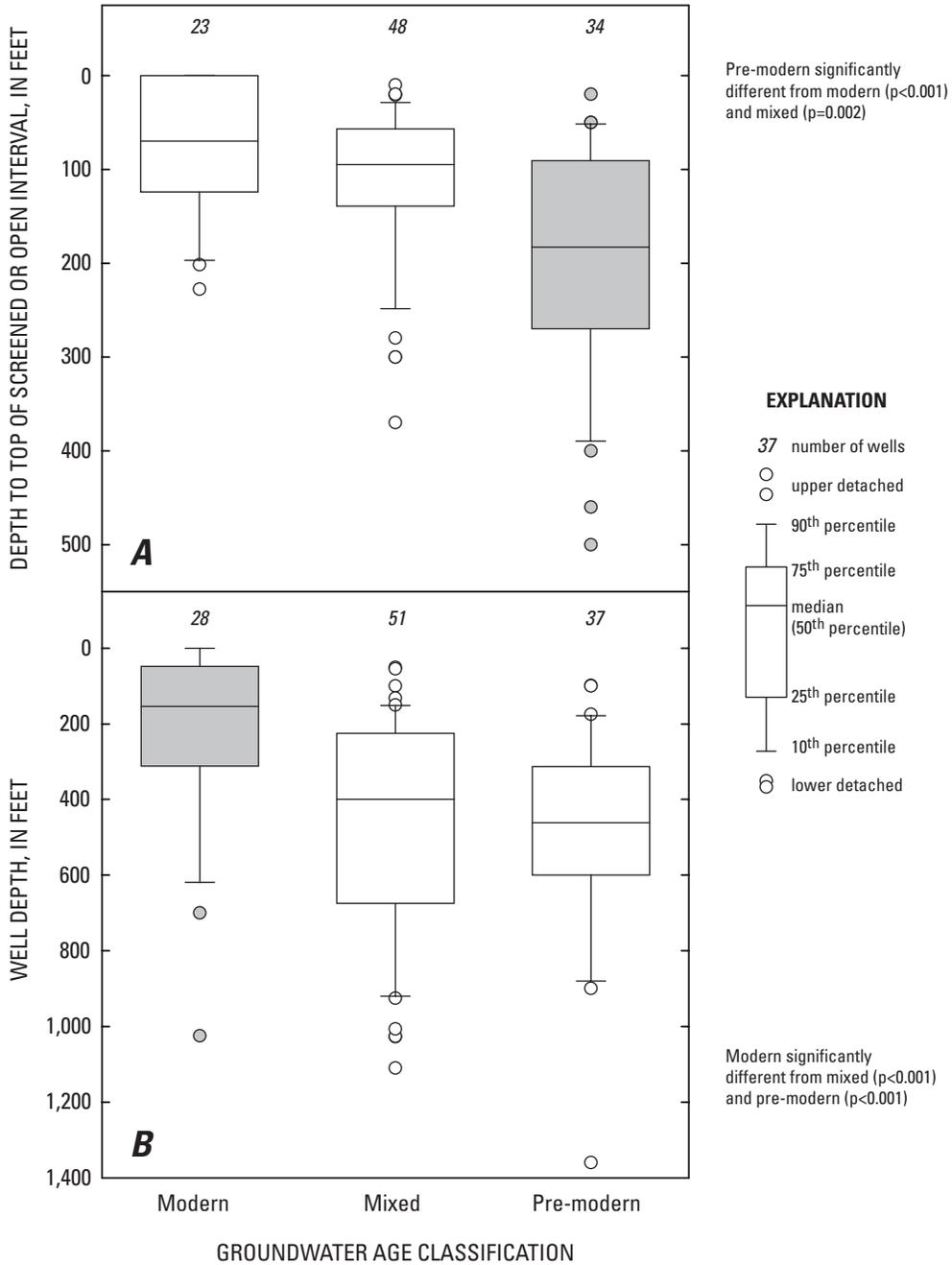


Figure 13. (A) Depths to top of screened or open interval and (B) well depths for wells with groundwater classified as modern, mixed, or pre-modern in age, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Classified groundwater ages were used to create a 3-factor classification system for well depth. Wells of depth less than a critical depth were defined as shallow; wells with screened or open intervals beginning above the critical depth and ending below the critical depth were defined as mixed; and wells with screened or open intervals entirely below the critical depth were defined as deep. The critical depth of 170 ft bls was selected by optimizing the segregation of modern-age groundwater into shallow wells, mixed-age groundwater into mixed-depth wells, and pre-modern-age groundwater into deep wells.

In the Tahoe-Martis study unit, most shallow wells had modern-age groundwater, most mixed-depth wells had mixed-age groundwater, and most deep wells had pre-modern-age groundwater (fig. 14A). Most of the wells in the Central Sierra study unit were classified as mixed depth, and the majority had mixed-age groundwater (fig. 14B). The segregation of groundwater ages into well depth classes was least strong in the Southern Sierra study unit (fig. 14C). Three depth categories in the Tahoe-Martis and Southern Sierra study units and the mixed-depth category in the Central Sierra study unit had some wells with each of the classified ages. These results indicate that there are local variations in the general age-depth relation.

Classified well depth	Well depth	Depth to top of the screened or open interval
Shallow	< 170 ft bls	< 170 ft bls
Mixed	≥ 170 ft bls	< 170 ft bls
Deep	≥ 170 ft bls	≥ 170 ft bls

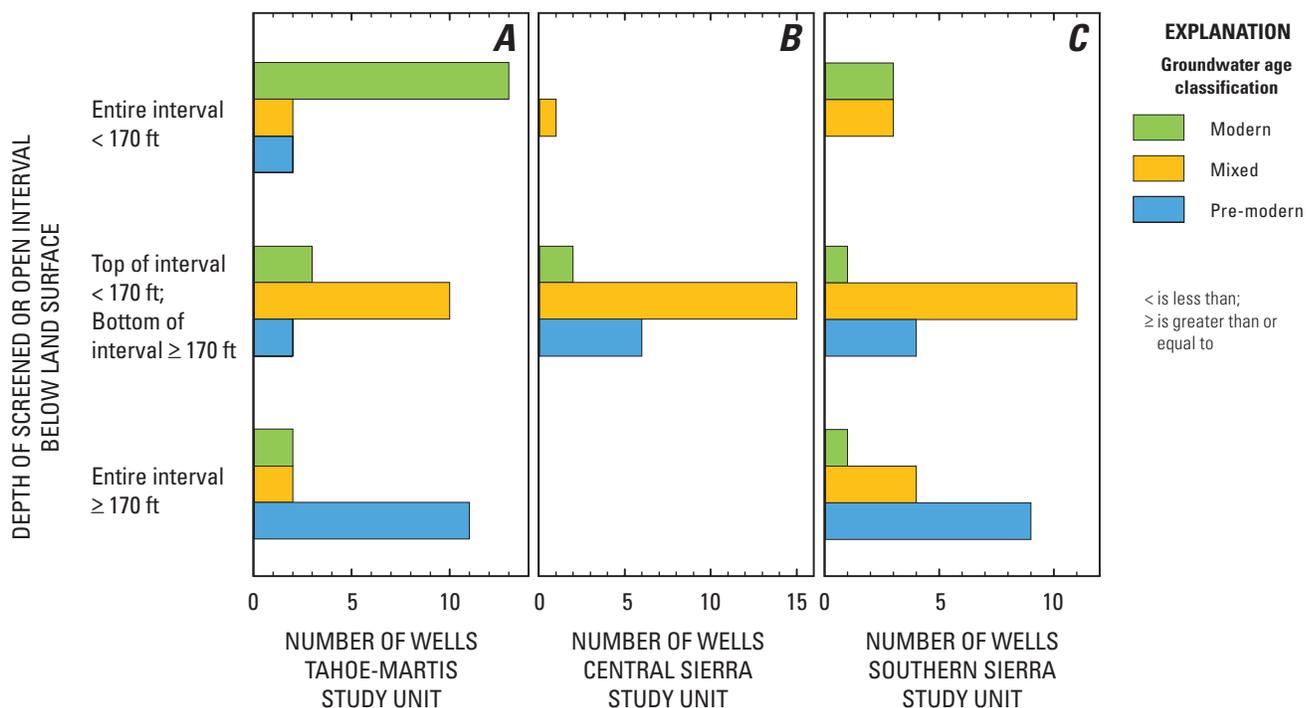


Figure 14. Relation between groundwater age classification and well depth classification for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

Geochemical Conditions

Sufficient chemical data, including dissolved oxygen (DO) concentration, were available for 125 wells to classify their groundwater oxidation-reduction (redox) conditions (appendix C). Groundwater conditions were primarily oxic (76%), with 20% of the wells anoxic and 4% of the wells with mixed oxic/anoxic conditions (table C5). Wells with volcanic or sedimentary aquifer lithology typically had oxic conditions, regardless of well depth (fig. 15A). Anoxic conditions (DO < 0.5 mg/L) were more prevalent in wells with granitic or metamorphic aquifer lithology, particularly in deeper wells (fig. 15A). Anoxic conditions were further subdivided into suboxic, nitrate-reducing, manganese-reducing, and manganese-and-iron-reducing conditions (table C5).

Values for pH ranged from 5.3 to 9.4 (table C5; fig. 15B). Wells with granitic aquifer lithology included groundwater spanning the full range of pH values observed in the three study units. The range of pH values observed in groundwater from wells with sedimentary aquifer lithology was slightly narrower (6.0 to 9.2). All of the wells with sedimentary aquifer lithology and pH values > 8.1 were from the Tahoe Valley South subbasin. Wells with volcanic aquifer lithology had groundwater with the most restricted range of pH values (6.9 to 8.2).

Correlations Between Explanatory Factors

Apparent correlations between potential explanatory factors and water-quality constituents could result from correlations among potential explanatory factors; therefore, identification of statistically significant correlations between potential explanatory factors is important (tables 6A,B,C). The potential explanatory factors examined for the three study units are extensively correlated with one another.

Nearly all of the potential explanatory factors are significantly correlated with aquifer lithology (tables 6A,C). Sedimentary aquifer lithology is positively correlated with urban and agricultural land use and negatively correlated with undeveloped land use. These relations reflect the fact that urban and agricultural development preferentially occur on sedimentary basin deposits because the land is flatter and the soil is typically more suitable for agriculture. Higher aridity index is significantly correlated with volcanic and granitic lithologies because it also is significantly greater in the two more northern study units (fig. 11; table 6A): nearly all of the wells with volcanic aquifer lithology are in the Tahoe-Martis

study unit and three-quarters of the wells with granitic aquifer lithology are in the Central Sierra or Tahoe-Martis study units (fig. 10; table 6C). Aridity index typically increases with elevation and with latitude because of increasing precipitation.

Correlations between aquifer lithology and the geochemical potential explanatory factors, DO and pH, likely reflect causative relationships, but these may be partially obscured by the non-causative relations between aquifer lithology and other explanatory factors. DO concentrations and pH values are significantly greater in wells with sedimentary or volcanic aquifer lithology than in wells with granitic or metamorphic aquifer lithology (table 6A). DO has a significant inverse correlation with well depth (table 6B); however, wells with volcanic aquifer lithology and depths > 800 ft bls have DO concentrations of 4–10 mg/L (fig. 15A). Higher DO concentrations are significantly associated with groundwater with modern age distributions and well sites at higher elevations. Relatively recently recharged groundwater in shallow wells (and springs) near the proximal end of the regional groundwater system likely has not interacted extensively with organic matter or reduced inorganic aquifer materials, and thus would not have had its DO consumed. Well depth and depth to the top of screened or open interval have significant positive correlations with pH (fig. 15B; table 6B), and higher pH values are significantly associated with groundwater with pre-modern age distributions (table 6A). Precipitation is dilute and generally has low pH values controlled by equilibration between atmospheric carbon dioxide and dissolved carbonic acid (H₂CO₃). As this water recharges an aquifer, pH values generally rise as the carbonic acid is converted to bicarbonate (HCO₃⁻) by hydrolysis reactions with silicate minerals and dissolution of carbonate minerals (if present) (Stumm and Morgan, 1996).

Agricultural land use is positively correlated with depth to top of screened or open interval and negatively correlated to elevation and aridity index, which reflects the fact that agricultural land use is primarily located in centers of the Tehachapi-Cummings Valley of the Southern Sierra study unit, where wells and tops of screened intervals are relatively deep. The positive correlations between urban land use and sedimentary aquifer lithology and location in the Tahoe-Martis study unit are driven by the high degree of urbanization in the TTAHO study area (fig. 6B).

Many other complex patterns of correlations involving aquifer lithology are evident in the statistical results (tables 6A,B,C), and these are discussed later in the report as part of the analysis of factors affecting individual constituents.

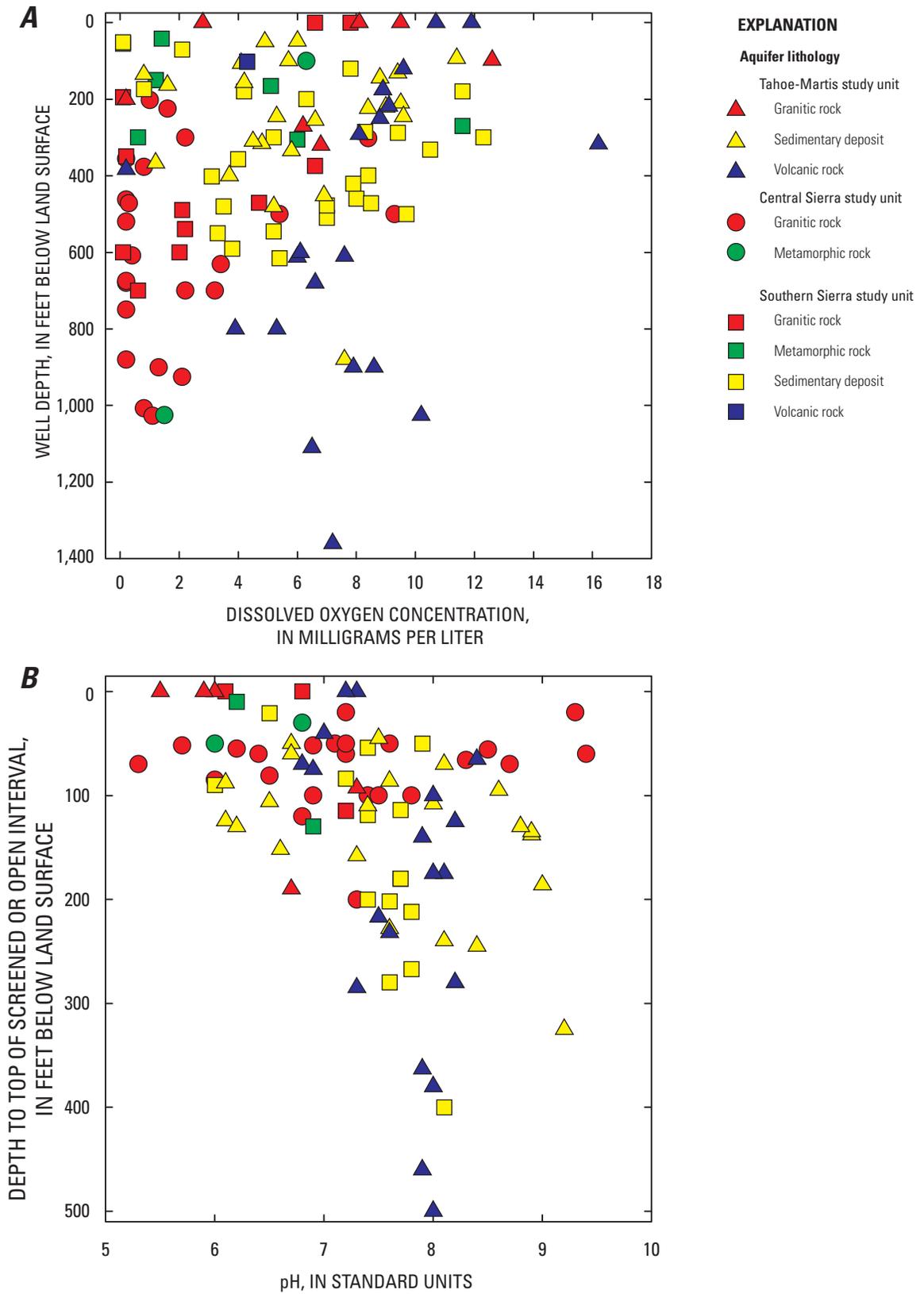


Figure 15. Relations between (A) well depth and dissolved oxygen concentration and (B) depth to top of screened or open interval and pH for wells with various aquifer lithologies, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Table 6A. Results of Kruskal-Wallis and Wilcoxon rank-sum tests for differences in values of selected potential explanatory factors between samples classified into groups by aquifer lithology, groundwater age, study unit, or well depth, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Relation of median values in sample groups tested shown for Kruskal-Wallis and Wilcoxon rank-sum tests in which the populations were determined to be significantly different (two-sided test) on the basis of p-values (not shown) less than threshold value (α) of 0.05; ns, test indicated no significant differences between the sample groups. p-values were calculated using the Kruskal-Wallis test; if significant, then Wilcoxon rank-sum tests used to determine which differences were significant. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Study unit:** T, Tahoe-Martis; C, Central Sierra; S, Southern Sierra. **3-factor depth class:** shallow (Shal), well depth < 170 ft; Mixed (Mix), top of perforations < 170 ft and well depth > 170 ft; Deep (Deep) well depth > 170 ft and top of perforations > 170 ft. **2-factor age class:** young, tritium > 0.5 TU; old, tritium < 0.5 TU. **3-factor age class:** Mod, modern; Mix, mixed modern and pre-modern; Pre, pre-modern (see [appendix C](#) for explanation). **Other abbreviations:** ns, no significant differences; TU, tritium units; ft, feet below land surface; >, greater than; <, less than]

Potential explanatory factor	Significant differences				
	Aquifer lithology class (G, M, S, V)	Study unit (T, C, S)	3-Factor depth class (Shal, Mix, Deep)	2-Factor age class (young, old)	3-Factor age class (Mod, Mix, Pre)
Percent agricultural land use	S > GV M > V	S > CT	Deep > ShalMix	ns	ns
Percent undeveloped land use	GMV > S	C > S	ns	ns	ns
Percent urban land use	S > GMV	T > S	ns	ns	ns
Density of septic tanks	GM > S	C > ST	Mix > ShalDeep	ns	MixPre > Mod
Aridity index	V > G > MS	T > C > S	ns	ns	Mod > MixPre
Elevation	V > S > GM	T > S > C	ShalDeep > Mix	ns	Mod > Pre > Mix
Well depth	GV > MS	C > ST	MixDeep > Shal	old > young	MixPre > Mod
Depth to top of perforation	SV > GM	ST > C	Deep > Mix > Shal	old > young	Pre > ModMix
pH	V > GM S > G	ns	Deep > Mix > Shal	old > young	Pre > Mix > Mod
Dissolved oxygen concentration	SV > GM	T > S > C	ns	ns	Mod > MixPre

Explanation:

How to read results for significant differences. “GM > S” for density of septic tanks means the following:

G has significantly greater density than S.

M has significantly greater density than S.

Density in G is not significantly different than density in M.

Density in V is not significantly different than density in G, M, or S.

Table 6C. Results of contingency table tests for associations between aquifer lithology, study unit, well depth, and groundwater age, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Factors determined to be significantly associated on the basis of p-values (not shown) less than threshold value (α) of 0.05 for contingency table test; ns, test indicated no significant association between factors. For factors with significant association, combinations of classes contributing more than 10 percent to test statistic are listed; black text, classes occur together; red text, classes do not occur together. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Study Unit:** T, Tahoe-Martis; C, Central Sierra, S, Southern Sierra. **3-factor depth class:** shallow (Shal), well depth < 170 ft; Mixed (Mix), top of perforations < 170 ft and well depth > 170 ft; Deep (Deep) well depth > 170 ft and top of perforations > 170 ft. **2-factor age class:** young, tritium > 0.5 TU; old, tritium < 0.5 TU. **3-factor age class:** Mod, modern; Mix, mixed modern and pre-modern; Pre, pre-modern (see [appendix C](#) for explanation). **Other abbreviations:** ns, no significant differences; TU, tritium units; ft, feet below land surface; >, greater than; <, less than]

Potential explanatory factor	Most significant associations				
	Aquifer lithology class (G, M, S, V)	Study unit (T, C, S)	3-Factor depth class (Shal, Mix, Deep)	2-Factor age class (young, old)	3-Factor age class (Mod, Mix, Pre)
Aquifer lithology class (G, M, S, V)		C + G T + V C – S	Shal + M Deep + C Deep – M Mix + G	ns	ns
Study unit (T, C, S)			Mix + C Deep – C Shal – C Mix – T	ns	Mod + T Mix – T Mod – C Mix + C Mod – S
3-Factor depth class (Shal, Mix, Deep)				old + Deep young – Deep old – Shal	Mod + Shal Pre + Deep Mix + Mix
2-Factor age class (young, old)					Pre + old Pre – young Mix – old Mod – old
3-Factor age class (Mod, Mix, Pre)					

Explanation: How to read results for factors with significant associations:

Study unit and aquifer lithology are significantly associated. The most important combinations of classes contributing to the significance of the association are: (1) Central Sierra study unit has wells with granitic aquifer lithology, (2) Tahoe-Martis study unit has wells with volcanic aquifer geology, and (3) Central Sierra study unit does not have wells with sediment aquifer lithology.

Status and Understanding of Water Quality

The *status assessment* was designed to identify the constituents or classes of constituents most likely to be water-quality concerns on the basis of their high RCs or their prevalence. The assessment applies only to constituents having regulatory or non-regulatory health-based or aesthetic-based benchmarks established by the USEPA or the CDPH (U.S. Environmental Protection Agency, 1999, 2009a,b; California Department of Public Health, 2006, 2008, 2010). The spatially distributed, randomized approach to well selection and data analysis yields a view of groundwater quality in which all areas of the primary aquifers are weighted equally; regions with a high density of groundwater use or with high density of potential contaminants were not preferentially sampled (Belitz and others, 2010).

The *understanding assessment* was designed to help answer the question of why specific constituents are, or are not, observed in the groundwater, and may improve our understanding of how human and natural sources of contaminants affect groundwater quality in the three study units. The assessment addresses a subset of the constituents selected for additional evaluation in the *status assessment*, and is based on statistical correlations between water quality and a finite set of potential explanatory factors. The assessment was not designed to identify specific sources of constituents to specific wells.

The following discussion of the *status* and *understanding assessment* results is divided into two parts, one for inorganic constituents and the other for organic constituents, and each part has a tiered structure. Each part begins with a survey of how many constituents were detected at any concentration in USGS-GAMA samples compared to the number analyzed and a graphical summary of the RCs of constituents detected in the grid wells. Aquifer-scale proportions are presented for the subset of constituents that met criteria for additional evaluation based on RC, or for organic constituents, prevalence. *Understanding assessment* results are presented for the subset of *status assessment* constituents that had statistically significant correlations to potential explanatory factors. For constituents that have *understanding assessment* results, those results are presented immediately following the *status assessment* results for that constituent.

Inorganic Constituents

Inorganic constituents generally occur naturally in groundwater, although their concentrations may be influenced by human activities as well as by natural factors. All 50 inorganic constituents analyzed by USGS-GAMA were detected in groundwater from at least one of the three study units, and most were detected in all three study units ([table 7A](#)). Of these 50 constituents, 27 had regulatory or non-regulatory health-based benchmarks, 8 had non-regulatory aesthetic-based benchmarks, and 15 had no established benchmarks. Of the 35 inorganic constituents with benchmarks, 23 were identified for additional evaluation in the *status assessment* ([table 3](#)). The 27 inorganic constituents not selected for additional evaluation either had no established benchmarks or were only detected at low concentrations relative to their benchmarks ([table 4](#)). Most of the constituents without benchmarks are major or minor ions that are present in nearly all groundwater.

Nineteen of the 23 inorganic constituents selected for additional evaluation in the *status assessment* were included because they were detected at moderate or high RCs in the grid wells for at least one of the three study units: nitrate, arsenic, boron, fluoride, lead, molybdenum, strontium, uranium, iron, manganese, zinc, chloride, sulfate, total dissolved solids (TDS), specific conductance, gross alpha particle activity, uranium activity (sum of uranium-234, uranium-235, and uranium-238), radium activity (sum of radium-226 and radium-228), and radon-222 activity ([table 3](#); [figs. 16A,B,C](#)). The majority of these 19 constituents were detected at moderate or high RCs in more than 10% of the grid wells for at least one of the three study units ([figs. 17A,B,C](#)).

Uranium is shown as both a radioactive constituent and a trace element in [figures 16A,B,C](#) and [17A,B](#) to demonstrate that similar results were obtained for comparison of uranium in groundwater to the MCL-CA of 20 picocuries per liter (pCi/L) or to the MCL-US of 30 µg/L. Uranium is classified as a radioactive constituent for calculations of aquifer-scale proportions of constituent classes. Similarly, total dissolved solids and specific conductance are both shown on [figures 16A,B,C](#) and [17C](#) to demonstrate that similar results were obtained with these two different measures of groundwater salinity, and with grid-well datasets dominated by USGS-GAMA and CDPH data. For the Southern Sierra study unit, most of the specific conductance data were from USGS-grid wells, and most of the total dissolved solids data were from CDPH-grid wells ([table 2](#)).

Table 7A. Number of inorganic constituents analyzed and detected by U.S. Geological Survey–Groundwater Ambient Monitoring and Assessment (USGS–GAMA) by benchmark and constituent type, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Regulatory health-based benchmarks include: MCL-US, USEPA maximum contaminant level; AL-US, USEPA action level; and MCL-CA, CDPH maximum contaminant level. Non-regulatory health-based benchmarks include: HAL-US, USEPA lifetime health advisory level; and NL-CA, CDPH notification level. Non-regulatory aesthetic benchmarks include SMCL-CA, CDPH secondary maximum contaminant levels. **Abbreviations:** USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health]

Benchmark type	Number analyzed	Number detected at any concentration			
		Tahoe-Martis	Central Sierra	Southern Sierra	All
Major, minor, and trace elements					
Regulatory health-based	15	¹ 14	15	14	15
Non-regulatory health-based	4	4	4	4	4
Non-regulatory aesthetic-based	8	7	7	8	8
No benchmark	12	12	12	12	12
Total:	39	37	38	38	39
Nutrients					
Regulatory health-based	2	2	2	2	2
Non-regulatory health-based	1	1	1	1	1
Non-regulatory aesthetic-based	0	0	0	0	0
No benchmark	3	² 2	3	3	3
Total:	6	5	6	6	6
Radioactive					
Regulatory health-based	5	5	5	³ 4	5
Non-regulatory health-based	0	0	0	0	0
Non-regulatory aesthetic-based	0	0	0	0	0
No benchmark	0	0	0	0	0
Total:	5	5	5	4	5
Sum inorganic constituents					
Regulatory health-based	22	21	22	20	22
Non-regulatory health-based	5	5	5	5	5
Non-regulatory aesthetic-based	8	7	7	8	8
No benchmark	15	14	15	15	15
Total:	50	47	49	48	50

¹ Mercury not analyzed in the Tahoe-Martis study unit.

² Dissolved organic carbon not analyzed in the Tahoe-Martis study unit.

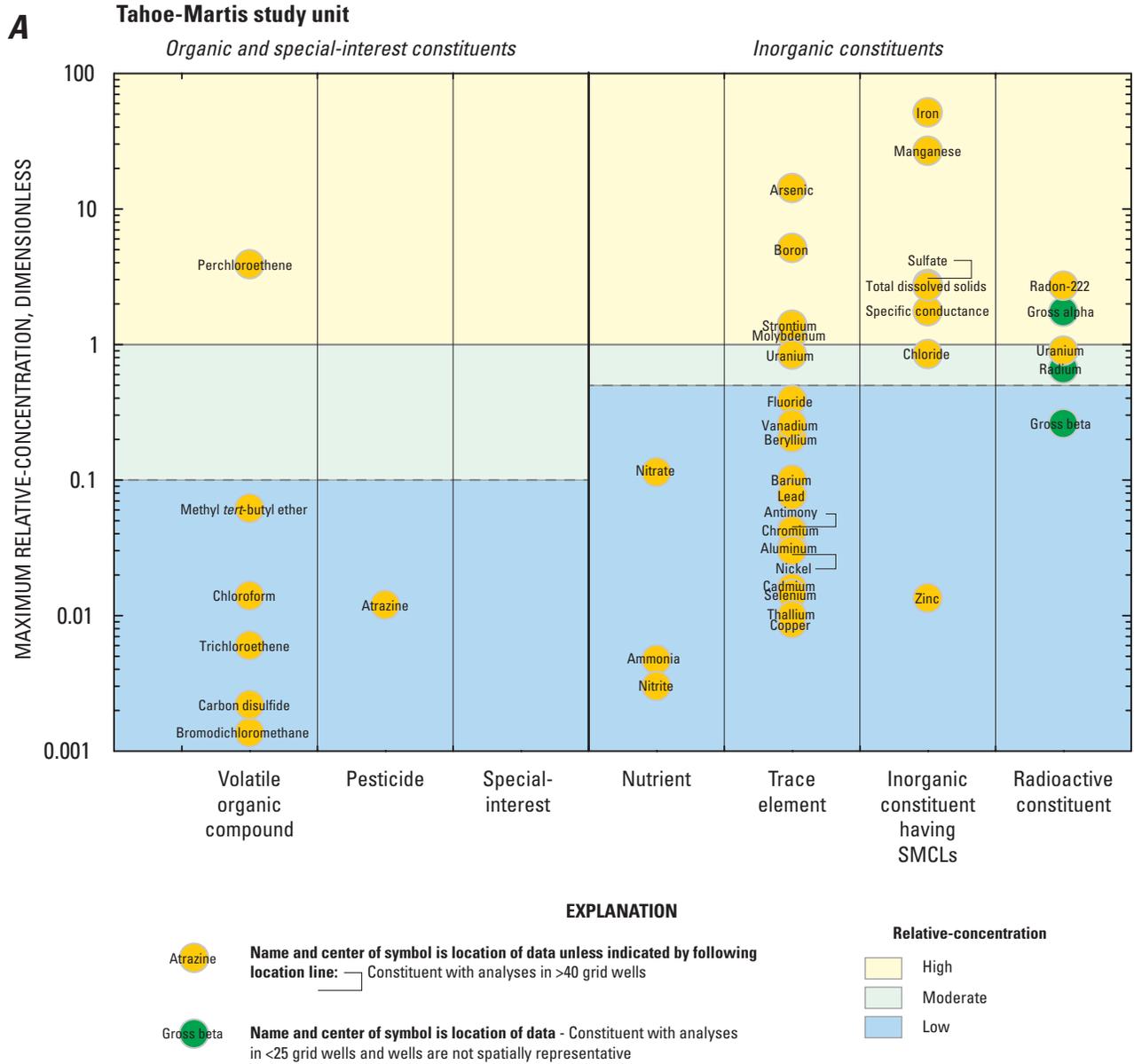
³ Uranium isotopes not analyzed in the Southern Sierra study unit.

Table 7B. Number of organic constituents analyzed and detected by U.S. Geological Survey-Groundwater Ambient Monitoring and Assessment (USGS-GAMA) by benchmark type and constituent type, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Regulatory health-based benchmarks include: MCL-US, USEPA maximum contaminant level; and MCL-CA, CDPH maximum contaminant level. Non-regulatory health-based benchmarks include: HAL-US, USEPA lifetime health advisory level; RSD5-US, USEPA risk-specific dose; NL-CA, CDPH notification level. **Abbreviations:** USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health; VOC, volatile organic carbon]

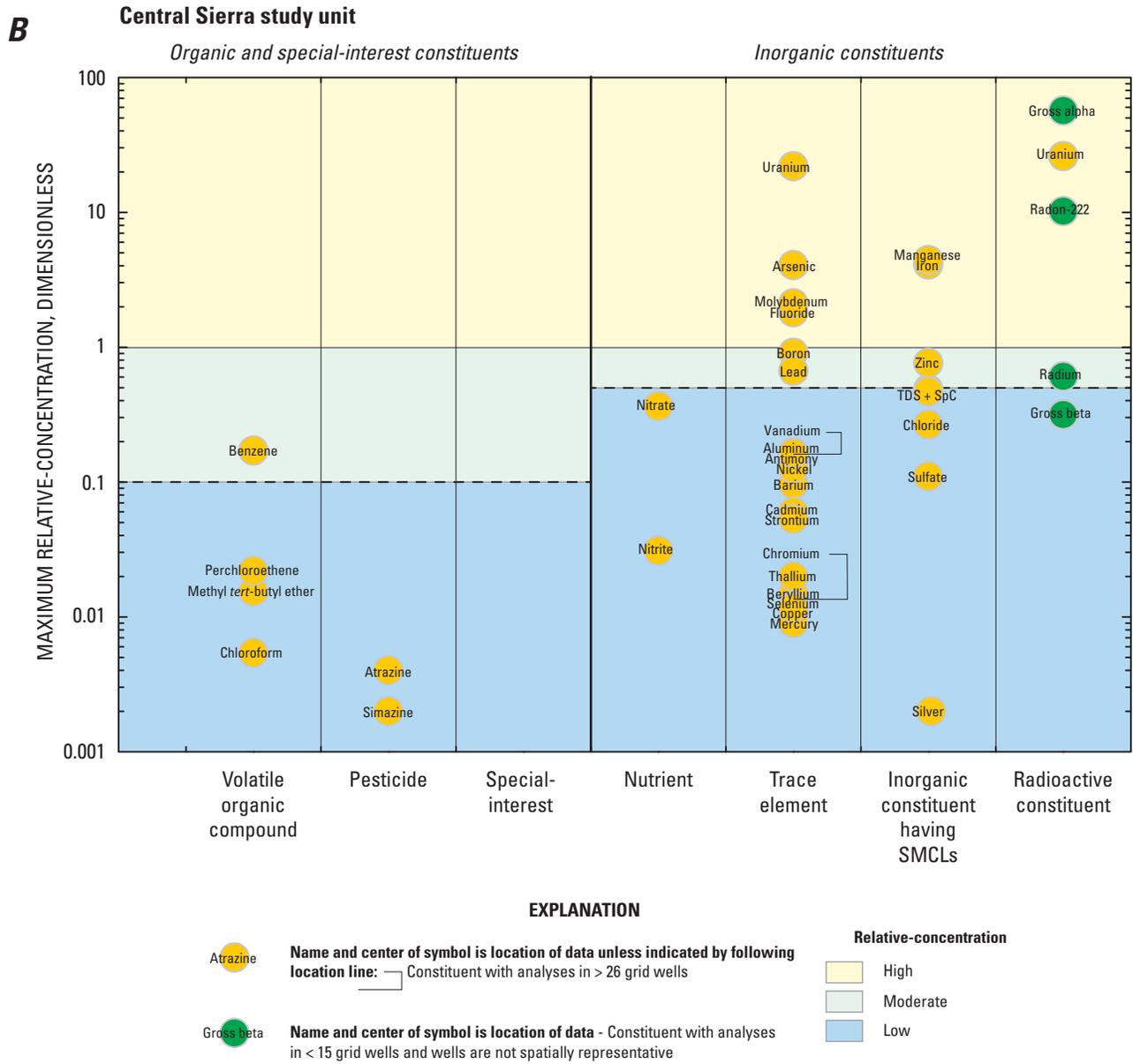
Benchmark type	Number analyzed	Number detected at any concentration			
		Tahoe-Martis	Central Sierra	Southern Sierra	All
VOCs					
Regulatory	33	7	4	9	12
Non-regulatory	26	1	1	1	2
No benchmark	29	1	0	0	1
Total:	88	9	5	10	15
Pesticides and degradates¹					
Regulatory	7	1	2	2	2
Non-regulatory	19	0	0	1	1
No benchmark	59	2	2	2	4
Total:	85	3	4	5	7
Special interest					
Regulatory	1	0	0	1	1
Non-regulatory	2	0	0	1	1
No benchmark	0	0	0	0	0
Total:	3	0	0	2	2
Sum organic and special-interest constituents					
Regulatory	41	8	6	12	15
Non-regulatory	47	1	1	3	4
No benchmark	88	3	2	2	5
Total:	176	12	9	17	24

¹ Number analyzed refers to the Central Sierra study unit (table 1). For the Tahoe-Martis and Southern Sierra study units, the total number of pesticides and pesticide degradates analyzed was 63 (3 with regulatory benchmarks, 17 with non-regulatory benchmarks, and 43 with no benchmarks).



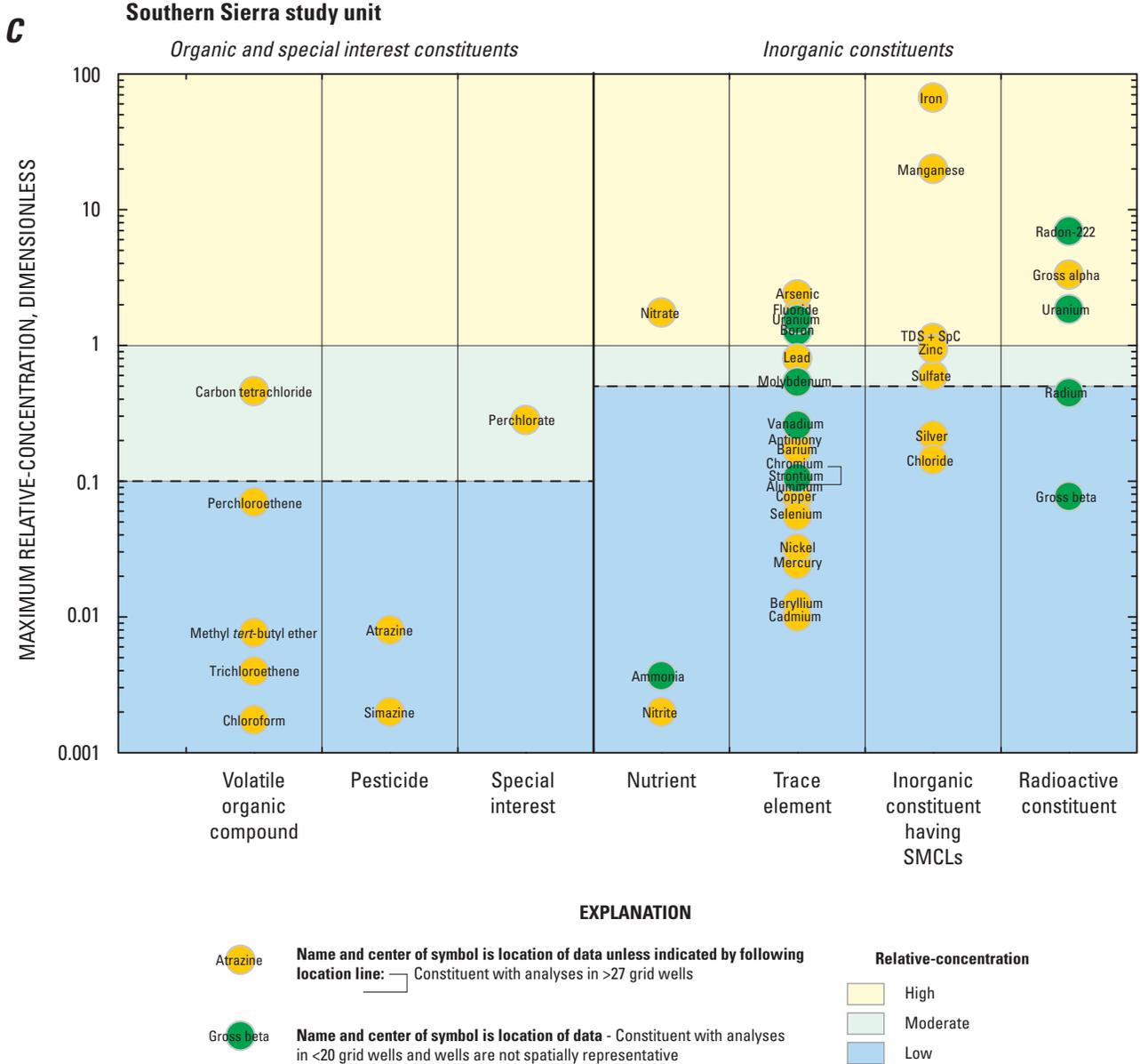
One volatile organic compound was detected at relative-concentration <0.001. SMCL, secondary maximum contaminant level; upper water-quality benchmark used for calculating relative-concentrations for constituents with an upper and recommended SMCL; >, greater than; <, less than

Figure 16. Maximum relative-concentrations of constituents detected in grid wells by constituent class for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.



One volatile organic compound and one nutrient were detected at relative-concentration <0.001. SMCL, secondary maximum contaminant level; upper water-quality benchmark used for calculating relative-concentrations for constituents with an upper and recommended SMCL; >, greater than; <, less than

Figure 16.—Continued



Three volatile organic compounds were detected at relative-concentration <0.001. SMCL, secondary maximum contaminant level; upper water-quality benchmark used for calculating relative-concentrations for constituents with an upper and recommended SMCL; >, greater than; <, less than

Figure 16.—Continued

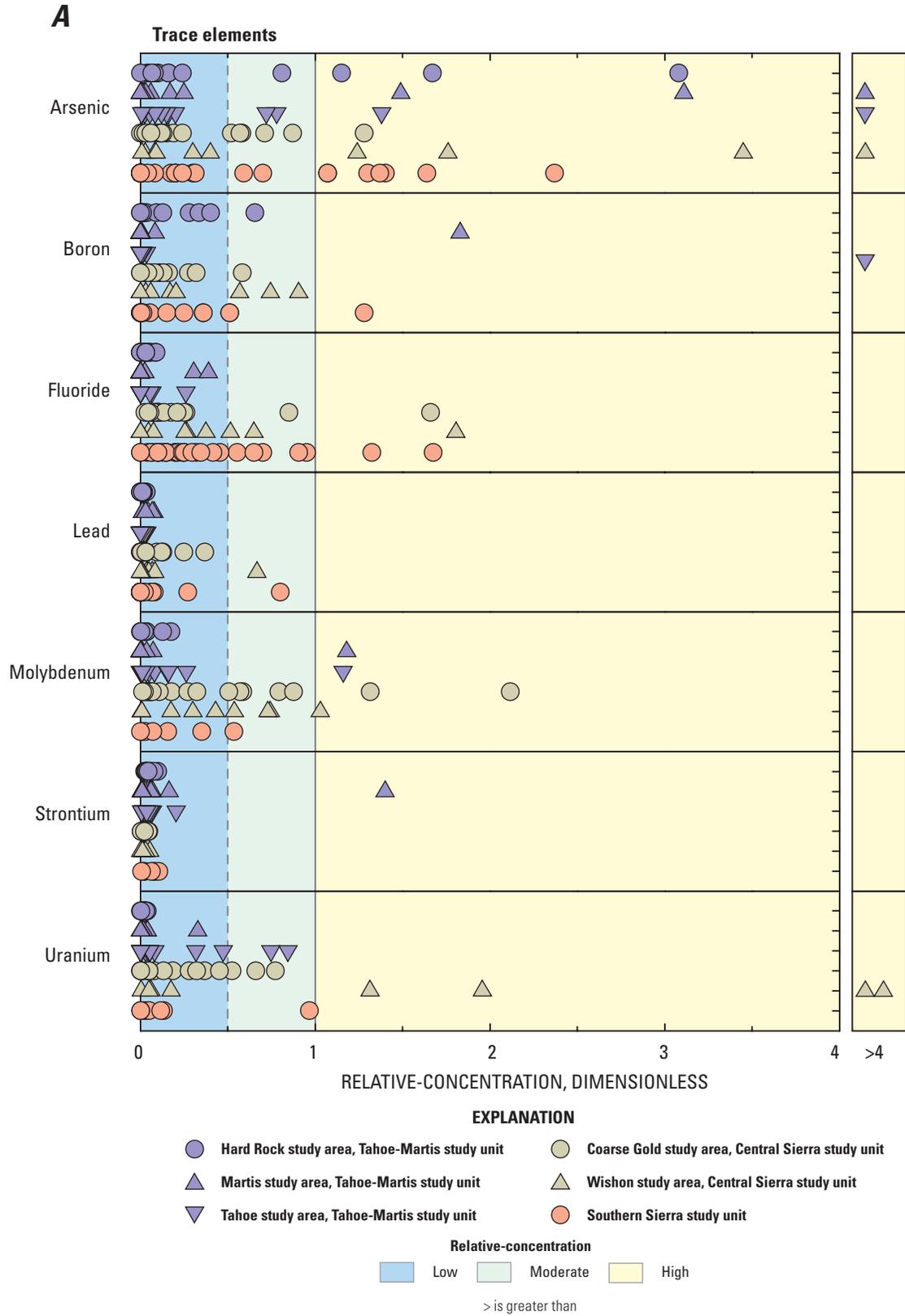


Figure 17. Relative-concentrations of selected (A) trace elements with regulatory and non-regulatory health-based benchmarks, (B) nutrients and radioactive constituents with regulatory health-based benchmarks, and (C) salinity indicators and trace elements with non-regulatory SMCL benchmarks, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

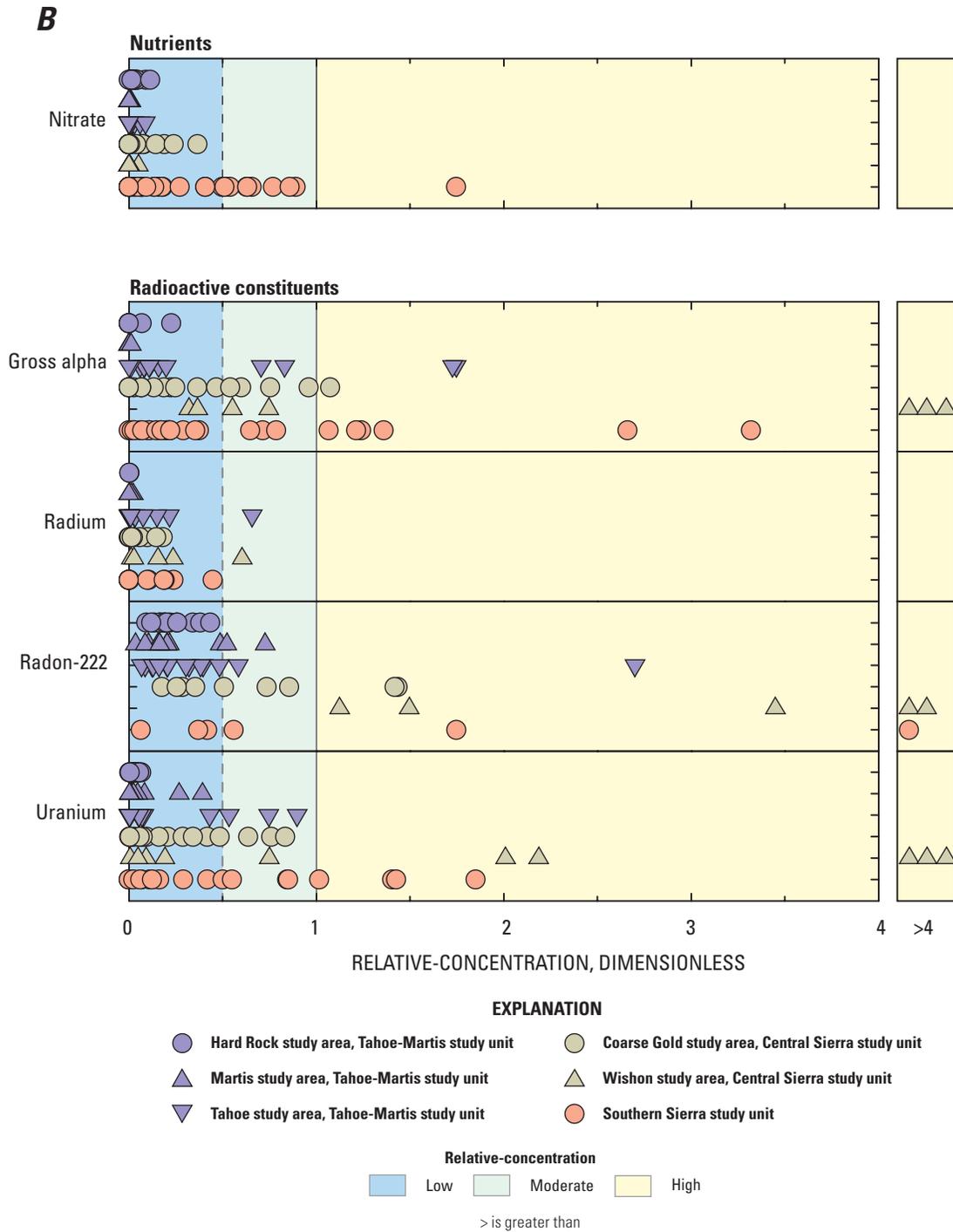


Figure 17.—Continued

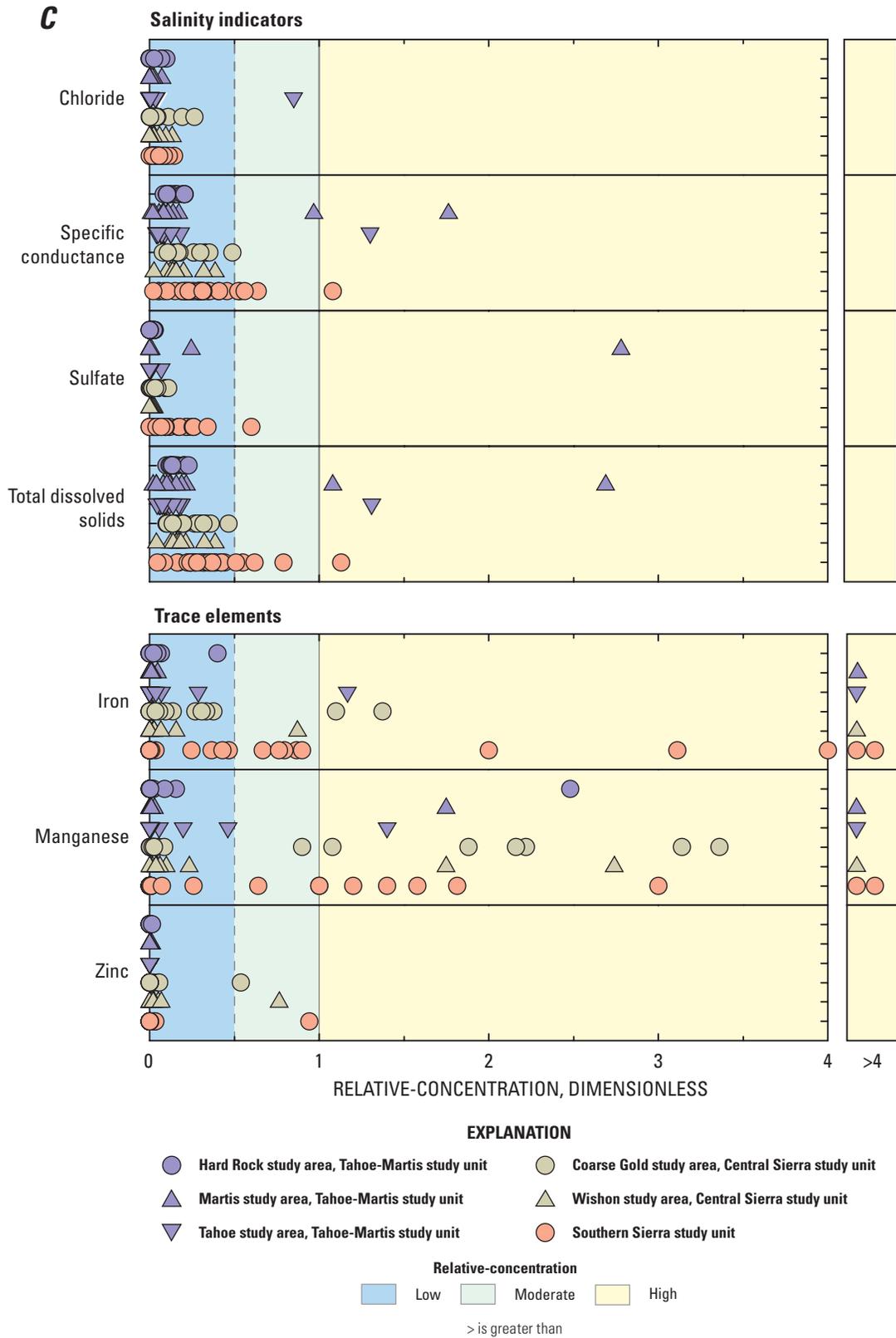


Figure 17.—Continued

Four of the 23 inorganic constituents selected for additional evaluation in the *status assessment* were included because they were reported at high or moderate RCs in the CDPH databases for at least one of the study units during the 3-year interval prior to USGS-GAMA sampling: chromium, selenium, aluminum, and antimony (table 3).

Aquifer-scale proportions for the constituents listed in table 3 are summarized in tables 8A,B,C for the three study units. Spatially weighted high aquifer-scale proportions fell within the 90% confidence intervals for their respective grid-based aquifer high proportions, providing evidence that the grid-based approach yields statistically equivalent results to the spatially weighted approach. Aquifer-scale proportions for classes of inorganic constituents are summarized in table 9A.

The high aquifer-scale proportion for any inorganic constituent having health-based benchmarks (nutrients, trace elements, and radioactive constituents) was 20% in the Tahoe-Martis study unit, 41% in the Central Sierra study unit, and 32% in the Southern Sierra study unit (table 9A). High RCs of trace elements in all three study units, and high RCs of radioactive constituents in the Central Sierra and Southern Sierra study units, contributed most to these high aquifer-scale proportions. For any inorganic constituent having non-health-based benchmarks (SMCL constituents), the high aquifer-scale proportion was 14% in the Tahoe-Martis study unit, 34% in the Central Sierra study unit, and 24% in the Southern Sierra study unit (table 9B). High RCs of manganese accounted for most of the high aquifer-scale proportion.

Trace Elements

The constituent class trace elements includes a variety of metallic and non-metallic constituents that typically are present in groundwater at concentrations <1 mg/L. Trace elements with health-based benchmarks had high aquifer-scale proportions of 19, 25, and 28% in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively (table 9A). Arsenic, fluoride, boron, and molybdenum accounted for most of the high and moderate RCs of trace elements (fig. 17A; tables 8A,B,C).

Arsenic had high RCs in 18, 15, and 22% of the primary aquifers in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively (tables 8A,B,C; fig. 17A). High RCs occurred in all study areas within the study units (figs. 18A,B,C; tables B1A–E). An estimated 8% of groundwater resources used for drinking water in the United States have high RCs of arsenic (>10 µg/L)

(Focazio and others, 1999), and high concentrations of arsenic in groundwater resources used for drinking water are a worldwide concern (Smedley and Kinniburgh, 2002; Welch and others, 2006).

High aquifer-scale proportions for fluoride were 6.6% in the Central Sierra study unit, and 6.5% in the Southern Sierra study unit. Fluoride was not detected at moderate or high RCs in the Tahoe-Martis study unit (fig. 17A). Boron had high RCs in 5.9% of the Tahoe-Martis study unit and in 6.7% of the Southern Sierra study unit, and was detected at moderate RCs in all three study units. Molybdenum had high RCs in 5.9% of the Tahoe-Martis study unit and in 11% of the Central Sierra study unit, and was detected at moderate RCs in the Central Sierra and Southern Sierra study units.

Six trace elements were infrequently detected at high RCs or were only detected at moderate RCs. Lead was not detected at high RCs in any of the three study units, but was detected at moderate RCs in the Central Sierra and Southern Sierra study units (fig. 17A, tables 8B,C). The high aquifer-scale proportion for strontium was 4.9% in the Tahoe-Martis study unit; however, strontium was not detected at moderate RCs in any of the study units. Chromium and selenium in the Central Sierra study unit (table 8B) and aluminum and antimony in the Southern Sierra study unit (table 8C) were each reported at high RC in one well in the CDPH database during the 3-year intervals used for the *status assessment*. The resulting spatially weighted high aquifer-scale proportions were <1% for chromium, selenium, and antimony, and 1.6% for aluminum, compared to 0% for the grid-based approach. The spatially weighted approach includes data from a larger number of wells than the grid-based approach, and therefore is more likely to include constituents present at high concentrations in small proportions of the primary aquifers. (Uranium is discussed in the section on radioactive constituents.)

Aluminum, cadmium, lead, and mercury in the Tahoe-Martis study unit; antimony, copper, and thallium in the Central Sierra study unit; and barium, beryllium, cadmium, mercury, nickel, selenium, and thallium in the Southern Sierra study unit were reported at high RCs historically in the CDPH database, but were not reported at high or moderate RCs in the CDPH database during the 3-year intervals used for the *status assessment* (table 5). For most of these historically high trace elements, a high RC was reported in just one well. For 75% of the cases, all later samples from the same well had low RCs for the historically high trace element. For the remaining cases, the high RC occurred in the only sample collected from the well and analyzed for trace elements. (See appendix D for additional discussion.)

Table 8A. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Tahoe-Martis study unit, 2006–2007, California GAMA Priority Basin Project.

[**Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level; DBCP, 1,2-dibromo-3-chloropropane]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)			90-percent confidence interval for grid-based high proportion ³ (percent)	
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high	Lower	Upper
Trace elements											
Arsenic	95	8.4	15.8	41	2.9	17	41	3.6	18	9.9	29
Boron	56	1.8	3.6	41	1.6	5.9	41	1.6	5.9	2.0	14
Molybdenum	48	2.1	4.2	41	0.5	5.4	41	0	5.9	1.5	13
Strontium	48	0	2.1	41	0	4.9	41	0	4.9	1.5	13
Uranium	49	6.1	0	41	2.0	0	41	2.0	0	0	3.2
Inorganic constituents with SMCL benchmarks											
Iron	95	2.1	7.4	41	0.2	5.7	41	0	6.9	2.4	16
Manganese	94	0	6.4	41	0	10	41	0	13	6.6	24
Chloride	94	1.1	0	41	0.3	0	41	1.0	0	0	3.2
Specific conductance	95	0	3.1	41	5	2.8	41	5	6	2.0	14
Sulfate	94	0	1.1	41	0	2.5	41	0	4.9	1.5	13
Total dissolved solids (TDS)	96	0	3.1	41	0	7.7	41	0	11	4.9	21
Radioactive constituents											
Adjusted gross alpha activity	60	1.7	3.3	25	0.3	0.5	24	1.1	1.1	0.1	10
Gross alpha particle activity	60	13	10	25	3.5	1.9	24	2.1	2.1	0.2	12
Radium activity	39	2.6	0	19	0.4	0	17	1.3	0	0	7.5
Radon-222 activity	67	7.5	6.0	40	11	0.9	40	12	1.0	0.1	6.7
Uranium activity	75	13	0	41	2.5	0	41	3.0	0	0	3.2
Volatile organic compounds - solvents											
Carbon tetrachloride	96	0	1.0	41	0	0.4	41	0	0	0	3.2
1,2-Dichloroethane	96	0	1.0	41	0	0.2	41	0	0	0	3.2
Chloroform	96	0	0	41	0	0	41	0	0	0	3.2
Chloromethane	96	1.0	0	41	0.4	0	41	0	0	0	3.2
Perchloroethene (PCE)	96	2.1	1.0	41	0.3	0.2	41	0	1.0	0.1	6.6
Volatile organic compounds - fumigants											
1,2-Dichloropropane	96	0	1.0	41	0	0.4	41	0	0	0	3.2
DBCP	72	0	1.4	41	0	0.2	41	0	0	0	3.2

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during May 1, 2004–April 30, 2007, combined with data from U.S. Geological Survey (USGS) grid wells, and selected USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 41 grid wells during June–October 2007.

³ Based on the Jeffreys interval for the binomial distribution (Brown and others, 2001).

Table 8B. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Central Sierra study unit, 2006–2007, California GAMA Priority Basin Project.

[**Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)			90-percent confidence interval for grid-based high proportion ³ (percent)	
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high	Lower	Upper
Nutrients											
Nitrate	165	3.6	0	29	3.1	0	29	0	0	0	4.5
Trace elements											
Arsenic	98	10	22	29	15	19	29	19	15	6.6	28.0
Boron	33	15	0	27	13	0	27	13	0	0.0	4.8
Chromium	90	0	1.1	29	0	0.4	29	0	0	0	4.5
Fluoride	100	6.0	3.0	29	5.5	7.3	29	9.3	6.6	1.8	17
Lead	95	3.2	0	29	5.0	0	29	2.7	0	0	4.5
Molybdenum	30	33	10	27	29	9.1	27	29	11	4.1	24
Selenium	90	0	1.1	29	0	0.4	29	0	0	0	4.5
Uranium	53	15	17	27	13	16	27	12	15	6.6	29
Inorganic constituents with SMCL benchmarks											
Iron	101	4.0	24	29	3.9	19	29	2.7	11	4.4	24
Manganese	101	6.9	36	29	1.9	29	29	3.8	32	20	47
Zinc	98	3.1	0	29	4.5	0	29	6.6	0	0	4.5
Chloride	100	2.0	3.0	29	1.0	1.3	29	0	0	0	4.5
Specific conductance	100	5.0	3.0	29	2.9	1.3	29	0	0	0	4.5
Total dissolved solids (TDS)	95	4.2	3.2	29	2.2	1.4	29	0	0	0	4.5
Radioactive constituents											
Adjusted gross alpha activity	111	5.5	1.8	24	3.0	1.3	24	8.2	3.9	0.6	14
Gross alpha particle activity	111	16	18	24	15	22	24	25	16	6.9	31
Radium activity	15	7.1	0	15	5.5	0	15	5.5	0	0	8.5
Radon-222 activity	14	21	50	14	24	44	14	24	44	24	65
Uranium activity	77	16	21	28	11	18	28	15	14	5.9	27
Pesticides											
Simazine	71	0	0	27	0	0	26	0	0	0	5.0

Table 8B. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Central Sierra study unit, 2006–2007, California GAMA Priority Basin Project.—Continued

[**Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)			90-percent confidence interval for grid-based high proportion ³ (percent)	
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high	Lower	Upper
Volatile organic compounds											
Benzene	84	1.2	0	27	2.0	0	27	4.0	0	0	4.8
Chloroform	87	2.3	0	27	1.1	0	27	0	0	0	4.8
Perchloroethene (PCE)	84	1.2	0	27	0.5	0	27	0	0	0	4.8
Methyl <i>tert</i> -butyl ether (MTBE)	84	2.4	0	27	1.6	0	27	0	0	0	4.8
1,4-Dichlorobenzene	84	1.2	0	27	0.4	0	27	0	0	0	4.8

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during June 1, 2003–May 31, 2006, combined with data from U.S. Geological Survey (USGS) grid wells, and USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 27 grid wells during May 2006.

³ Based on the Jeffreys interval for the binomial distribution (Brown and others, 2001).

Table 8C. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Southern Sierra study unit, 2006–2007, California GAMA Priority Basin Project.

[Relative-concentration categories: high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). Other abbreviations: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)			90-percent confidence interval for grid-based high proportion ³ (percent)	
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high	Lower	Upper
Nutrients											
Nitrate	199	17	5.5	37	18	4.1	37	24	2.7	0.5	10
Trace elements⁴											
Aluminum	158	1.3	0.6	31	0.4	1.6	31	0	0	0	4.2
Antimony	158	0	0.6	31	0	0.3	31	0	0	0	4.2
Arsenic	168	14	15	32	9.3	18	32	6.3	22	12	36
Boron	75	9.3	4.0	19	11	6.4	15	13	6.7	1.2	23
Chromium	151	0.7	0	30	1.7	0	30	0	0	0	4.4
Fluoride	163	8.6	6.7	33	17	6.7	31	16	6.5	1.9	17
Lead	158	1.9	0	31	1.1	0	31	3.2	0	0	4.2
Molybdenum	17	5.9	0	11	9.1	0	7	14	0	0	23
Uranium	22	4.5	4.5	14	7.1	7.1	8	13	0	0	15
Inorganic constituents with SMCL benchmarks											
Iron	154	12	18	31	14	13	30	17	13	5.7	26
Manganese	154	9.1	23	31	11	17	30	10	23	13	38
Zinc	153	2.0	0	30	2.4	0	30	3.3	0	0	4.4
Sulfate	155	1.3	0	30	3.3	0	30	3.3	0	0	4.4
Specific conductance	167	11	1.2	34	13	2.9	34	12	2.9	0.5	11
Total dissolved solids (TDS)	154	11	1.9	31	20	4.3	30	13	3.3	0.6	12
Radioactive constituents											
Adjusted gross alpha activity	143	5.6	0.7	29	9.6	0.3	28	7.1	7.1	2.1	18
Gross alpha particle activity	143	7.7	13	29	12	18	28	11	21	12	37
Radium activity	30	0.0	3.3	12	0	1.2	12	0	0	0	11
Radon-222 activity	10	10	40	9	11	44	6	17	33	10	66
Uranium activity	77	12	14	21	12	19	19	16	21	14	44
Pesticides											
Atrazine	161	0	0	37	0	0	35	0	0	0	3.8
Simazine	161	0	0	37	0	0	35	0	0	0	3.8

Table 8C. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Southern Sierra study unit, 2006–2007, California GAMA Priority Basin Project.—Continued

[Relative-concentration categories: high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). Other abbreviations: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)			90-percent confidence interval for grid-based high proportion ³ (percent)	
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high	Lower	Upper
Volatile organic compounds											
Carbon tetrachloride	161	0.6	0	37	0.3	0	35	2.9	0	0	3.8
Chloroform	161	0	0	37	0	0	35	0	0	0	3.8
Perchloroethene (PCE)	162	0.6	0	37	0.3	0	35	0	0	0	3.8
Special-interest constituent											
Perchlorate	89	11	0	35	10	0	35	8.6	0	0	3.8

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during February 1, 2003–January 31, 2006, combined with data from U.S. Geological Survey (USGS) grid wells, and USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 35 grid wells during June 2006.

³ Based on the Jeffreys interval for the binomial distribution (Brown and others, 2001).

⁴ Mercury and nickel were each reported at moderate relative-concentration in one CDPH well during February 1, 2003–January 31, 2006; the most recent values were low.

Table 9A. Summary of aquifer-scale proportions for inorganic constituent classes with health-based benchmarks, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Relative-concentration categories: high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.5 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.5 of benchmark]

Study unit	Number of cells	Aquifer-scale proportion (percent)		
		Low	Moderate	High
Radioactive constituents with health-based benchmarks¹				
Tahoe-Martis	41	85	12	3.0
Central Sierra	28	43	26	31
Southern Sierra	29	62	17	21
Nutrients with health-based benchmarks				
Tahoe-Martis	41	100	0	0
Central Sierra ²	29	97	3.0	0
Southern Sierra	37	73	24	2.7
Trace elements with health-based benchmarks				
Tahoe-Martis	41	77	3.6	19
Central Sierra	29	43	32	25
Southern Sierra	32	56	16	28
All inorganic constituents with health-based benchmarks³				
Tahoe-Martis	41	67	13	20
Central Sierra	29	23	36	41
Southern Sierra	38	34	34	32

¹ Aquifer-scale proportions for radioactive constituents were calculated using gross alpha activity. If adjusted gross alpha activity were used instead, the high and moderate aquifer-scale proportions would be as follows: Tahoe-Martis, 2.0 percent high, 13 percent moderate; Central Sierra, 27 percent high, 30 percent moderate; and Southern Sierra, 18 percent high, 18 percent moderate.

² Based on spatially weighted calculation.

³ Aquifer-scale proportions for all inorganic constituents with health-based benchmarks were calculated using gross alpha activity. If adjusted gross alpha activity were used instead, the high and moderate aquifer-scale proportions would be as follows: Tahoe-Martis, 19 percent high, 14 percent moderate; Central Sierra, unchanged; and Southern Sierra, 29 percent high, 34 percent moderate.

Table 9B. Summary of aquifer-scale proportions for inorganic constituent classes with secondary maximum contaminant level (SMCL) benchmarks, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Relative-concentration categories: high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.5 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.5 of benchmark. Abbreviations: SMCL, secondary maximum contaminant level]

Study unit	Number of cells	Aquifer-scale proportion (percent)		
		Low	Moderate	High
Major ions with SMCL benchmarks				
Tahoe-Martis ¹	41	92	0	7.7
Central Sierra ¹	29	95	3.4	1.8
Southern Sierra	34	82	15	2.9
Trace elements with SMCL benchmarks				
Tahoe-Martis	41	86	0	14
Central Sierra	29	58	9.3	32
Southern Sierra	30	57	20	23
All constituents with SMCL benchmarks				
Tahoe-Martis	41	86	0	14
Central Sierra	29	55	11	34
Southern Sierra	34	56	21	24

¹ Based on spatially weighted calculation.

Table 9C. Summary of aquifer-scale proportions for organic constituent classes with health-based benchmarks, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Relative-concentration categories: high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.1 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.1 of benchmark]

Study unit	Number of cells	Aquifer-scale proportions (percent)			
		Not detected	Detected at low concentration	Detected at moderate concentration	Detected at high concentration
Volatile organic compounds					
Tahoe-Martis	41	81	17	¹ 0.7	1.0
Central Sierra	27	77	19	4.0	0
Southern Sierra	35	69	29	2.9	0
Pesticides					
Tahoe-Martis	41	97	3.0	0	0
Central Sierra	26	83	17	0	0
Southern Sierra	35	80	20	0	0
Any organic constituent					
Tahoe-Martis	41	80	19	¹ 0.7	1.0
Central Sierra	27	73	23	4.0	0
Southern Sierra	35	60	37	2.9	0

¹ Spatially weighted proportion.

A

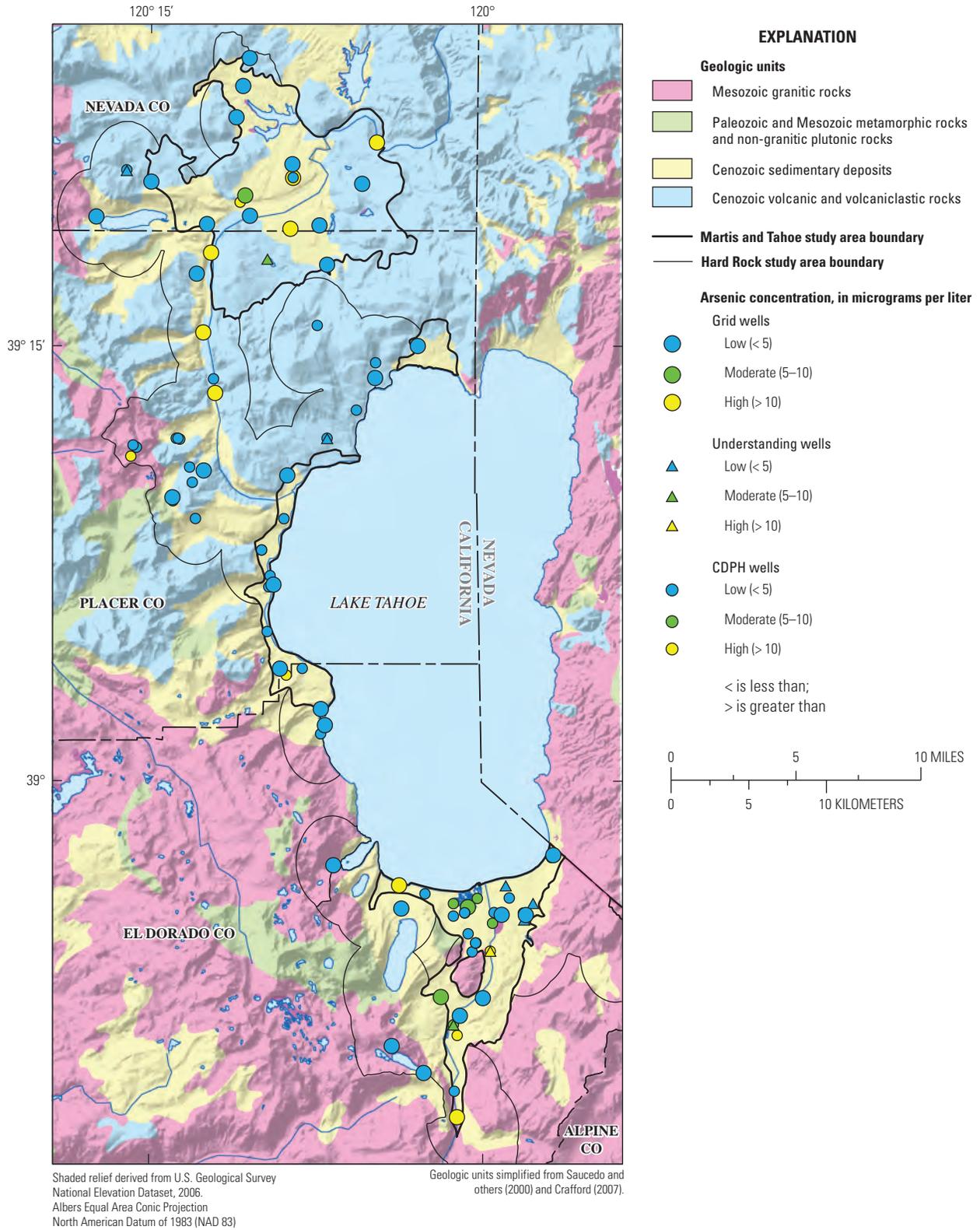


Figure 18. Relative-concentrations of arsenic for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for arsenic during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

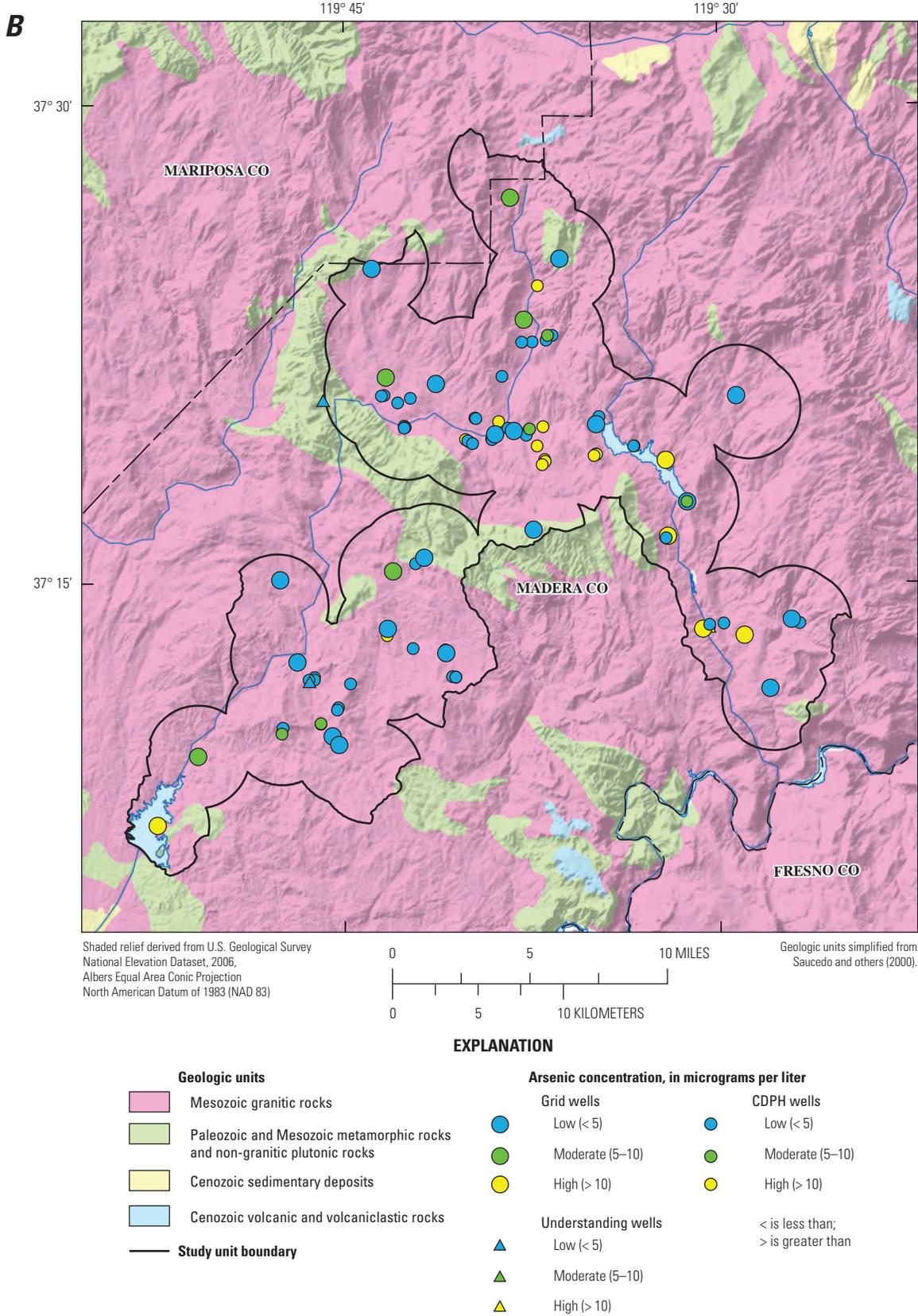


Figure 18.—Continued

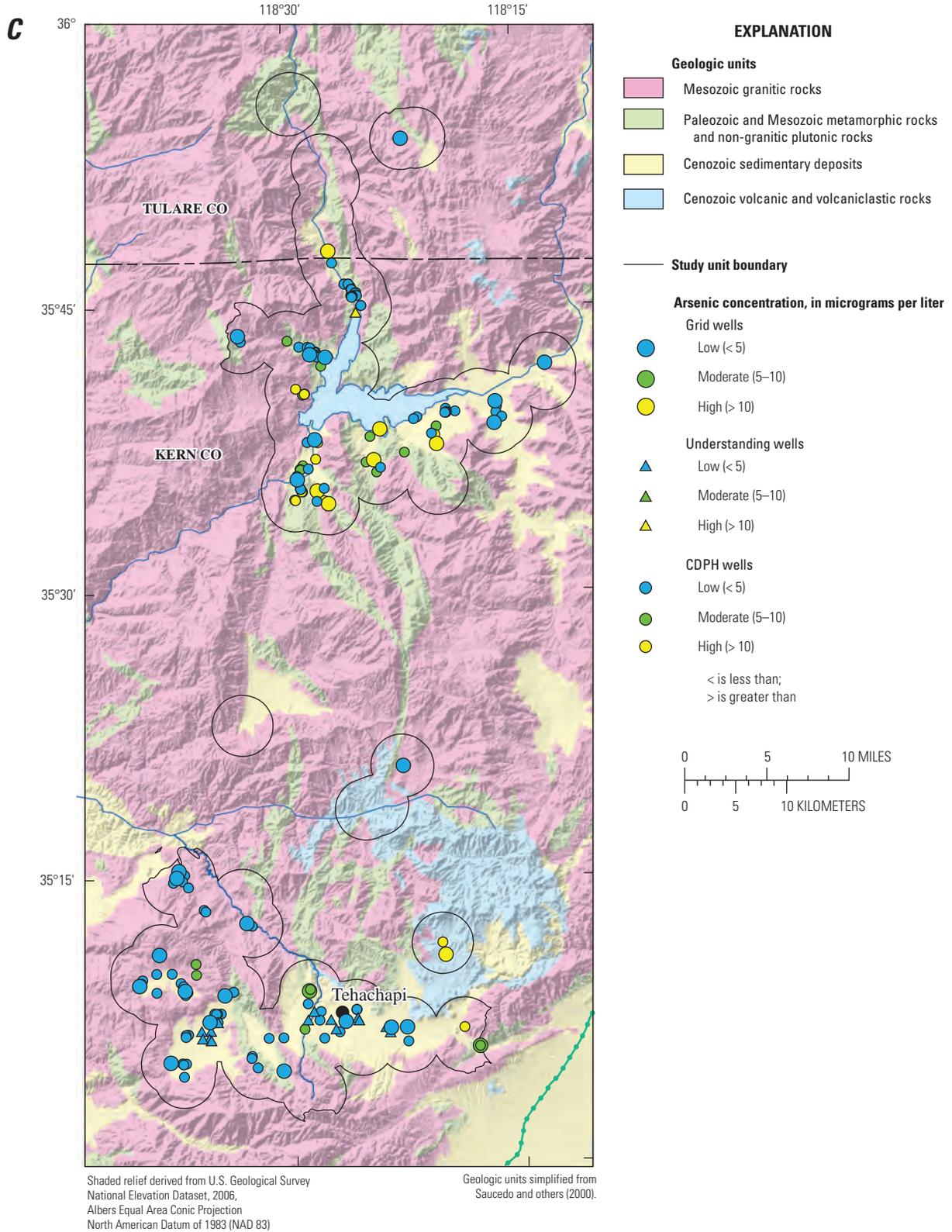


Figure 18.—Continued

Factors Affecting Arsenic

Arsenic is a semi-metallic trace element. Natural sources of arsenic in groundwater include dissolution of arsenic-bearing minerals and desorption of arsenic from mineral surfaces. Pyrite, the most common sulfide mineral in aquifer materials, may contain up to several percent arsenic. Potential anthropogenic sources of arsenic include copper ore smelting, coal combustion, arsenical pesticides, arsenical veterinary pharmaceuticals, and wood preservatives. The MCL-US for arsenic was lowered from 50 µg/L to 10 µg/L in 2002, and chronic exposure to arsenic concentrations between 10 and 50 µg/L in drinking water has been linked to increased cancer risk and to non-cancerous effects including skin damage and circulatory problems (U.S. Environmental Protection Agency, 2010).

The presence of elevated arsenic concentrations in groundwater typically is not related to high arsenic concentrations in aquifer sediments or rock, but rather to

geochemical conditions that enhance arsenic solubility and hydrologic conditions that favor arsenic accumulation in groundwater (Smedley and Kinniburgh, 2002). In the Tahoe-Martis, Central Sierra, and Southern Sierra study units, high and moderate arsenic RCs occurred under two different sets of geochemical conditions: in oxic groundwater with relatively high pH values, and in anoxic groundwater, typically with relatively low pH values (fig. 19). Arsenic concentration had a significant positive correlation with pH and a significant negative correlation with DO (table 10B). Previous investigations of the occurrence of elevated arsenic in groundwater have identified two mechanisms corresponding to these two sets of conditions: (1) desorption from, or inhibition of sorption to, aquifer materials with increasing pH, and (2) release of arsenic from dissolution of iron or manganese oxyhydroxides under iron- or manganese-reducing conditions (Smedley and Kinniburgh, 2002; Belitz and others, 2003; Welch and others, 2006; and many references therein).

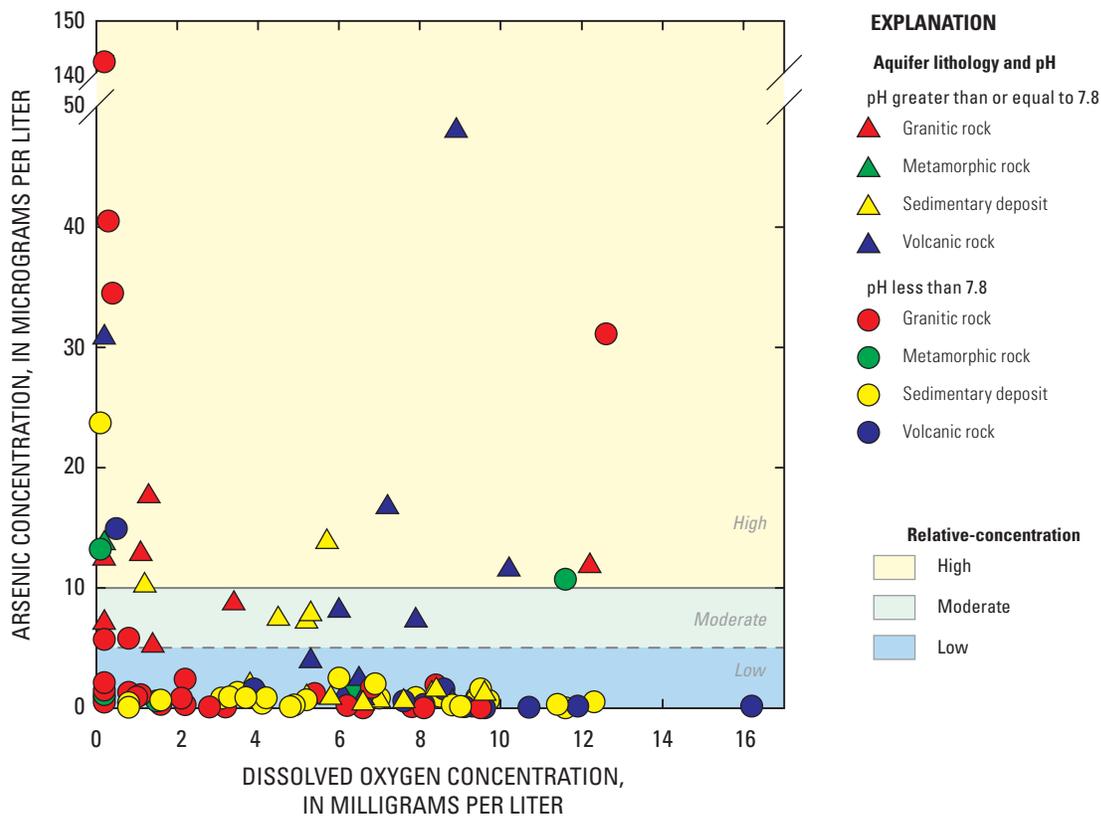


Figure 19. Relation between arsenic concentration and dissolved oxygen concentration, pH, and aquifer lithology, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Table 10A. Results of Kruskal-Wallis and Wilcoxon rank-sum tests for differences in values of selected water-quality constituents between samples classified into groups by aquifer lithology, groundwater age, study unit, or well depth, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Relation of median values in sample groups tested shown for Kruskal-Wallis and Wilcoxon rank-sum tests in which the populations were determined to be significantly different (two-sided test) on the basis of p-values (not shown) less than threshold value (α) of 0.05; ns, test indicated no significant differences between the sample groups. p-values were calculated using the Kruskal-Wallis test; if significant, then Wilcoxon rank-sum tests were used to determine which differences were significant. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Study unit:** T, Tahoe-Martis; C, Central Sierra; S, Southern Sierra. **3-factor depth class:** shallow (Shal), well depth < 170 ft; Mixed (Mix), top of perforations < 170 ft and well depth > 170 ft; Deep (Deep) well depth > 170 ft and top of perforations > 170 ft. **2-factor age class:** young, tritium > 0.5 TU; old, tritium < 0.5 TU. **3-factor age class:** Mod, modern; Mix, mixed modern and pre-modern; Pre, pre-modern (see [appendix C](#) for explanation). **Other abbreviations:** SMCL, secondary maximum contaminant level; ns, no significant differences; TU, tritium units; ft, feet below land surface; >, greater than; <, less than; TDS, total dissolved solids; THM, trihalomethanes]

Water-quality constituents	Significant differences				
	Aquifer lithology class (G, M, S, V)	Study unit (T, C, S)	3-Factor depth class (Shal, Mix, Deep)	2-Factor age class (young, old)	3-Factor age class (Mod, Mix, Pre)
Nutrients and trace elements with health-based benchmarks					
Nitrate	S > GV and M > G	S > CT	ns	ns	Mix > ModPre
Fluoride	GM > S > V	CS > T	MixDeep > Shal	old > young	PreMix > Mod
Arsenic	ns	ns	ns	ns	PreMix > Mod
Boron	ns	CS > T	MixDeep > Shal	old > young	PreMix > Mod
Molybdenum	GMS > V	CS > T	MixDeep > Shal	old > young	PreMix > Mod
Inorganic constituents with SMCL benchmarks					
TDS	M > GSV	S > C > T	MixDeep > Shal	ns	PreMix > Mod
Iron	M > SV	C > ST	ns	ns	ns
Manganese	G > SV	C > ST	ns	ns	ns
Radioactive constituents					
Radon-222 activity	GM > SV	C > T	Mix > Deep	ns	Mix > ModPre
Gross alpha particle activity	GMS > V	ns	ns	ns	Mix > ModPre
Uranium activity	GMS > V	CS > T	Mix > Deep	ns	Mix > ModPre
Organic and special-interest constituents					
Herbicides	ns	S > T	ns	young > old	ModMix > Pre
Solvents	S > GMV	ns	ns	ns	ns
THM	M > GSV	ns	ns	young > old	Mix > Pre
Perchlorate	S > GMV	S > CT	ns	ns	ns

Explanation: How to read results for significant differences. “G > SV” for manganese means the following:

- G has significantly greater manganese than S,
- G has significantly greater manganese than V,
- Manganese in S is not significantly different than manganese in V,
- Manganese in M is not significantly different than manganese in G, S, or V.

Table 10B. Results of Spearman’s rho tests for correlations between selected potential explanatory factors and selected water-quality constituents, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[ρ (rho), Spearman’s correlation statistic; p values are shown for tests in which the variables were determined to be significantly correlated on the basis of p values (significance level of the Spearman’s test) less than threshold value (α) of 0.05 (not shown); ns, Spearman’s test indicates no significant correlation between factors; black text, significant positive correlation; red text, significant negative correlation. SMCL, secondary maximum contaminant level; TDS, total dissolved solids; THM, trihalomethanes]

ρ	Percent land use			Density of septic tanks	Aridity index	Elevation	Well depth	Depth to top of perforation	pH	Dissolved oxygen concentration
	Agricultural	Natural	Urban							
Nutrients and trace elements with health-based benchmarks										
Nitrate	0.55	-0.38	ns	ns	-0.59	-0.25	ns	0.22	ns	0.28
Fluoride	0.39	ns	-0.21	0.45	-0.62	-0.74	0.29	ns	ns	-0.42
Arsenic	-0.22	ns	ns	0.28	ns	-0.26	0.26	ns	0.44	-0.27
Boron	0.25	ns	ns	0.41	-0.36	-0.53	0.44	ns	0.34	-0.34
Molybdenum	0.22	ns	ns	0.35	-0.50	-0.57	0.28	ns	0.35	-0.40
Inorganic constituents with SMCL benchmarks										
TDS	0.50	ns	-0.21	0.39	-0.59	-0.55	ns	ns	ns	-0.20
Iron	ns	ns	ns	ns	ns	-0.23	ns	ns	-0.31	-0.34
Manganese	ns	0.22	ns	ns	ns	-0.29	ns	ns	-0.33	-0.52
Radioactive constituents										
Radon-222 activity	ns	ns	ns	0.29	-0.32	-0.30	ns	-0.26	ns	-0.32
Gross alpha particle activity	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Uranium activity	ns	ns	ns	0.22	-0.31	-0.39	ns	ns	ns	-0.22
Organic and special-interest constituents										
Herbicides	0.28	-0.23	ns	0.20	-0.29	-0.26	ns	ns	ns	ns
Solvents	0.18	-0.32	0.23	ns	-0.18	ns	ns	ns	ns	ns
THM	ns	ns	0.27	ns	ns	ns	ns	ns	ns	ns
Perchlorate	0.51	-0.32	ns	ns	-0.34	ns	ns	ns	ns	0.22

Half of the groundwater samples from the three study units that had pH ≥ 7.8 and oxic (DO > 1 mg/L) conditions had moderate or high RCs of arsenic, compared to just 2% of the oxic groundwater samples with pH < 7.8 (fig. 20). Under oxic conditions, sediment grains and fracture surfaces often have coatings of iron and (or) manganese oxyhydroxides, resulting from weathering of primary iron oxide, iron sulfide, and ferro-magnesian silicate minerals. At high pH, the surfaces of these oxyhydroxides may be negatively charged and therefore inhibit sorption of anions to the surfaces. The dominant form of arsenic in solution can be predicted from the ratio of arsenic redox species, As^{+5}/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). In samples with moderate or high RCs of arsenic, As^{+5}/As^{+3} ratios ranged from 3.5 to > 10 , with 11 of the 15 samples having $As^{+5}/As^{+3} > 10$, indicating that the more oxidized form of dissolved arsenic, arsenate, was the dominant form. At pH ≥ 7.8 , the primary arsenate species is $HAsO_4^{-2}$, a relatively soluble oxyanion under those conditions (Smedley and Kinniburgh, 2002). The groundwater samples with elevated arsenic under oxic, high-pH conditions included wells with volcanic, granitic, and sedimentary aquifer lithologies (fig. 19). Previous studies have reported elevated arsenic concentrations under these geochemical conditions in groundwater from a range of aquifer lithologies (Ayotte and others, 1999; Smedley and Kinniburgh, 2002; Senior and Sloto, 2006).

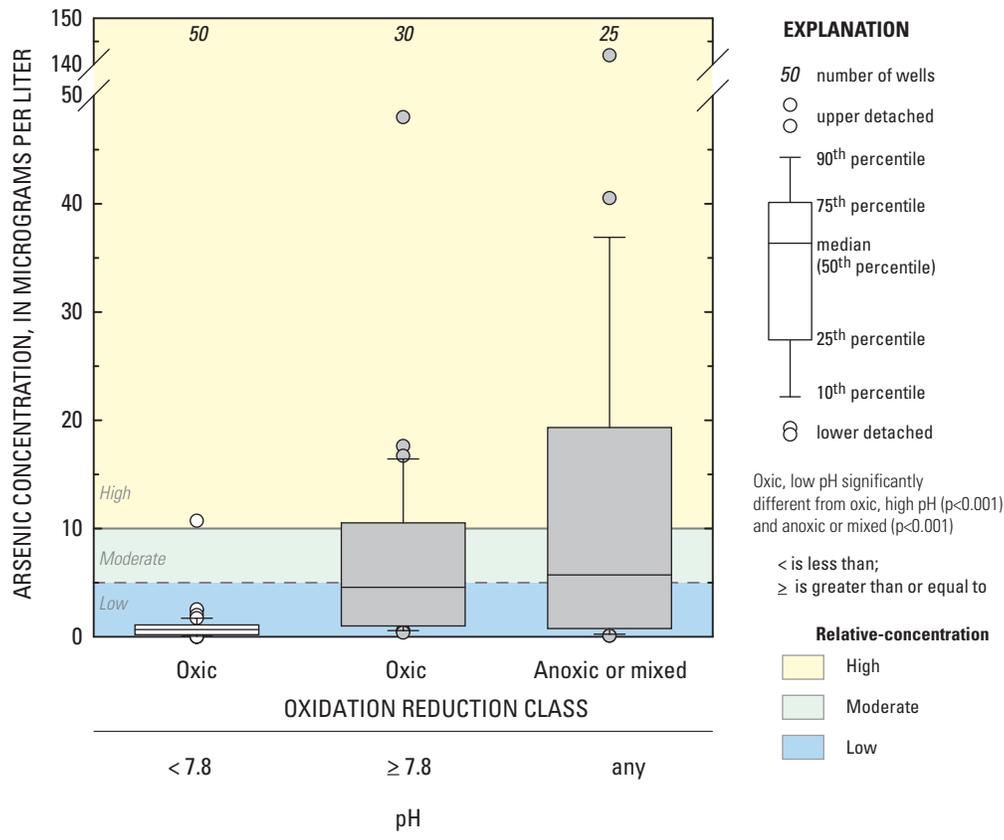


Figure 20. Arsenic concentrations in groundwater samples grouped by oxidation-reduction class and pH, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

The primary mechanisms for increasing the pH of groundwater under oxic conditions are hydrolysis of silicate minerals and dissolution of calcite (which may be driven by cation exchange between calcium and magnesium in groundwater and sodium in clay minerals). Both mechanisms also result in increasing TDS. Aquifers in volcanic rocks generally have alkaline groundwater because dissolution and hydrolysis of volcanic glass, forming clay and zeolite minerals, cause groundwater to evolve towards higher pH (Hay and Sheppard, 1977; Gysi and Stefánsson, 2008). For oxic groundwater from wells with volcanic aquifer lithology (present in the Tahoe-Martis study unit only), arsenic was significantly positively correlated with pH and TDS (figs. 21A,B; $p=0.005$ and 0.012 , respectively). All of the samples with moderate or high arsenic RCs from wells with volcanic aquifer lithology had mixed or pre-modern age distributions (figs. 21A,B), suggesting that increased contact time resulted in more water–rock interaction and more desorption of arsenic from iron and manganese oxyhydroxide surfaces.

In oxic groundwater from wells with sedimentary aquifer lithology in the Tahoe-Martis study unit, however, arsenic concentrations were significantly positively correlated with pH ($p=0.010$), but not correlated with TDS ($p=0.388$) (figs. 21A,B), suggesting that different mechanisms may have been responsible for the elevated pH. In addition, the presence of groundwater with pre-modern age distributions and low TDS (fig. 21B) suggests that increased contact time does not necessarily result in more hydrolysis and dissolution of minerals in aquifer materials. The occurrence of groundwater with high arsenic RC, high pH, and low TDS with pre-modern age distributions in the Tahoe-Martis study unit cannot be fully explained without further investigation using geochemical modeling.

Nearly half of the groundwater samples from the three study units that had anoxic ($DO < 1$ mg/L) or mixed oxidation conditions had moderate or high RCs of arsenic (fig. 20). Of the 16 anoxic or mixed oxidation groundwater samples with moderate or high RCs of arsenic, 13 also had moderate or high RCs of iron and (or) manganese, suggesting reductive dissolution of iron or manganese oxides as the source of arsenic. Anoxic and mixed oxidation groundwater samples with moderate or high RCs of arsenic had significantly lower As^{+5}/As^{+3} ratios (0.1 to >10 ; median 2.5) than oxic groundwater samples with moderate or high RCs of arsenic (3.5 to >10 ; median >10) (Wilcoxon rank-sum test, $p=0.015$), indicating greater relative abundance of the more reduced form of dissolved arsenic, arsenite, in the anoxic and mixed oxidation groundwater samples. Arsenite species typically are

more toxic than arsenate species (National Research Council, 2001). At $pH < 9$, the primary arsenite species at equilibrium is $H_3AsO_3^0$, which is a relatively soluble species under those conditions (Smedley and Kinniburgh, 2002). The large range of As^{+5}/As^{+3} may reflect the complexities introduced by the slow kinetics of arsenic redox transformations (Lindberg and Runnels, 1984) or by groundwater mixing. Moderate and high RCs of arsenic under reducing conditions were detected in wells with all four aquifer lithologies, although most had granitic aquifer lithology (fig. 19).

Whether arsenic was released by desorption under oxic, high-pH conditions, or by dissolution under anoxic conditions, accumulation of elevated concentrations of arsenic in groundwater also requires favorable hydrologic conditions. Arsenic accumulation is favored by longer contact times between groundwater and aquifer materials, minimizing the amount of flushing of the system and maximizing the reaction times of minerals in the aquifer materials (Smedley and Kinniburgh, 2002). Arsenic concentrations were significantly higher in groundwater with pre-modern and mixed age distributions than in groundwater with modern age distributions (table 10A; fig. 22).

The significant negative correlations between arsenic and agricultural land use and elevation and significant positive correlation between arsenic and septic tank density (table 10B) likely reflect the fact that many of the samples with high and moderate RCs of arsenic were located in the Central Sierra study unit and in the Kern River Valley part of the Southern Sierra study unit (figs. 18B,C). Lower elevations and greater density of septic tanks were significantly associated with location in the Central Sierra and Southern Sierra study units (table 6A), and although the Southern Sierra study unit was the only study unit with agricultural land use, most of the agriculture land use was in the Tehachapi-Cummings Valley (fig. 5C). Inorganic arsenic-based insecticides were used extensively in agriculture, particularly in fruit orchards, prior to introduction of organochlorine pesticides around 1950, and use continued until they were banned in the 1980s (Welch and others, 2000). Neither the Central Sierra study unit nor the Kern River Valley part of the Southern Sierra study unit had extensive agricultural land use in the past. Arsenical compounds currently are used as pesticides and wood preservatives in non-agricultural settings in California (Kegley and others, 2010). However, arsenic concentrations were not significantly correlated with anthropogenic organic constituents (Spearman's rho test, $p = 0.69$ to 0.95), nitrate ($p=0.84$), urban land use (table 10B), or modern groundwater (table 10A), suggesting that human activities were not a noticeable source of arsenic to groundwater.

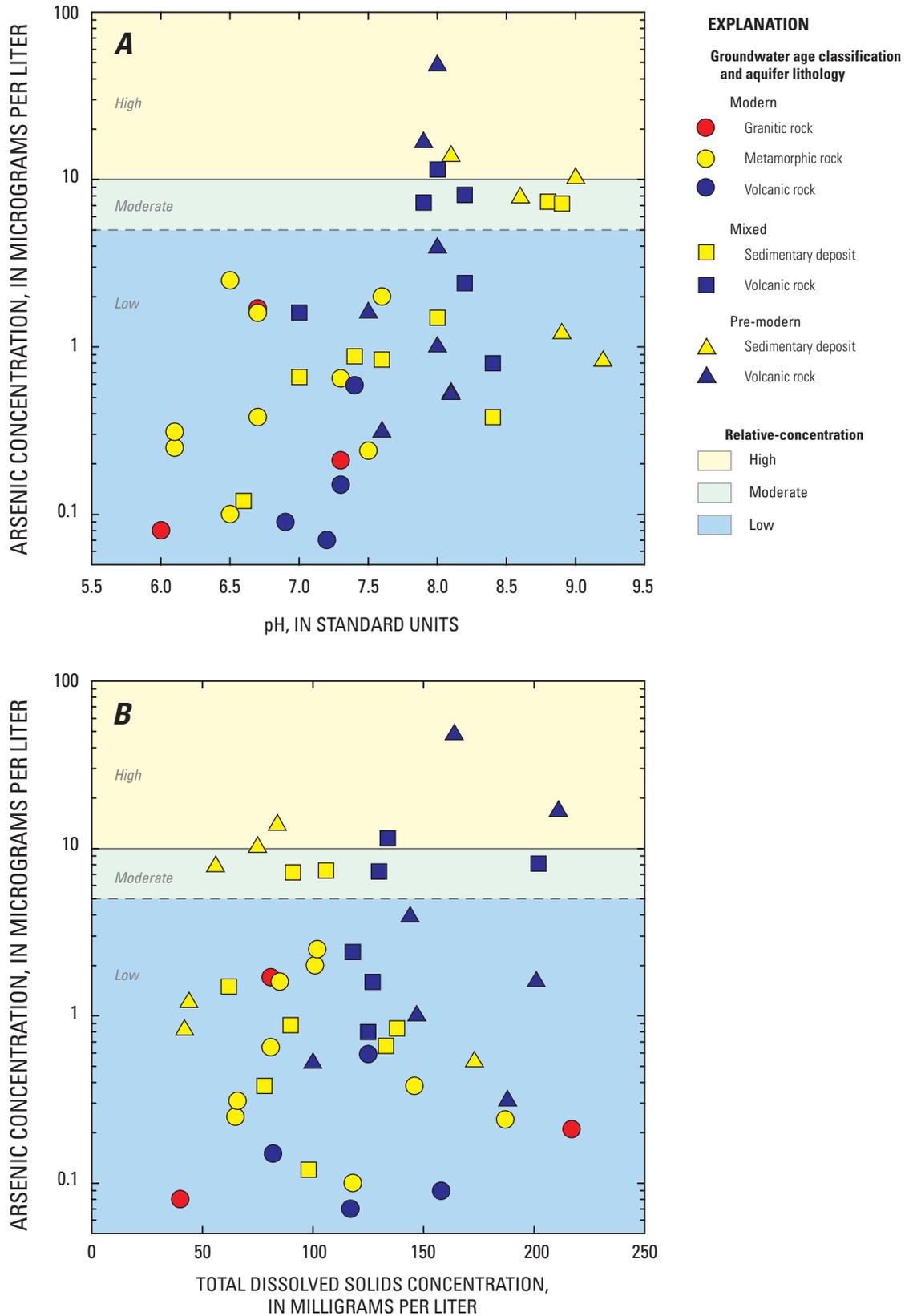


Figure 21. Relations among arsenic concentration, groundwater age classification, aquifer lithology, and (A) pH and (B) total dissolved solids for oxic groundwater samples from the Tahoe-Martis study unit, California GAMA Priority Basin Project.

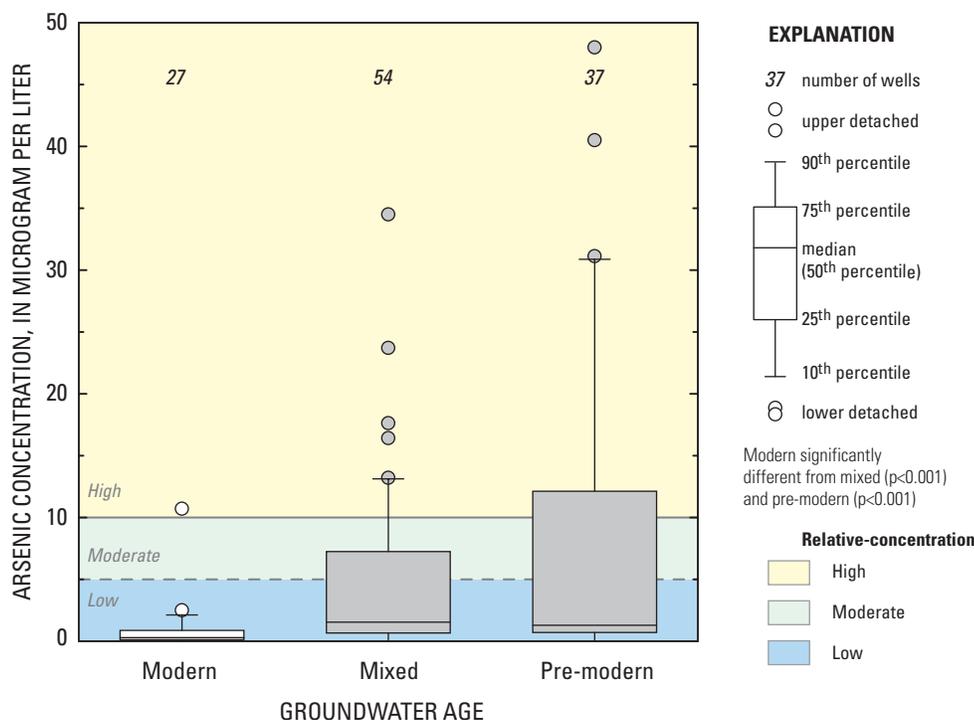


Figure 22. Relation between arsenic concentration and groundwater age classification, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Factors Affecting Fluoride

Fluoride is the anion form of the element fluorine. Natural sources of fluoride in groundwater include dissolution of fluoride-bearing minerals, such as fluorite (CaF_2) and fluorapatite [$\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{OH})$]. 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. Hexafluorosilicic acid is a byproduct of production of phosphate fertilizers and hydrofluoric acid and the processing of aluminum. The MCL-CA for fluoride, 2 mg/L, is lower than the MCL-US for fluoride, 4 mg/L. Chronic exposure to fluoride concentrations in drinking water above the MCL may result in bone disease and tooth discoloration. Fluoride was detected at low RCs in the Tahoe-Martis study unit, and at low, moderate, and high RCs in the Central Sierra and Southern Sierra study units (figs. 17A,B,C and 23A,B,C).

Fluoride, molybdenum, and boron had significant positive correlations with each other ($p < 0.001$) and had similar patterns of significant correlations with potential explanatory factors (tables 10A,B). All three had significant positive correlations with agricultural land use and septic tank density and significant negative correlations with aridity index and elevation (table 10B). However, because the three constituents

also had significant positive associations with location in the Central Sierra and Southern Sierra study units (table 10A), these correlations may reflect the significant associations between these potential explanatory factors and location in the Central Sierra and (or) the Southern Sierra study units (tables 6A,C). All three constituents had significant positive correlations with well depth and pH, and significant negative correlations with DO (table 10B). All were significantly associated with groundwater with pre-modern or mixed age distributions (table 10A), and all also had significant positive correlations with TDS (Spearman's rho test, $p < 0.001$), manganese ($p = 0.001$ to $p = 0.004$), uranium ($p < 0.001$), and arsenic ($p < 0.001$).

Elevated concentrations of fluoride in groundwater typically are associated with long residence times and granitic aquifer lithology (Nordstrom and others, 1989; Kim and Jeong, 2005). Granitic rocks vary in mineralogical composition; high fluoride concentrations in groundwater typically are associated with granitic rocks containing more alkali feldspar than plagioclase feldspar, such as syenites and alkali granites. For the Tahoe-Martis, Central Sierra, and Southern Sierra study unit dataset, greater fluoride concentrations were significantly associated with granitic and metamorphic aquifer lithologies, and with groundwater with pre-modern and mixed age distributions (table 10A).

A

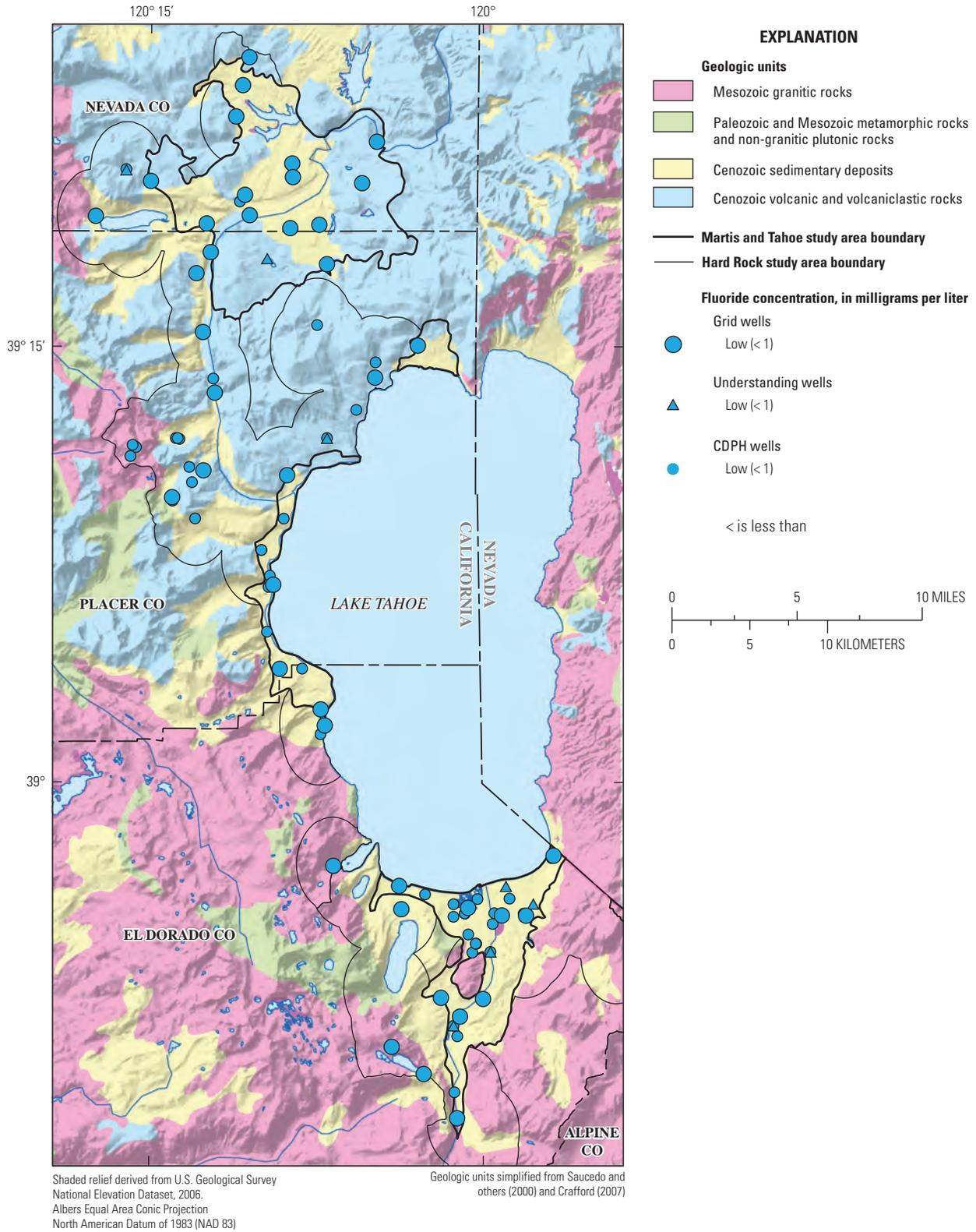


Figure 23. Relative-concentrations of fluoride for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for fluoride during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

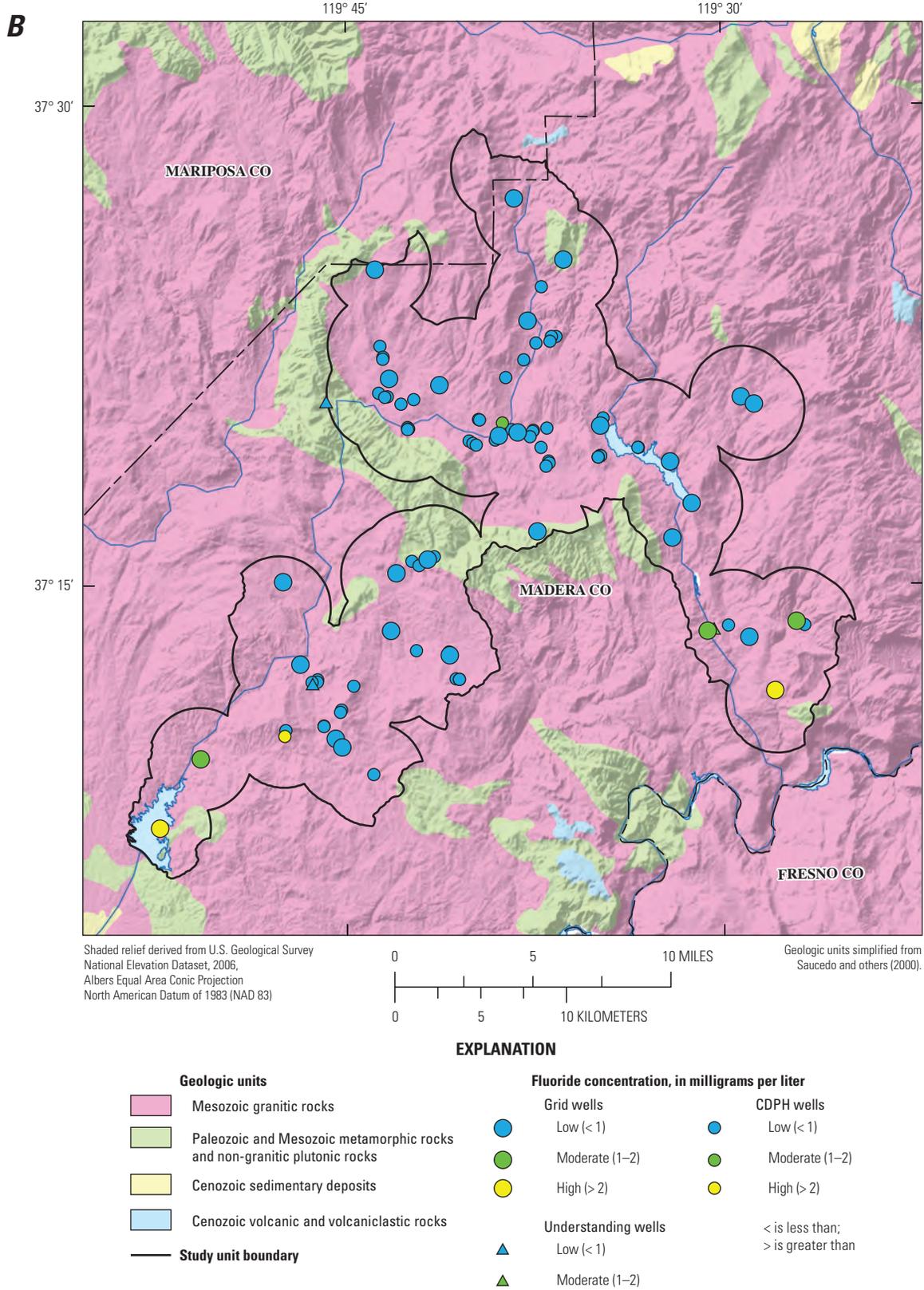


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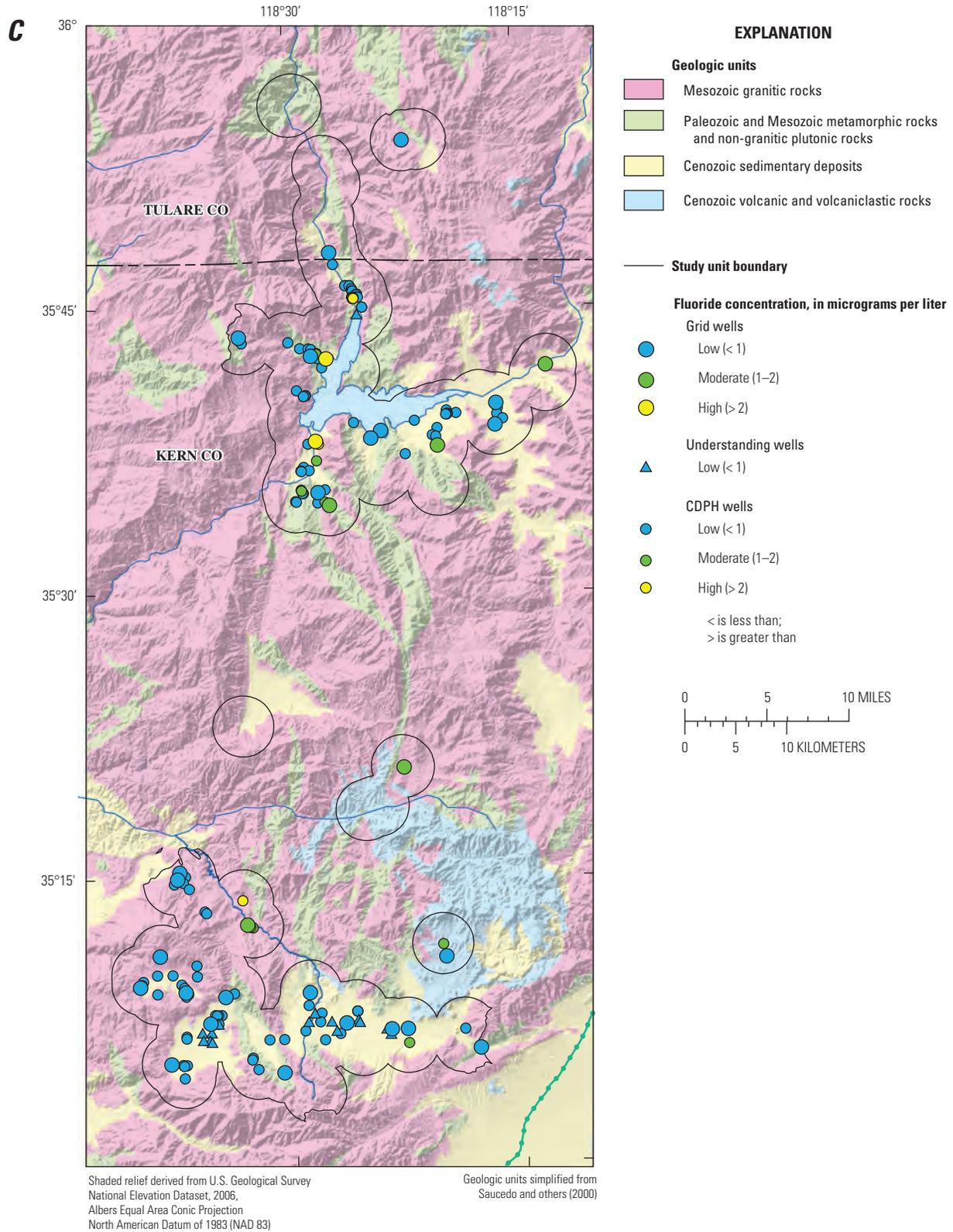
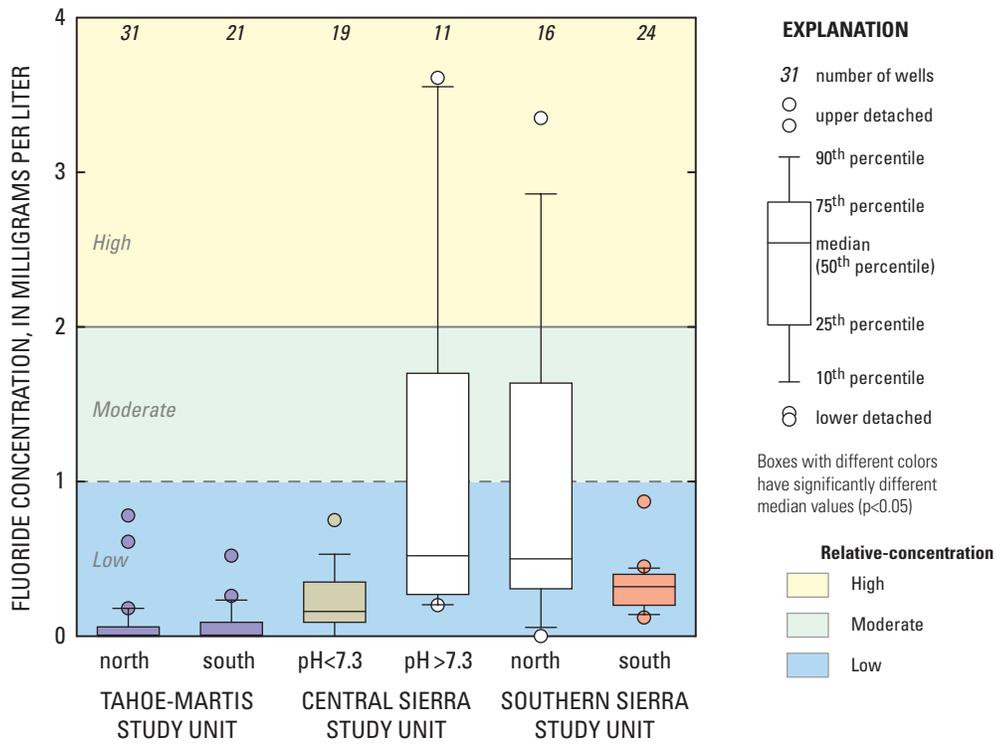


Figure 23.—Continued

Granitic and metamorphic rocks in the three study units yielded groundwater with different fluoride concentrations. None of the groundwater samples from the Tahoe-Martis study unit had moderate or high concentrations of fluoride (fig. 23A), and there was no significant difference in fluoride concentrations between groundwater from the southern and northern portions of the study unit (fig. 24). The northern portion of the study unit consists primarily of volcanic rocks and sediments derived from volcanic rocks, whereas the southern portion is granitic rocks and sediments derived from granitic rocks (fig. 4A). Fluoride concentrations in groundwater from the Central Sierra study unit and the Kern River Valley part of the Southern Sierra study unit

were significantly higher than those in groundwater from the southern parts of the Tahoe-Martis and Southern Sierra study units (fig. 24). The Central Sierra study unit primarily consists of granitic rocks (figs. 4B, 10), and a large portion of the Southern Sierra study unit is either granitic rocks or sediments largely derived from granitic rocks (fig. 4C). Within the Southern Sierra study unit, fluoride concentrations in groundwater from the Kern River Valley watershed were greater than fluoride concentrations in groundwater from the Tehachapi-Cummings Valley watershed, similar to the spatial distribution of arsenic concentrations in groundwater (figs. 18C, 23C).



Tahoe-Martis study unit: north includes the Martis, Tahoe West, and Tahoe North Valleys and surrounding watersheds; south includes the Tahoe South Valley and surrounding watershed.
 Central Sierra study unit: samples divided into two groups by pH.
 Southern Sierra study unit: north includes the Kern River Valley and surrounding watershed; south includes the Tehachapi-Cummings Valleys and surrounding watershed.

Figure 24. Relation between fluoride concentration and geographic location within the Tahoe-Martis and Southern Sierra study units and between fluoride concentration and pH for the Central Sierra study unit, California GAMA Priority Basin Project.

The differences among fluoride concentrations in groundwater in the southern part of the Tahoe-Martis study unit, the Central Sierra study unit, and the northern and southern parts of the Southern Sierra study unit likely reflect regional differences in the composition of the plutons of the Sierra Nevada batholith. Ague and Brimhall (1987, 1988) defined the regional variations in the batholith on the basis of compositional systematics of the most commonly occurring mafic mineral, biotite $[K(Mg,Fe)_3(AlSi_3O_{10})(OH,F)_2]$. They infer that the batholith was formed from I-type granitic magmas (igneous protolith) with variable contamination from sedimentary protolith materials. On a regional scale, the amount of contamination increases from west to east as the batholith overlaps the continental margin of the Precambrian continental craton. The granitic rocks fall into four types on the basis of magnesium/iron and fluoride/hydroxide ratios in biotite. Three types have high magnesium/iron ratios reflecting oxidized conditions, and have progressively increasing fluoride/hydroxide ratios from west to east, reflecting increased contamination from fluorine-rich rocks of the craton (called I-WC, I-MC, and I-SC for I-type granitic magma with weak, moderate, and strong contamination, respectively). The fourth type has low magnesium/iron ratio, reflecting anoxic conditions, and moderate to high fluoride/hydroxide ratios, and consists of I-type granitic magmas contaminated with reduced phyllites and pelitic schists (called I-SCR for I-type granitic magma with strong contamination by reduced materials). Reduced phyllites and pelitic schists are common lithologies in the pendants of metamorphic rocks exposed in both the Central Sierra and Southern Sierra study units. The I-SCR rocks are confined to a narrow belt extending from approximately 37°30' to approximately 35°30' between the foothills and the High Sierra (Ague and Brimhall, 1987, 1988). The northern end of the belt passes through the Central Sierra study unit, and the southern end passes through the Kern River Valley portion of the Southern Sierra study unit. Within the boundaries of the belt, I-SCR rocks are interspersed with the west to east gradation of I-WC and I-MC rocks. The observation that higher fluoride concentrations were detected in groundwater from the Central Sierra study unit and northern part of the Southern Sierra study unit compared to fluoride concentrations in groundwater from the southern parts of the Tahoe-Martis and Southern Sierra study units (fig. 24) may indicate a correlation between higher groundwater fluoride concentrations and presence of I-SCR rocks.

Among the groundwater samples from the Central Sierra study unit, samples with pH > 7.3 had significantly greater fluoride concentrations than samples with pH < 7.3 (fig. 24). Fluoride concentrations in groundwater typically are limited by the low solubility of fluorite (CaF_2) in waters containing calcium (Nordstrom and others, 1989; Kim and Jeong, 2005). For the Central Sierra study unit, the highest fluoride concentrations occurred in samples with low calcium concentrations and high pH values (figs. 25A, B).

The relations among groundwater age, pH, and calcium and fluoride concentrations suggest a possible mechanism for

generating the elevated fluoride concentrations: long residence times lead to increased reaction between groundwater and the granitic aquifer materials; pH increases with mineral reactions, contributing to precipitation of calcite; and the lower calcium concentrations result in increased dissolution of fluorite (Kim and Jeong, 2005, and references therein). Fluorite (CaF_2) is an accessory mineral typically found in late-crystallizing, hydrothermal facies of evolved granitic systems, and is a common mineral in pegmatite veins (Deer and others, 1995).

Results from geochemical modeling support this suggested mechanism. Saturation indices (SI) for calcite and fluorite in groundwater samples from the Central Sierra study unit were calculated using PHREEQC (version 2.17; Parkhurst and Appelo, 1999). Groundwater samples along the trend of decreasing calcium with increasing pH are all close to saturation with calcite ($-0.40 < SI < +0.13$) (fig. 25A), indicating that calcite precipitation is a plausible mechanism for the decreasing calcium concentrations. Among the samples close to saturation with calcite, fluoride concentration increases as the degree of undersaturation with fluorite decreases, suggesting dissolution of fluorite is occurring (fig. 25B).

Not all of the samples with high pH and low calcium have high fluoride concentrations (fig. 25A), despite being strongly undersaturated with fluorite. This suggests that both favorable geochemical conditions and rocks containing sufficient fluorite are needed to produce groundwater with high fluoride concentrations.

Factors Affecting Molybdenum

Molybdenum is a metallic trace element used in high-strength steel alloys. The main natural source of molybdenum to groundwater is dissolution of molybdenum-bearing minerals in aquifer materials, the most common of which is the sulfide molybdenite (MoS_2). Molybdenite generally forms in high-temperature environments and therefore occurs as a primary mineral in many igneous and contact metamorphic rocks. It may also precipitate at low temperatures in sediments under anoxic conditions. Potential anthropogenic sources include manufacture and use of molybdenum steel alloys, dry lubricants, and other industrial products. Molybdenum has a HAL-US of 40 $\mu\text{g/L}$ in drinking water, and is included on the USEPA's Contaminant Candidate List 3 (U.S. Environmental Protection Agency, 2009c). Molybdenum is an essential trace nutrient for plants, in particular, for nitrogen-fixing species such as legumes. High levels of molybdenum in animals (including humans) may interfere with uptake of copper.

High RCs of molybdenum were detected in wells sampled by USGS-GAMA in the Tahoe-Martis and Central Sierra study units, and moderate RCs of molybdenum were detected in wells sampled by USGS-GAMA in all three study units (figs. 26A, B, C). There were no data for molybdenum concentrations in the CDPH database during the 3-year intervals used for the status assessment in any of the three study units.

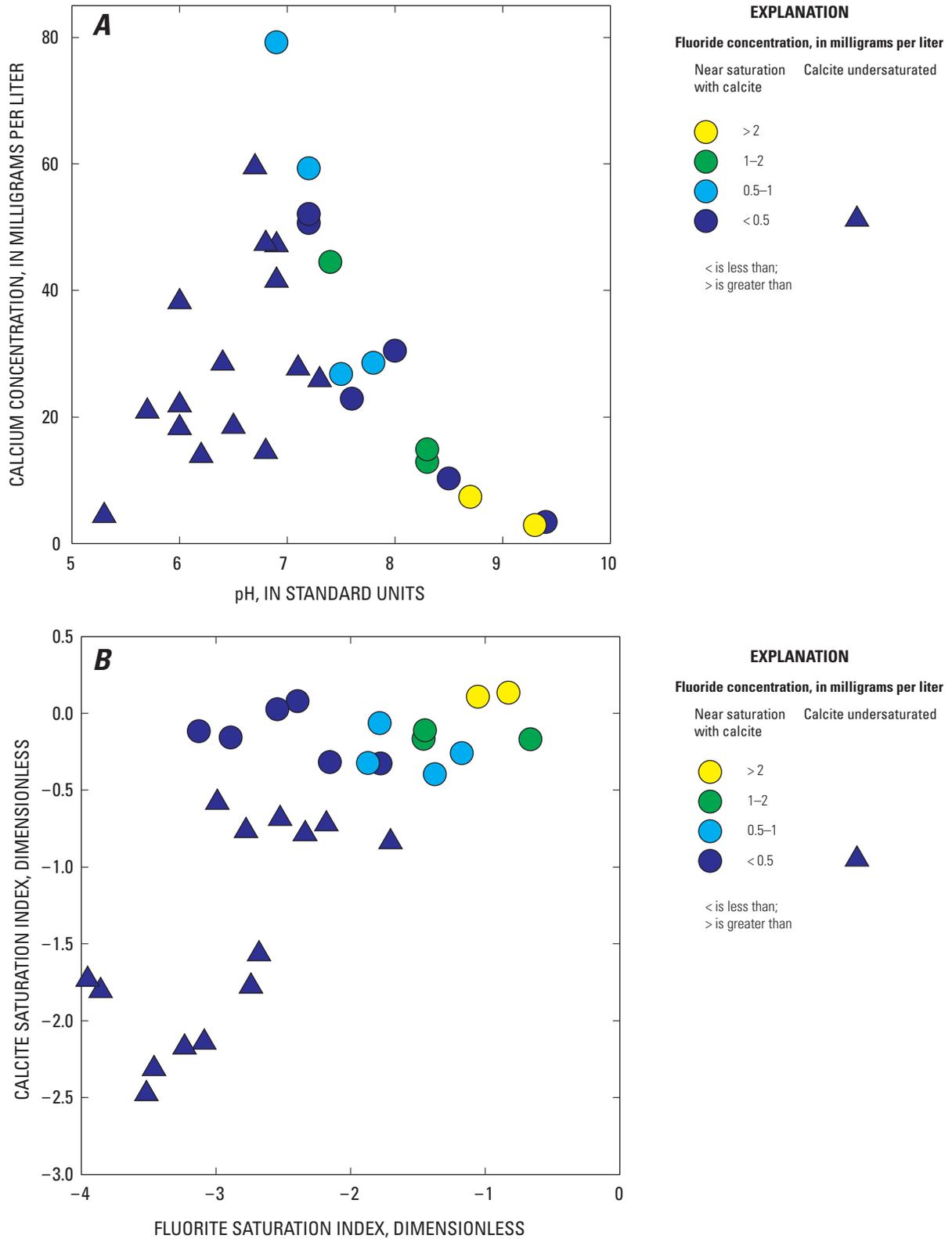


Figure 25. Relations between fluoride concentration and (A) pH and calcium concentration, and (B) fluorite and calcite saturation indexes, Central Sierra study unit, California GAMA Priority Basin Project.

A

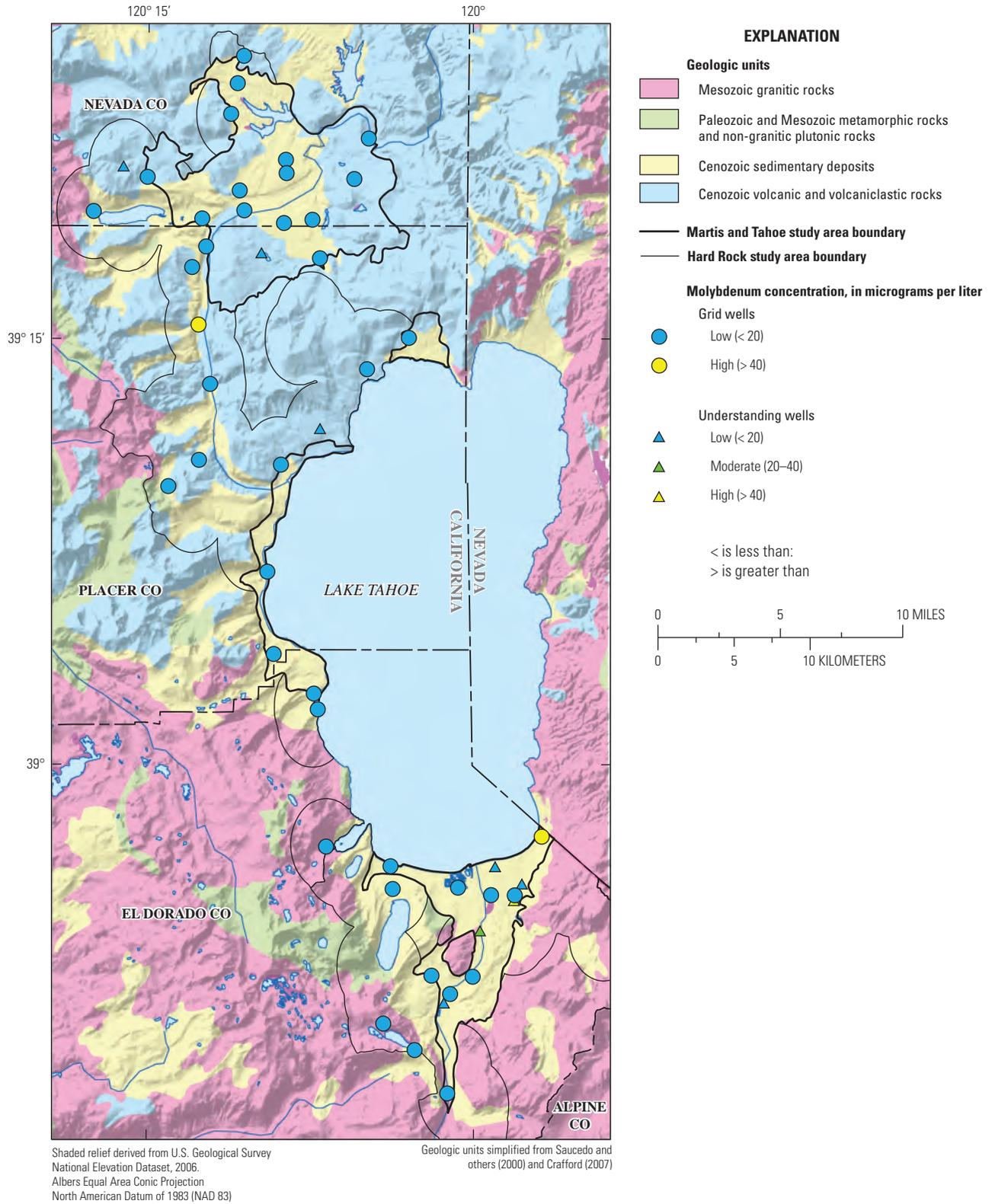


Figure 26. Relative-concentrations of molybdenum for USGS- and CDPH-grid wells, and USGS-understanding wells for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

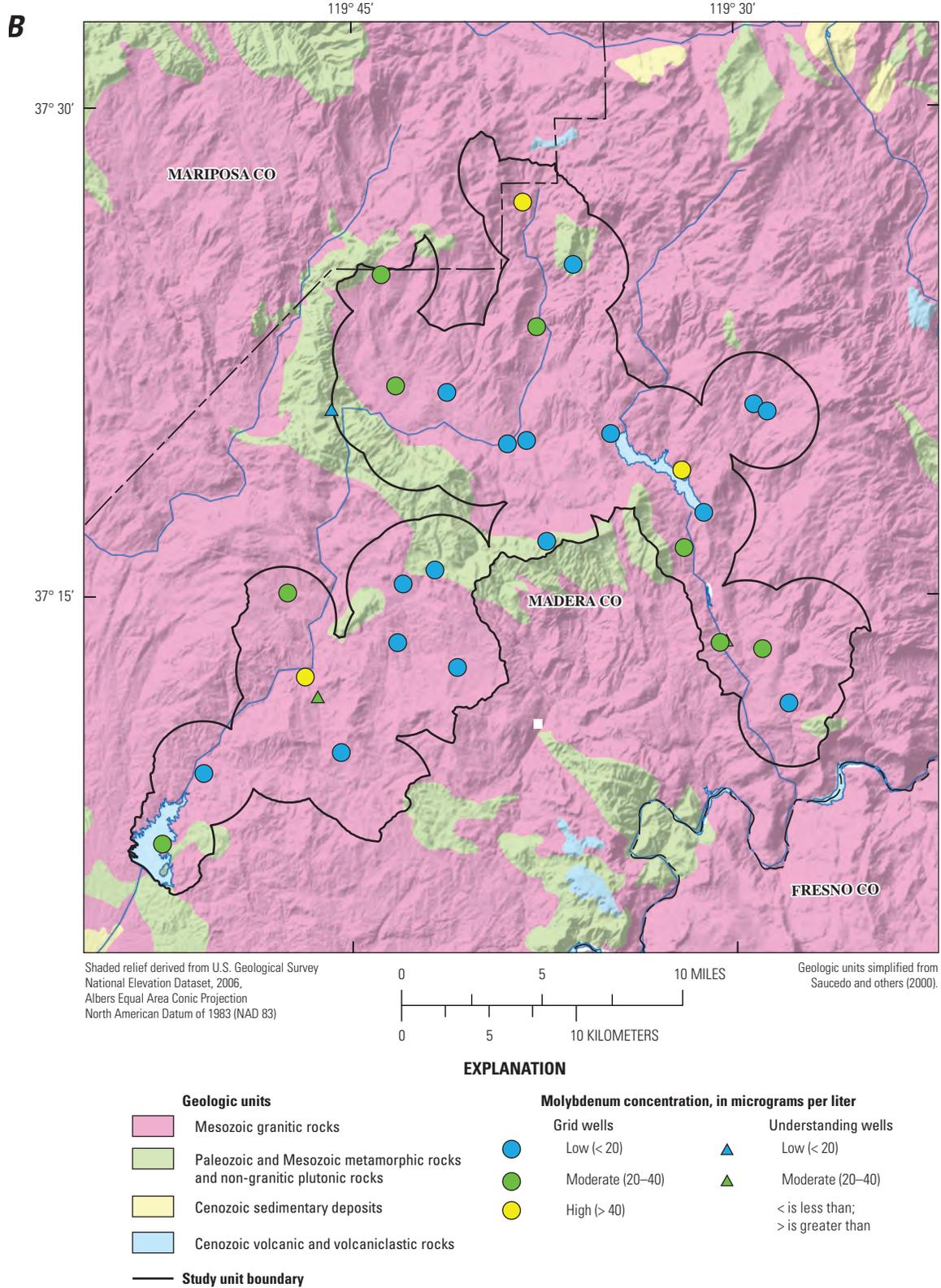


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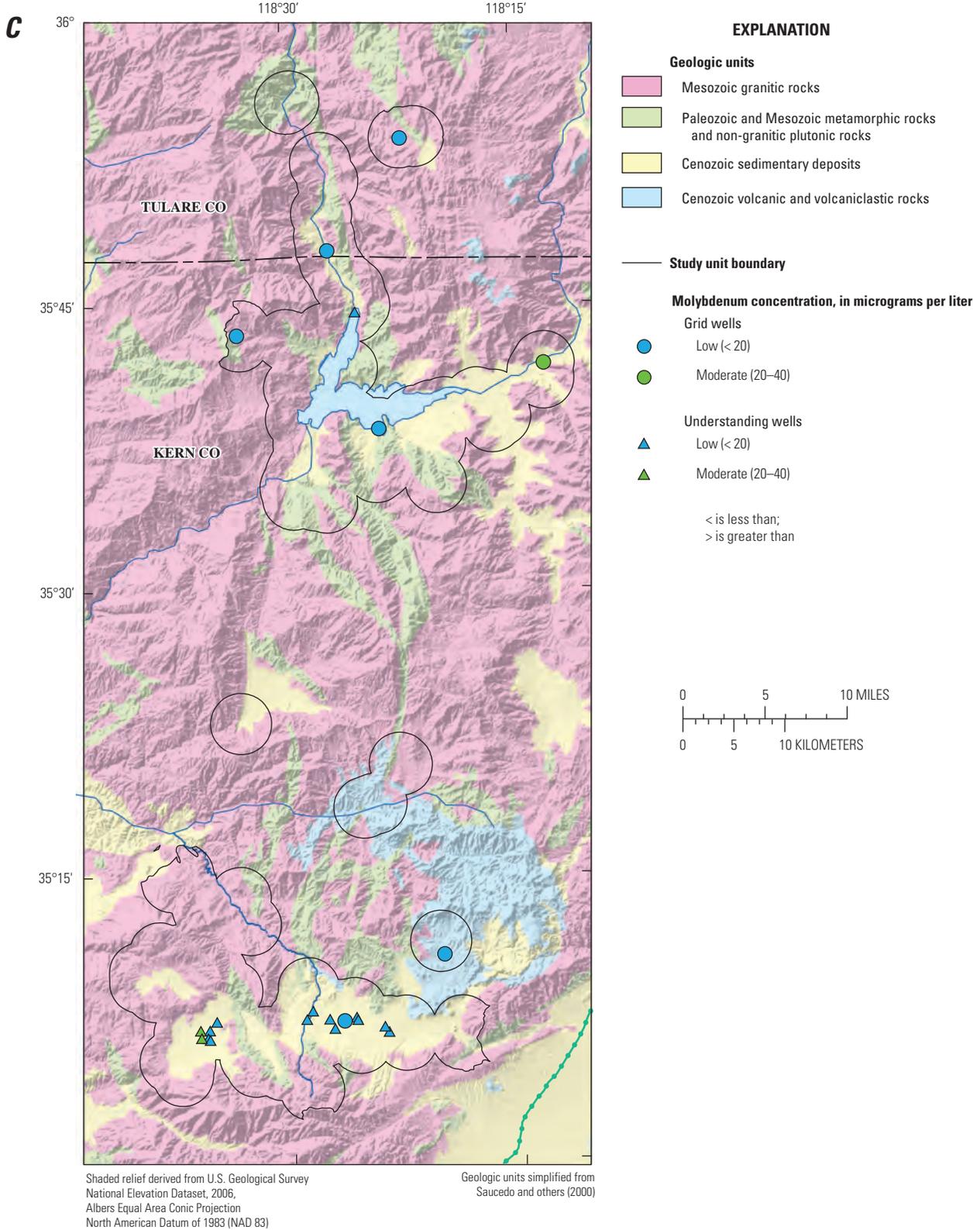


Figure 26.—Continued

Molybdenum concentrations were significantly correlated with the same set of potential explanatory factors as fluoride concentrations (tables 10A,B); however, subdivision of the data by study unit, geography, and pH, as was done for fluoride, did not yield the same pattern of significant differences among groups. For molybdenum, the correlations with oxidation-reduction conditions, pH, and aquifer lithology had the greatest explanatory value. Groundwater with moderate or high RCs of molybdenum occurred in wells with granitic aquifer or sedimentary aquifer lithologies, and molybdenum concentrations were lowest in wells with volcanic aquifer lithology (table 10A). The positive correlations between molybdenum and septic tank density and well depth (table 10B) likely reflect that greater

septic tank density and deeper wells (table 6A) and granitic aquifer lithology (table 6C) were significantly associated with location in the Central Sierra study unit. In wells with granitic aquifer lithology, moderate and high RCs of molybdenum typically were associated with groundwater with either oxic and high pH conditions, or anoxic conditions with a range of pH values (fig. 27). The major soluble species of molybdenum at pH >5 is the molybdate oxyanion MoO_4^{-2} (Evans and Barabash, 2010). Among the groundwater samples with anoxic conditions, all of the moderate and high RCs of molybdenum occurred in groundwater that was suboxic, nitrate-reducing, or manganese-reducing, and groundwater that was iron-reducing had significantly lower molybdenum concentrations (fig. 28).

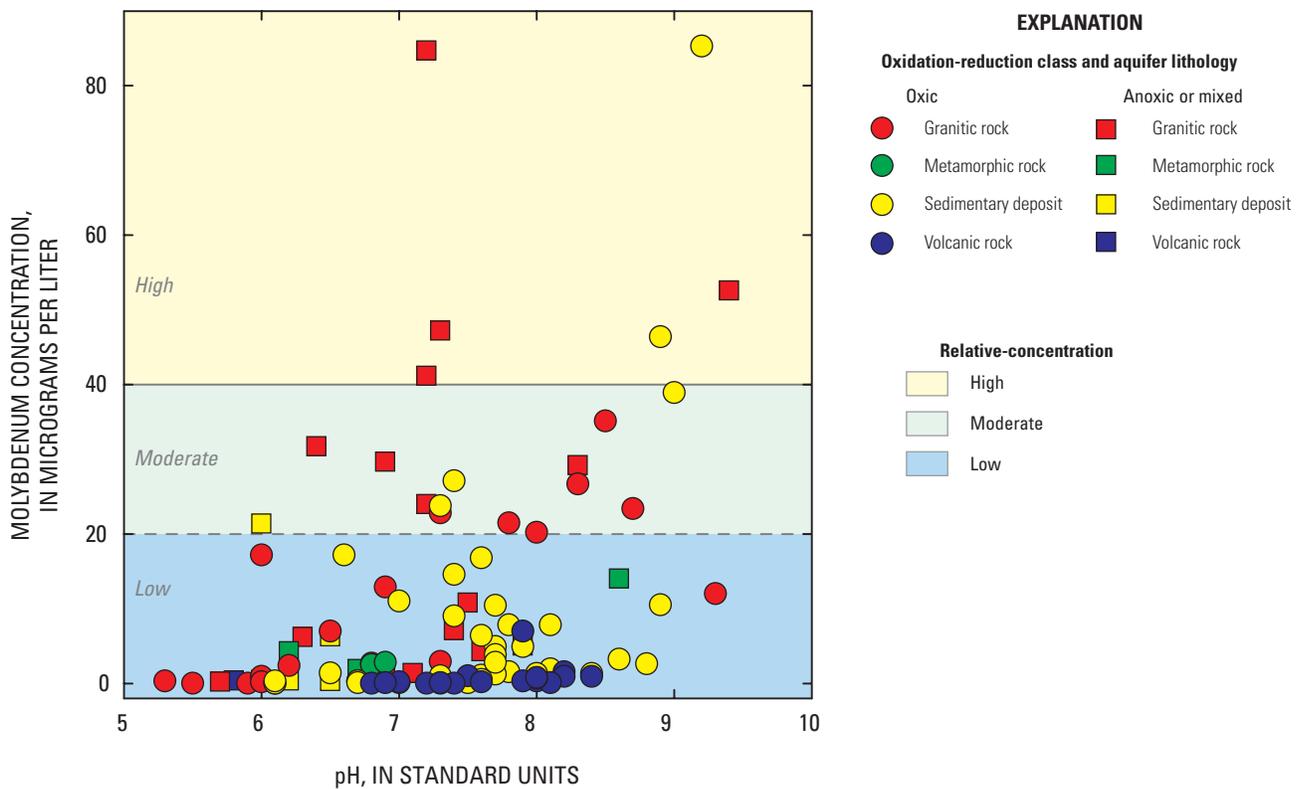
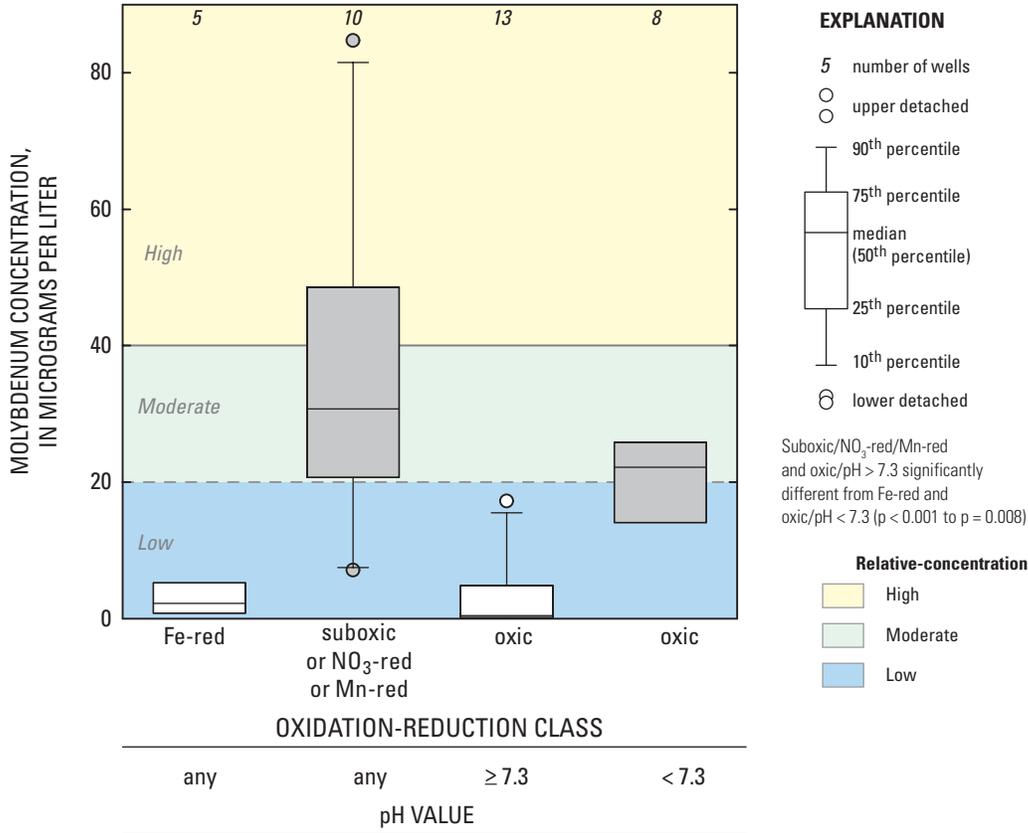


Figure 27. Relations among molybdenum concentration, pH, aquifer lithology, and oxidation-reduction class, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.



Oxidation-reduction classes: Fe-red, iron-reduction; Mn-red, manganese-reduction; NO₃-red, nitrate-reduction; suboxic, dissolved oxygen (DO) < 1 and not Fe-red, Mn-red, or NO₃-red; oxic, DO > 1.

Figure 28. Relations among molybdenum, oxidation-reduction class, and pH for wells with granitic aquifer geology, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Molybdenum present as the molybdate oxyanion adsorbed to manganese oxide minerals may be released during reductive dissolution of these oxides, similar to the way adsorbed arsenic is released during reductive dissolution of the oxides to which it is adsorbed. The reduction of iron from the +3 oxidation state (Fe⁺³, ferric iron) to the +2 oxidation state (Fe⁺², ferrous iron), of molybdenum from the +6 oxidation state (Mo⁺⁶) to the +4 oxidation state (Mo⁺⁴), and of sulfur from the +6 oxidation state (S⁺⁶ in sulfate) to the -2 oxidation state (S⁻² in sulfide) occur at similar oxidation-reduction

potentials. Mo⁺⁴ is highly insoluble in waters containing sulfide, and precipitates as molybdenite (MoS₂) or other sulfide minerals and complexes (Anbar, 2004). Thirteen of the 14 wells with moderate or high RCs of molybdenum were in the Central Sierra study unit (fig. 26B). This may largely reflect that few groundwater samples from wells with granitic aquifer lithology in the Tahoe-Martis and Southern Sierra study units had either anoxic oxidation-reduction conditions (fig. 15A) or high pH values (fig. 15B).

In wells with sedimentary aquifer lithology, moderate and high RCs of molybdenum were detected in oxic groundwater from the Cummings Valley basin, in the southern part of the Southern Sierra study unit, and in deeper wells in the Tahoe Valley South subbasin in the Tahoe-Martis study unit (figs. 26A,C and 29). The differentiation between deep and shallow wells in the Tahoe Valley South subbasin is 135 ft bls; this depth was selected based on molybdenum data and not on information about groundwater ages or stratigraphic data for

the basin. Molybdenum in the Mo^{+6} oxidation state is highly soluble in oxic water and primarily exists as the molybdate oxyanion (Anbar, 2004). Similar to many other metal oxyanions, molybdate can sorb to manganese oxyhydroxides, and sorbtion is weaker at higher pH. The three samples with the highest molybdenum concentrations were from the Tahoe Valley South subbasin, and all three samples had pH values >8.7 (fig. 27). Granitic rocks are the primary source of sediments to the valley (fig. 4A).

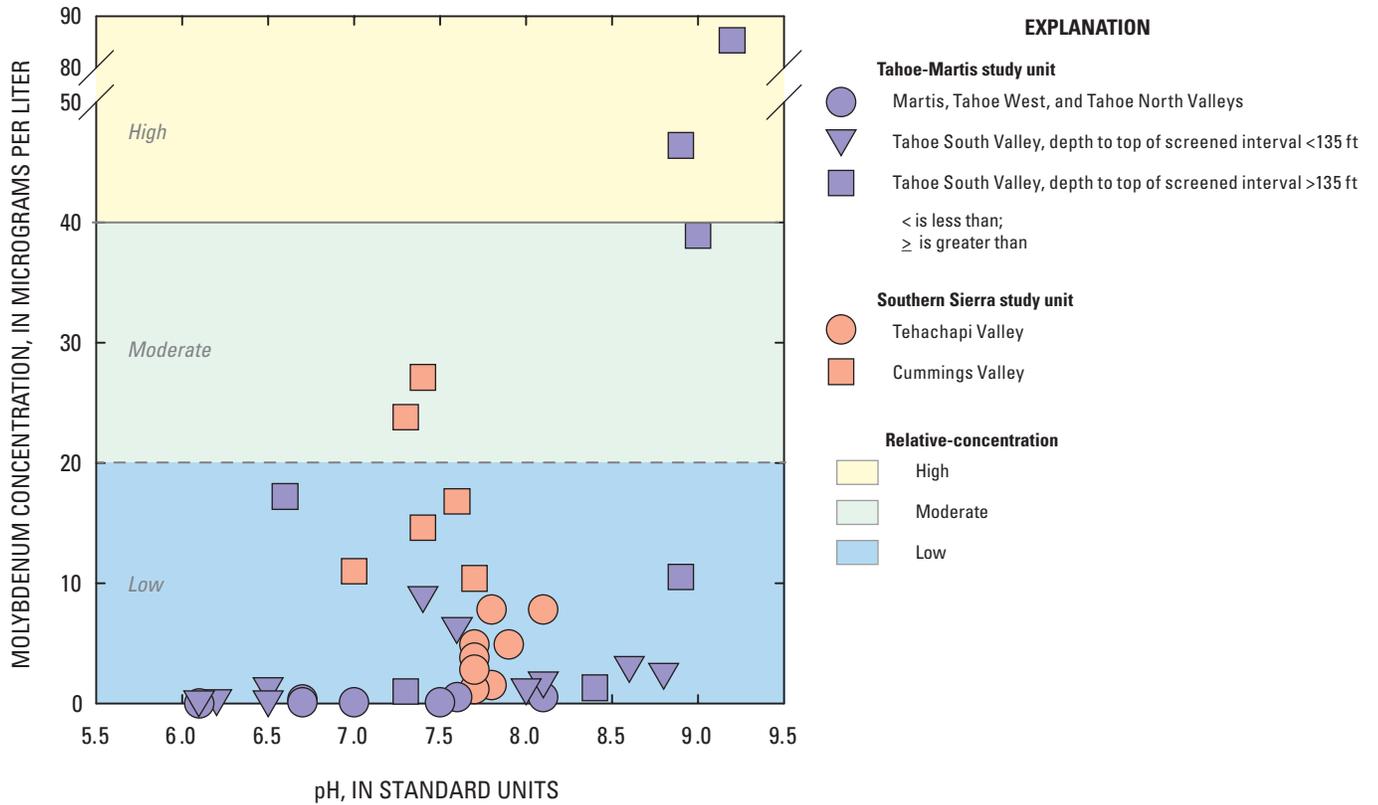


Figure 29. Relation between molybdenum concentration and well location for wells with oxic groundwater and sedimentary aquifer lithology, Tahoe-Martis and Southern Sierra study units, California GAMA Priority Basin Project.

Factors Affecting Boron

Boron is a naturally occurring metalloid element with high solubility in water. Natural sources of boron include evaporate minerals, such as borax, ulexite, and colemanite, and boron-bearing silicate minerals, such as tourmaline, that are primarily found in igneous rocks (Hem, 1989; Klein and Hurlbut, 1993). Seawater contains approximately 4,500 µg/L of boron, and boron also is associated with thermal springs and volcanic activity (Hem, 1989). Boron occurs in wastewater because borax is a component of many detergents. Other anthropogenic uses of boron compounds include borosilicate glass, boric acid insecticide, chemical reagents, semi-conductors, and fertilizers. Boron is an essential nutrient for plants, but is toxic to plants at high concentrations. The NL-CA for boron is 1,000 µg/L, and at higher concentrations, boron may adversely affect fetal development (U.S. Environmental Protection Agency, 2008). High RCs of boron were detected in samples from the Tahoe-Martis and Southern Sierra study units, and moderate RCs were detected in samples from all three study units (figs. 30A,B,C).

In the Tahoe-Martis, Central Sierra, and Southern Sierra study units, boron concentrations in groundwater had significant positive correlations with septic tank density, well depth, pH, and percent agricultural land use and significant negative correlations with elevation, aridity index, and DO (table 10B). Higher boron concentrations were significantly associated with pre-modern and mixed-age groundwater, and with location in the Central and Southern Sierra study units (table 10A). Boron had the same pattern of significant relations to potential explanatory factors as did fluoride and molybdenum, except that boron was not significantly related to aquifer lithology. Many of the correlations between boron and potential explanatory factors likely reflect correlations among the explanatory factors rather than causative relations explanatory of boron distribution in groundwater.

High and moderate RCs of boron occurred in three settings in the Tahoe-Martis, Central Sierra, and Southern Sierra study units: groundwater with high RCs of TDS, groundwater from wells with volcanic aquifer lithology, and groundwater from areas of the Central and Southern Sierra study units that also have high and moderate RCs of fluoride, molybdenum, arsenic, and uranium in groundwater. The only three samples with high RCs of boron corresponded to three of the four samples with high RCs of TDS (TTAHO-11, TROCK-13, SOSA-35). These three samples also had high RCs of arsenic, anoxic or mixed oxic/anoxic oxidation-reduction conditions, and were from wells with metamorphic or granitic aquifer lithology.

In the Tahoe-Martis study unit, boron concentrations were significantly greater in wells with volcanic aquifer lithology than in wells with any other aquifer lithology (figs. 30A, 31). Fossil hot springs and other features associated with volatile emanations during volcanism are the likely sources of boron in the volcanic rocks.

In the Central Sierra study unit, boron concentrations were significantly correlated with major-ion chemistry. Anion compositions of Central Sierra study unit groundwater primarily range from bicarbonate-dominated to chloride-dominated (see section “[Factors Affecting Total Dissolved Solids](#)” for more information). Boron concentrations in groundwater samples with $\geq 20\%$ chloride in the anions were significantly greater than boron concentrations in groundwater samples with $< 20\%$ chloride in the anions (fig. 31). Fluoride, arsenic, and molybdenum concentrations and pH also were significantly higher in samples with $\geq 24\%$ chloride in the anions (Wilcoxon $p = 0.007, 0.006, 0.005, \text{ and } 0.009$, respectively); however, there was no significant difference in TDS concentrations between the two groups (Wilcoxon $p = 0.28$). These relations suggest the presence of at least two different compositional types of groundwater in the Central Sierra study unit: one with bicarbonate as the dominant anion and relatively lower concentrations of trace elements, and another with chloride as the dominant anion and relatively higher concentrations of trace elements.

The geographic distribution of high and moderate RCs of boron in the Southern Sierra study unit was similar to those of arsenic and fluoride (figs. 18C, 23C, and 30C). For all three constituents, most of the wells with high and moderate RCs were located in the northern part of the study unit, in the Kern River Valley and surrounding watershed.

For the set of samples from the Central Sierra study unit and the northern part of the Southern Sierra study unit, boron concentrations were significantly positively correlated with fluoride concentrations (Spearman’s rho test, $p < 0.001$), and boron and fluoride concentrations were significantly positively correlated with lithium concentrations ($p = 0.006$ and 0.002 , respectively). Boron, fluoride, and lithium are concentrated in hydrothermal fluids associated with granitic magmatism, and boron- and lithium-bearing minerals such as tourmaline and lepidolite (a lithium- and fluoride-bearing mica) co-occur with fluorite in pegmatite veins and contact aureoles around granitic plutons (Leeman and Sisson, 1996; London and others, 1996). The close relations among boron, fluoride, and lithium concentrations in the groundwater samples suggest that the primary source of boron is hydrothermal fluids or mineral assemblages deposited from hydrothermal fluids.

A

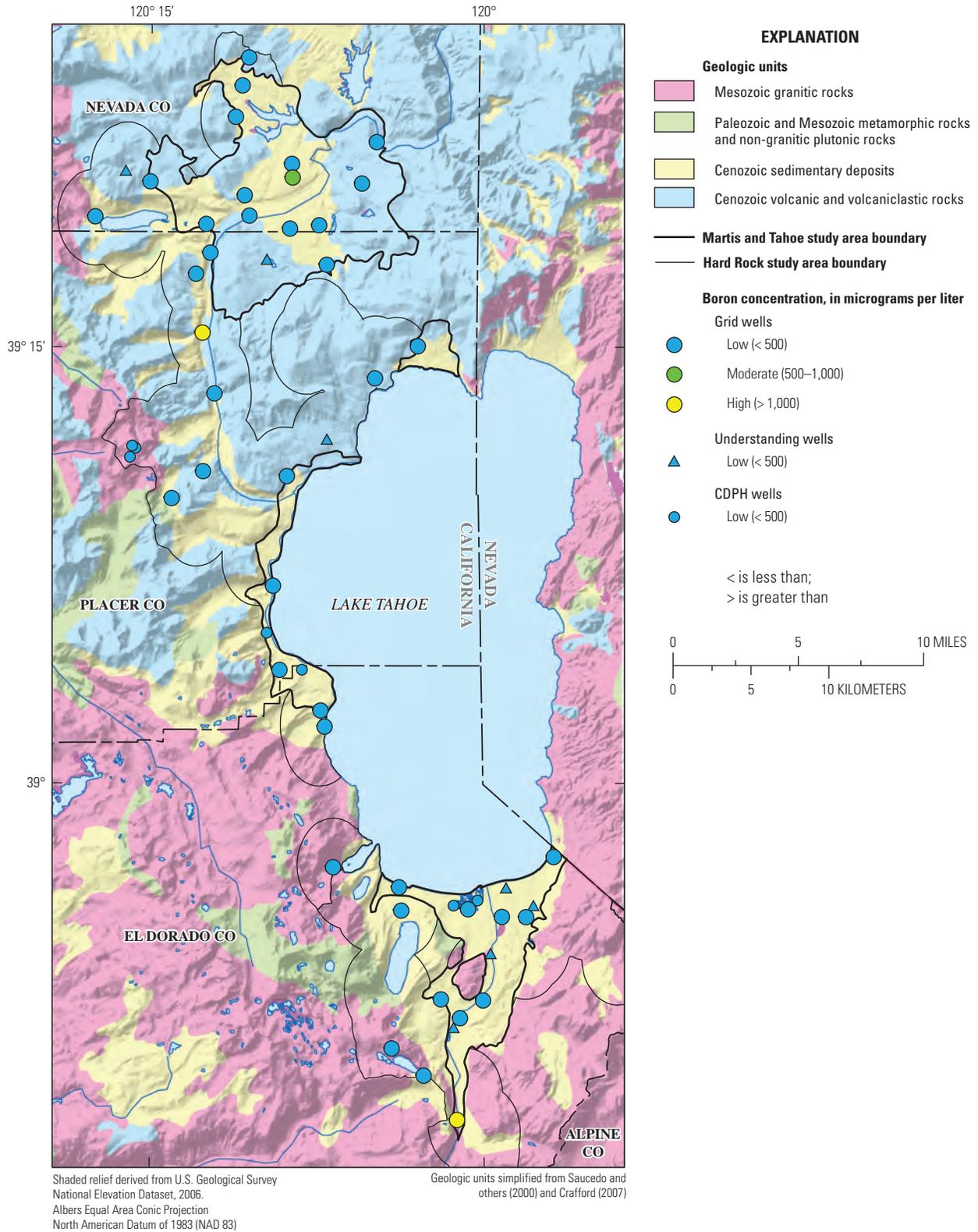


Figure 30. Relative-concentrations of boron for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for boron during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

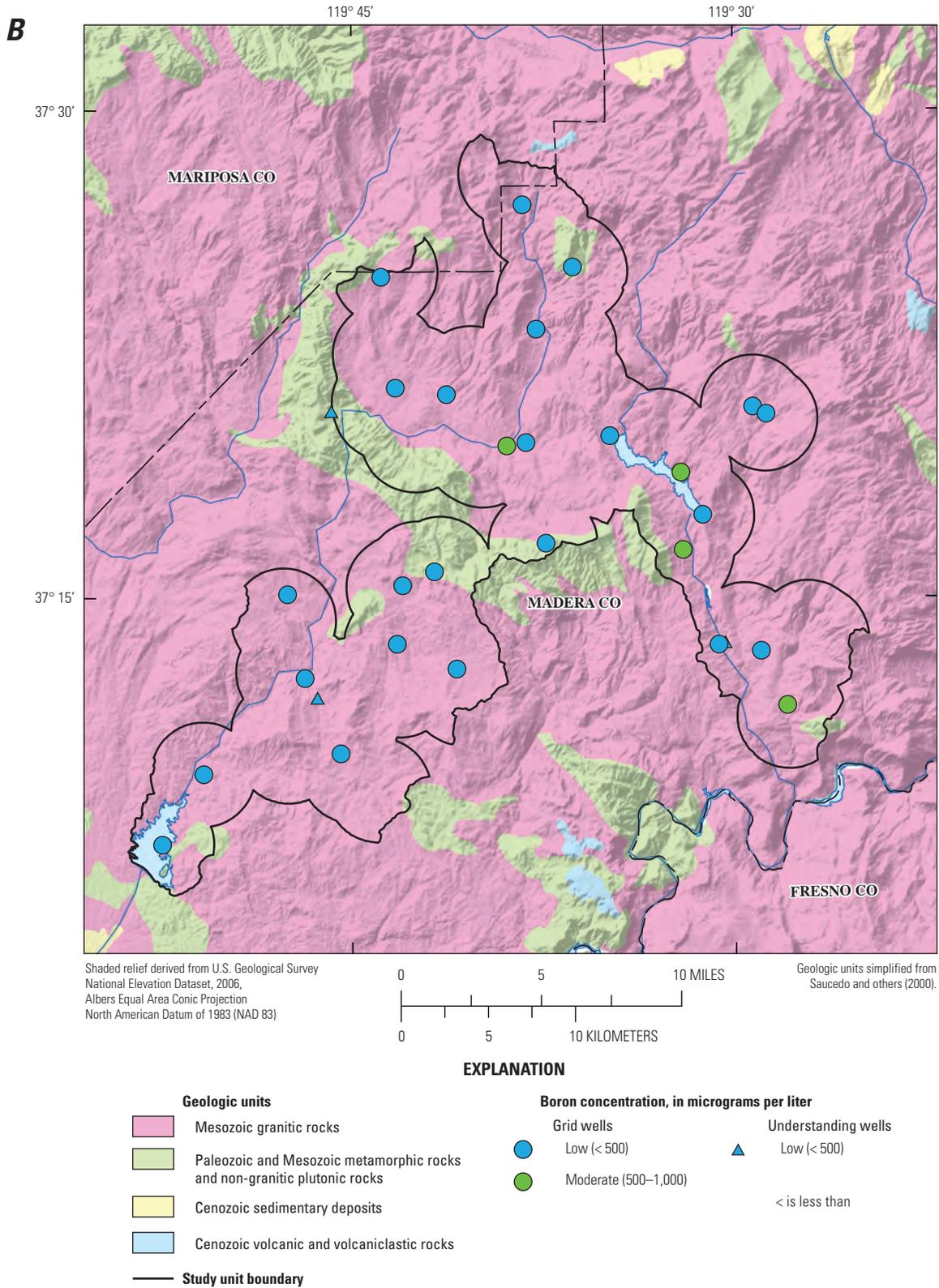


Figure 30.—Continued

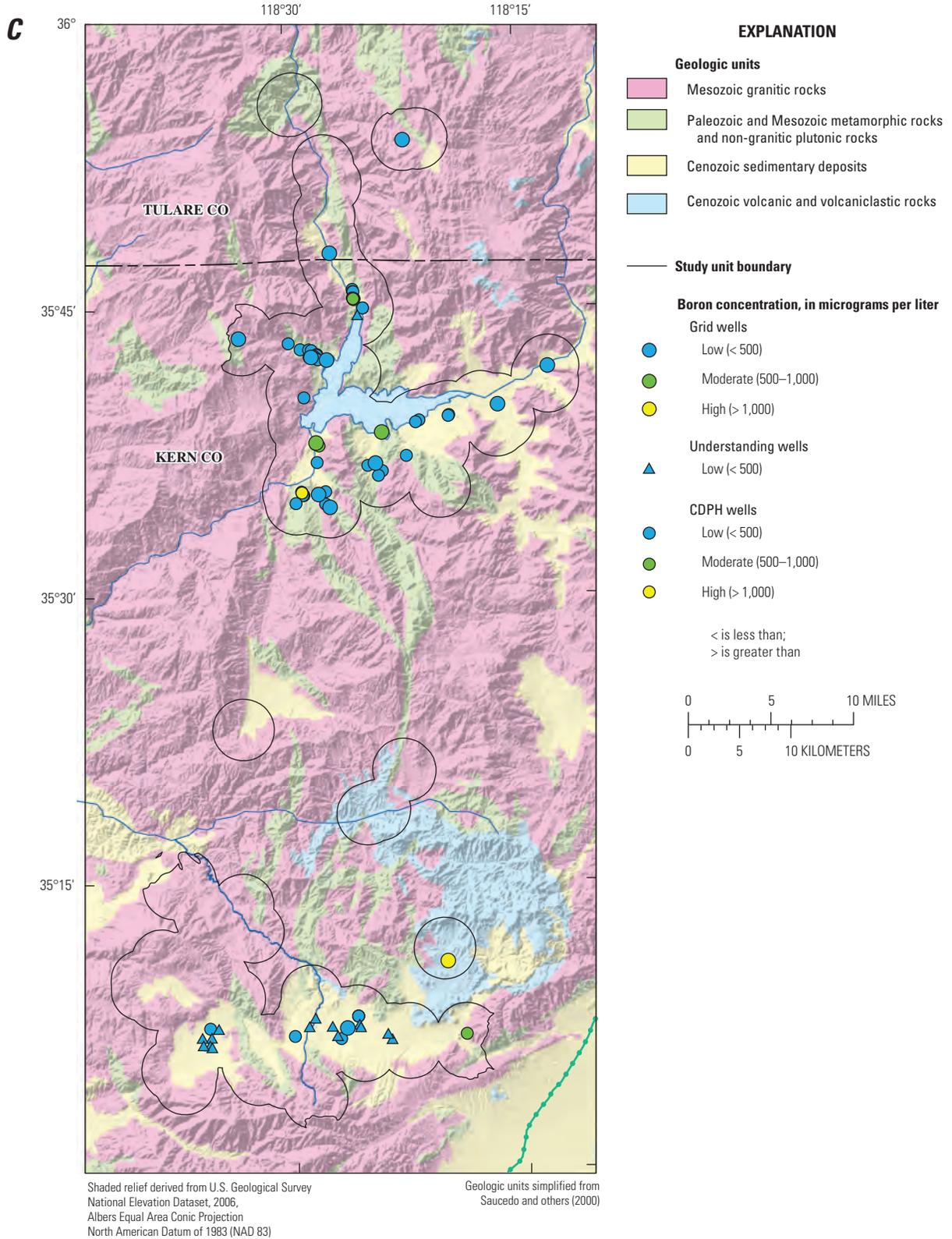


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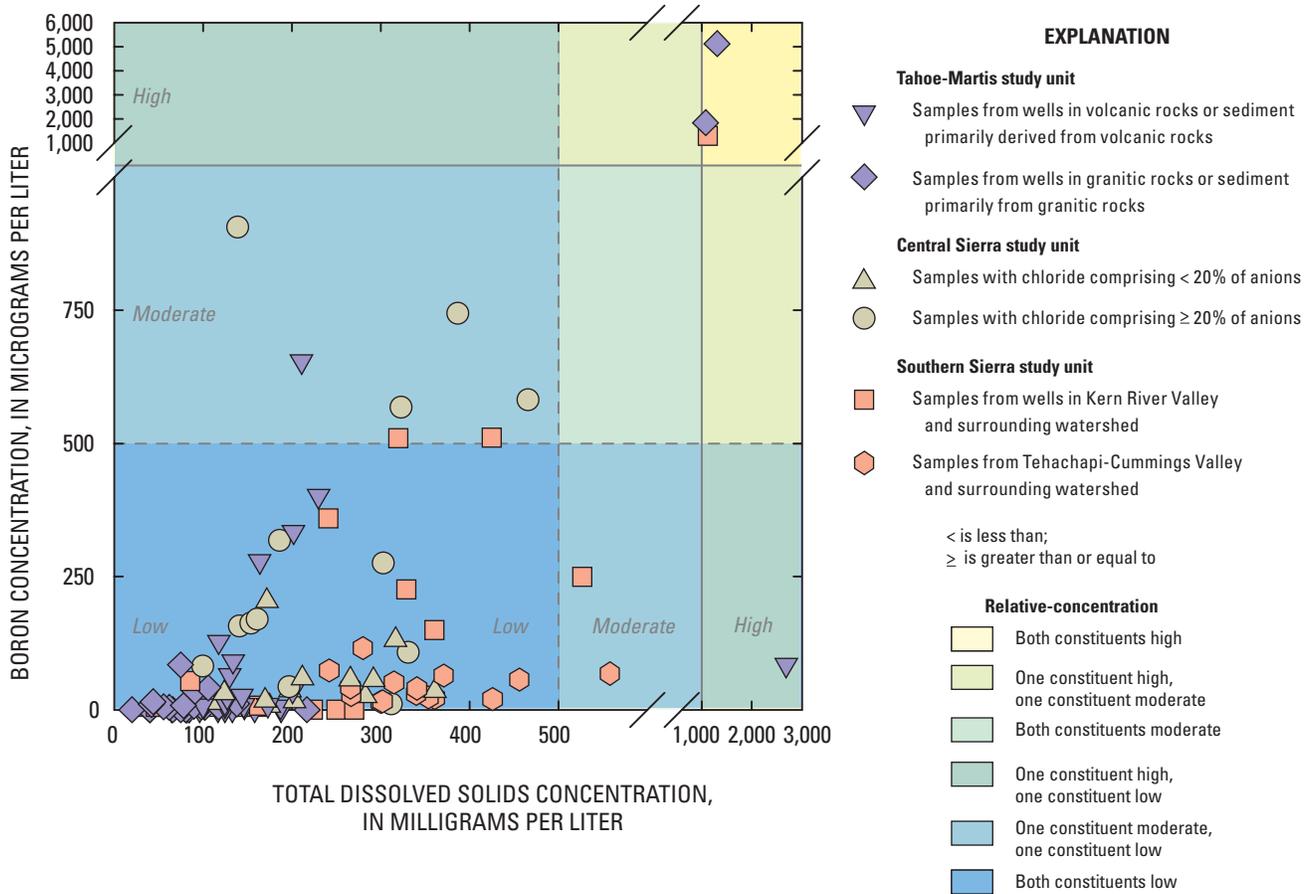


Figure 31. Relation between boron and total dissolved solids concentrations, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Nutrients

Nitrate was not detected at moderate or high RCs in the USGS-GAMA dataset or reported in the 3-year interval of the CDPH database used in the *status assessment* for the Tahoe-Martis study unit (fig. 32A). The CDPH database reported a high RC for nitrate in one well in 1987 (table 5), and during a survey of 32 wells around Lake Tahoe in 1990–1992, a high RC of nitrate was detected in one well in Stateline, Nevada, which is just over the State line from the city of South Lake Tahoe (Thodal, 1997). The CDPH database for the Central Sierra study unit reported a high RC of nitrate

in one well, but the high RC occurred prior to the 3-year interval used in the *status assessment* (table 5). The moderate aquifer-scale proportion for nitrate was 3.1%, based on the spatially weighted calculation (table 8B). The wells with moderate RCs primarily were located near areas of urban land use (fig. 32B).

The aquifer-scale proportions for nitrate in the Southern Sierra study unit were 2.7% high and 24% moderate (table 8C). Most of the wells with high or moderate RCs of nitrate were located in the centers of the Tehachapi and Cummings Valleys in the southern part of the study unit or along the margin of Lake Isabella in the northern part of the study unit (fig. 32C).

A

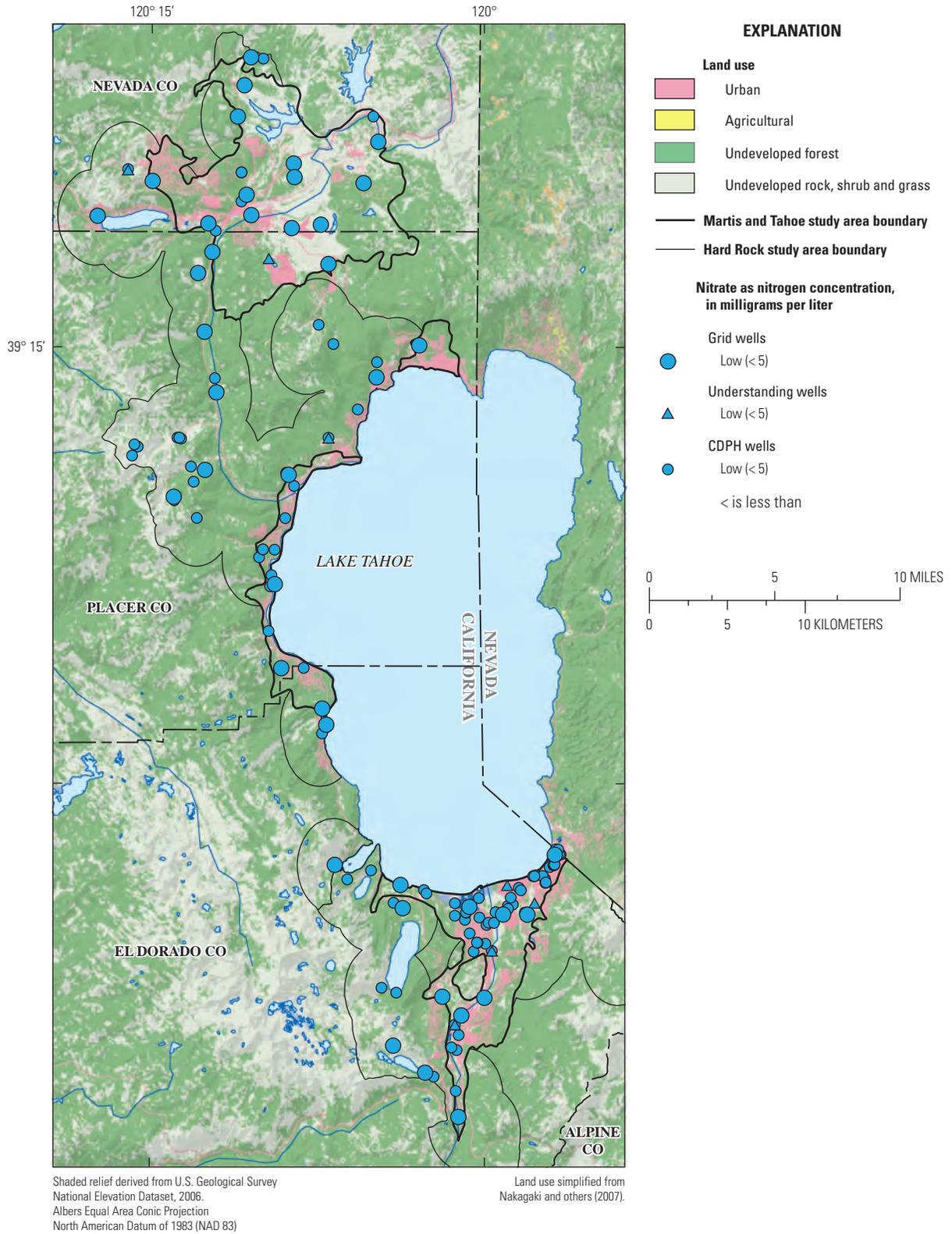


Figure 32. Relative-concentrations of nitrate for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for nitrate during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

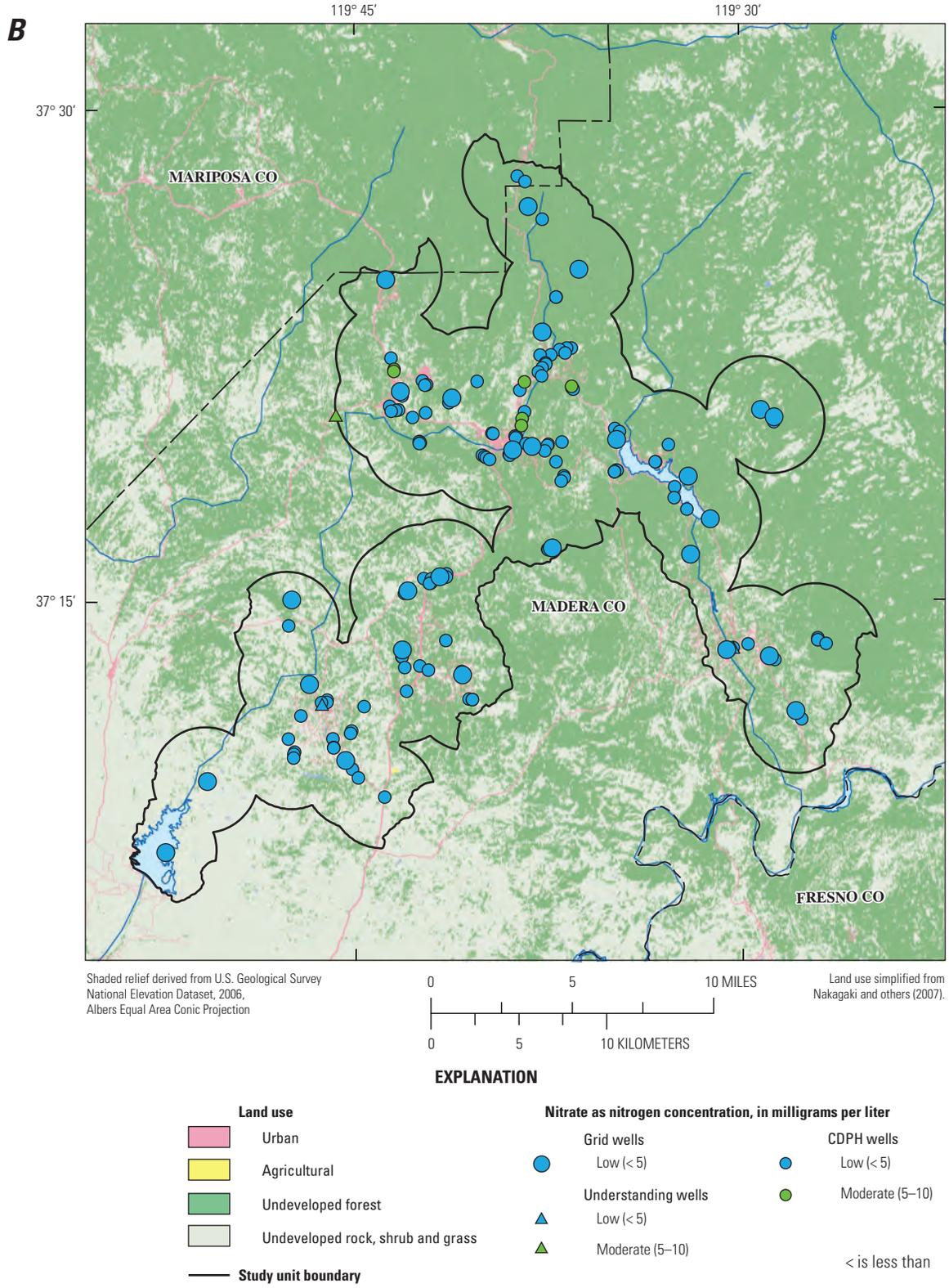


Figure 32.—Continued

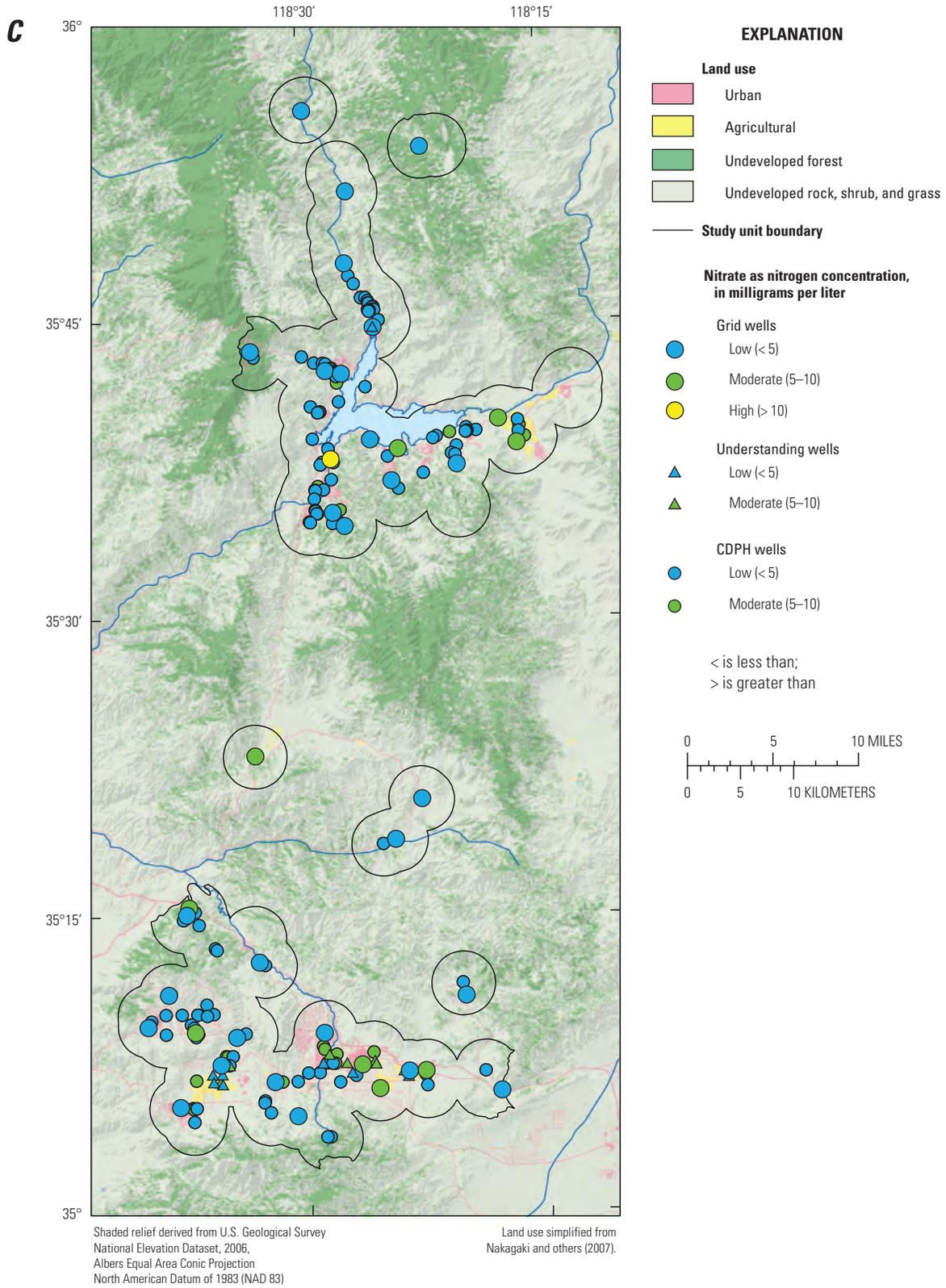


Figure 32.—Continued

Factors Affecting Nitrate

Nitrate concentration had a significant positive correlation with percentage of agricultural land use (table 10B). Because all of the agricultural land use in the three study units is in the Southern Sierra study unit, many of the other correlations between nitrate and potential explanatory factors may reflect correlations between explanatory factors and location in the Southern Sierra study unit. For example, higher nitrate concentrations were significantly associated with metamorphic and sedimentary aquifer lithologies (table 10A), consistent with the greater abundance of these lithologies among wells from the Southern Sierra study unit compared to lithologies of wells from the Tahoe-Martis or Central Sierra study units (fig. 10). Nitrate concentrations had significant negative correlations with elevation and aridity index (table 10B), also reflecting location in the Southern Sierra study unit (fig. 11).

Groundwater samples with detections of herbicides and (or) solvents had significantly higher nitrate concentrations than those without detections of those organic constituents (Wilcoxon $p < 0.001$). More than half of the wells with detections of herbicides and (or) solvents and $>5\%$ agricultural land use had moderate or high RCs of nitrate (fig. 33). Groundwater samples with no detections of herbicides or solvents and from sites with $<5\%$ agricultural land use had significantly lower nitrate concentrations than samples from wells with either characteristic. Positive correlations between nitrate and agricultural land use and application of agricultural chemicals commonly are observed in groundwater nationally (Nolan and others, 2002).

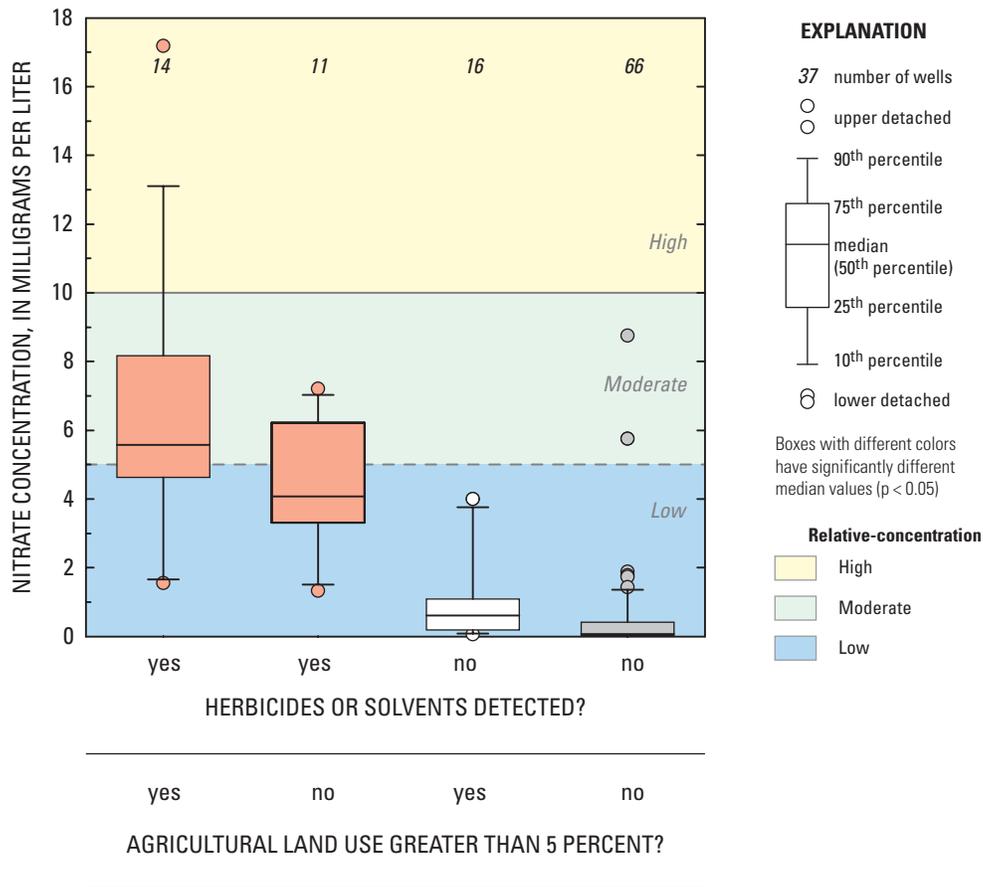


Figure 33. Relations among nitrate concentration and agricultural land use and detection of herbicides and solvents, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

For the entire dataset, nitrate concentration had a significant positive correlation with depth to the top of the screened or open interval ([table 10B](#)) because wells in the Southern Sierra study unit had significantly greater depths to the top of the screened or open interval than wells in the Central Sierra study unit and Hard Rock study area of the Tahoe-Martis study unit ([fig. 12B](#)). However, nitrate concentration was not significantly correlated with depth to top of screened or open interval in any of the study units (Spearman's rho test: Tahoe-Martis, $p=0.11$; Central Sierra, $p=0.81$; and Southern Sierra, $p=0.16$).

Radioactive Constituents

The class of radioactive constituents includes constituents whose abundance is measured as activity rather than concentration. Activity is measured in units of picocuries per liter (pCi/L), and one picocurie equals approximately two atoms decaying per minute. The number of atoms decaying is equal to the number of alpha or beta particles emitted. Radioactive constituents with health-based benchmarks were present at high RCs in 3, 31, and 21% of the primary aquifers in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively ([table 9A](#)). Gross alpha particle, uranium, and radon-222 activities accounted for most of the moderate and high RCs in all three study units ([tables 8A,B,C](#); [fig. 17B](#)).

The MCL-US (15 pCi/L) for gross alpha particle activity applies to adjusted gross alpha activity, which is equal to measured gross alpha activity minus uranium activity (U.S. Environmental Protection Agency, 2009b). Data collected by USGS-GAMA and data compiled in the CDPH database are reported as gross alpha activity without correction for uranium activity. Gross alpha is used a screening tool to determine whether other radioactive constituents must be analyzed. For regulatory purposes, analysis of uranium is only required if gross alpha activity is greater than 15 pCi/L; therefore, the CDPH database contains far more data for gross alpha activity than for uranium. As a result, it is not always possible to calculate adjusted gross alpha activity. The CDPH database contains even fewer data for radium and radon-222 than it does for uranium. The primary contributors to gross alpha activity are uranium and radium, and samples with high or moderate RCs of gross alpha generally have high or moderate RCs of uranium. Because of the lack of data for other radioactive constituents in the CDPH database, gross alpha data without correction for uranium are the primary data used in this report to avoid underestimating the prevalence of groundwater with moderate and high RCs of radioactive constituents as a class.

Aquifer-scale proportions for both gross alpha and adjusted gross alpha are listed in [tables 8A,B,C](#) for comparison purposes. Uranium data were not available for all CDPH wells with gross alpha data; in these cases, the adjusted gross

alpha was estimated from the relation between gross alpha and adjusted gross alpha in the 31 samples with USGS-GAMA data for both gross alpha and uranium (Fram and Belitz, 2007; Ferrari and others, 2008; Fram and others, 2009). High and moderate proportions for gross alpha are larger than those for adjusted gross alpha. Aquifer-scale proportions for radioactive constituents as a class were calculated using gross alpha, uranium, radium, and radon data ([table 9A](#)). The resulting high and moderate proportions were slightly greater than the high and moderate proportions calculated using adjusted gross alpha, uranium, radium, and radon data, although the differences were not significant.

In the Tahoe-Martis study unit, the high aquifer-scale proportions for gross alpha particles and radon-222 were 2.0 and 1.0%, respectively ([table 8A](#)). Neither uranium nor radium were present at high RCs during the period of study, although both were reported at high RCs in the CDPH database historically ([table 5](#)). A high RC of uranium was detected in one USGS-understanding well (TTAHOU-08), but this well was not included in the dataset for the spatially weighted calculation of aquifer-scale proportion because it is a shallow monitoring well not representative of the primary aquifer. Gross alpha particles, radium, and uranium each had moderate aquifer-scale proportions of less than or equal to 3.0%, and the moderate aquifer-scale proportion for radon-222 was 12% ([table 8A](#), [fig. 17B](#)). In the Tahoe-Martis study unit, all of the wells with moderate or high RCs of radioactive constituents were located in the Tahoe Valley South subbasin and surrounding watershed ([fig. 34A](#)).

High RCs of gross alpha particle radiation and uranium were present in 16 and 14%, respectively, of the primary aquifer in the Central Sierra study unit ([table 8B](#)). The moderate aquifer-scale proportions for gross alpha particle radiation and uranium were 25 and 15%, respectively. Radium and radon-222 data were available for only half of the grid cells; thus, the estimates of aquifer-scale proportions have greater uncertainty. Radon-222 was detected at high RCs, and both constituents were detected at moderate RCs ([table 8B](#), [fig. 17B](#)). Wells with moderate or high RCs of radioactive constituents were distributed across both study areas within the study unit ([fig. 34B](#)). The CWISH study area had greater moderate and high aquifer-scale proportions for all radioactive constituents than did the CGOLD study area ([appendix B](#), [tables B1D,E](#) and [B2A](#)).

The high aquifer-scale proportions for gross alpha particle radiation and uranium in the Southern Sierra study unit were both 21%, and the moderate aquifer-scale proportions were 11 and 16%, respectively ([table 8C](#); [fig. 17B](#)). Radium and radon-222 data were available for less than one-third and less than one-sixth, respectively, of the grid cells; thus, the estimates of aquifer-scale proportions may not be representative. Most of the wells with moderate or high RCs of radioactive constituents were located in the Kern River Valley and surrounding watershed ([fig. 34C](#)).

A

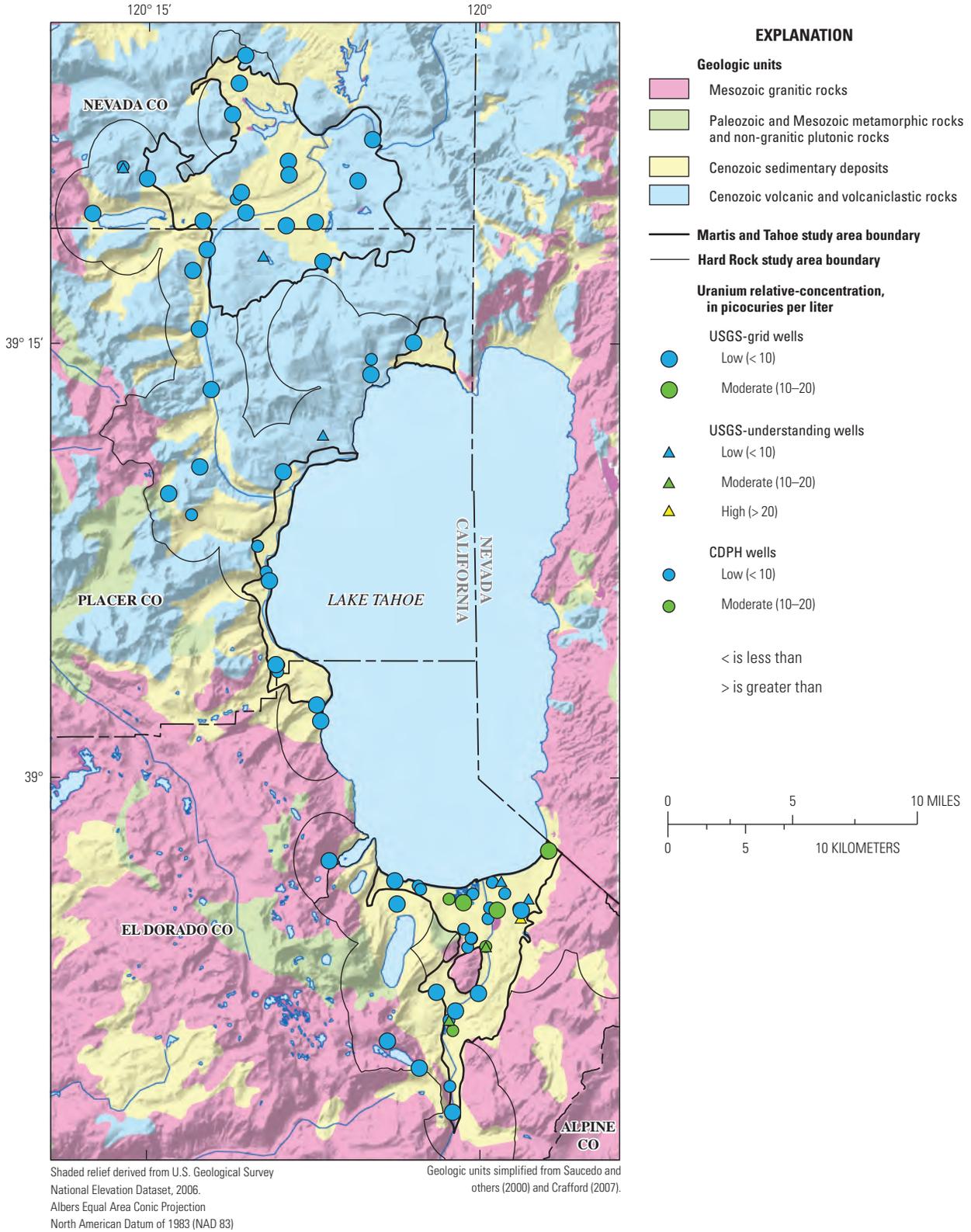


Figure 34. Relative-concentrations of uranium for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for uranium during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

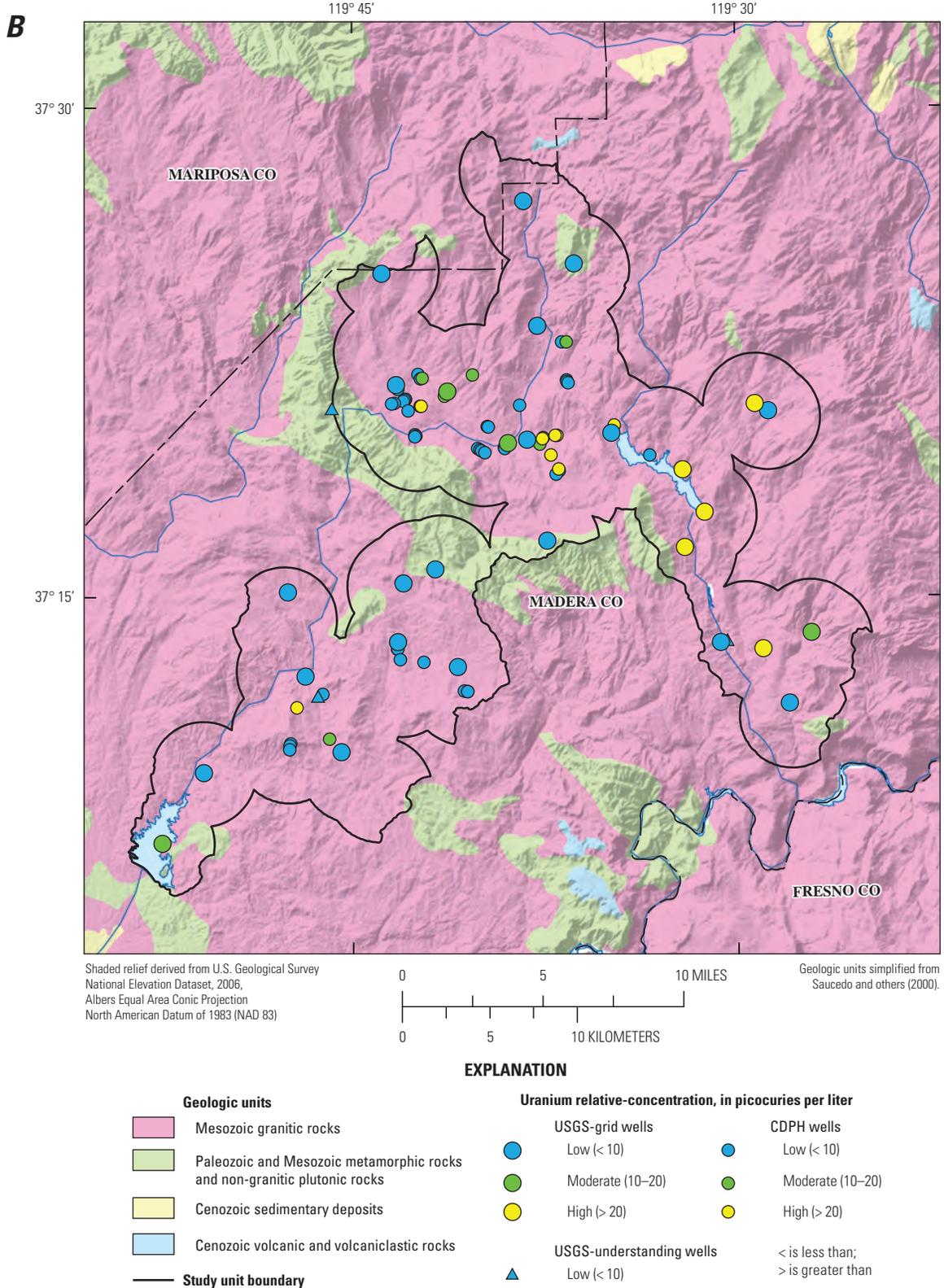


Figure 34.—Continued

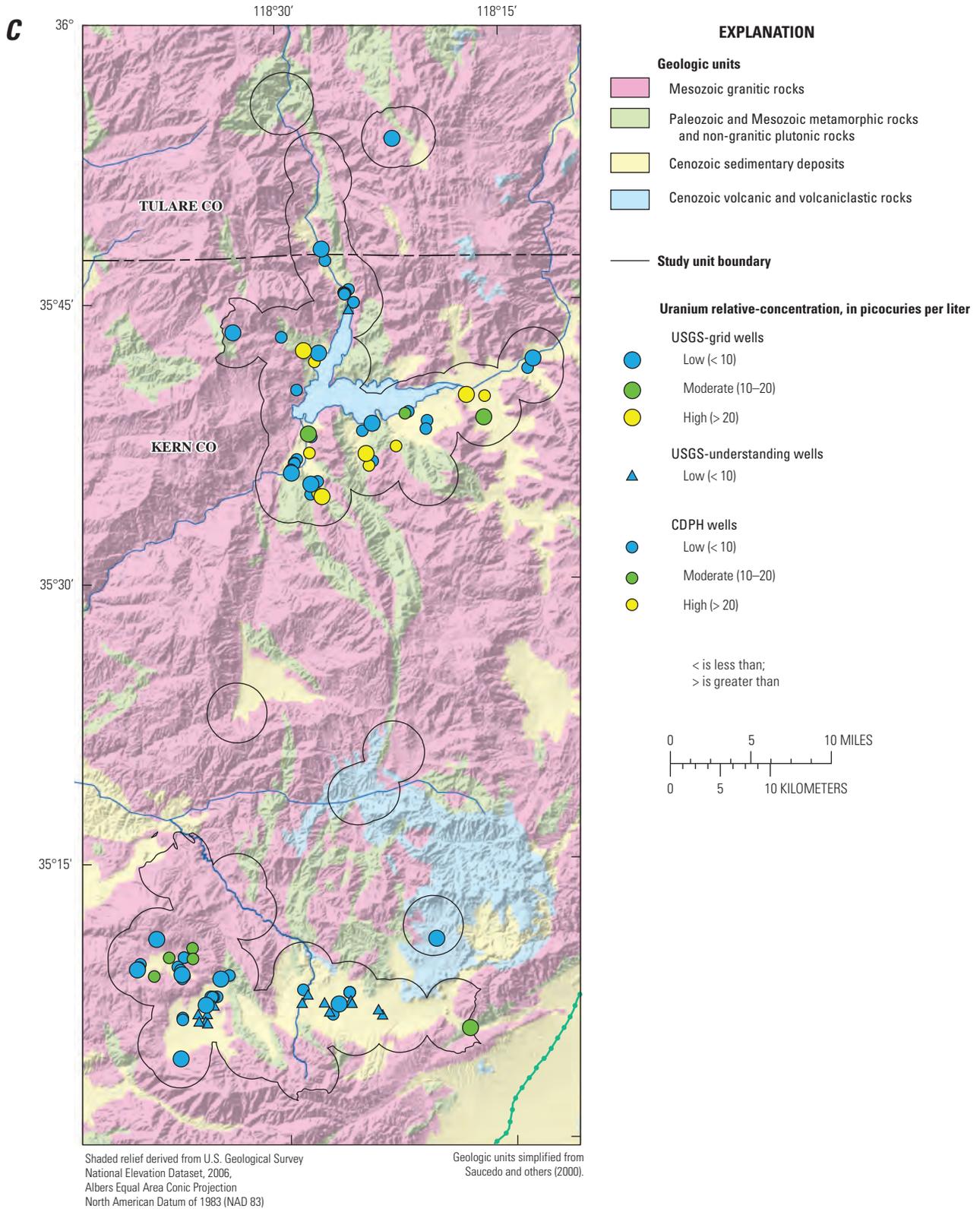


Figure 34.—Continued

Factors Affecting Uranium, Gross Alpha Particle Activity, and Radon

Uranium, gross alpha particle, and radon-222 activities had significant positive correlations with one another, although the correlation between uranium and gross alpha particle activities (Spearman’s rho test, $p < 0.001$, $\rho = 0.89$) was considerably stronger than the correlation between uranium and radon-222 activities ($p < 0.001$, $\rho = 0.49$) (fig. 35). The primary source of the alpha particles counted during laboratory analysis of gross alpha particle activity is the decay of dissolved uranium in the sample, thus a high degree of correlation was expected (Thomas and others, 1993).

The source of radon-222 in groundwater is the decay of radium-226 (a member of the uranium-238 decay series) in aquifer materials. Groundwater in crystalline rocks typically

has low radium activities because radium sorbs strongly to mineral surfaces, particularly to altered feldspars (Zapecza and Szabo, 1988; Thomas and others, 1993). Radon, however, is an inert gas that readily diffuses out of the aquifer materials and into the groundwater. Ayotte and others (2007) observed greater activities of radon-222 in groundwater from crystalline bedrock aquifers in the northern United States compared to aquifers composed of glacial sediments derived from the crystalline bedrock. They attributed the greater radon-222 activities in the crystalline bedrock aquifers to concentrations of sorbed radium on fracture surfaces. Because of the complicating geological and sorptive factors between uranium and radon, a less strong correlation was expected compared to the correlation between gross alpha particle activity and uranium (fig. 35).

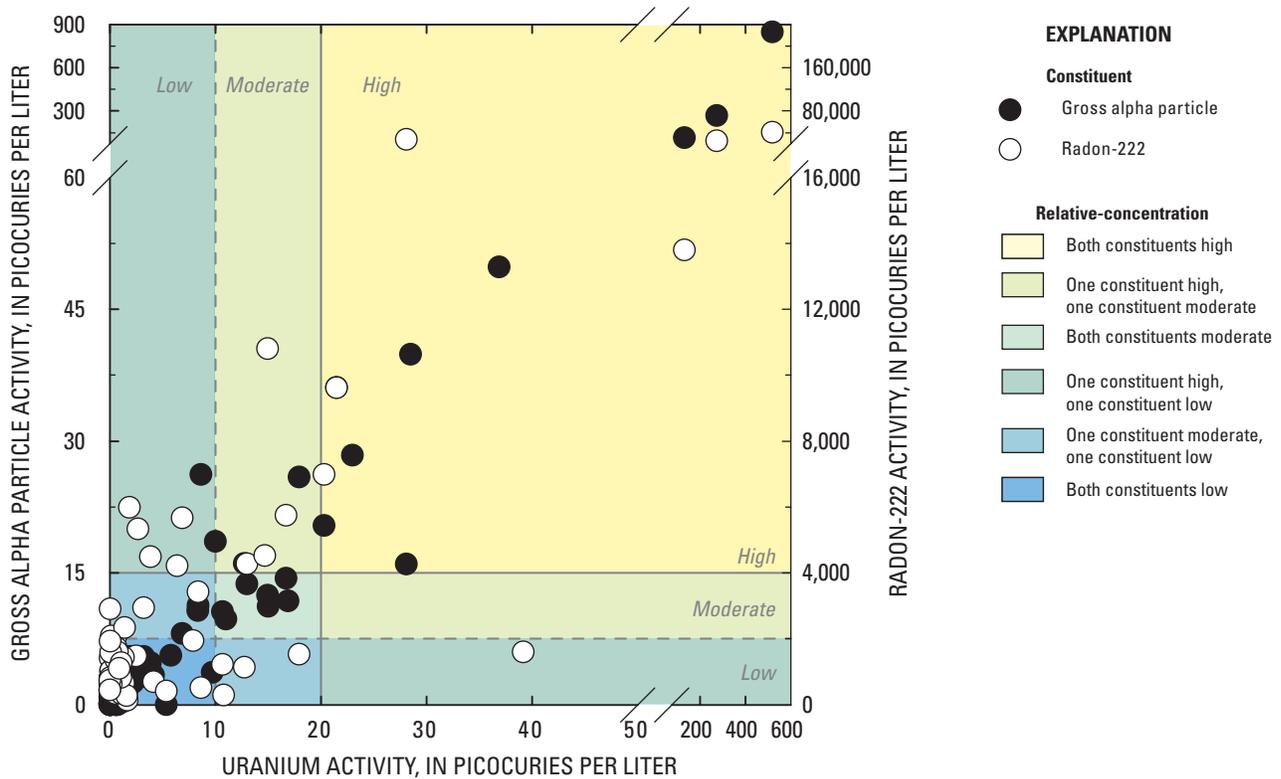


Figure 35. Relations among uranium, radon-222, and gross alpha particle activities, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

The following discussion of factors affecting the radioactive constituents primarily is focused on uranium. The Central Sierra study unit and the Kern River Valley area of the Southern Sierra study unit correspond to the northwestern and southeastern ends, respectively, of a band of granitic rocks in the western Sierra Nevada known to have groundwater with greater radioactivity than groundwater elsewhere in the Sierra Nevada (California Department of Water Resources, 1990). Uranium activities had significant positive associations with location in the Central and Southern Sierra study units (table 10A). This relation between uranium activity and location accounts for the significant negative correlations between uranium activity and aridity index and elevation, and the significant positive correlation with septic tank density (table 10B).

Median uranium activities in samples in the three groundwater age classes were significantly different: uranium activities were lowest in groundwater with modern age

distribution, higher in groundwater with pre-modern age distribution, and highest in groundwater with mixed age distribution (table 10A). The relations between uranium activity and groundwater age in part reflect the complex interrelations among groundwater age, aquifer lithology, study unit, and well depth (tables 6A,B).

Uranium activity had a significant negative correlation with DO concentration (table 10B). However, the relations between uranium and DO in individual samples from the three study units indicated that elevated uranium activities occurred under oxic and anoxic conditions (fig. 36). Elevated uranium activities in groundwater from wells with granitic or metamorphic aquifer lithologies primarily occurred in samples with DO concentrations <2.2 mg/L; however, elevated uranium activities in groundwater from wells with sedimentary aquifer lithology primarily occurred in samples with DO concentrations >4 mg/L.

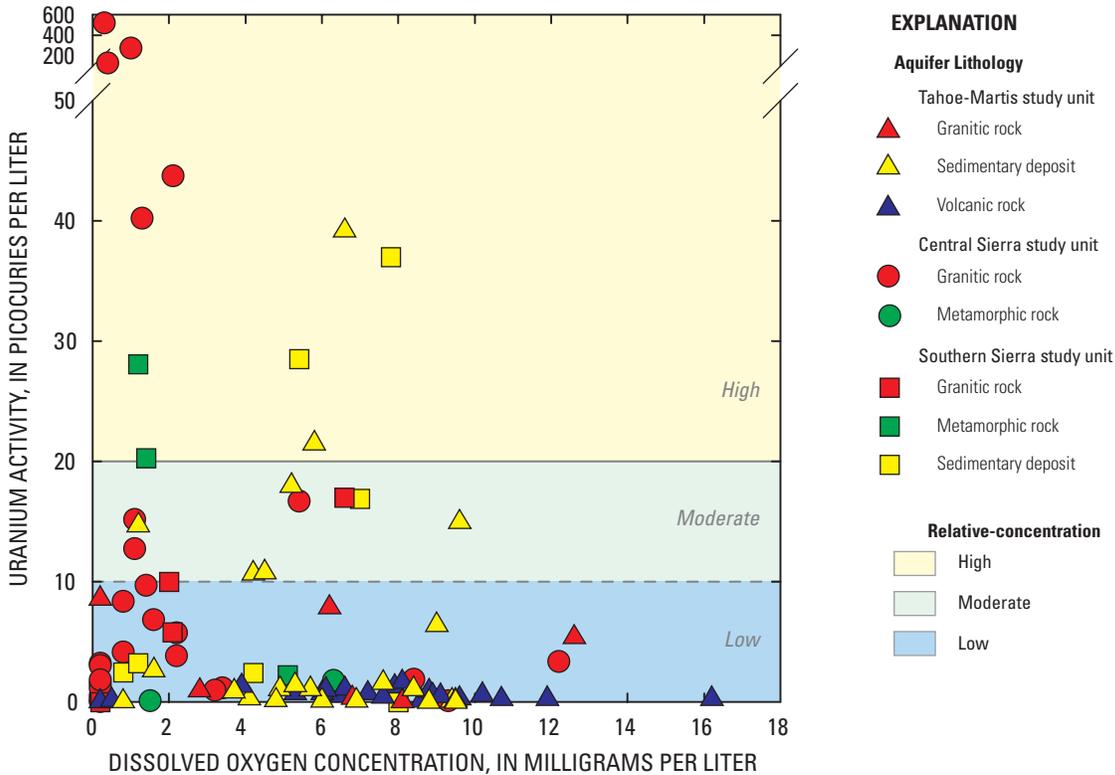


Figure 36. Relations among uranium activity, dissolved oxygen concentration, and aquifer lithology, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Uranium activities in the 29 groundwater samples with granitic or metamorphic aquifer lithologies and either anoxic conditions or DO concentrations < 2.2 mg/L ranged from 0.05 to 519 pCi/L (fig. 36), and were significantly higher than uranium activities in the 18 groundwater samples with DO concentrations \geq 2.2 mg/L (Wilcoxon rank-sum test, $p = 0.024$). The 29 low-oxygen samples also came from significantly deeper wells ($p = 0.023$). High uranium activities are typically associated with oxic groundwater (Hem, 1989). Geochemical modeling was done to evaluate the occurrence of high uranium activities in anoxic groundwater.

Speciation of dissolved uranium and saturation indices of uranium minerals in groundwater were calculated using PHREEQC, version 2.17 (Parkhurst and Appelo, 1999) with updated thermodynamic constants for uranium complexes (Jurgens and others, 2010). For each sample, the saturation index for uraninite was calculated at a range of oxidation-reduction potentials (by adjusting the variable pe , the electron activity, in PHREEQC). Uraninite, UO_2 , occurs as an accessory mineral in granitic rocks and pegmatites. The pe value for saturation ($SI = 0$) with uraninite ranged from approximately -1 to $+2$. At lower pe , uraninite is supersaturated ($SI > 0$) and would be expected to precipitate from the groundwater, and at higher pe , uraninite is undersaturated ($SI < 0$) and would be expected to dissolve, if it were present. Reduction of iron oxides typically occurs at pe values < 0 , whereas reduction of manganese oxides, nitrate, and oxygen typically occurs at pe values above 0 (Stumm and Morgan, 1996; Appelo and Postma, 2005). Thus, the calculations suggest that groundwater with oxic, suboxic, nitrate-reducing, and manganese-reducing oxidation-reduction conditions had sufficiently high oxidation potential to dissolve uraninite. All of the groundwater samples with granitic or metamorphic aquifer lithology and high or moderate relative activities of uranium (> 10 pCi/L) were classified as either oxic, suboxic, nitrate-reducing, or manganese-reducing. Calculated pe for manganese-reducing samples with data for iron oxidation-reduction species (table C6) ranged from 2.1 to 3.7. No samples classified as iron-reducing had high or moderate relative activities of uranium.

Note that approximately one-quarter of the groundwater samples with granitic or metamorphic aquifer lithologies and sufficiently oxidizing conditions had high or moderate RCs of uranium, indicating that sufficiently oxidizing conditions are a necessary, but not sufficient, condition for producing groundwater with elevated uranium activities (fig. 36). The PHREEQC speciation calculations indicate that dissolved uranium primarily occurs in complexes with calcium and carbonate $Ca_2UO_2(CO_3)_3^0$ and $CaUO_2(CO_3)_3^{-2}$. Uranium was significantly correlated with calcium (Spearman's rho test, $p < 0.001$, $\rho = 0.59$) and bicarbonate ($p = 0.001$, $\rho = 0.53$). The groundwater samples with granitic

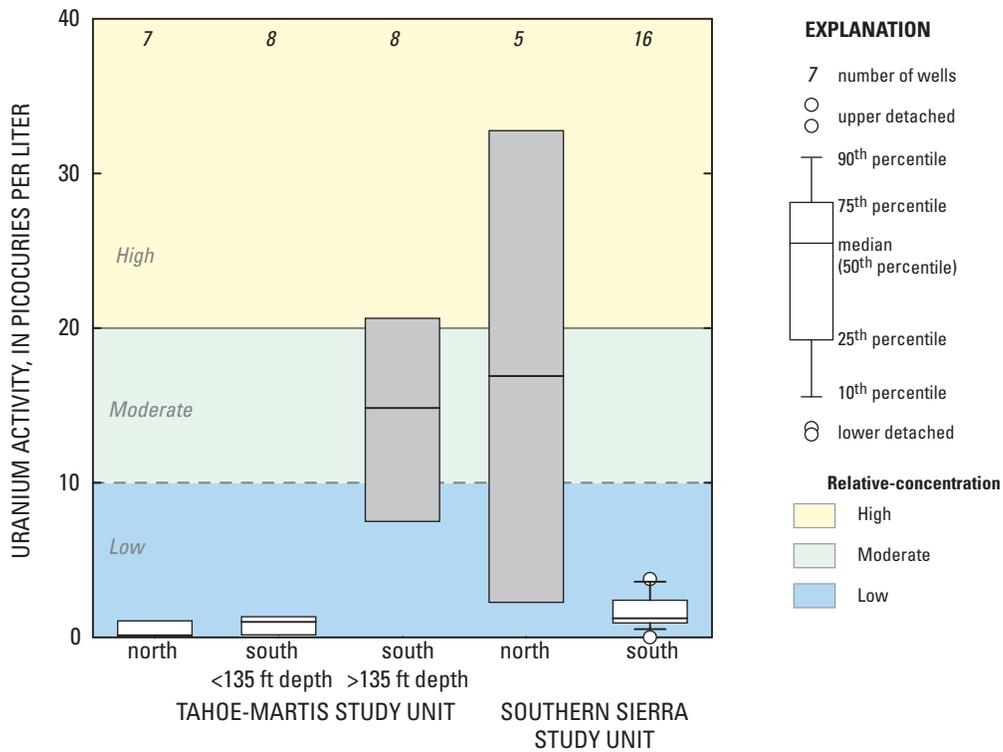
or metamorphic aquifer lithologies, sufficiently oxidizing conditions, and high or moderate RCs of uranium had bicarbonate concentrations of 89 to 251 mg/L; however, only approximately one-third of the groundwater samples with bicarbonate concentration > 89 mg/L had high or moderate RCs of uranium (Ferrari and others, 2008). This indicates that sufficiently high concentrations of bicarbonate and calcium are a necessary, but not sufficient, condition for producing groundwater with elevated uranium activities.

The distribution of uranium in groundwater in granitic rocks may be quite heterogeneous, even within a single pluton. For example, wells CWISH-08 and CWISH-09 are located less than half of a mile apart, are screened or open over a similar depth interval in the same granitic pluton, have similar oxidation-reduction conditions, and have groundwater with mixed age distributions. Yet, groundwater from CWISH-09 has uranium activity of 1 pCi/L, and groundwater from CWISH-08 has uranium activity of 44 pCi/L. Twenty-three of the USGS-GAMA sites in the Central Sierra study unit were located in the Bass Lake Tonalite. In the 20 samples with oxidation-reduction conditions favoring uranyl as the dominant uranium species, uranium activities ranged from < 1 to 519 pCi/L. Similarly large ranges of uranium concentrations in groundwater from a relatively small geographic area within a granitic pluton have been observed elsewhere (Asikainen and Kahlos, 1979; Gascoyne, 1989).

Mineralogical observations of granitic rocks of the Sierra Nevada suggest that weathering of uraniferous titanite may be an important source of uranium to groundwater (Wollenberg and Smith, 1968; Thomas and others, 1993). Titanite commonly is present as an accessory mineral in Sierra Nevada granitic rocks (Ague and Brimhall, 1988). Uranium also occurs in apatite, another common accessory mineral. Weathering of biotite may also be a source, based on observations of uranium concentrated in the rims of biotite grains and in zircon inclusions in biotite grains in Sierra Nevada granitic rocks with abundant biotite (Wollenberg and Smith, 1968). In the several hundred samples of Bass Lake Tonalite examined by Bateman (1992), the modal abundances of biotite and hornblende varied from 5 to 25% and from 0 to 20%, respectively. These heterogeneities in relative abundances of the major silicate minerals suggest that the uranium-bearing accessory minerals, such as titanite and zircon, may also be heterogeneously distributed within the pluton. Uranium mobilized from primary minerals also may be redeposited; high concentrations of uranium adsorbed to iron oxyhydroxide coatings on fractures have been observed in granitic rocks (Gascoyne, 1989). Small-scale heterogeneities in groundwater flow patterns in fractured rock systems may therefore result in a wide range of groundwater uranium concentrations, even within a small geographic area.

Uranium activity in groundwater samples from wells with sedimentary aquifer lithology ranged from below detection to 39 pCi/L (figs. 36, 37). High and moderate RCs of uranium were detected in groundwater from the Tahoe Valley South subbasin and the Kern River Valley (figs. 34, 37). Within the Tahoe Valley South subbasin, uranium activity was significantly higher in wells with depth to top of screened or

open interval > 135 ft bls. Sources of sediment to the Tahoe Valley South subbasin likely had some variation over time because variation in the extent of glaciation may have drawn sediment from different areas. Elevated activity of uranium in sediment of the Kern River Valley may reflect that the source of sediment is the surrounding granitic rocks, which include rocks with elevated uranium.



Tahoe-Martis study unit north: Martis, Tahoe North, and Tahoe South Valleys;
 Tahoe-Martis study unit south: Tahoe South Valley (divided into two groups by depth to top of screened interval in well);
 Southern Sierra study unit north: Kern River Valley;
 Southern Sierra study unit south: Tehachapi-Cummings Valleys

Tahoe-Martis study unit south >135 ft and Southern Sierra north significantly different than the three other categories (p<0.001 to p=0.013)

Figure 37. Relation between uranium activity and location for groundwater samples from wells with sedimentary aquifer lithology, Tahoe-Martis and Southern Sierra study units, California GAMA Priority Basin Project.

The mechanisms for mobilizing uranium from sediment in the Tahoe Valley South subbasin appear to be different than the mechanism inferred for mobilization of uranium from sediment of the Eastern San Joaquin Valley, which primarily is composed of material derived from Sierra Nevada granitic rocks. In the Eastern San Joaquin Valley, Jurgens and others (2010) reported higher uranium concentration groundwater with modern age distribution from the shallower parts of the aquifer system, and reported a strong positive correlation between uranium and bicarbonate. Jurgens and others (2010) concluded that the uranium is mobilized from aquifer sediment by downward moving irrigation return water that has high concentrations of bicarbonate. In contrast, in the Tahoe Valley South subbasin, uranium activity was positively correlated with depth to top of screened or open interval ($p=0.005$, $\rho=0.67$), high and moderate RCs of uranium occurred in pre-modern and mixed-age groundwater, and uranium was not correlated with bicarbonate ($p=0.53$). Further investigation with geochemical modeling would be needed to understand the mechanism for solubilization of uranium in this high-pH, low-bicarbonate groundwater.

Major Ions and Trace Elements with SMCL Benchmarks

Constituents with SMCL benchmarks were present at high RCs in 14, 34, and 24% of the primary aquifers in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively (table 9B). The constituent most commonly responsible for the high RCs was manganese, which was present at high RCs in 13, 32, 23% of the three study units, respectively (tables 8A,B,C; fig. 17C). High aquifer-scale proportions for iron were 6.9, 11, and 13% for the three study units, respectively. Manganese, iron, and zinc also were detected at moderate RCs in the Central Sierra and Southern Sierra study units, but not in the Tahoe-Martis study unit.

The high aquifer-scale proportion for TDS in the Tahoe-Martis study unit was 11% (table 8A). No moderate or high RCs of TDS or specific conductance were reported in the CDPH database for the Tahoe-Martis study unit (fig. 38A).

However, two of the three wells with high RCs of TDS in the grid well dataset were CDPH wells, but had no TDS or specific conductance data reported in the CDPH database. Of the three wells with high RCs for TDS, one had moderate RC for chloride, and one had high RC for sulfate (fig. 17C).

The high aquifer-scale proportion for TDS in the Central Sierra study unit was 1.4% (spatially weighted; table 8B). The CDPH database reported high and moderate RCs of TDS or specific conductance in several wells in the vicinity of Oakhurst and Ahwanee (figs. 2B, 38B). The high and moderate RCs of TDS or specific conductance were all associated with high or moderate RCs of chloride. No high or moderate RCs of sulfate were reported in the CDPH database.

The high aquifer-scale proportion for TDS in the Southern Sierra study unit was 3.3% (table 8C), and groundwater samples with moderate and high RCs of TDS or specific conductance were collected from the northern and southern portions of the study unit (fig. 38C). A subset of the samples with moderate or high RCs of TDS or specific conductance also had moderate RCs of sulfate (fig. 17C). No high or moderate RCs of chloride were reported.

Factors Affecting Total Dissolved Solids

Higher TDS concentration was significantly associated with location in the Southern Sierra study unit, and lower TDS concentration was significantly associated with location in the Tahoe-Martis study unit (table 10A). TDS concentration had significant positive correlations with agricultural land use, and septic tank density, and significant negative correlations with urban land use, aridity index, elevation, and DO (table 10B). Many of these correlations reflect correlations between the explanatory factors and study unit location (table 6A), and therefore may not indicate causative relations. In the *understanding assessment* dataset, all of the groundwater samples with high RCs of TDS had anoxic or mixed oxic/anoxic oxidation-reduction conditions (table C5, SOSA-35, TTAHO-11, TROCK-12, -13). Anoxic groundwater may be more chemically aggressive because redox reactions in which oxygen is consumed produce hydrogen ions that are then available to participate in hydrolysis or dissolution of minerals.

A

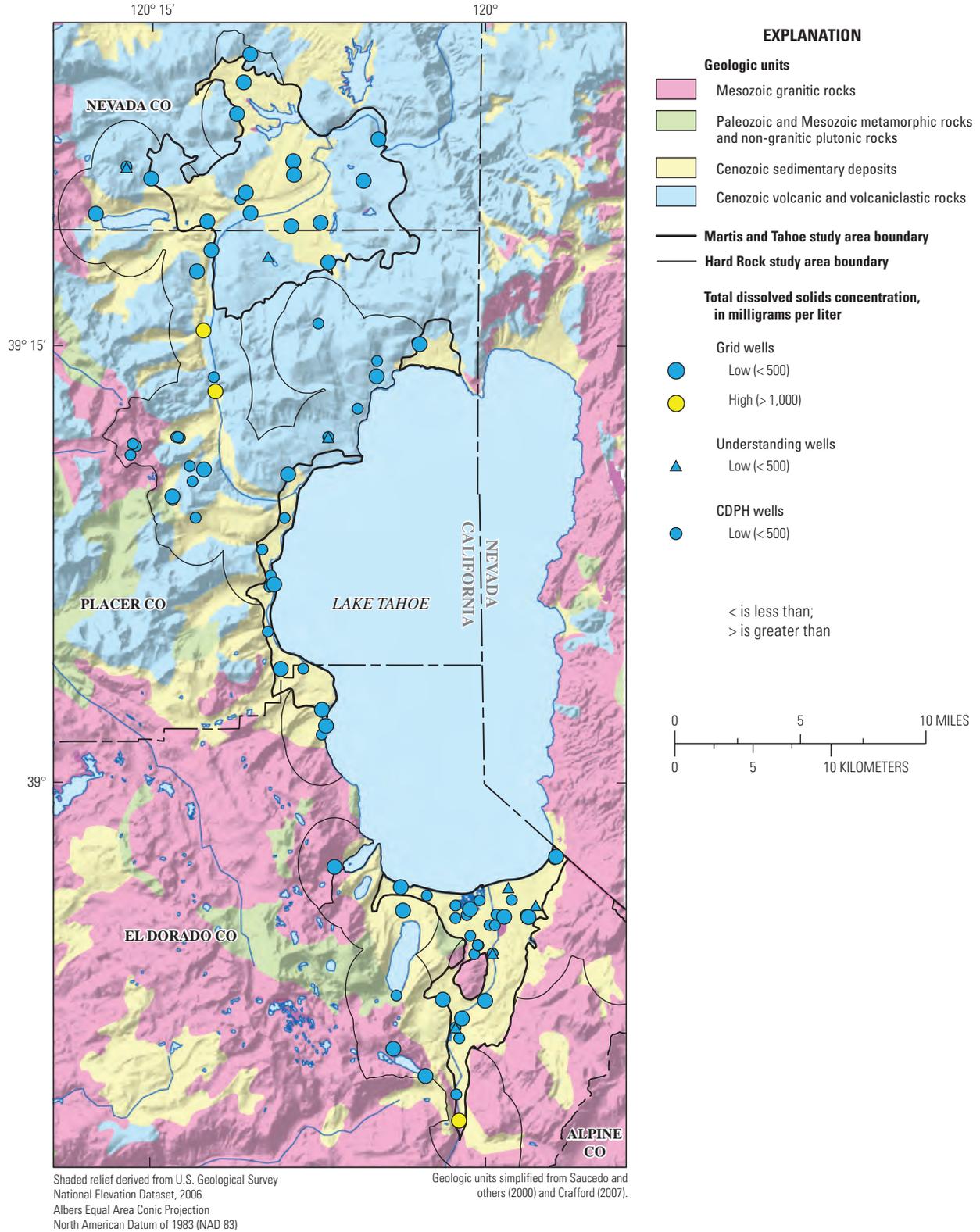


Figure 38. Relative-concentrations of total dissolved solids for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for total dissolved solids during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

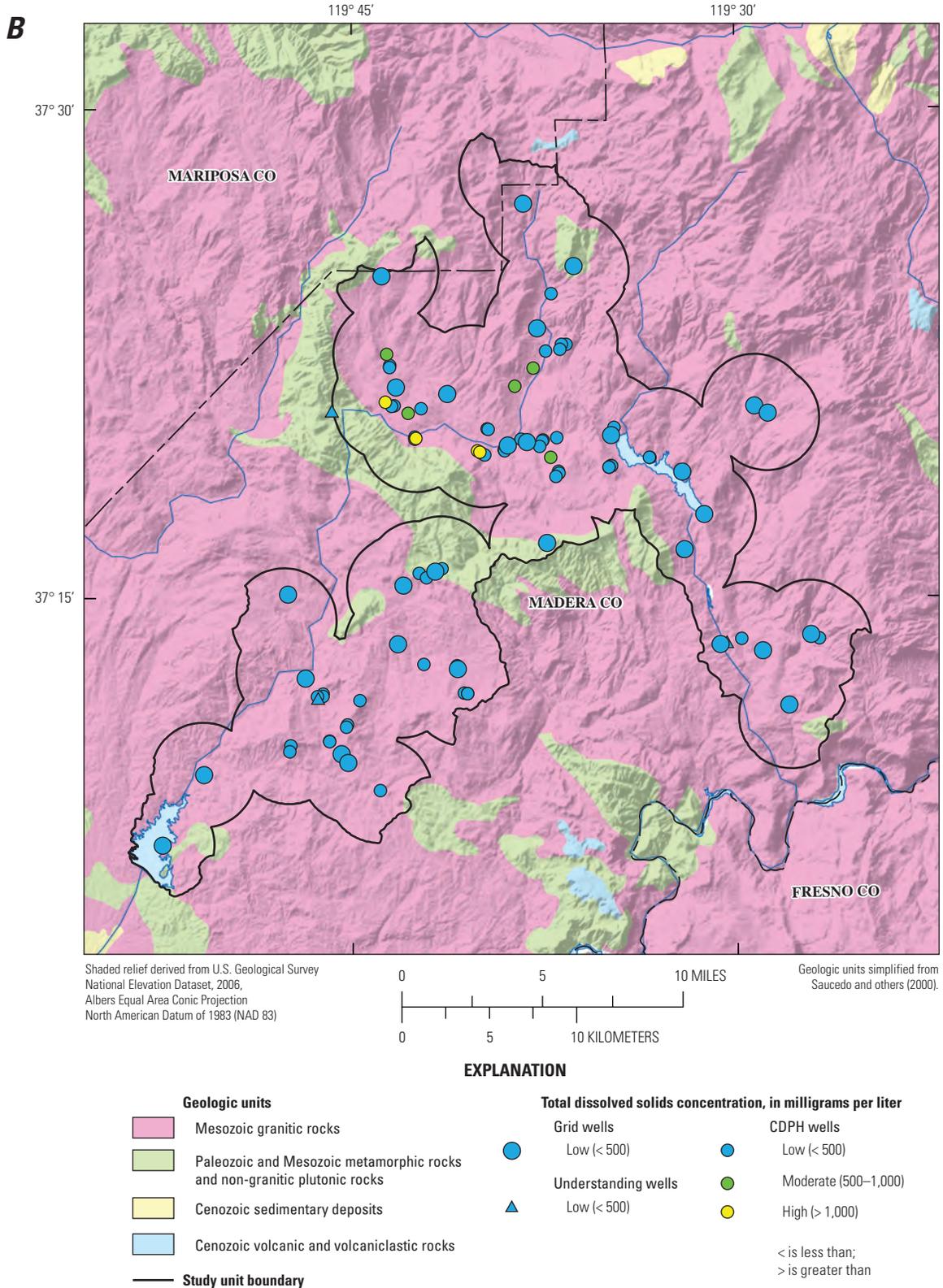


Figure 38.—Continued

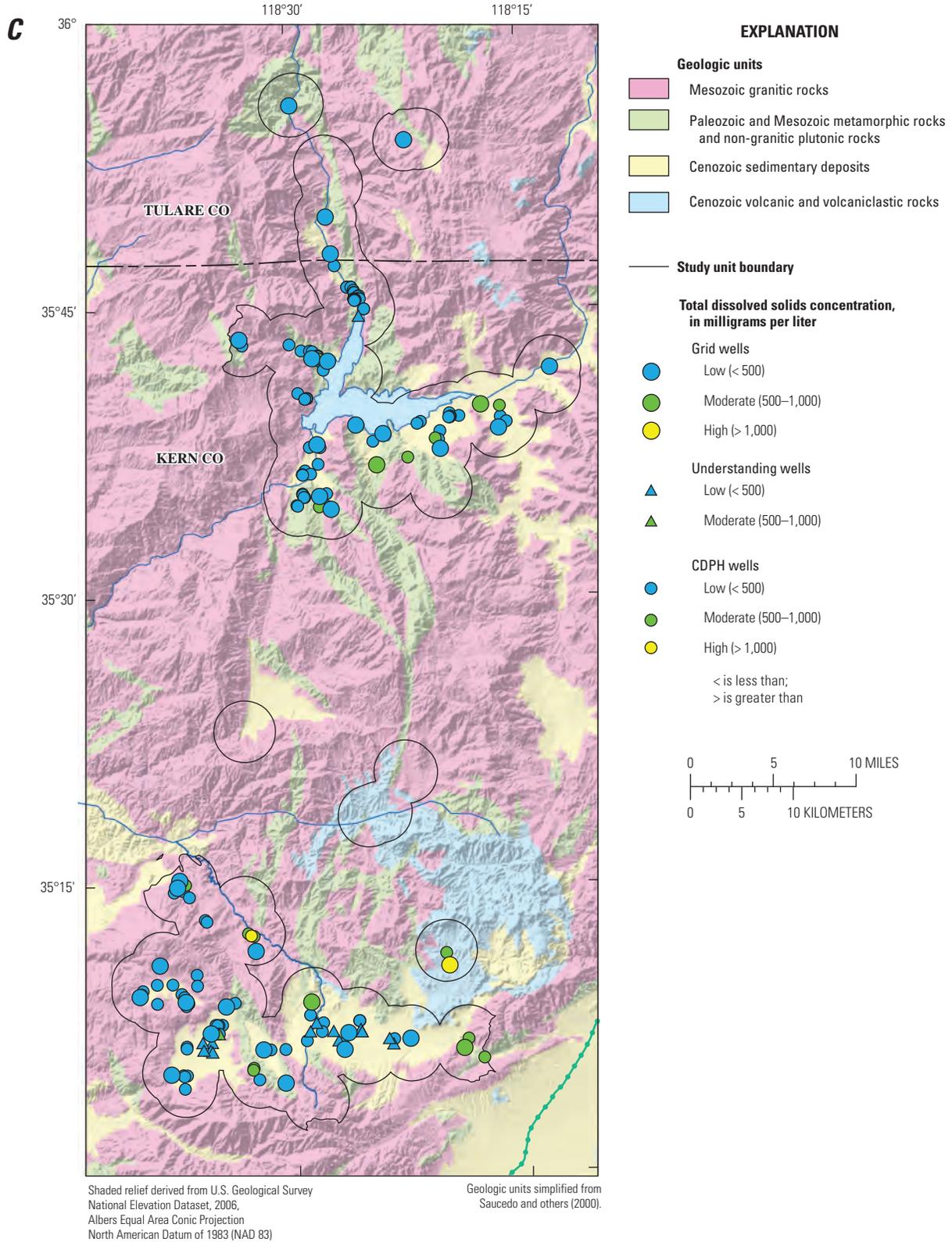


Figure 38.—Continued

In the Central Sierra study unit, high and moderate RCs of TDS were associated with groundwater anion compositions dominated by chloride. All of the samples with moderate or high RCs (>500 mg/L) had anion compositions with >60% chloride and <15% sulfate; however, most groundwater with low RCs of TDS had anion compositions with >75% bicarbonate (fig. 39). The Central Sierra study unit wells with high and moderate RCs of TDS were located in granitic rocks in the vicinities of Ahwanee and Oakhurst (fig. 2B, 38B). This area is near the northern end of a 60-mile long, northwest-trending band of granitic rocks in which some springs and wells yield groundwater with high chloride concentrations compared to most of the groundwater in the region (Mack and Ferrell, 1979; Mack and Schmidt, 1981). All of the data for samples with moderate or high RCs of TDS were from the CDPH database, thus, no groundwater age distribution data are available to evaluate the potential hypothesis that the chloride-rich groundwater is a mixture of meteoric water and connate water derived from metamorphosed Paleozoic and early Mesozoic marine sedimentary rocks beneath the Sierra Nevada batholith (Mack and Ferrell, 1979; Mack and Schmidt, 1981).

In the Southern Sierra study unit, TDS concentration was significantly higher in wells with sedimentary aquifer lithology than in wells with granitic or metamorphic aquifer lithology (Wilcoxon, $p=0.001$). Wells with granitic or metamorphic aquifer lithology typically were located in the hills surrounding the alluvial basins or were relatively deep wells at the margin of the basin where sediment thickness was small. Groundwater from these wells may be representative of water recharging the basins by mountain-front or mountain-block recharge (fig. 3).

For the wells with sedimentary aquifer lithology in the Southern Sierra study unit, TDS concentration was significantly higher in wells with shallower depths to the top of the screened or open interval (Spearman's rho test, $p=0.039$, $\rho=-0.44$), but not significantly associated with groundwater age ($p=0.23$). TDS concentration had a significant positive correlation with percent sulfate in the anions ($p < 0.001$, $\rho=0.57$) (fig. 40). The major ion composition of current State Water Project water (T. Kraus, U.S. Geological Survey, California Water Science Center, written commun., 2010) is not similar to groundwater sampled by CDPH and USGS-GAMA wells (fig. 40), suggesting that artificial recharge in the Tehachapi-Cummings Valley has not yet infiltrated to the depths tapped by the wells. This is in accord with the prevalence of groundwater with pre-modern age distributions (SWP water has modern age distributions).

Factors Affecting Manganese and Iron

Concentrations of iron and manganese in groundwater are strongly influenced by oxidation-reduction conditions in the aquifer, and as such, both had significant negative correlations with DO concentration (table 10B), and a significant positive correlation with each other (Spearman's rho test, $p < 0.001$). Groundwater with low DO was present in all three study units and in wells in all four aquifer lithologies, although the majority of the samples with low DO were from wells with granitic aquifer lithology (fig. 15A). Accordingly, high RCs of manganese were present in all three study units and most commonly present in the Central Sierra study unit (figs. 41A,B,C).

The dominant form of iron in solution can be predicted from the ratio of iron redox species, $\text{Fe}^{+3}/\text{Fe}^{+2}$, 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 arsenic present in the more reduced +2 oxidation state (ferrous iron). Of the 52 samples with detection of iron and data for iron species, the 10 with moderate or high RCs of iron all had $\text{Fe}^{+3}/\text{Fe}^{+2} < 0.08$, and the 42 with low RCs of iron all had $\text{Fe}^{+3}/\text{Fe}^{+2} > 0.25$ (table C5). The greater relative abundance of Fe^{+2} (lower $\text{Fe}^{+3}/\text{Fe}^{+2}$) in samples with moderate or high RCs of iron confirms that elevated iron concentration was indeed associated with reduced conditions. Two of the samples with high or moderate RCs of iron also had DO concentration > 1 mg/L, suggesting that they represented mixtures of oxic and iron-reducing anoxic groundwaters (table C5, TTAHO-12 and CWISH-04).

Of the groundwater samples classified as iron-reducing (iron > 100 $\mu\text{g/L}$), three-quarters were also classified as manganese-reducing (manganese > 50 $\mu\text{g/L}$); however, of the groundwater samples classified as manganese-reducing, only one-half were also classified as iron-reducing. The difference reflects the sequence of terminal electron-accepting processes (TEAP) in which manganese-reduction is energetically more favorable than iron-reduction (McMahon and Chappelle, 2008), and may also reflect relative abundances of iron and manganese oxides available for reduction in specific aquifer types.

Low DO concentration was significantly associated with granitic and metamorphic aquifer lithologies, groundwater with mixed or pre-modern age distributions (table 6A), and higher manganese concentration (table 10B). Higher manganese concentration was significantly associated with granitic aquifer lithology, but manganese concentration was not significantly associated with groundwater age distribution (table 10A). These relations may suggest both residence time and aquifer lithology may be important causative factors for elevated manganese concentrations in groundwater.

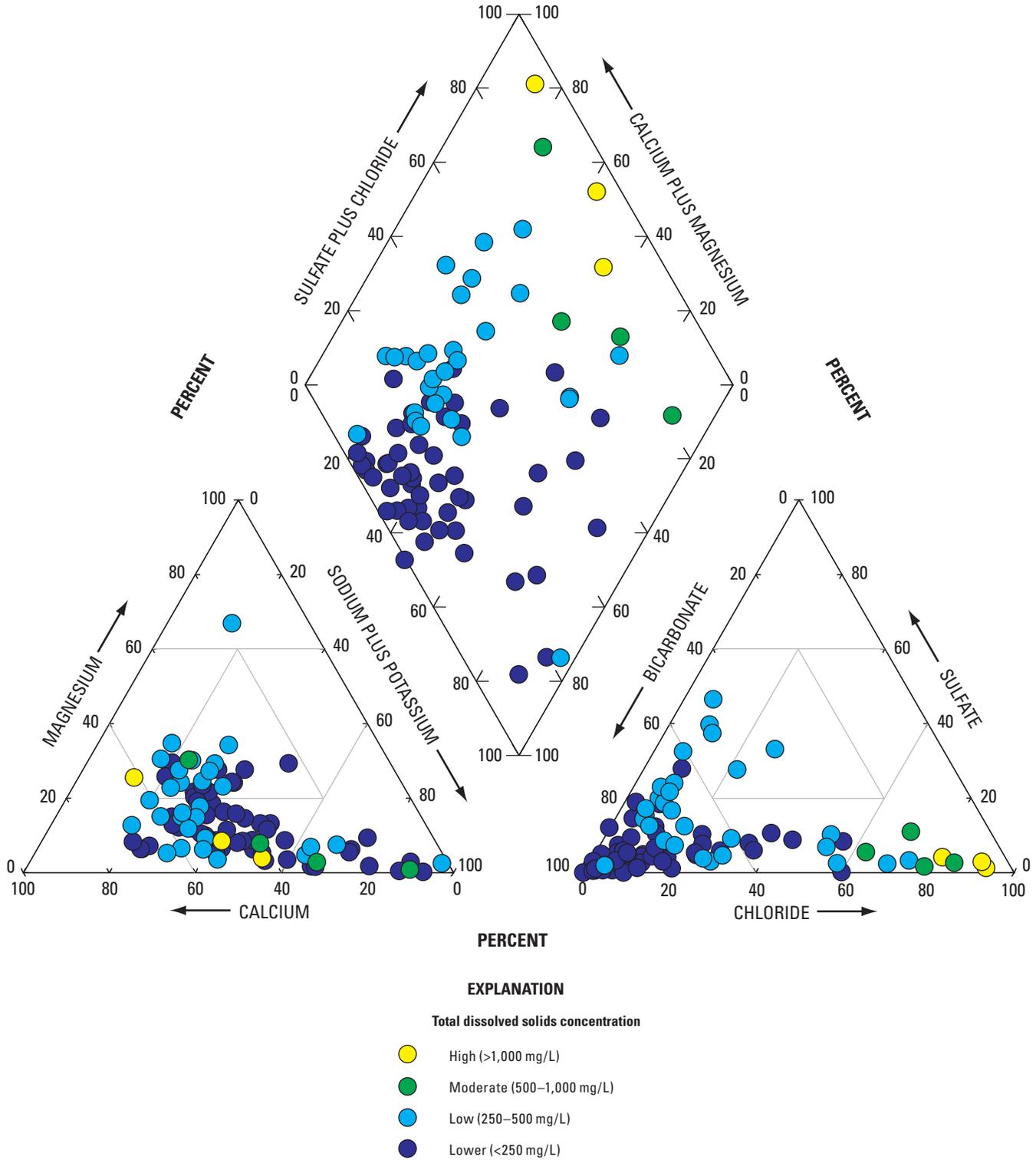


Figure 39. Major-ion composition and total dissolved solids concentration for groundwater samples analyzed by USGS-GAMA or with data in the 3-year interval used in the status assessment in the CDPH database, Central Sierra study unit, California GAMA Priority Basin Project.

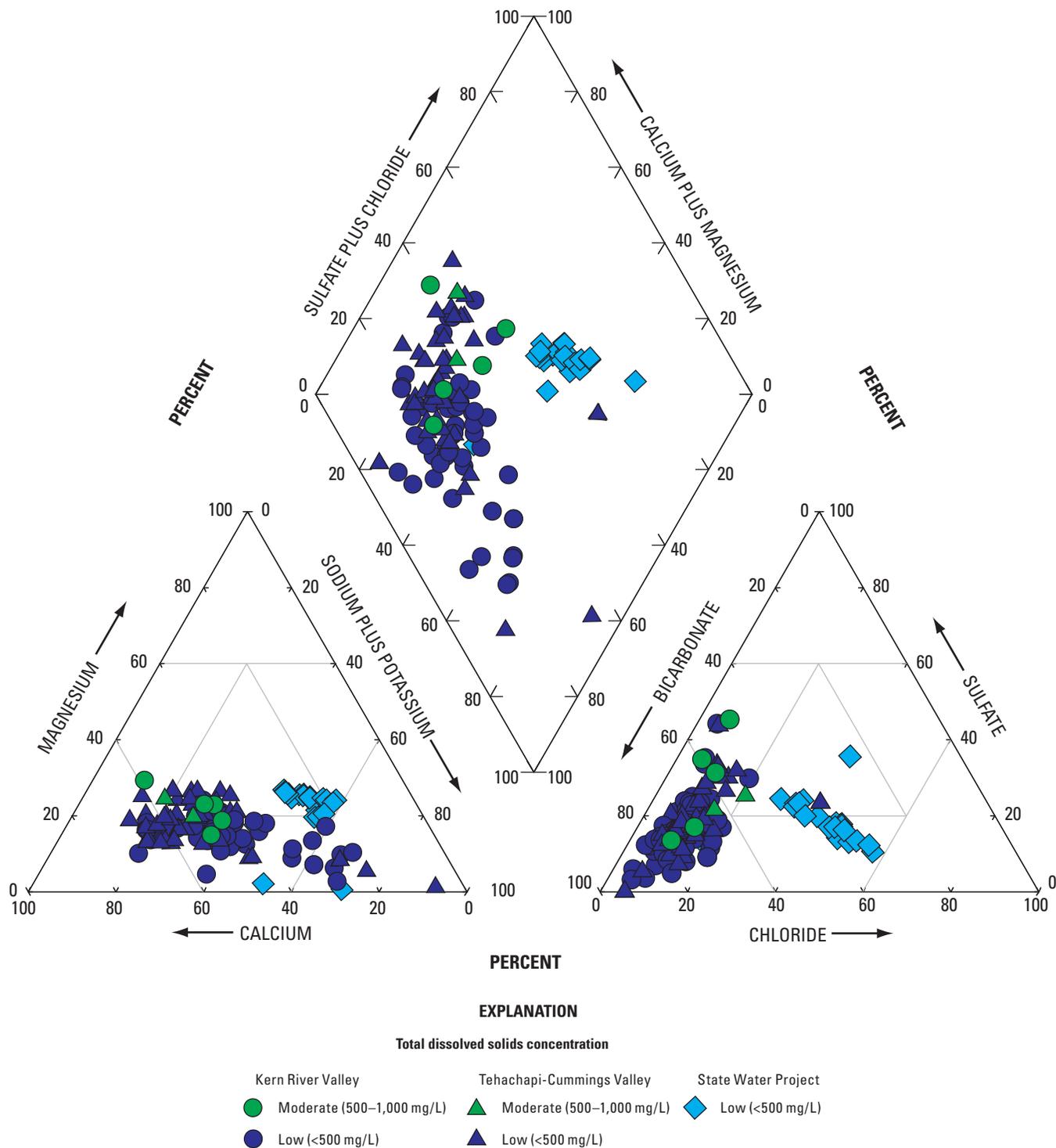


Figure 40. Major-ion composition and total dissolved solids concentration for samples from the State Water Project California Aqueduct and from groundwater samples analyzed by USGS-GAMA or data in the 3-year interval used in the status assessment in the CDPH database, Southern Sierra study unit, California GAMA Priority Basin Project.

A

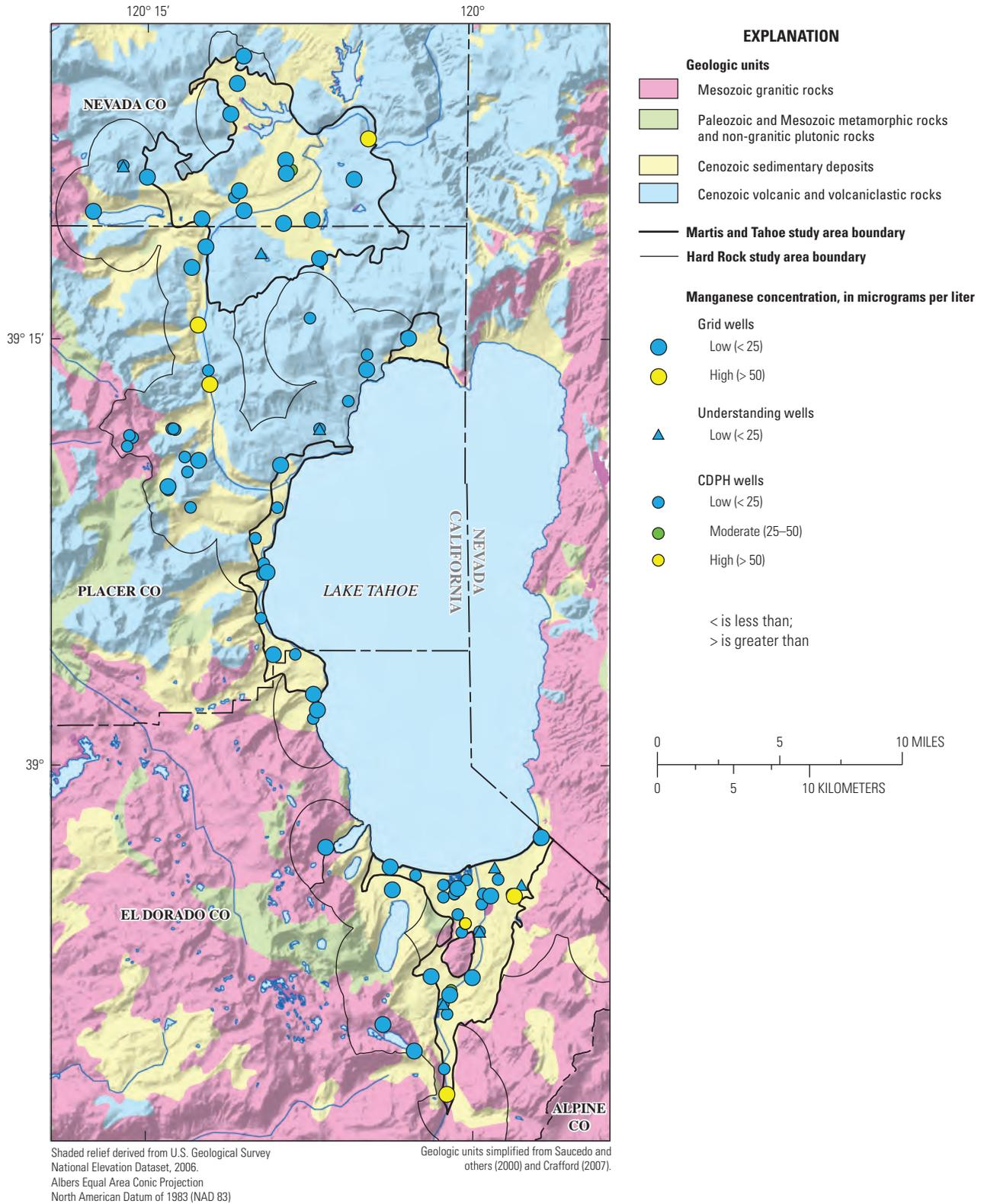


Figure 41. Relative-concentrations of manganese for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for manganese during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

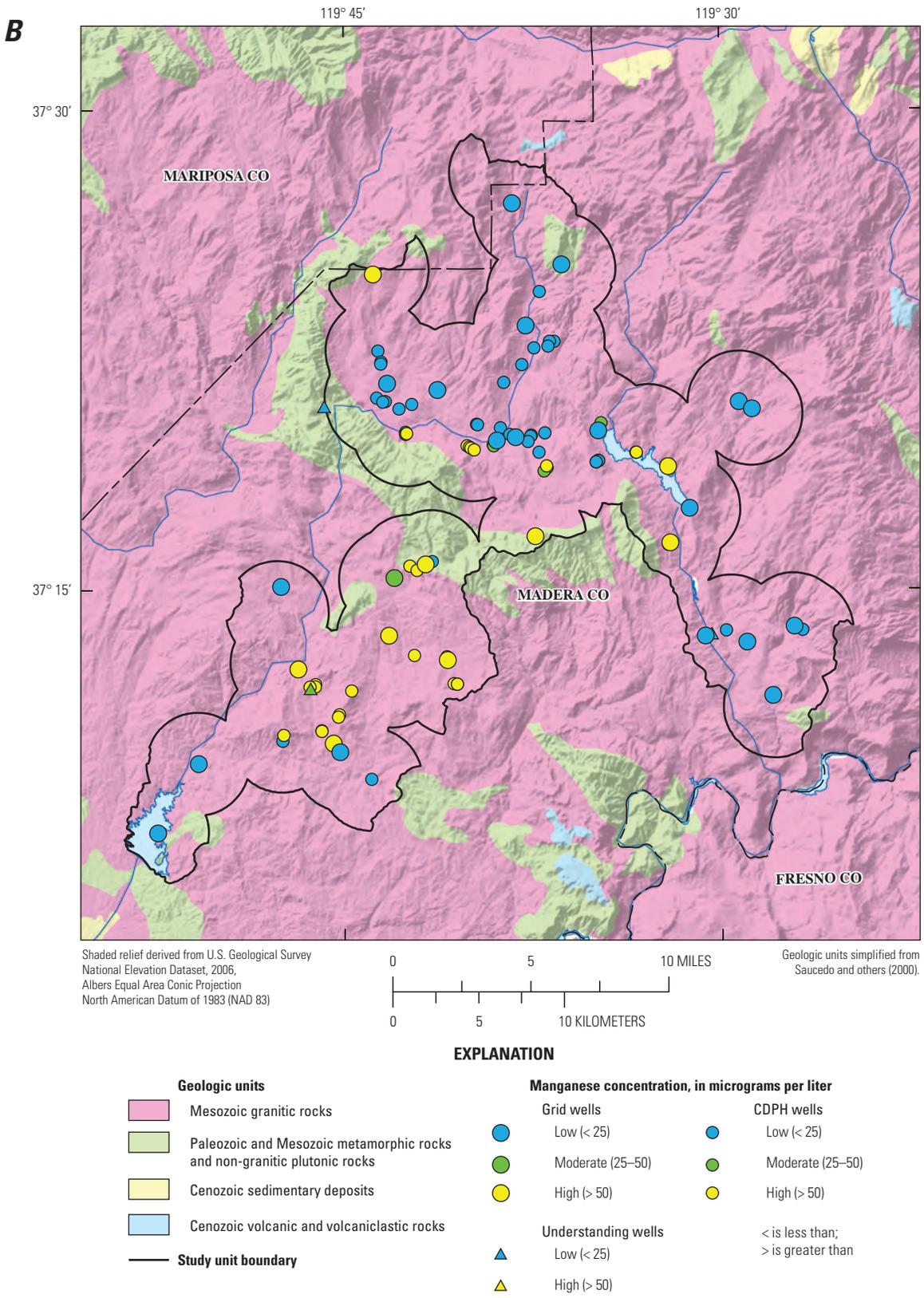


Figure 41.—Continued

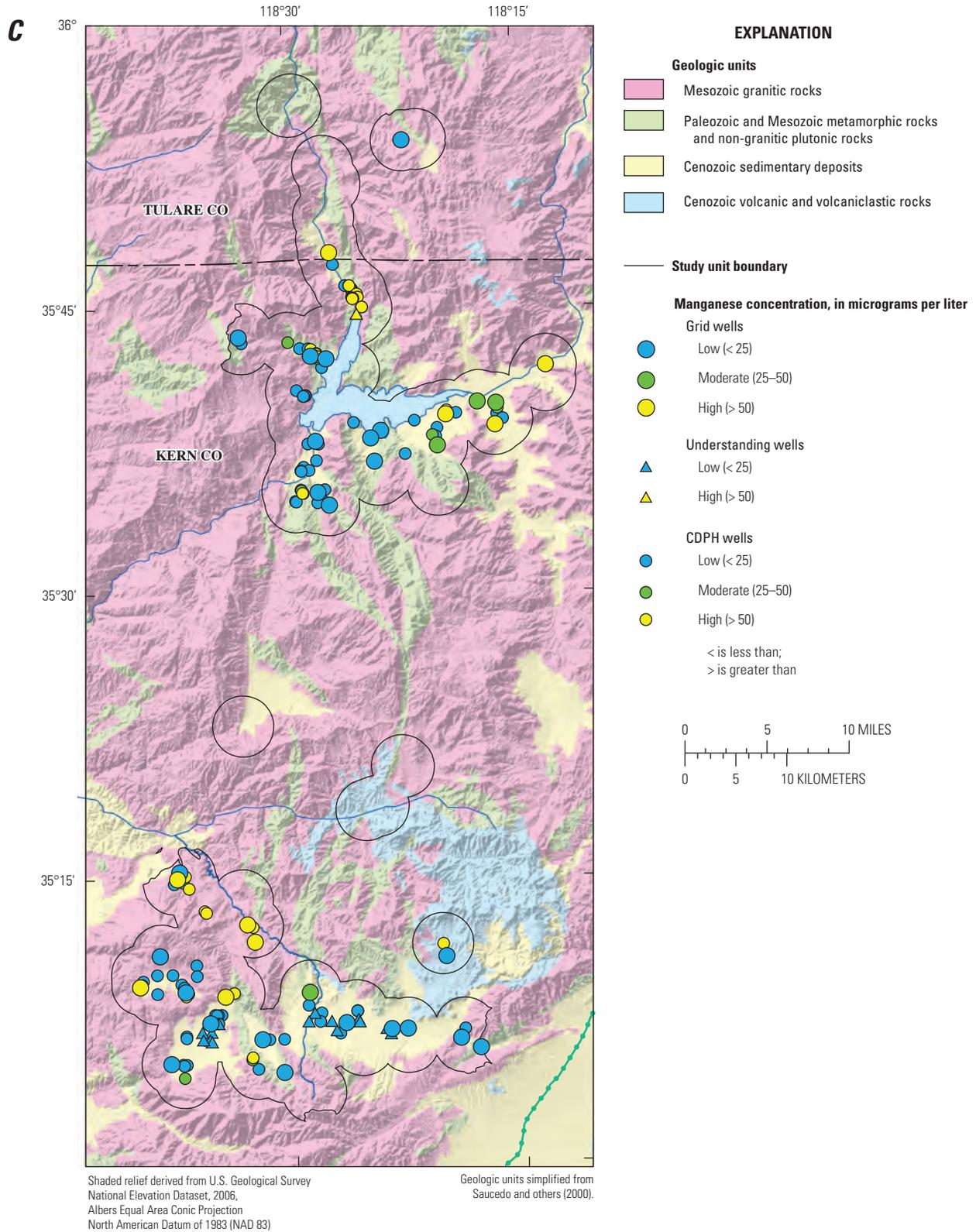


Figure 41.—Continued

Among the samples from wells with granitic aquifer lithology, 60% of samples with pre-modern age had a high RC of manganese, compared to 26% of samples with mixed age, and 10% with modern age (fig. 42). Given sufficiently long residence times, the oxidation state of groundwater in granitic aquifers typically is controlled by the $Fe^{+3} - Fe^{+2}$ redox couple because minerals containing ferrous iron are prevalent in granitic rocks (Gascoyne, 1997; MacQuarrie and Mayer, 2005; Sidborn and Neretnicks, 2007). Biotite typically is most abundant; chlorite, magnetite, pyrite, hornblende, and other ferrous-iron bearing silicates and oxides may also be important. Non-oxidative dissolution of biotite, followed by essentially instantaneous oxidation of the released ferrous iron to ferric iron oxyhydroxides, consumes DO. Oxidation of the iron may be coupled with nitrate reduction, followed by manganese reduction once the DO has been consumed.

Reducing conditions in aquifers with sedimentary lithology typically are produced by consumption of DO by oxidation of sedimentary organic matter (Appelo and Postma, 2005). In the Tahoe-Martis and Southern Sierra study units, approximately 10% of samples with mixed or modern groundwater ages from wells with sedimentary aquifer lithologies had a high RC of manganese, and none of the samples with pre-modern groundwater ages had a high RC of manganese (fig. 42). Absence of reducing conditions, even with long residence times, suggests sediment in the Tahoe Valley and Tehachapi-Cummings Valley basins has relatively low organic matter content.

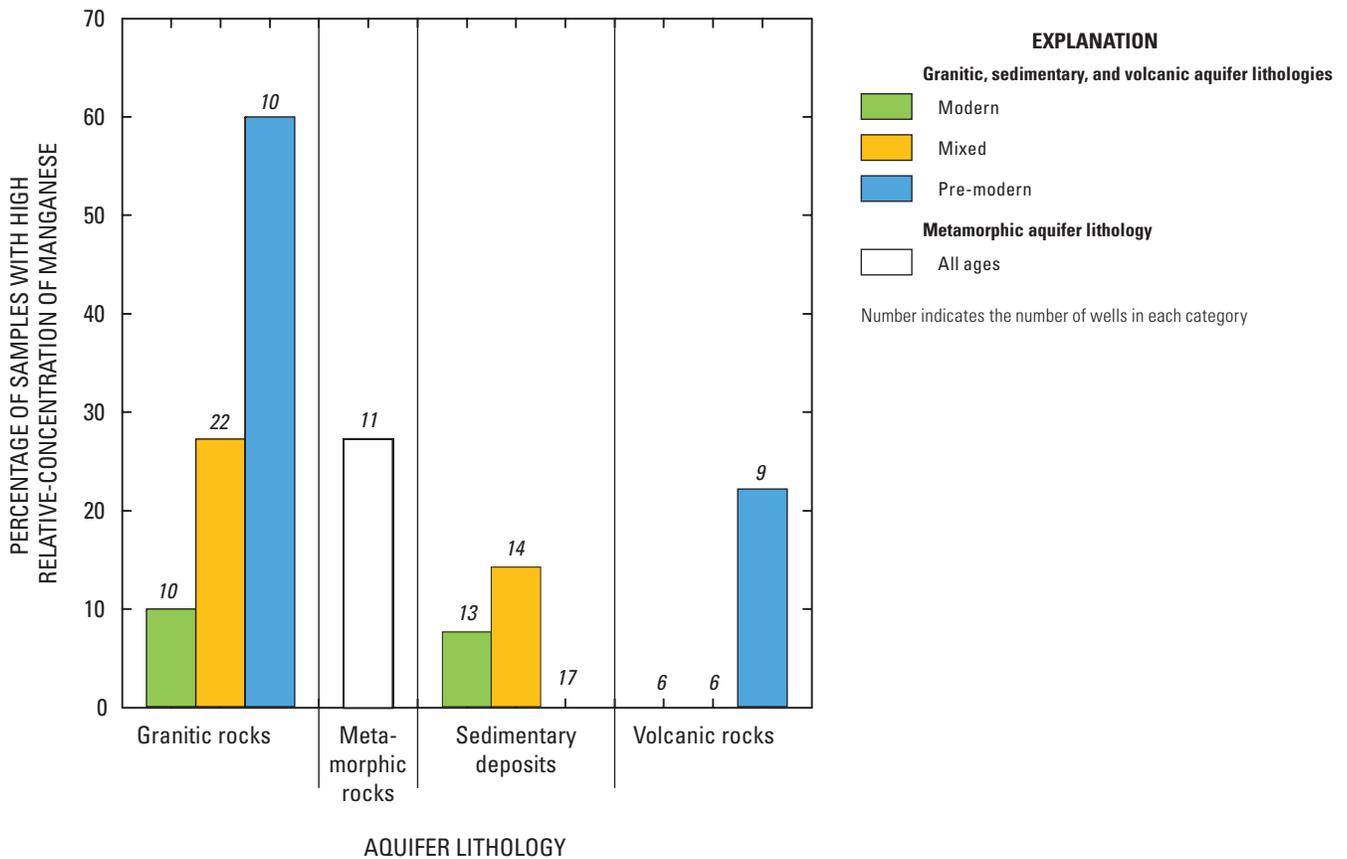


Figure 42. Relations among manganese relative-concentration, aquifer lithology, and groundwater age, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Organic and Special-Interest Constituents

The organic and special-interest constituents are organized by constituent class: volatile organic compounds (VOCs), pesticides, and special interest. VOCs are present in paints, solvents, fuels, fuel additives, refrigerants, fumigants, and disinfected water, and are characterized by their tendency to evaporate. VOCs typically persist longer in groundwater than in surface water because groundwater is 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 three chemically unrelated constituents (perchlorate, *N*-nitrosodimethylamine, and 1,2,3-trichloropropane) that are of interest in California because they have recently been found in groundwater because of recent advances in analytical methods.

USGS-GAMA included analysis of a large number of organic constituents, many of which are not subject to any regulation in drinking water, and used analytical methods with lower detection limits than required for regulatory sampling. In the Tahoe-Martis, Central Sierra, and Southern Sierra study units, however, the vast majority of organic constituents detected were ones already subject to regulation in drinking water. Of the 88 VOCs analyzed, 15 were detected at least once, and of these, 12 have MCL-US or MCL-CA benchmarks (table 7B). Of the 63 pesticides and pesticide degradates analyzed, 7 were detected at least once, and of these, 2 were parent compounds with MCL-US or MCL-CA benchmarks. In all, of the 72 organic constituents with no health-based benchmarks analyzed, 5 were detected in groundwater (table 7B, table 4).

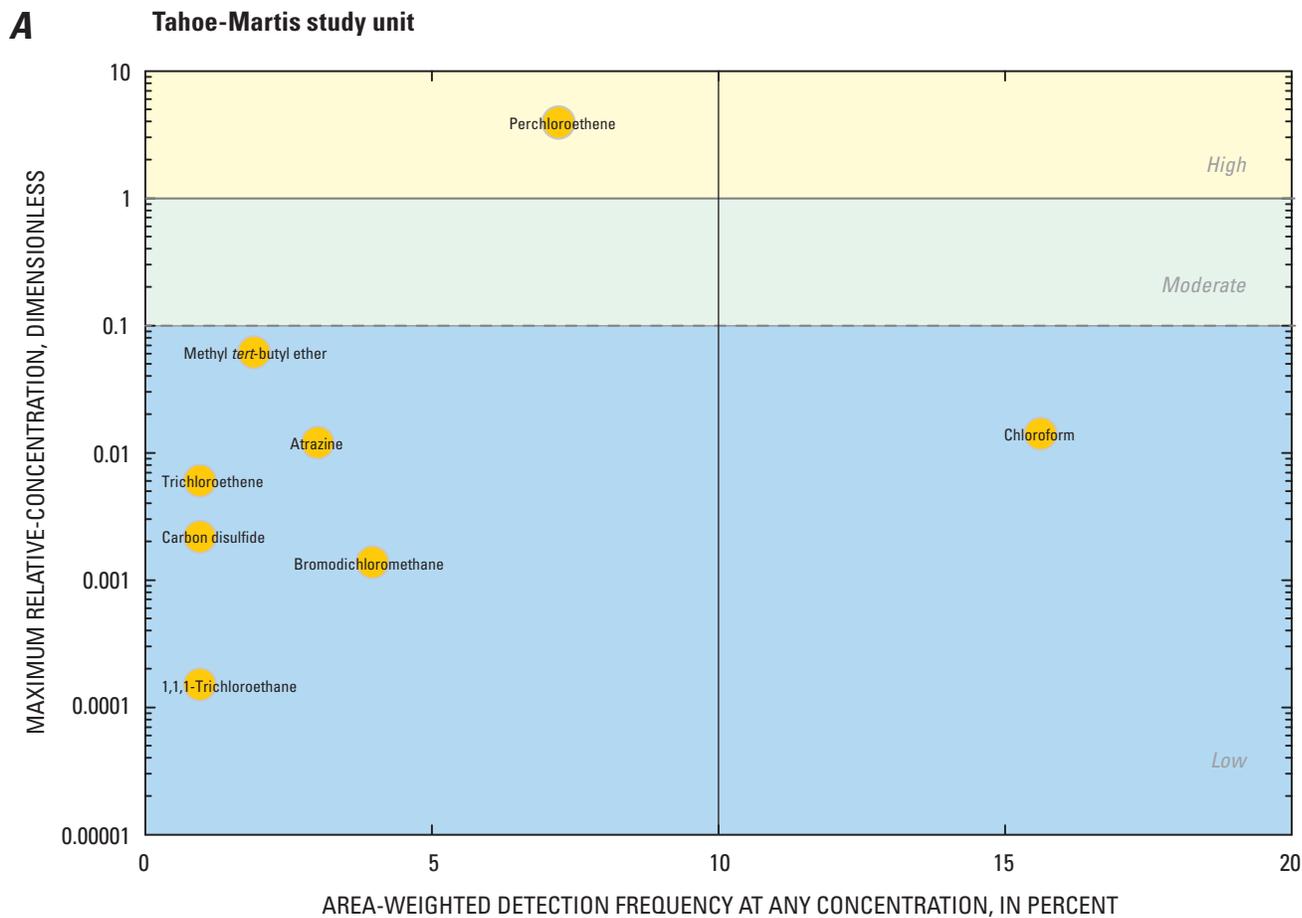
Figures 43A,B,C summarize the study-unit detection frequencies and maximum RCs of organic constituents and constituents of special interest detected in the grid wells for the three study units. In the Tahoe-Martis study unit grid well dataset, two organic constituents met criteria for additional evaluation: perchloroethene (PCE), because it had a maximum RC >1, and chloroform, because it had a study-unit detection frequency >10% (figs. 43A, 44). Six other organic constituents were detected in grid wells at RCs <0.1 and study-unit detection frequencies <10%: methyl *tert*-butyl ether (MTBE), atrazine, bromodichloromethane, trichloroethene (TCE), 1,1,1-trichloroethane, and carbon disulfide (fig. 43A). Five

additional organic constituents were selected for additional evaluation in the *status assessment* because they were reported at RCs >0.1 in the CDPH database during the 3-year interval used for the *status assessment*: carbon tetrachloride, 1,2-dichloroethane, chloromethane, 1,2-dichloropropane, and DBCP (table 3).

In the Central Sierra study unit grid well dataset, three organic constituents met criteria for additional evaluation: benzene, because it had a maximum RC >0.1, and chloroform and simazine, because they had study-unit detection frequencies >10% (figs. 43B, 44). Four other organic constituents were detected in grid wells at RCs <0.1 and study-unit detection frequencies <10%: MTBE, atrazine, PCE, and carbon disulfide (fig. 43B; table 3). MTBE and PCE, and one additional constituent, 1,4-dichlorobenzene, were selected for additional evaluation because they were reported at RCs >0.1 in the CDPH database during the 3-year interval used for the *status assessment* (table 3).

In the Southern Sierra study unit grid well dataset, six organic and special-interest constituents met criteria for additional evaluation in the *status assessment*: carbon tetrachloride and perchlorate, because they had maximum RCs >0.1, and chloroform, PCE, simazine, and atrazine, because they had study-unit detection frequencies >10% (figs. 43C, 44). Five other organic constituents were detected in grid wells at RCs <0.1 and study-unit detection frequencies <10%: MTBE, TCE, trichloroethene (CFC-11), 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113), and prometon (fig. 38C). Three other organic constituents were detected only in understanding wells at RCs <0.1: 1,2-dichlorobenzene, *cis*-1,2-dichloroethene, and 1,2-dichloropropane (tables 3, 4).

Results of the *status assessment* for individual constituents are listed in tables 8A,B,C and for constituent classes in table 9C. Note that the organic constituent class does not include the constituents of special interest. Organic constituents with health-based benchmarks were not present at high RCs in the primary aquifers of the Central Sierra and Southern Sierra study units, and were present in 1.0% of the Tahoe-Martis study unit primary aquifers. Aquifer-scale proportions for moderate RCs of organic constituents were <5% in all three study units. Organic constituents were detected at low RCs in 19, 23, and 37% of the primary aquifers in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively (table 9C).



EXPLANATION

 **Atrazine** Name and center of symbol is location of data

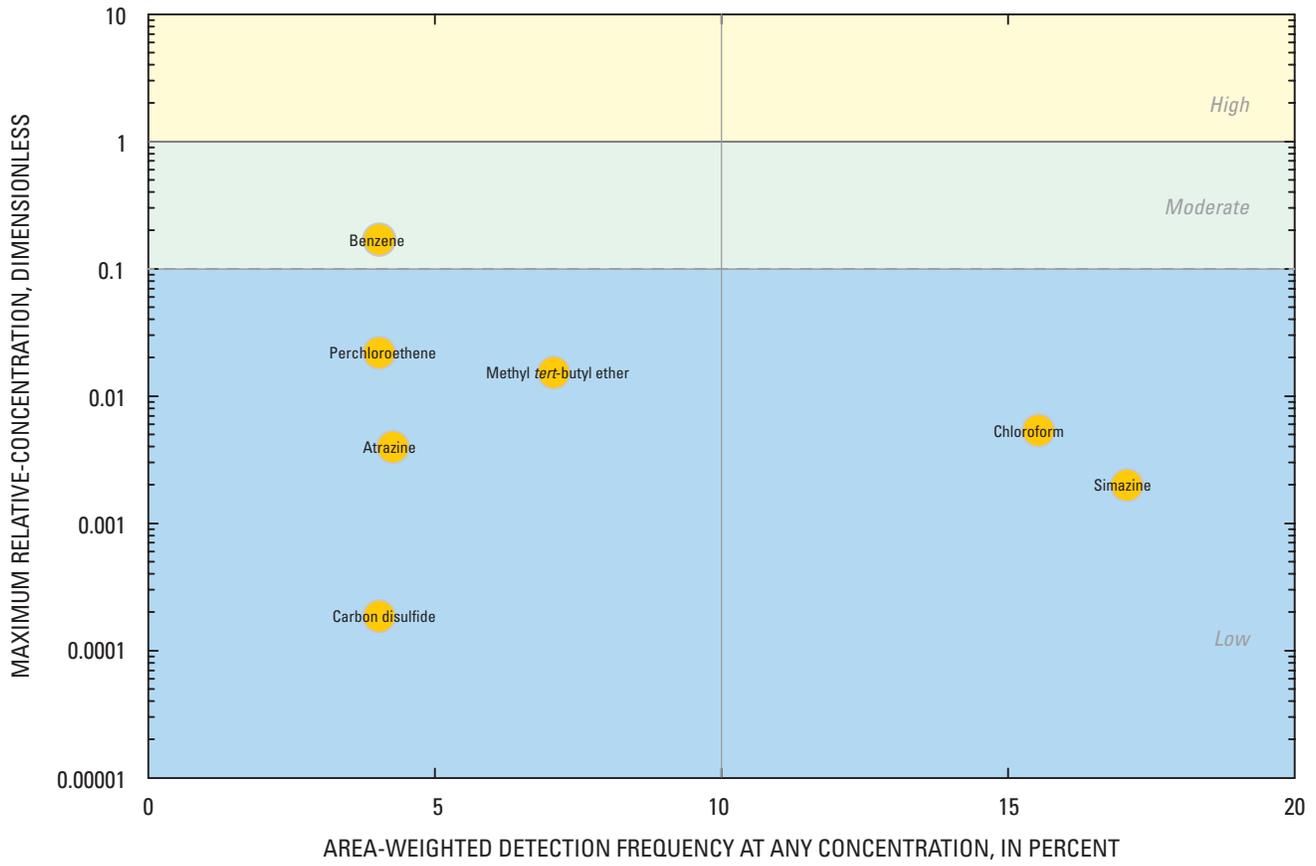
Carbon tetrachloride, 1,2-dichloroethane, 1,2-dichloropropane, and 1,2-dibromo-3-chloropropane each were reported at relative-concentration greater than 1 in one well in the Tahoe-Martis study unit in the California Department of Public Health database for May 1, 2004, to April 30, 2007

Relative-concentration

 Low  Moderate  High

Figure 43. Area-weighted detection frequency and maximum relative-concentration of organic and special-interest constituents detected in USGS-grid wells in the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

B Central Sierra study unit



EXPLANATION

Name and center of symbol is location of data

Relative-concentration

Low Moderate High

Figure 43.—Continued

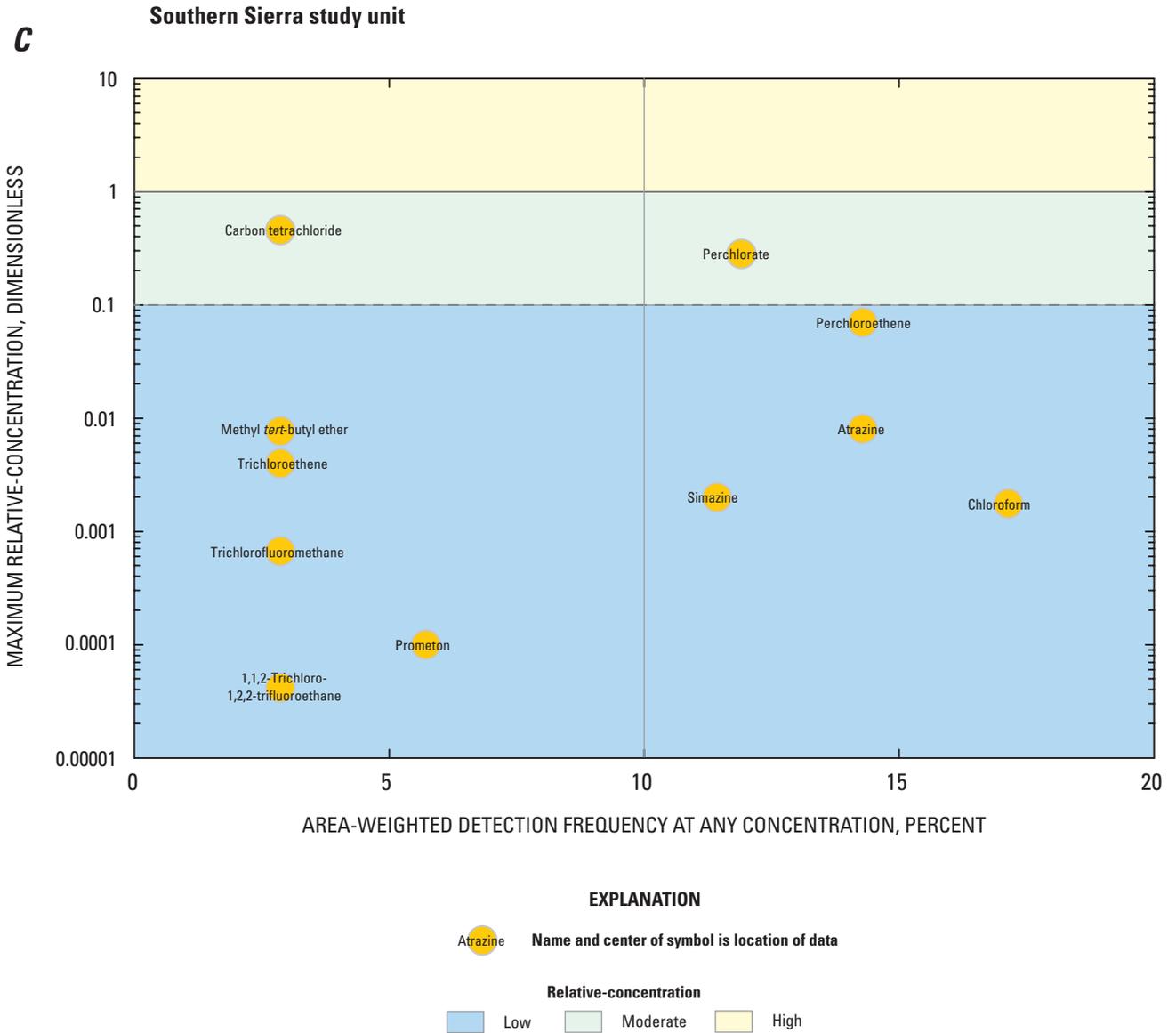


Figure 43.—Continued

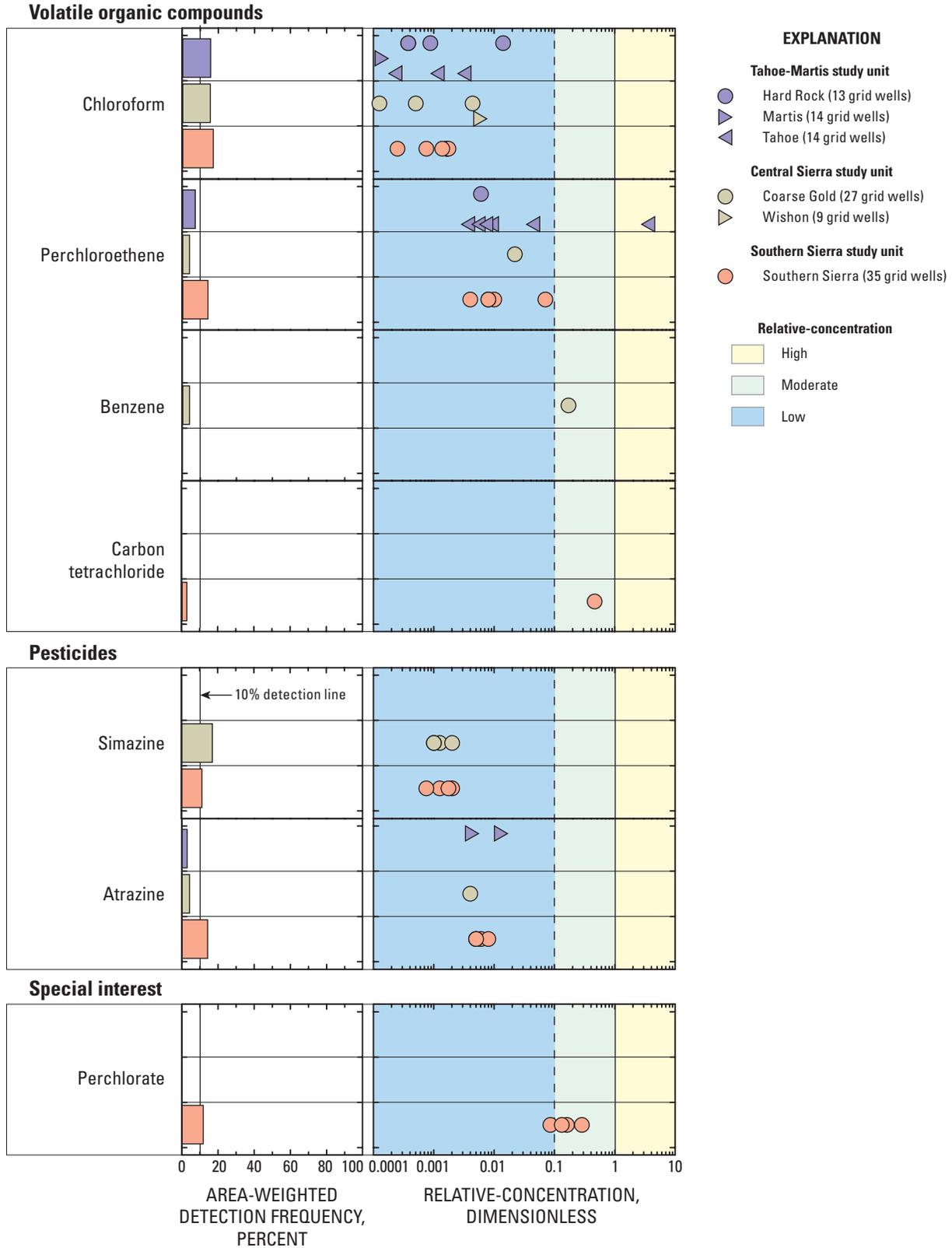


Figure 44. Area-weighted detection frequency and graph of relative-concentrations of organic and special-interest constituents detected in USGS-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Herbicides

Herbicides were not detected at high or moderate concentrations in any of the three study units ([tables 8A,B,C](#); [figs. 45A,B,C](#)). The maximum RC detected was 0.012 (atrazine in the Tahoe-Martis study unit; [fig. 44](#)). No detections of herbicides analyzed by USGS-GAMA were reported in the CDPH databases for the three study units; however, the detection limits for pesticide compounds in the CDPH database are greater than an RC of 0.1 ([fig. 7](#)). No herbicides had a study-unit detection frequency >10% in the Tahoe-Martis study unit. The study-unit detection frequency for simazine was 15% in the Central Sierra study unit, and the detection frequencies for simazine and atrazine in the Southern Sierra study unit were 11 and 15%, respectively ([fig. 44](#)). Ninety-two percent of the samples containing atrazine also contained low concentrations of deethylatrazine, a degradation product of atrazine that does not have a benchmark. Co-occurrence of atrazine and deethylatrazine may reflect the relatively high degree of persistence of atrazine in groundwater environments (Kolpin and others, 1998). Atrazine, deethylatrazine, and simazine were the most frequently detected pesticide compounds in groundwater in major aquifers across the USA (Gilliom and others, 2006). Simazine is most commonly used on orchards and vineyards and on rights-of-way for weed control; atrazine is most commonly used on forage grasses, corn, and managed forests, also for weed control (Kegley and others, 2010).

Factors Affecting Herbicides

Rather than consider atrazine and simazine separately for the *understanding assessment*, concentrations of all herbicides with benchmarks (simazine, atrazine, and prometon) were summed and treated as a constituent class. The presence of herbicides was significantly related to groundwater age ([table 10A](#)). Herbicide detection frequency in samples classified as modern or mixed age was 18%, compared to 0% in samples classified as pre-modern age ([fig. 46](#)). Despite the significant association between modern and mixed-age groundwaters and shallower well depths and depths to top of screened or open interval ([table 6A](#)), herbicides were not significantly related to classified well depth ([table 10A](#)) or significantly correlated to well depth or depth to top of screened or open interval ([table 10B](#)). The absence of the

expected significant correlation between herbicides and any measures of well depth may be because of insufficient data for statistical mass: only 12 of the 17 samples with herbicide detections had sufficient well construction information to classify well depth.

Herbicides had a significant positive correlation with agricultural land use, and a significant negative correlation with undeveloped land use ([table 10B](#); [figs. 47, 48](#)). The positive relation with agricultural land use reflects herbicide occurrence patterns in the Southern Sierra study unit, which is the only study unit with any agricultural land use ([fig. 6A](#)). Eleven of the 17 samples with herbicide detections are from the Southern Sierra study unit ([figs. 45A,B,C](#)), and of those 11, 10 have >5% agricultural land use within the 500-m buffer around the well. When land use and classified groundwater age are used together to stratify the dataset, the interrelations among herbicides, groundwater age, and land use are apparent. The detection frequency of herbicides in samples classified as modern or mixed age from wells with >5% agricultural land use is 66%, which is significantly greater than the detection frequency in pre-modern-age groundwater samples or in modern/mixed-age samples from wells with <5% agricultural land use or in the dataset as a whole (contingency table tests; $p < 0.001$; [fig. 49](#)).

Herbicides were not significantly correlated to either undeveloped or urban land use when only samples with <5% agricultural land use were considered (Spearman's rho test, $p = 0.19$ and $p = 0.16$, respectively). Among samples with <5% agricultural land use, the detection frequency of herbicides was greater in modern/mixed-age groundwater (9%) than in pre-modern-age groundwater (0%), although the difference was not statistically significant (contingency table test; $p = 0.057$; [fig. 49](#)). Simazine and atrazine both have non-agricultural applications, thus, the presence of herbicides in young water from non-agricultural settings is not unexpected.

The significant negative correlations between herbicides and elevation and aridity index, and significant positive correlation with septic tank density ([table 10B](#)) reflect that herbicides were more prevalent in the Central Sierra and Southern Sierra study units than in the Tahoe-Martis study unit ([table 6A](#)). Neither elevation nor septic tank density were significantly correlated to herbicides when samples with >5% agricultural land use were removed.

A

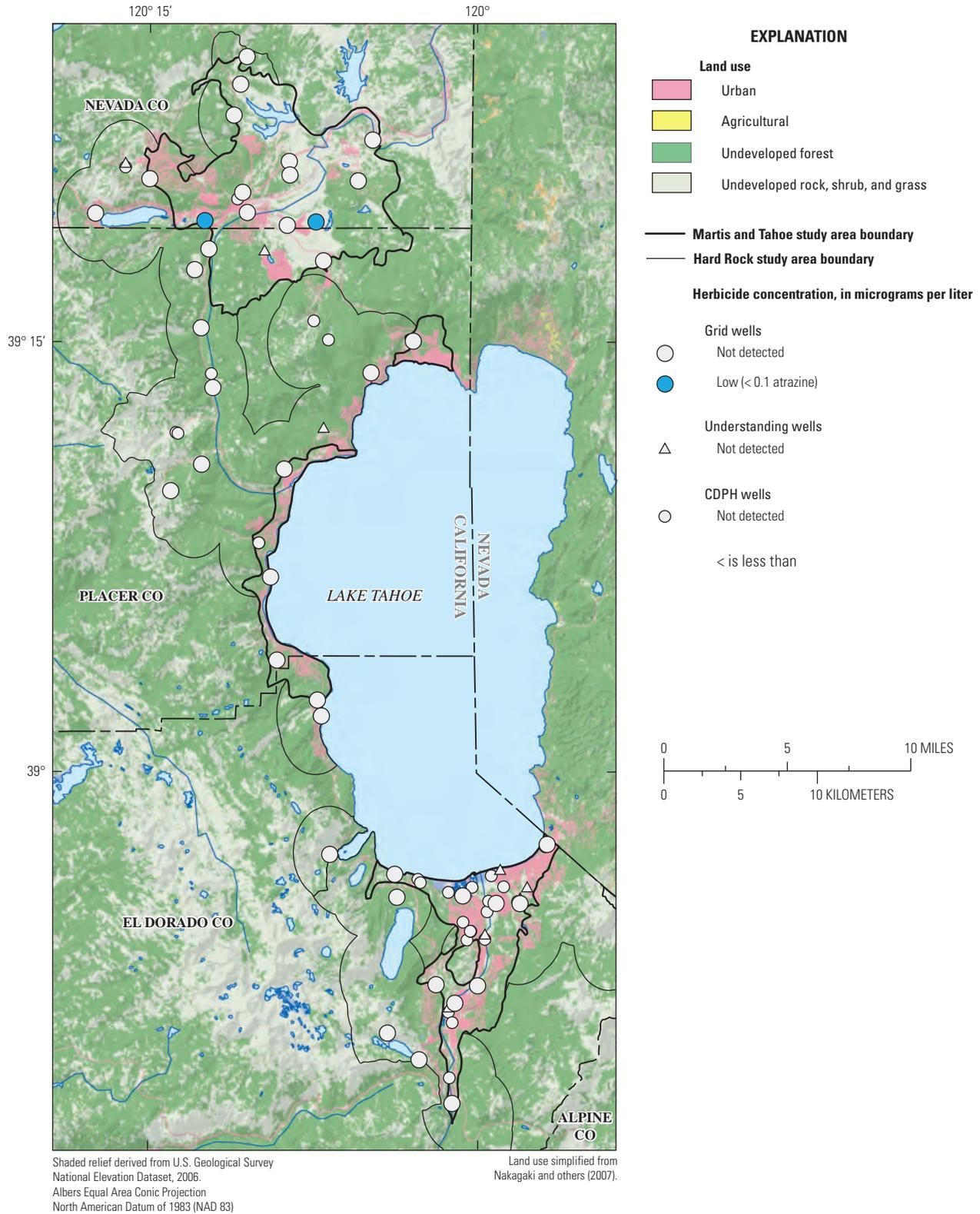


Figure 45. Relative-concentrations of herbicides for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for herbicides during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

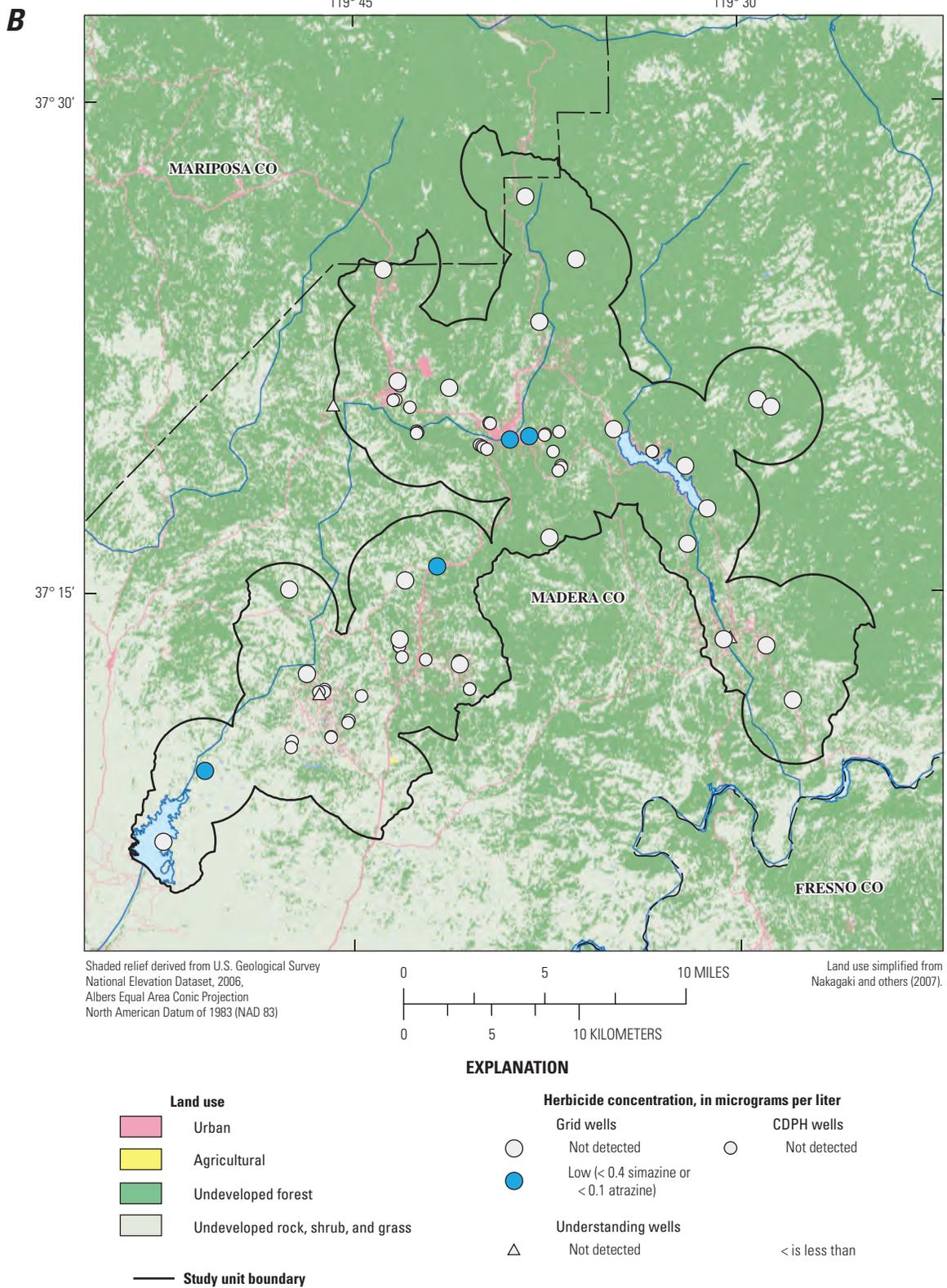


Figure 45.—Continued

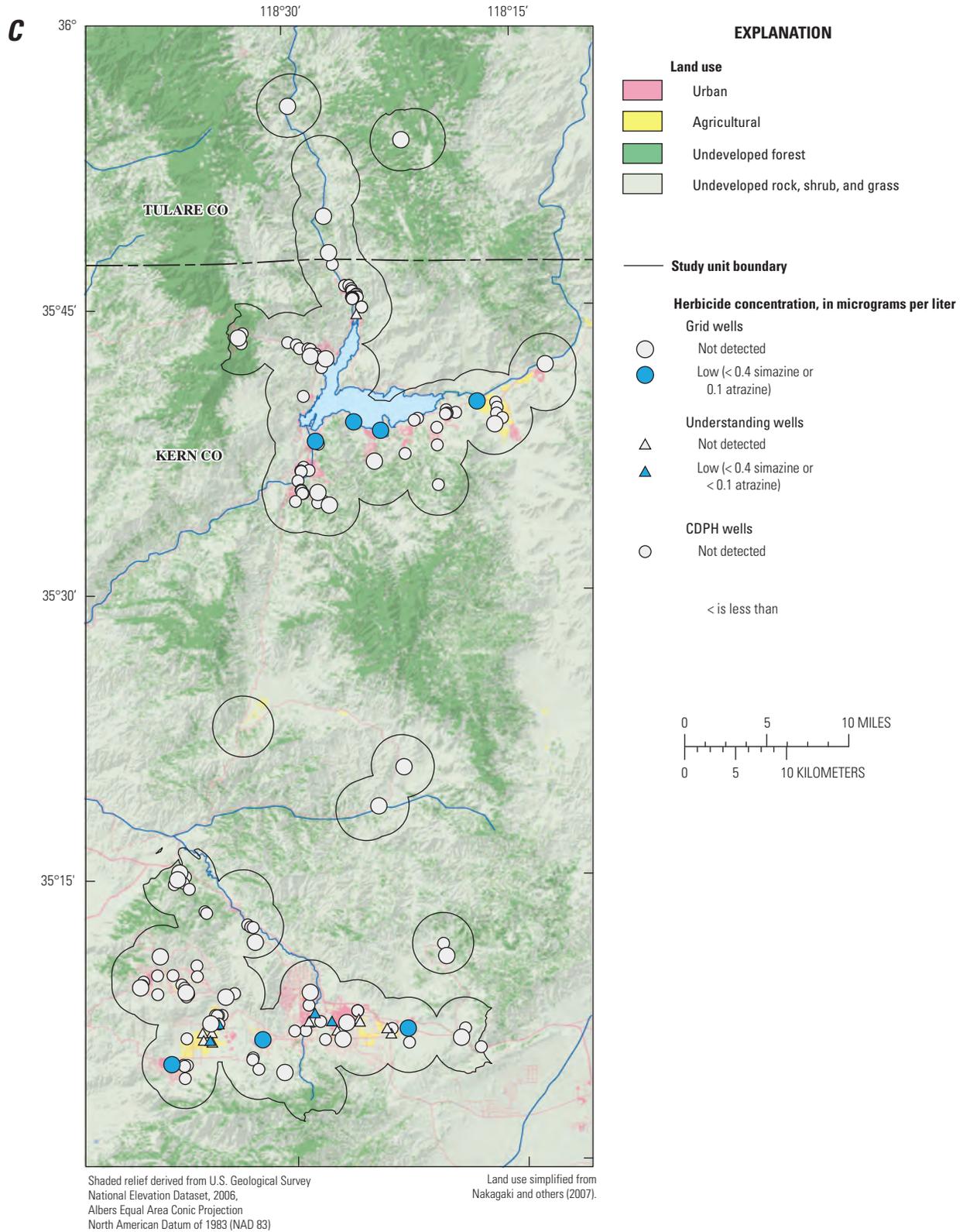


Figure 45.—Continued

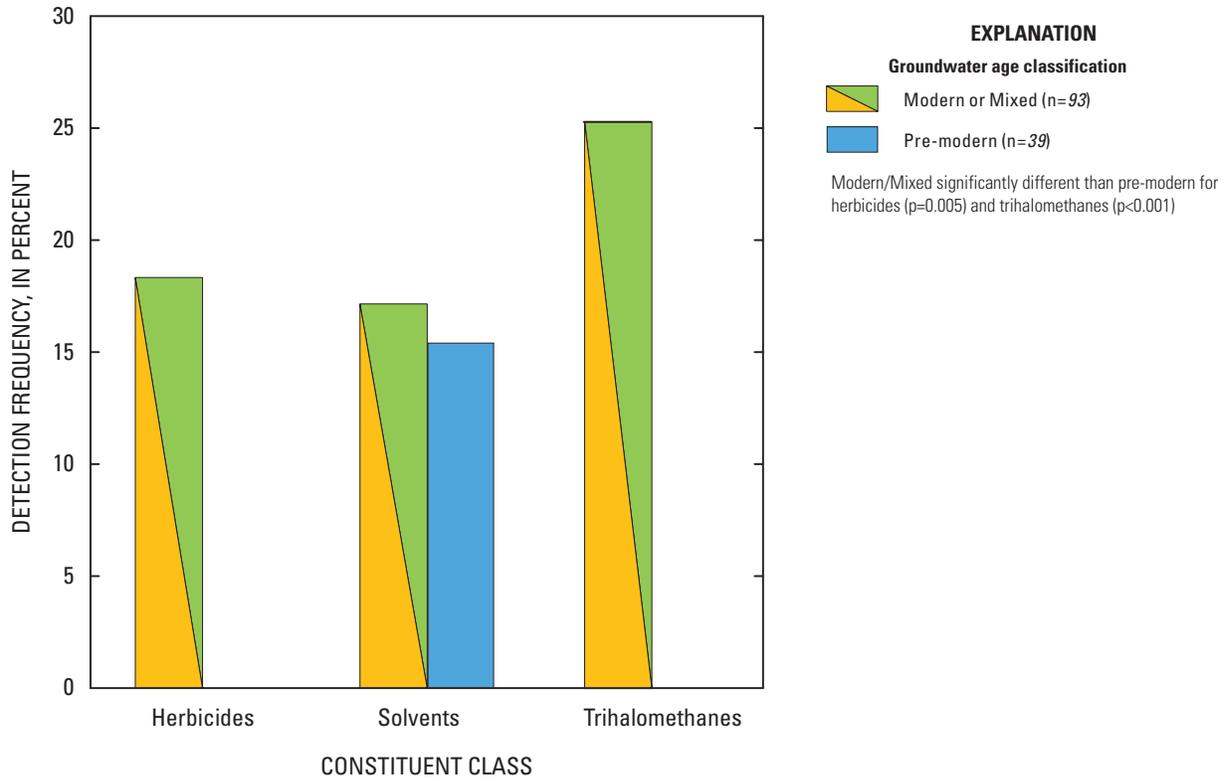
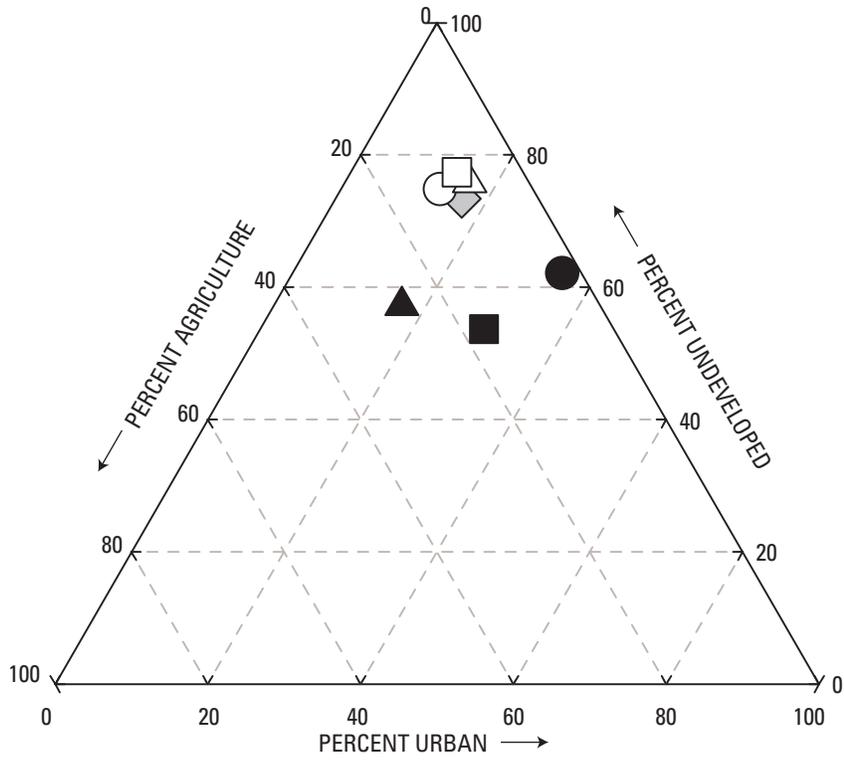


Figure 46. Relations among detection frequencies of herbicides, solvents, and trihalomethanes, and groundwater age class, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.



EXPLANATION

◇ Average land use for all USGS-grid and USGS-understanding wells

Organic constituent

	Herbicides	
	▲ △	
Data point: Average land use for wells with detection		Data point: Average land use for wells with no detection
	Trihalomethanes	
	● ○	
	Solvents	
	■ □	

Figure 47. Average percentages of agricultural, undeveloped, and urban land use in the areas surrounding wells with and without detections of herbicides, solvents, or trihalomethanes, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

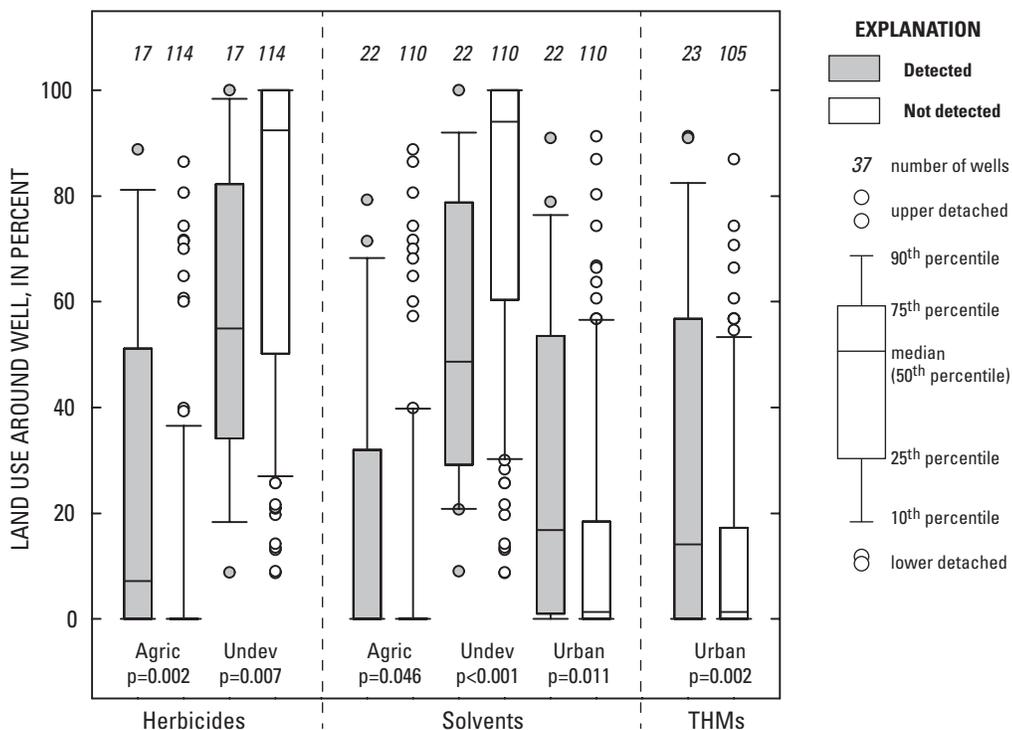
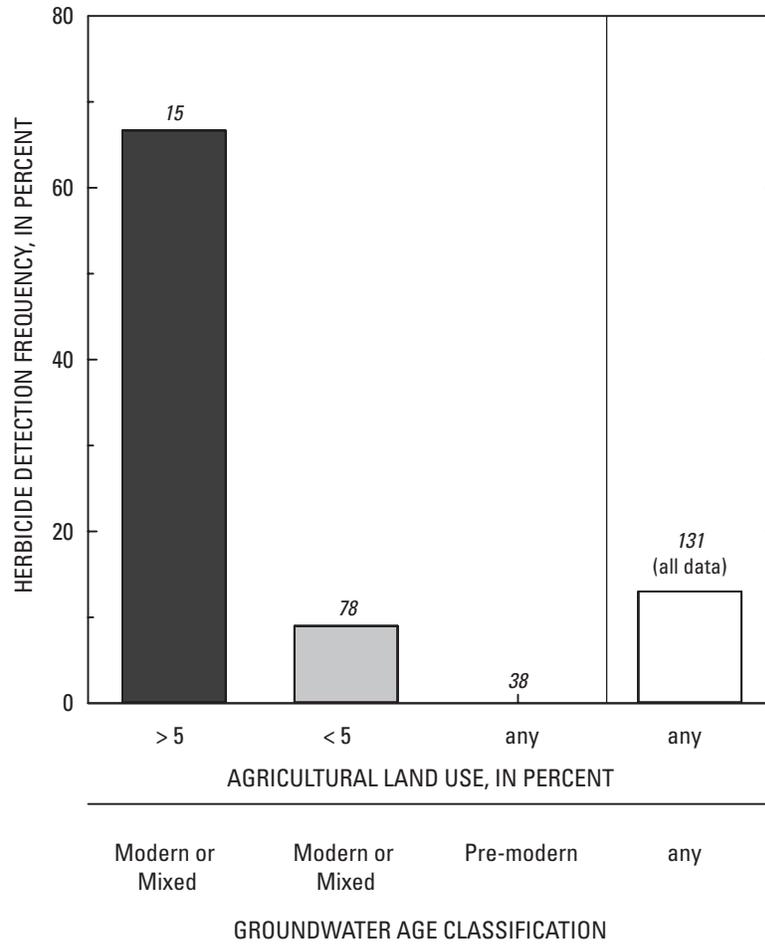


Figure 48. Percentages of agricultural, undeveloped, and urban land use in the areas surrounding wells with and without detections of herbicides, solvents, or trihalomethanes (THMs), Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.



Detection frequencies in the three sub-groups are all significantly different from one another ($p < 0.050$). Number of samples in each group indicated above bar. <, less than; >, greater than

Figure 49. Relation between detection frequency of herbicides and groundwater age and percentage of agricultural land use in the areas surrounding wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Trihalomethanes

Water used for drinking water and other household uses in domestic and public (municipal and community) systems commonly is disinfected with chlorine solutions (bleach). In addition to disinfecting the water, the chlorine reacts with organic matter to produce THMs and other chlorinated and (or) brominated disinfection byproducts.

The study detection frequencies of the THM chloroform were 15, 16, and 17% in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively ([fig. 44](#)). Note that these detection frequencies for the Tahoe-Martis and Central Sierra study units are lower than those reported by Fram and others (2009) and Ferrari and others (2008) for two reasons: (1) four wells with detections of chloroform (one from the TMART, two from the TROCK, and one from the CWISH study areas) were removed from the calculation because the sampling point was downstream from the chlorination point, and (2) the detection frequencies reported here are weighted by the areas of the study areas within the study units ([appendix B](#)). Chloroform is the most commonly detected VOC in groundwater nationally (Zogorski and others, 2006).

The maximum RC measured in the grid well networks for the three study units was 0.014 ([fig. 39](#)). Moderate RCs of chloroform were reported for two wells in the CDPH database for the Central Sierra study unit ([table 8B](#)). Both well sampling points were coded as “untreated” in the database. Because this coding is not necessarily reliable, the spatially weighted moderate aquifer-scale proportions may not be as reliable as the grid-based proportions. The high and moderate aquifer-scale proportions of chloroform in all three study units, calculated using the grid-based method, were zero ([tables 8A,B,C](#)).

Factors Affecting Trihalomethanes

The disinfection byproduct chloroform was the only organic constituent with a detection frequency of >10% in all three study units. Detections of chloroform were not distributed evenly within each of the three study units. In the Tahoe-Martis study unit, chloroform was detected most frequently in the Tahoe Valley South subbasin ([fig. 50A](#)). In the Central Sierra study unit, chloroform was detected more frequently in the CGOLD study area than in the CWISH study area ([fig. 50B](#)). In the Southern Sierra study unit, chloroform was detected more frequently in the Kern River Valley and surrounding watershed than it was in the Tehachapi-Cummings Valleys and surrounding watershed ([fig. 50C](#)).

Two samples with chloroform detections analyzed by USGS-GAMA and a number of samples in the CDPH databases with chloroform detections also had detections

of bromodichloromethane. The MCL-US benchmark for trihalomethanes applies to the sum of the four chlorinated and (or) brominated species. Therefore, the sum of both trihalomethane species was used for the *understanding assessment* rather than the chloroform concentration alone.

THM concentration was significantly correlated with percentage of urban land use ([table 10B](#); [figs. 47, 48](#)). Nationally, THMs have also been strongly correlated with percentage of urban land use (Zogorski and others, 2006). Potential urban sources of THMs include recharge from landscape irrigation with disinfected water, leakage from water distribution systems, and industrial and commercial usage of chlorinated disinfectants and reagents (Ivahnenco and Barbash, 2004). However, 9 of the 23 samples with detections of THMs had <10% urban land use, suggesting that other explanatory factors were also important.

The samples were divided into groups by groundwater age class (pre-modern or modern/mixed), percentage of urban land use (greater than or less than 10%), and septic tank density (greater than or less than 7 tanks/km²). The three groups with modern/mixed age groundwater and either urban land use >10% or septic tank density >7 tanks/km² or both had THM detection frequencies of 33–50% ([fig. 51](#)). THM detection frequencies in samples with pre-modern groundwater (0%) or with modern/mixed groundwater, urban land use <10%, and septic tank density <7 tanks/km² (4.6%) were significantly lower (contingency tests, $p < 0.004$). These results suggest septic systems may be a source of THMs to groundwater. However, the increased detection frequency of THMs in groundwater from non-urbanized areas with higher density of septic tanks may also be because of differences in well maintenance procedures. Shock chlorination is a recommended procedure for treatment of bacterial contamination and odor problems in domestic wells, and may result in a reservoir of chlorinated water in the well bore and surrounding aquifer material (Seiler, 2006). Small systems, such as schools, campgrounds, restaurants, small community associations, and domestic well owners, may be more likely to maintain their wells following guidelines for domestic wells than are large systems, such as municipalities.

THM concentration was significantly greater in wells with metamorphic aquifer lithology compared to any of the other aquifer lithology categories ([table 10A](#)). However, wells with metamorphic aquifer lithology did not have significantly higher percentages of urban land use or occurrence of younger water—two factors that are significantly correlated with THM concentration—suggesting that another factor was also important. Wells with metamorphic aquifer lithology had significantly higher densities of septic tanks in the 500-m buffers around the wells compared to wells with all other aquifer lithologies ([table 6A](#)).

A

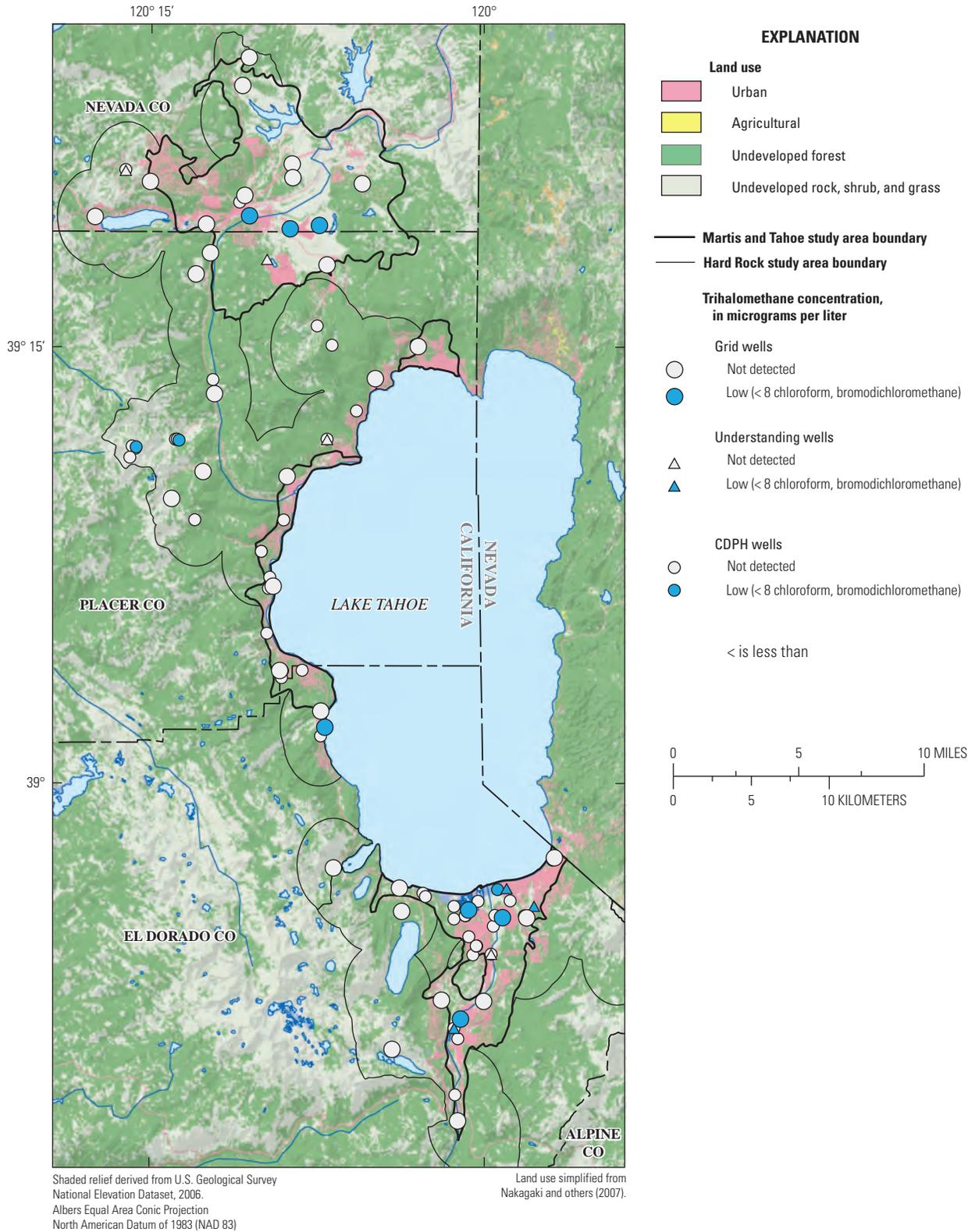
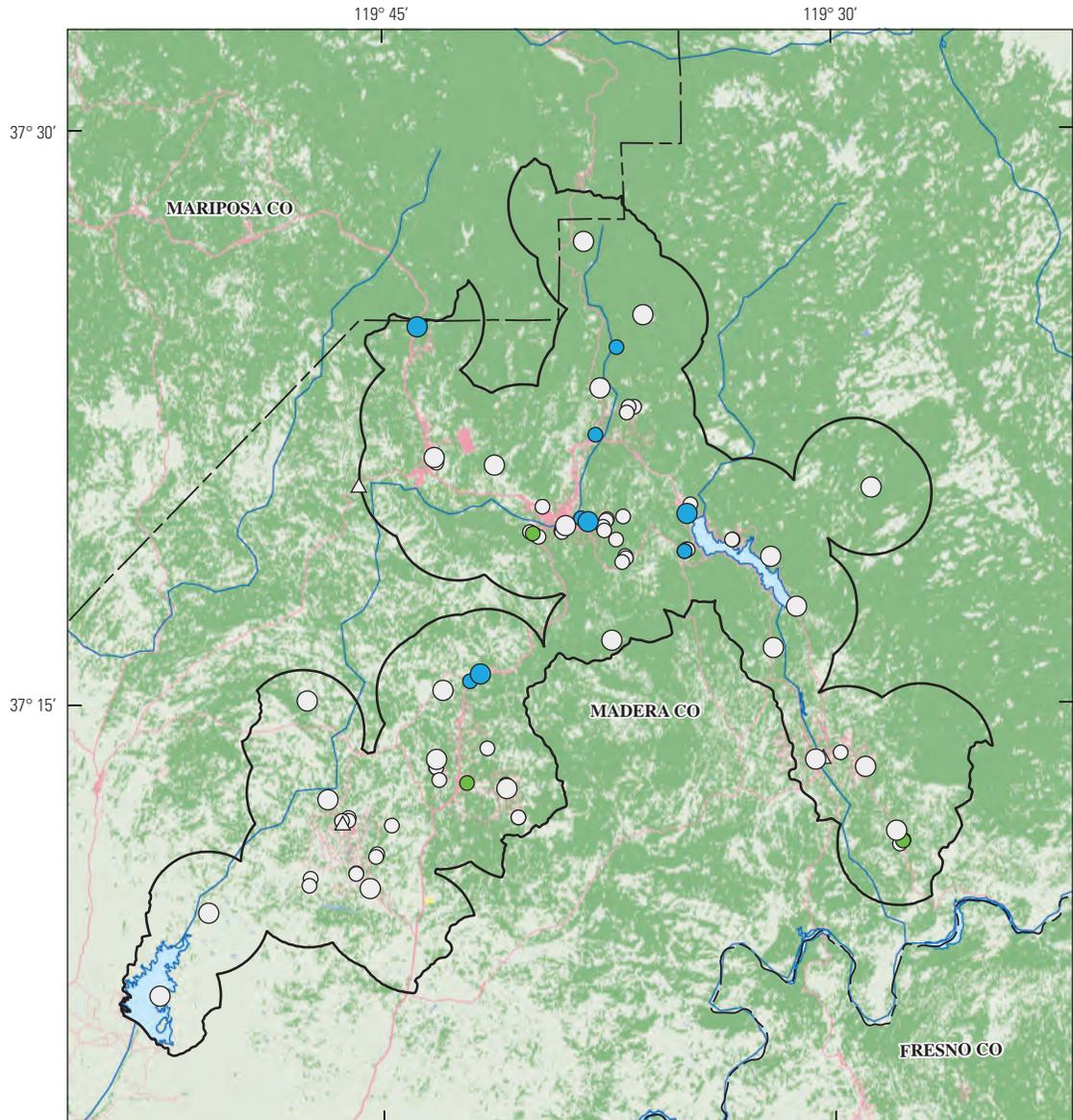


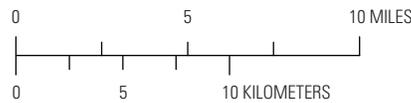
Figure 50. Relative-concentrations of trihalomethanes for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for trihalomethanes during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

B



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

Land use simplified from Nakagaki and others (2007).



EXPLANATION

- Land use**
- Urban
 - Agricultural
 - Undeveloped forest
 - Undeveloped rock, shrub, and grass
- Study unit boundary**
-

- Trihalomethane concentration, in micrograms per liter**
- | | |
|---|---|
| <p>Grid wells</p> <ul style="list-style-type: none"> Not detected Low (< 8 chloroform) <p>Understanding wells</p> <ul style="list-style-type: none"> Not detected | <p>CDPH wells</p> <ul style="list-style-type: none"> Not detected Low (< 8 chloroform or bromodichloromethane or dibromochloromethane or bromoform) Moderate (8–80 chloroform) |
|---|---|
- < is less than

Figure 50.—Continued

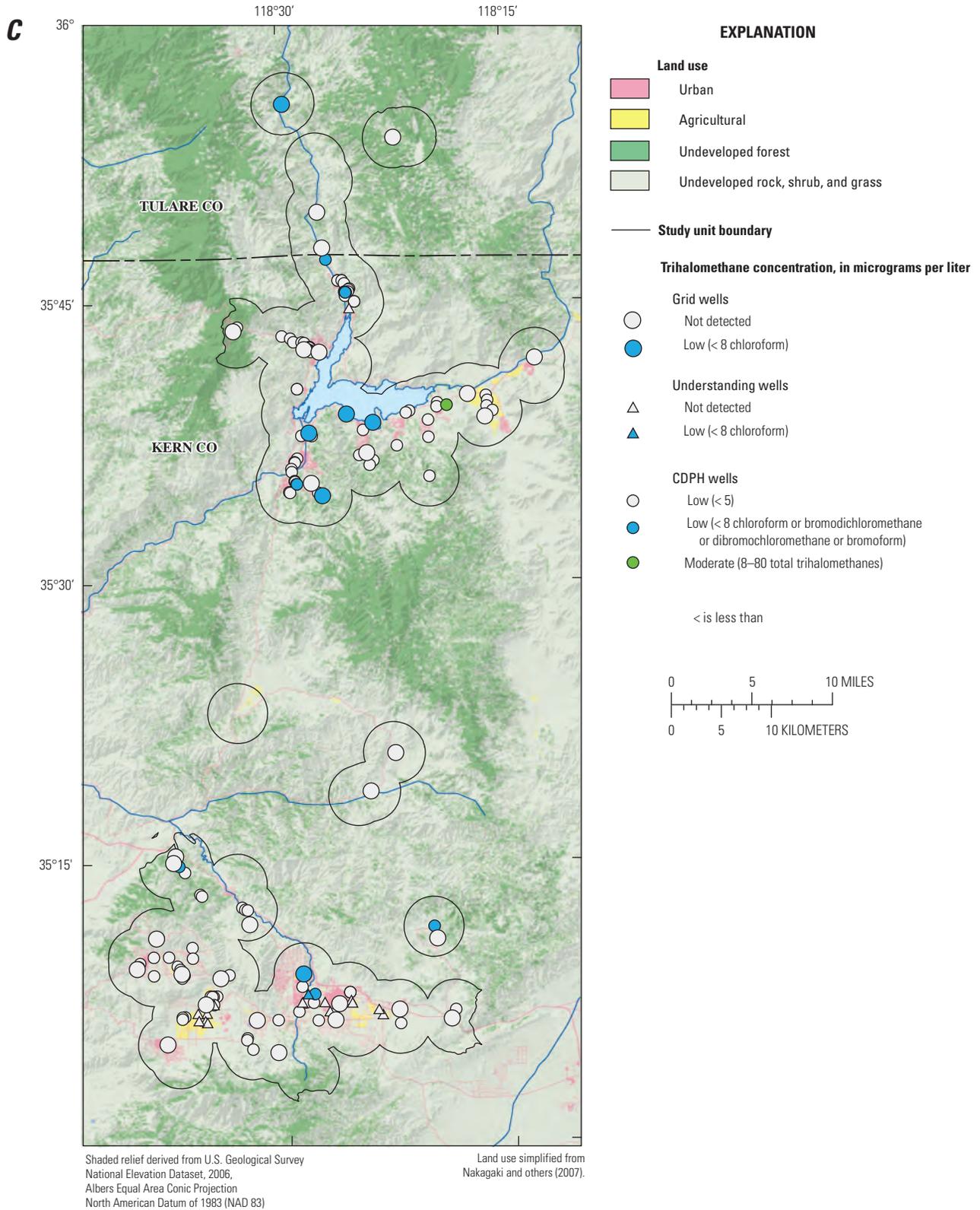
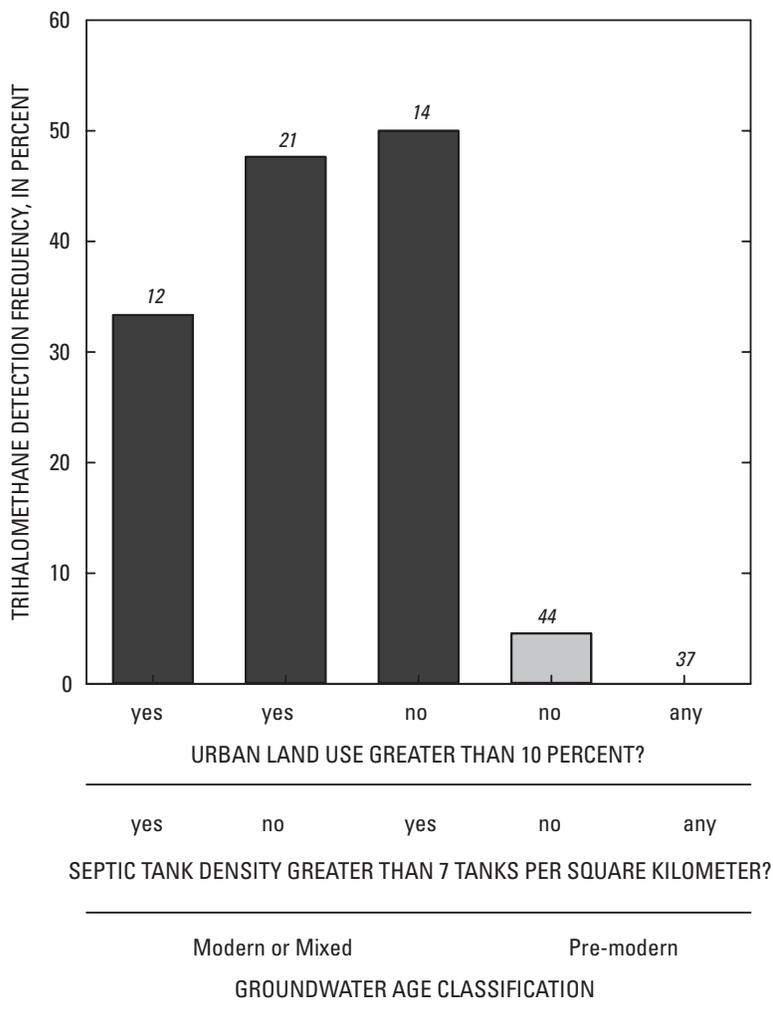


Figure 50.—Continued



Bars of different colors have significantly different detection frequencies.
 Number of samples in each group indicated above bar.

Figure 51. Relation between detection frequency of trihalomethanes and groundwater age, percentage of urban land use, and septic tank density, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Solvents

Solvents are used for a variety of industrial, commercial, and domestic purposes (Zogorski and others, 2006). The only solvent with a study-unit detection frequency > 10% was PCE, with a frequency of 14% in the Southern Sierra study unit (fig. 44). Note that Fram and others (2009) reported that 17% of the Tahoe-Martis study-unit grid wells had detections of PCE, but because the majority of the detections were in wells from the TTAHO study area (the smallest study area), the area-weighted detection frequency of PCE in the Tahoe-Martis study unit is <10% (fig. 44). PCE is primarily used for dry-cleaning of fabrics and degreasing metal parts, and is an ingredient in a wide range of products including paint removers, polishes, printing inks, lubricants, and adhesives (Doherty, 2000).

The high aquifer-scale proportion for solvents in the Tahoe-Martis study unit was 1.0%, and the solvents present at high RCs in 1% or less of the primary aquifers were PCE, carbon tetrachloride, and 1,2-dichloroethane (table 8A). Wells with high RCs of solvents were located in the Tahoe Valley South subbasin (fig. 52A). PCE and chloroethane were present at moderate RCs in <1% of the primary aquifer (spatially weighted).

No solvents were present at high RCs in the Central Sierra study unit (fig. 52B). The moderate aquifer-scale proportion of PCE was <1% (spatially weighted) (table 8B).

No solvents were present at high RCs in the Southern Sierra study unit. The moderate aquifer-scale proportion for solvents was 2.9%, composed of PCE and carbon tetrachloride (table 8C). Wells with moderate RCs of solvents were located in the Kern River and Tehachapi-Cummings Valleys (fig. 52C). Three additional solvents were reported at high RCs historically in the CDPH database (1,1-dichloroethane, 1,2-dichloroethane, and dichloromethane; table 5).

Factors Affecting Solvents

Because many of the factors associated with the occurrences of individual chlorinated solvents were similar in the NAWQA groundwater studies nationally (Zogorski and others, 2006), solvents were considered as a class rather than as individual constituents for the *understanding assessment*. Total solvent concentration was the sum of the concentrations of all chlorinated solvents with benchmarks. Twenty of the 26 solvent detections were PCE, which was also the most frequently detected solvent in groundwater nationally (Zogorski and others, 2006). Three detections were of solvents that are also breakdown products of PCE (trichloroethene and *cis*-1,2-dichloroethene; table 4).

Solvent concentration had significant positive correlations with percentages of both urban and agricultural land use and a significant negative correlation with percentage of undeveloped land use (table 10B; figs. 47, 48)—as would be expected given the myriad of uses for solvents in human activities. Solvent concentration was significantly greater in wells with sedimentary aquifer lithology (table 10A); wells with sedimentary aquifer lithology had significantly greater percentages of agricultural and urban land use (table 6A).

Although solvent concentration was significantly correlated to herbicide and THM concentrations (Spearman's rho test, $p = 0.002$ and $p = 0.004$, respectively), the relations of solvents to groundwater age and measures of depth were different from those of herbicides and THMs. Unlike herbicide and THM concentrations, solvent concentration was not significantly related to classified groundwater age (table 10A; fig. 46). THM, herbicide, and solvent concentrations were not significantly related to classified well depth (table 10A), nor were they significantly correlated to well depth or depth to top of screened or open interval (table 10B). Of the 11 wells with herbicide detections and well construction information, 9 (82%) had depth to top of screened or open interval <170 ft bls, and all had groundwater with modern or mixed age (fig. 53A). Similarly, 89% of the wells with THM detections had depth to top of screened or open interval <170 ft bls, and all had groundwater with modern or mixed age (fig. 53B). In contrast, of the 19 wells with solvent detections and well construction information, only 63% had depth to top of screened or open interval <170 ft bls, and 68% had groundwater with modern or mixed age (fig. 53C). The median depth to top of screened or open interval for wells with detections of herbicides or THMs and no detections of solvents (89 ft) was significantly less than the median depth to top of screened or open interval for wells with detections of solvents and no detections of herbicides or THMs (180 ft) (Wilcoxon rank-sum test, $p = 0.023$) (fig. 54).

The greater depth of penetration of solvents into the aquifer systems, compared to herbicides and THMs, may reflect differences in either patterns of usage of these organic compounds or chemical behavior of these constituents in aquifers. Because solvents have such a wide variety of uses (Doherty, 2000), it is possible that their widespread uses preceded herbicide use and water disinfection in these parts of the Sierra Nevada. Also, solvents generally are more mobile in groundwater than are herbicides because solvents typically sorb less to mineral surfaces and sedimentary organic matter.

A

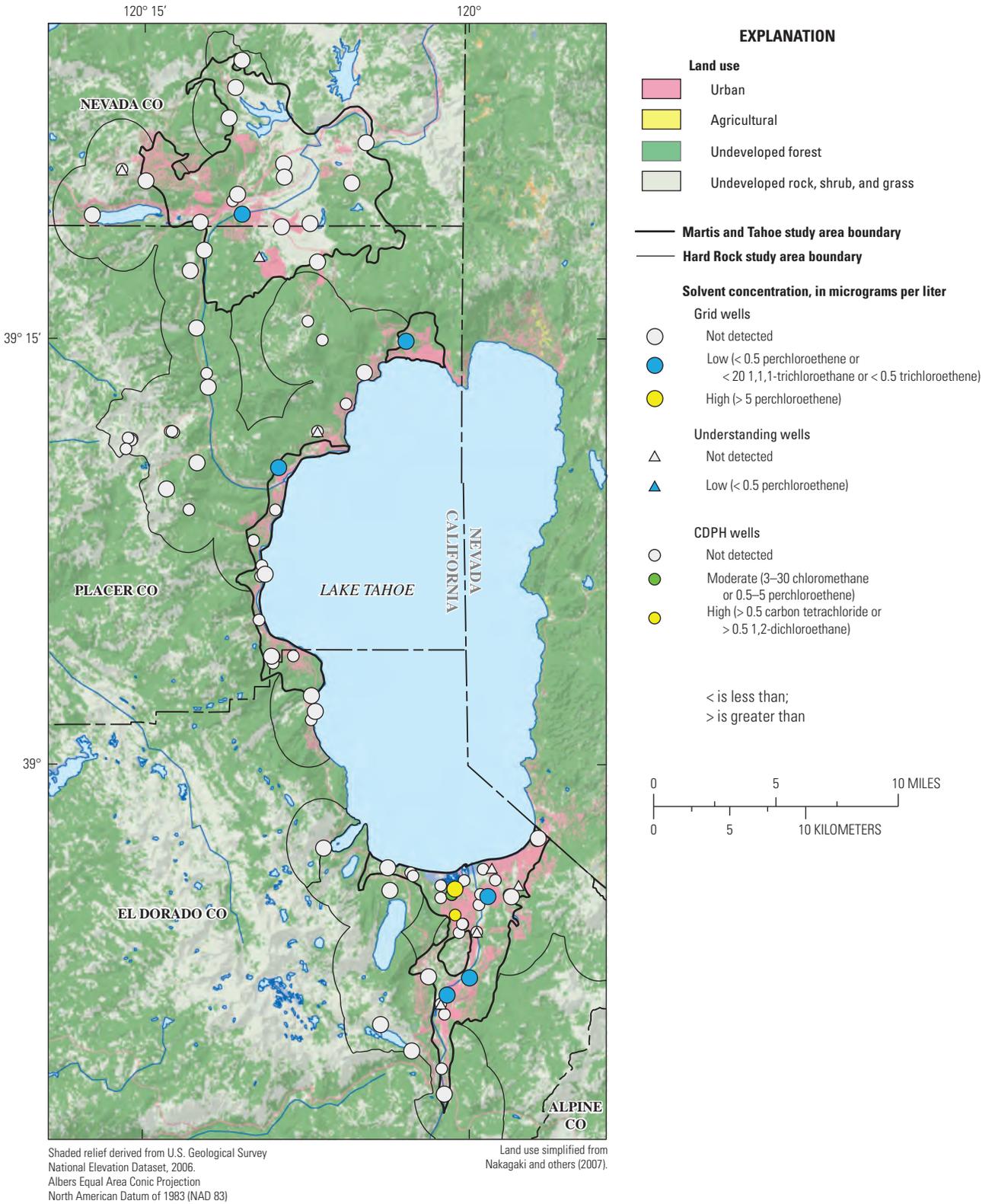


Figure 52. Relative-concentrations of solvents for USGS- and CDPH-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for solvents during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

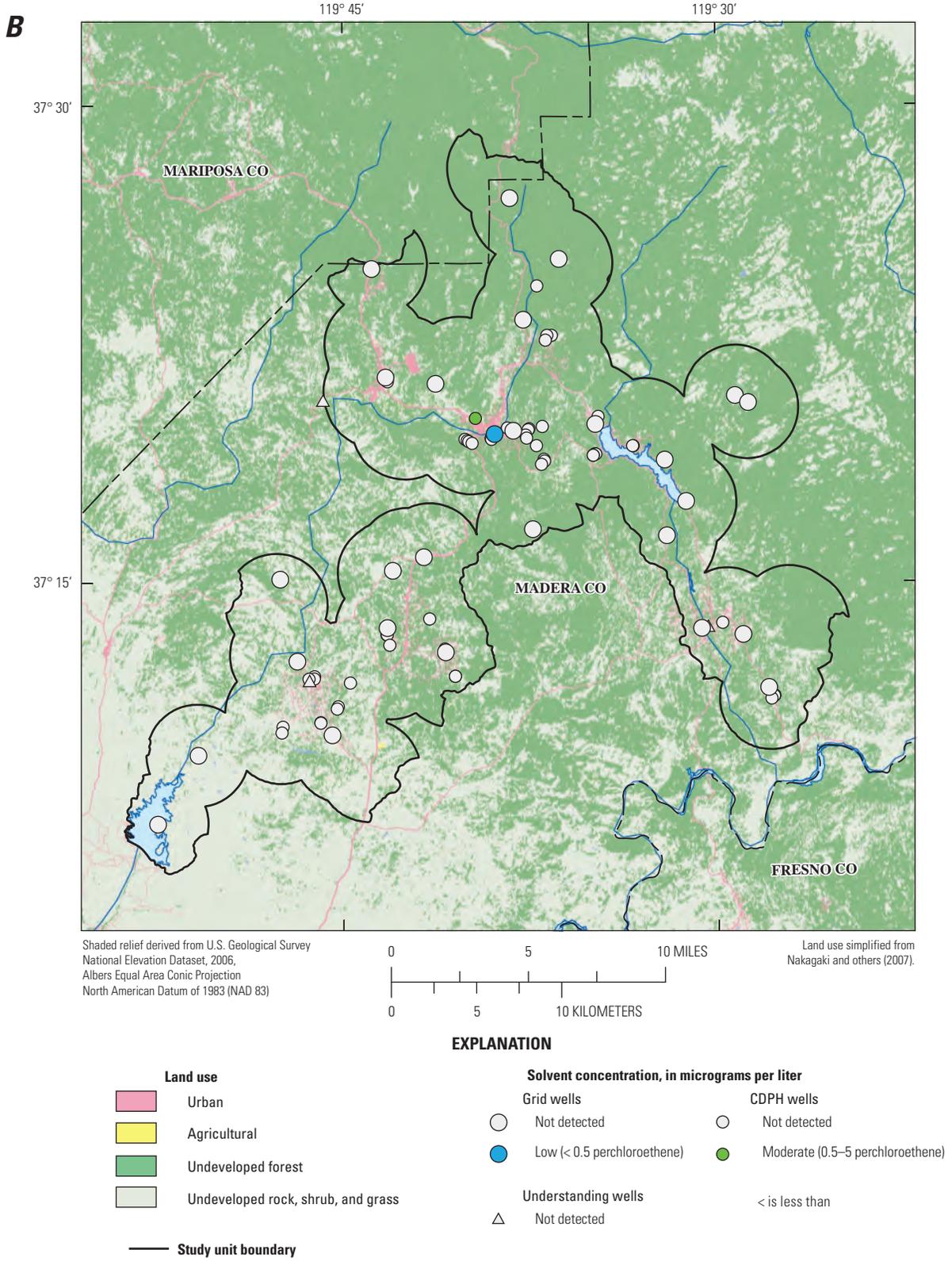


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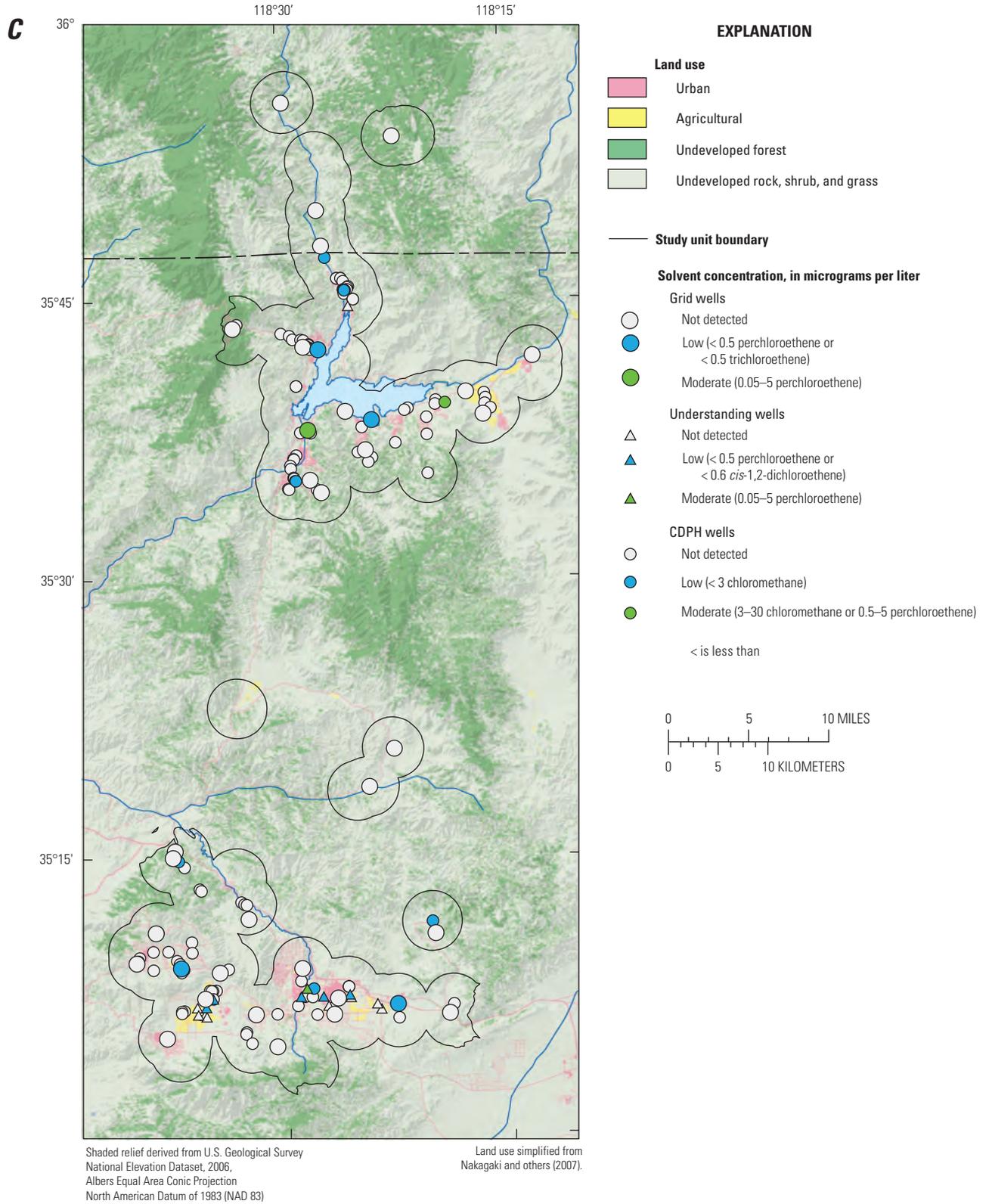


Figure 52.—Continued

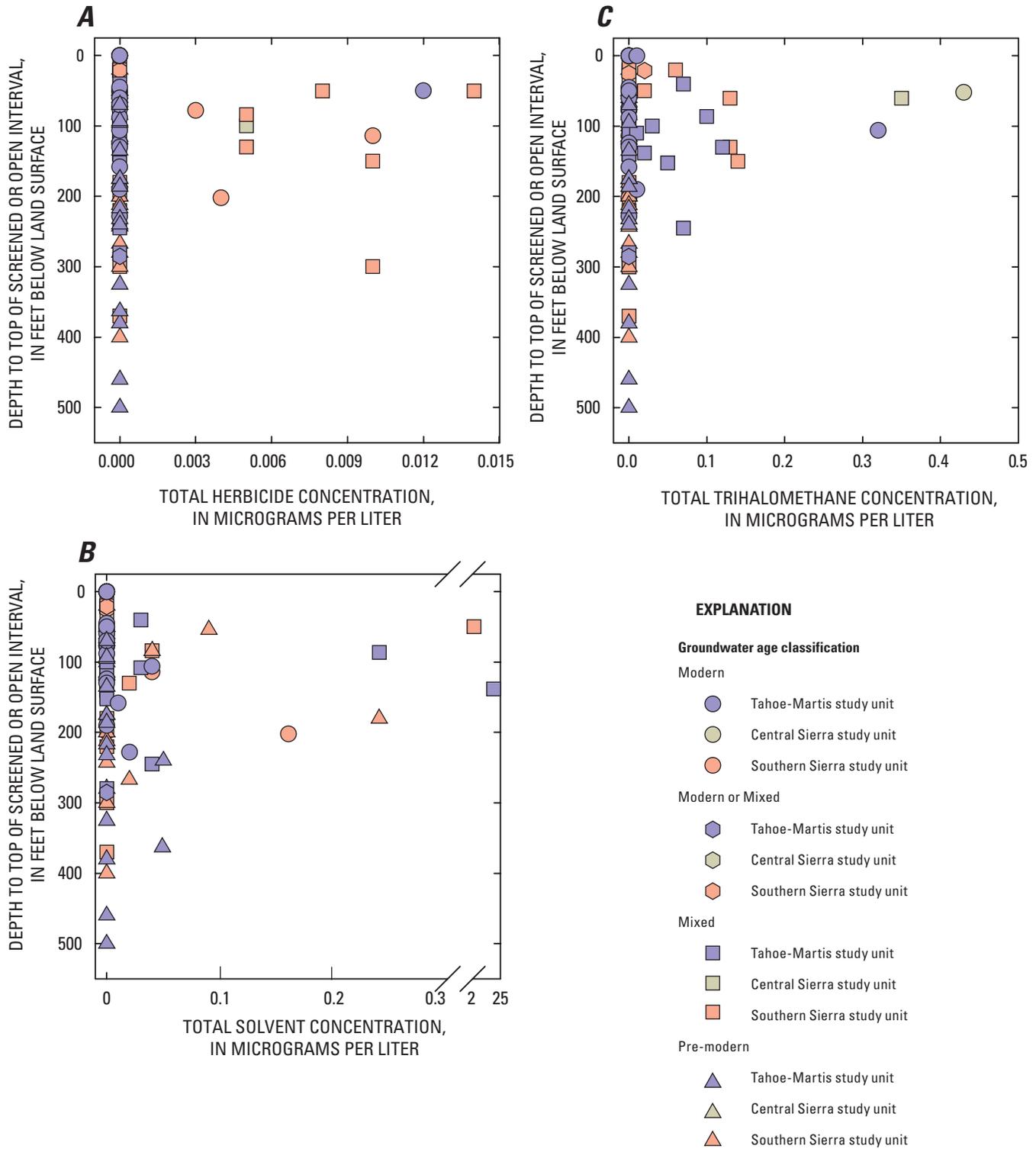


Figure 53. Relation among (A) total herbicide, (B) total solvent, and (C) total trihalomethane concentrations and depth to top of screened or open interval in wells and groundwater age classification, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

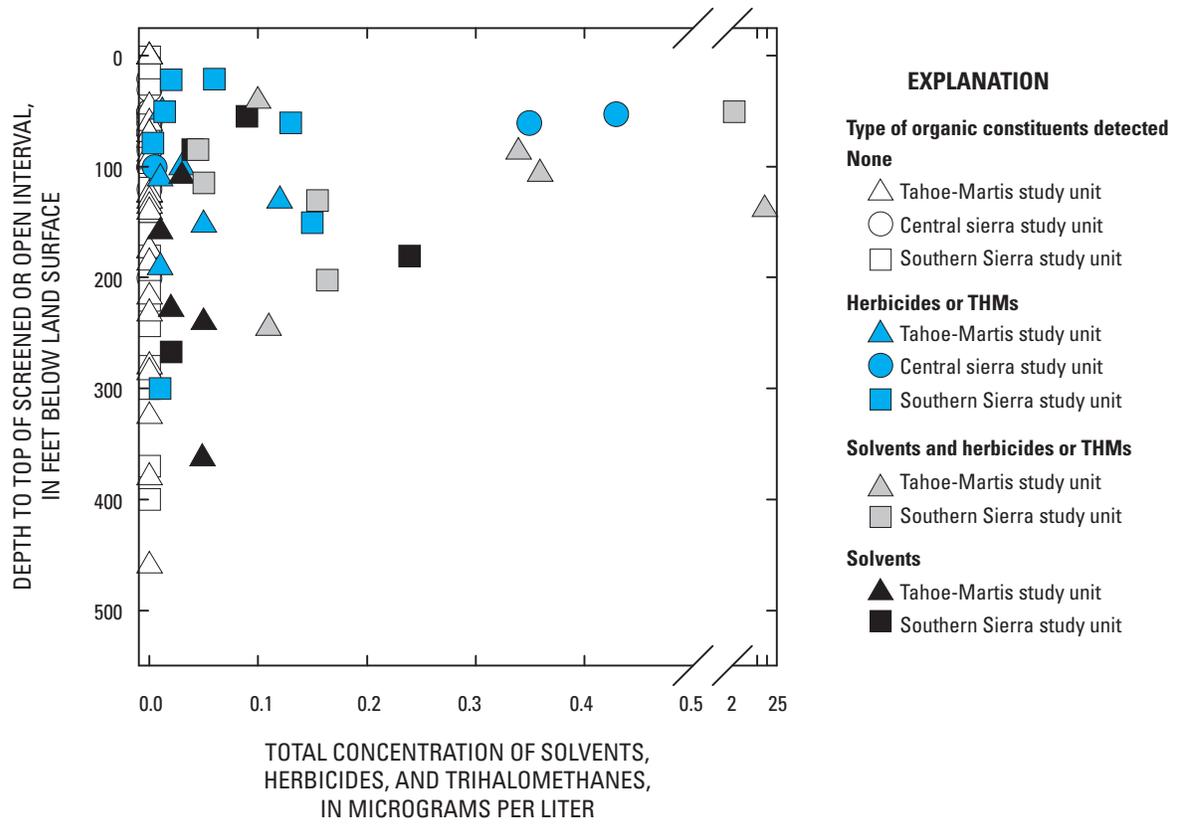


Figure 54. Relation between total concentration of organic constituents and depth to top of screened or open interval in wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Other Volatile Organic Compounds

No fuel components had detection frequencies of > 10% in any of the three study units (figs. 43A,B,C). The gasoline hydrocarbon benzene was detected in one Central Sierra study-unit grid well at an RC of 0.17 (fig. 43B), which resulted in a moderate aquifer-scale proportion of 4.0% (table 8B).

The gasoline oxygenate MTBE was reported at high RCs historically in the Tahoe-Martis and Central Sierra study units (table 5). Use of MTBE in gasoline was banned in the Lake Tahoe Basin in 2000 and in the State of California at the end of 2003 (State of California, 2003). Among the wells currently used in the Tahoe-Martis study unit, no moderate or high RCs of MTBE were reported in the CDPH database or were detected by USGS-GAMA (fig. 43A). MTBE was reported at moderate RCs in the Central Sierra study unit CDPH database; the moderate aquifer-scale proportion is 1.6% (table 8B). Note that this is a minimum estimate because the reporting limit for MTBE in the CDPH database for Central Sierra, 2 µg/L, is greater than one-tenth of the benchmark value for MTBE, which is the MCL-CA of 13 µg/L.

The CDPH database for the Tahoe-Martis study unit reported one detection each of two fumigants—1,2-dibromo-3-chloropropane (DBCP) and 1,2-dichloropropane—at high RCs in the 3-year interval (table 8A). Neither constituent had any other detections at any concentration in the USGS-GAMA dataset for the Tahoe-Martis study unit or in the entire period of record of the CDPH database available for this study.

Special-Interest Constituents

Perchlorate was analyzed at all USGS-GAMA wells in the three study units (table 1). *N*-nitrosodimethylamine (NDMA) was analyzed at all wells in the Central Sierra study unit and at a subset of the wells in the Tahoe-Martis and Southern Sierra study units. Low-level 1,2,3-TCP was analyzed at all wells in the Central Sierra study unit and at a subset of the wells in the Southern Sierra study unit.

NDMA was not detected in samples from any of the three study units, and perchlorate was not detected in samples from the Tahoe-Martis and Central Sierra study units. 1,2,3-TCP was detected at low RC in one USGS-understanding well in the Southern Sierra study unit. The CDPH database for the Tahoe-Martis study unit reported one detection of perchlorate at a high RC historically (table 5); this was the only detection of perchlorate reported in the CDPH database for the Tahoe-Martis study unit for the entire period of record. The study-unit detection frequency for perchlorate in the Southern Sierra study unit was 12% (fig. 43C). The moderate aquifer-scale proportion for perchlorate in the Southern Sierra study unit was 8.6%, and no high RCs of perchlorate were detected (table 8C; fig. 44).

Factors Affecting Perchlorate

Perchlorate concentration had significant positive correlations with agricultural land use, sedimentary aquifer lithology, and DO concentration, and significant negative correlations with aridity index and percentage of undeveloped land use (tables 10A,B). Perchlorate concentration also had significant positive correlation with nitrate, total herbicide, and TDS concentrations (Spearman's rho test, $p < 0.001$, $p = 0.009$, and $p < 0.001$, respectively). Many of these correlations reflect the fact that perchlorate was only detected in the Southern Sierra study unit (figs. 55A,B,C).

There are both natural and anthropogenic potential sources of perchlorate to groundwater. Perchlorate is formed naturally in the atmosphere, and very low concentrations are found in precipitation (Dasgupta and others, 2005; Parker and others, 2009; Rajagopalan and others, 2009). The distribution of perchlorate under natural conditions in groundwater is likely correlated with climate because the extent of evaporative concentration of precipitation in the hydrologic cycle is likely to increase with increasing aridity (Fram and Belitz, 2011). Perchlorate salts accumulate in unsaturated zones and soils (Rao and others, 2007).

Three main sources of anthropogenic perchlorate have potential to reach California groundwater: industrial, agricultural, and disinfection. Most known sites of perchlorate contamination from industrial sources are associated with facilities that manufactured or used solid rocket fuel; other sites include the following: military munitions storage, use, and disposal, and manufacturing and disposal of pyrotechnics, safety flares, and explosives (U.S. Environmental Protection Agency, 2005a; California Department of Toxic Substances Control, 2007; California State Water Resources Control Board, 2007). Colorado River water imported to southern California is contaminated with perchlorate downstream from perchlorate manufacturing facilities in southern Nevada (U.S. Environmental Protection Agency, 2005b). Agricultural sources include the Chilean nitrate fertilizer applied extensively in the early to mid-1900s (Aziz and others, 2006; Dasgupta and others, 2006; Böhlke and others, 2009). Irrigation can also be considered an agricultural source if it redistributes perchlorate salts that were originally naturally present in the unsaturated zone (Fram and Belitz, 2011). Redistribution likely results in higher concentrations and greater detection frequencies of perchlorate in deep groundwater than would be present under natural conditions. Finally, perchlorate is a degradation product of hypochlorite solutions that are widely used for drinking-water disinfection (Massachusetts Department of Environmental Protection, 2006; Greiner and others, 2008).

A

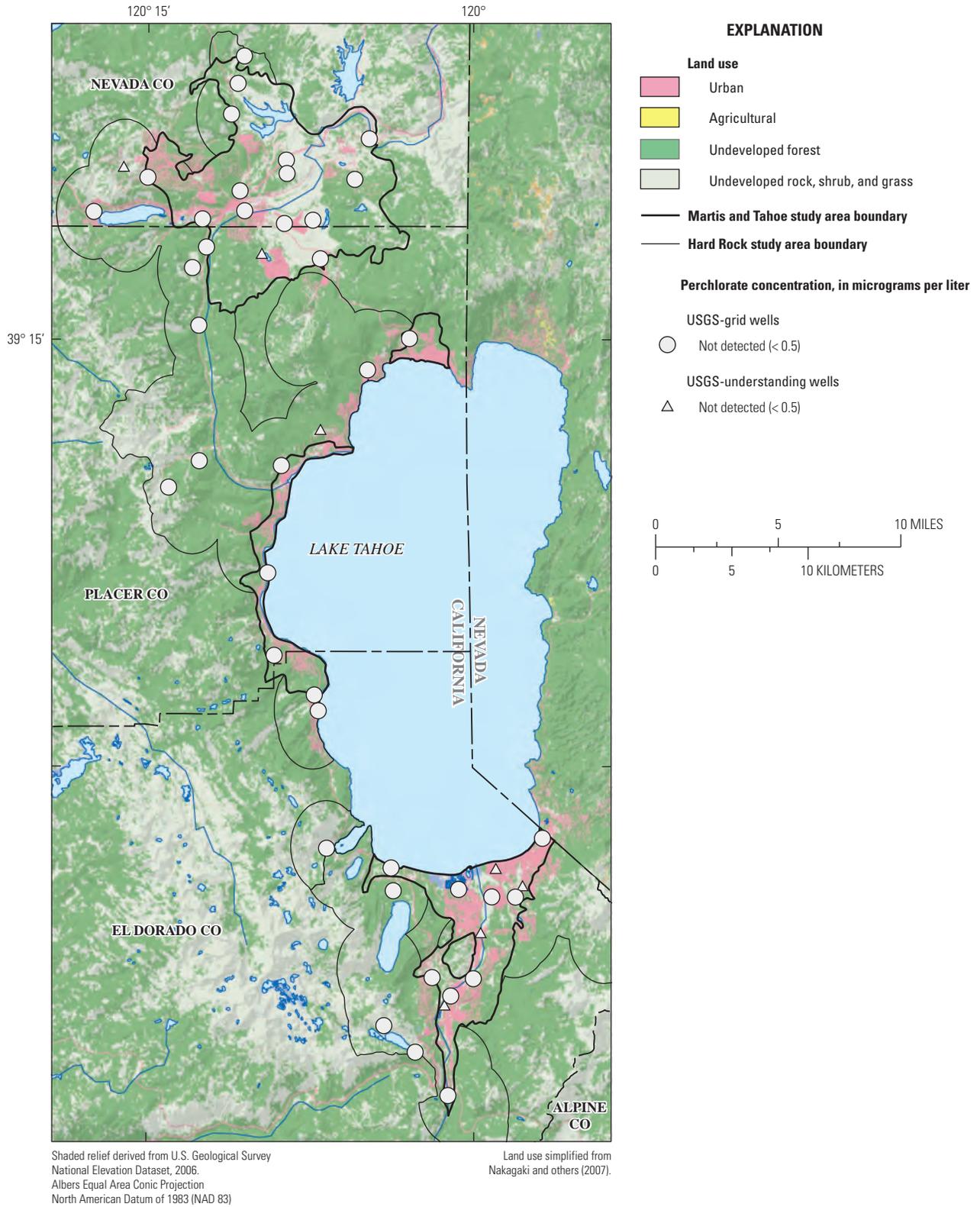


Figure 55. Relative-concentrations of perchlorate for USGS-grid wells, USGS-understanding wells, and all wells in the CDPH database with data for perchlorate during the 3-year intervals used in the status assessment, for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

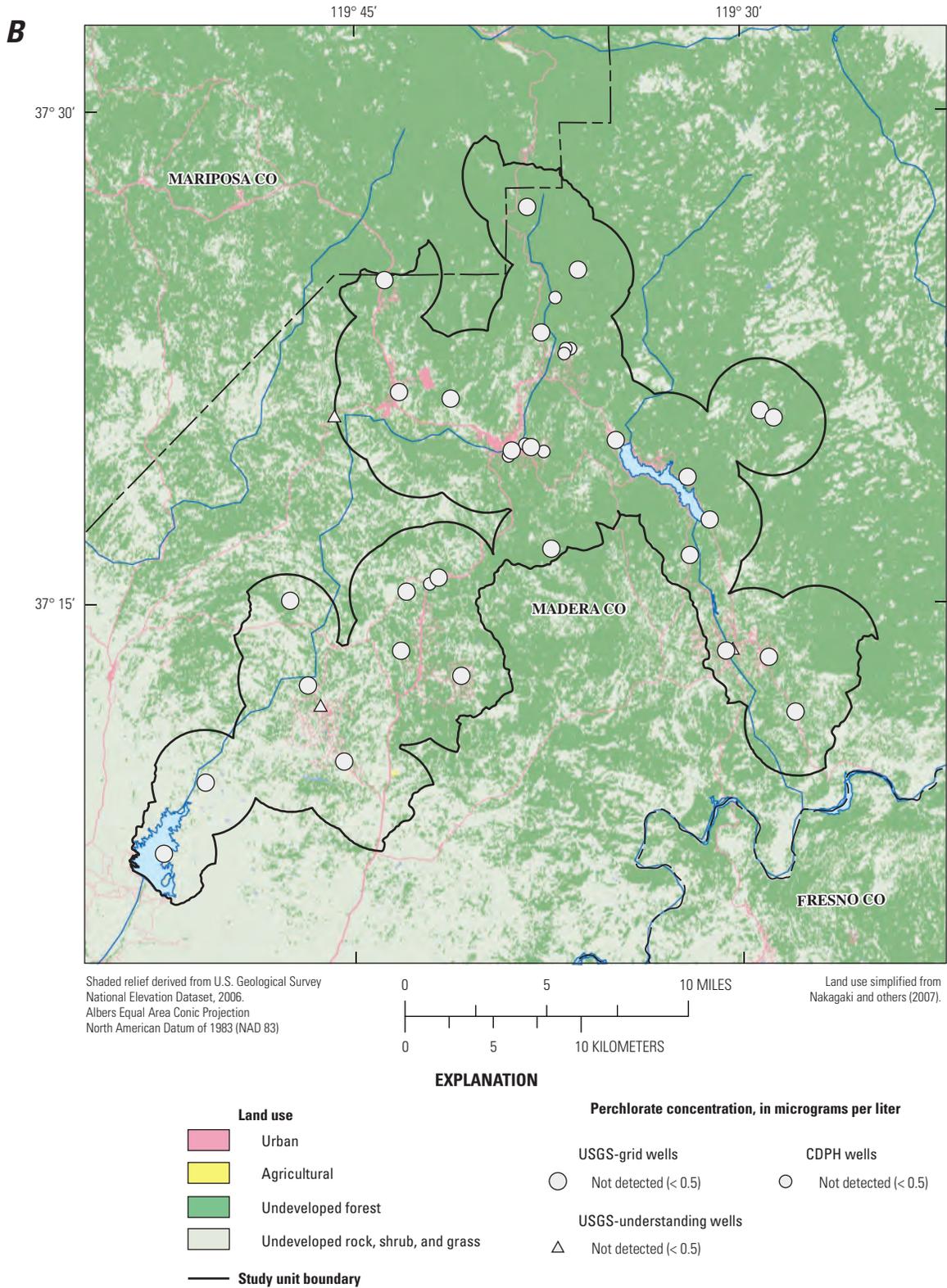


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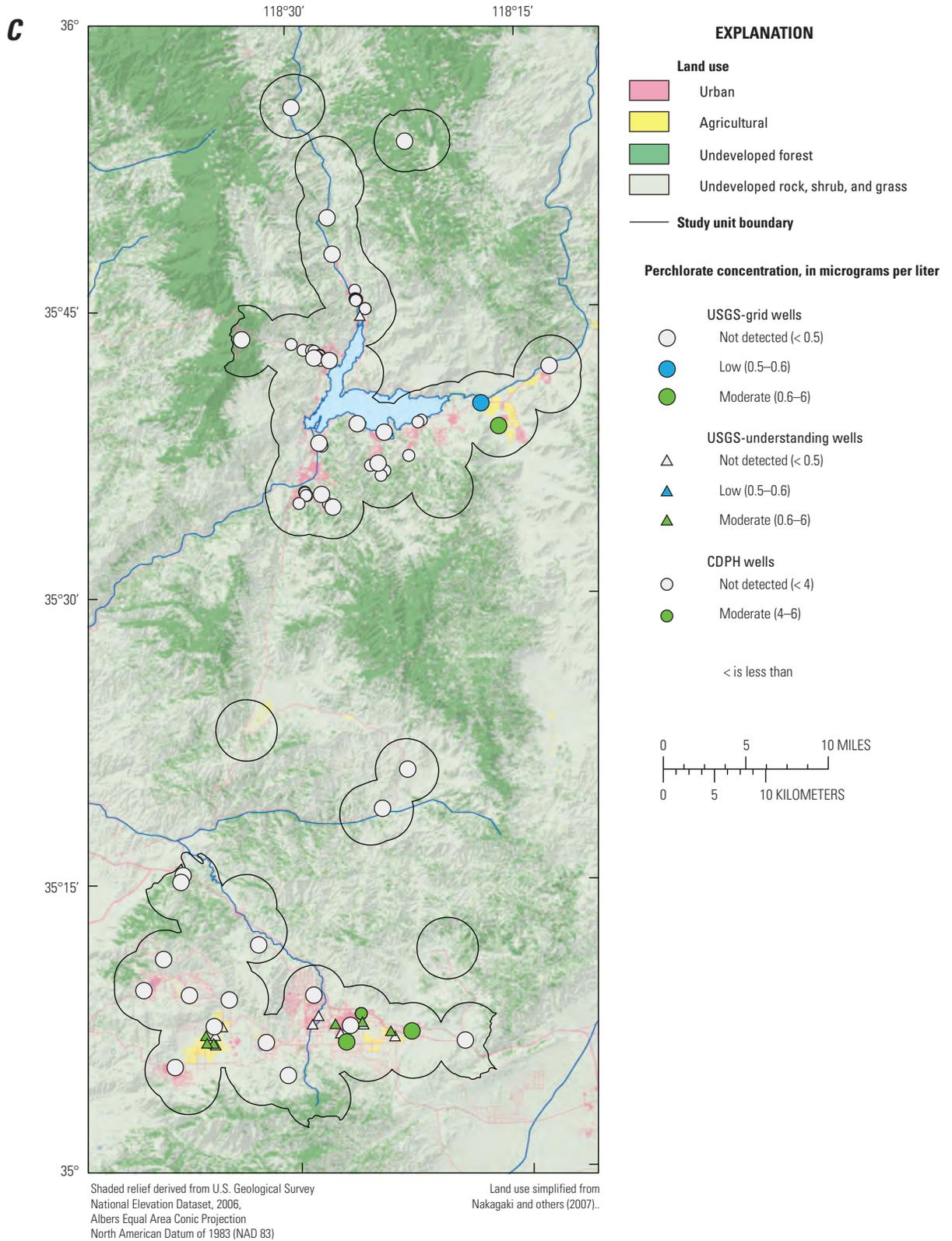


Figure 55.—Continued

Fram and Belitz (2011) used logistic regression to quantify the relation between the probability of perchlorate detection in groundwater resources sampled by the GAMA Priority Basin Project and water-quality indicators and other proxies of natural and anthropogenic perchlorate sources and processes. Their best-fit model was constructed with aridity index as the proxy for perchlorate under natural conditions, and an Anthropogenic Score as the proxy for anthropogenic sources and processes affecting perchlorate. The Anthropogenic Score summed four binary categorical variables: presence or absence of herbicides and fumigants, presence or absence of solvents and fuel components, nitrate-N concentration above or below 3 mg/L, and presence or absence of known sites of perchlorate contamination within a specific distance of the well. This model was applied to the data from the Tahoe-Martis, Central Sierra, and Southern Sierra study units to assess whether the observed concentrations and detection frequencies of perchlorate can be accounted for by natural conditions or require additional inputs of perchlorate from anthropogenic sources or processes.

Samples were assigned Anthropogenic Scores on the basis of nitrate concentrations and presence or absence of detections of herbicides, fumigants, solvents, and fuel components (Fram and Belitz, 2011). None of the well sites were near any of the known or suspected sites of groundwater contamination with industrial sources of perchlorate. Samples were then divided into groups by study unit, Anthropogenic Score, and aridity index for calculation of detection frequencies.

The observed detection frequencies were compared to predicted probabilities of detecting perchlorate as a function of Anthropogenic Score and aridity index (fig. 56). Sample groups from the Tahoe-Martis and Central Sierra study units with Anthropogenic Scores of 0 or 1 had detection frequencies

of 0% for perchlorate at concentrations ≥ 0.5 $\mu\text{g/L}$ and average aridity index values ranging from 0.55 to 1.0. The absence of detections of perchlorate is consistent with the low detection frequencies predicted under natural conditions (Anthropogenic Score = 0) for that range of aridity index (5.3% to 1.8%; fig. 56A). Sample groups from the Southern Sierra study unit with Anthropogenic Scores of 0, 1, or 2 and 3 had progressively increasing detection frequencies of perchlorate of 5.0%, 31%, and 38%, respectively, which are values consistent with predicted values (fig. 56A). The detection frequency of perchlorate at concentrations ≥ 1.0 $\mu\text{g/L}$ was 0% in all groups except for the group with Anthropogenic Score = 2 and 3 from the Southern Sierra study unit, which had a detection frequency of 31% (fig. 56B). These results suggest that both natural and anthropogenic sources of perchlorate may be identified in the Southern Sierra study unit.

The observed detection frequencies for concentrations ≥ 0.5 $\mu\text{g/L}$ for the groups with Anthropogenic Scores of 1 or 2 are significantly higher than the study-unit detection frequency of 12%. Of the 10 Southern Sierra study-unit samples with detection of perchlorate, 6 are USGS-understanding wells located in the centers of the Tehachapi-Cummings Valley basins (fig. 55C). These six wells have 30% to 86% (average 63%) agricultural land use, which is significantly higher than the average agricultural land use around the grid wells (20%; fig. 6A). Agricultural lands in the Tehachapi-Cummings Valley basins are heavily irrigated, suggesting that the source of the elevated perchlorate in groundwater may be redistribution of naturally deposited perchlorate salts in the unsaturated zone by recharge of irrigation water (Fram and Belitz, 2011). Three of the six USGS-understanding wells have perchlorate concentrations ≥ 1 $\mu\text{g/L}$, suggesting that these higher concentrations of perchlorate in groundwater are indicative of anthropogenic influence.

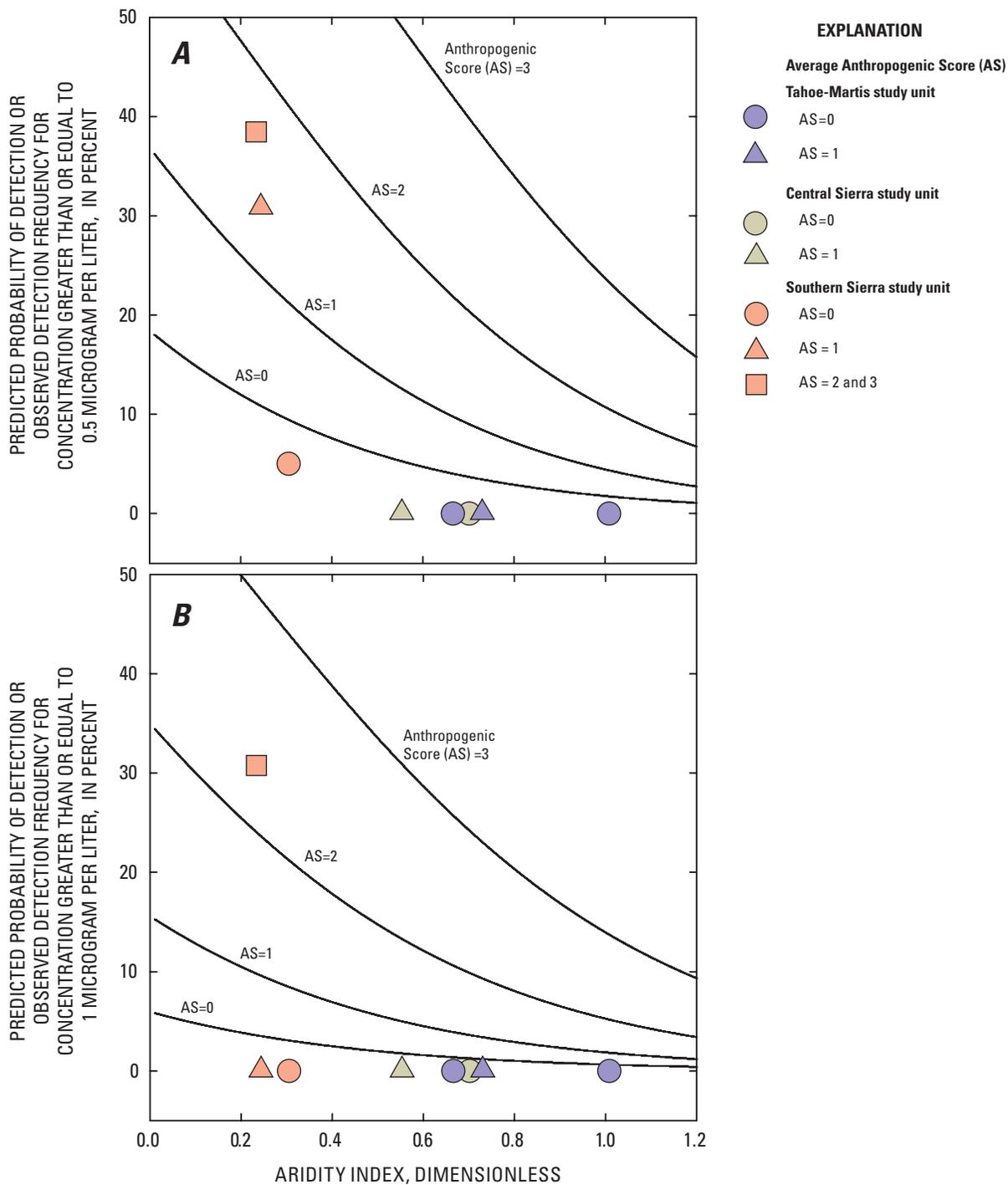


Figure 56. Predicted probability of detecting perchlorate in groundwater as a function of aridity index and Anthropogenic Score and observed detection frequency and average aridity index in groups of samples for perchlorate concentrations greater than or equal to (A) 0.5 microgram per liter ($\mu\text{g/L}$) and (B) 1.0 $\mu\text{g/L}$, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Summary

Groundwater quality in the Tahoe-Martis, Central Sierra, and Southern Sierra study units was investigated as part of the Priority Basin Project of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program. The three study units are located in the Sierra Nevada region of California in parts of Nevada, Placer, El Dorado, Madera, Tulare, and Kern Counties. The GAMA Priority Basin Project is designed to provide a statistically-robust characterization of untreated groundwater quality in the primary aquifers used for public and community drinking-water supplies.

The assessments are based on water-quality and ancillary data collected by the USGS from 132 wells in the three study units during 2006–2007, and water-quality data from the California Department of Public Health (CDPH) database. The primary aquifer systems are defined by the depths of the screened or open intervals of the wells listed in the CDPH database for each study unit. The quality of groundwater in shallower or deeper water-bearing zones may differ from that in the primary aquifers; shallower groundwater may be more vulnerable to contamination from the surface, and deeper groundwater may be more susceptible to water–rock interaction. Two types of assessments were made: (1) status, assessment of the current quality of the groundwater resource, and (2) understanding, identification of the natural and human factors affecting groundwater quality.

Relative-concentrations (sample concentrations divided by benchmark concentrations) were used for evaluating groundwater quality for those constituents that have Federal and (or) California regulatory or non-regulatory benchmarks for drinking-water quality. A relative-concentration (RC) greater than ($>$) 1.0 indicates a concentration above a benchmark. Organic (volatile organic compounds and pesticides) and special-interest (perchlorate) constituent RCs were classified as “high” ($RC > 1.0$), “moderate” ($1.0 \geq RC > 0.1$), or “low” ($RC \leq 0.1$). For inorganic (major ion, trace element, nutrient, and radioactive) 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 aquifer-scale proportion is defined as the percentage of the primary aquifer with $RC > 1.0$ for a particular constituent or class of constituents; moderate and low aquifer-scale proportions are defined as the percentage of the primary aquifer with moderate and low RCs, respectively. The methods used to calculate aquifer-scale proportions are based on an equal-area grid; thus, the proportions are areal rather than volumetric. Two statistical approaches—grid-based, which used one value per grid cell, and spatially weighted, which used multiple values per cell—were used to

calculate aquifer-scale proportions for individual constituents and classes of constituents. The spatially weighted estimates of high aquifer-scale proportions were within the 90-percent (%) confidence intervals of the grid-based estimates in all cases.

Inorganic constituents had significantly greater high and moderate aquifer-scale proportions than did organic constituents in all three study units. In the Tahoe-Martis study unit, RCs for inorganic constituents with health-based benchmarks (primarily arsenic) were high in 20% of the primary aquifer, moderate in 13%, and low in 67%. In the Central Sierra study unit, aquifer-scale proportions for inorganic constituents with health-based benchmarks (primarily arsenic, uranium, fluoride, and molybdenum) were 41% high, 36% moderate, and 23% low. In the Southern Sierra study unit, 32, 34, and 34% of the primary aquifer had high, moderate, and low RCs, respectively, of inorganic constituents with health-based benchmarks (primarily arsenic, uranium, fluoride, boron, and nitrate). The high aquifer-scale proportions for inorganic constituents with non-health-based benchmarks were 14, 34, and 24% for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively, and the primary constituent was manganese for all three study units.

Organic constituents with health-based benchmarks were not present at high RCs in the primary aquifers of the Central Sierra and Southern Sierra study units, and were present at high RCs in only 1% of the Tahoe-Martis study unit. Moderate aquifer-scale proportions for organic constituents were $< 5\%$ in all three study units. Of the 173 organic constituents analyzed for, 22 were detected, and of those 22, 17 have health-based benchmarks. Organic constituents were detected in 20, 27, and 40% of the primary aquifers in the Tahoe-Martis, Central Sierra, and Southern Sierra study units, respectively. Four organic constituents had study-unit detection frequencies of $> 10\%$: the trihalomethane chloroform in the Tahoe-Martis study unit; chloroform and the herbicide simazine in the Central Sierra study unit; and chloroform, simazine, the herbicide atrazine, and the solvent perchloroethene in the Southern Sierra study unit.

The *understanding assessment* used statistical correlations between concentrations of constituents and values of selected potential explanatory factors to identify the factors potentially affecting the concentrations and occurrences of constituents found at high RCs or, for organic constituents, with study-unit detection frequencies $> 10\%$. The potential explanatory factors evaluated were geographic location, land use, septic tank density, climate, relative position in the regional flow system, aquifer lithology, well depth and depth to the top of the screened or open interval in the well, groundwater age distribution, pH, and dissolved oxygen concentration. Data from the three study units were aggregated into one dataset for the statistical tests.

Aquifer lithology (granitic, metamorphic, sedimentary, or volcanic), groundwater age distribution (modern, mixed, or pre-modern), pH, DO, and geographic location were the most significant explanatory factors with potential causative value for most of the inorganic constituents evaluated in the *understanding assessment* (arsenic, fluoride, boron, molybdenum, nitrate, uranium, total dissolved solids, iron, and manganese). High and moderate RCs of arsenic were associated with pre-modern and mixed-age groundwater and two distinct sets of geochemical conditions, reflecting two mechanisms for solubilization of arsenic. Correlations between elevated arsenic concentrations and oxic, high-pH conditions, particularly in volcanic rocks, suggest desorption of arsenic from iron and manganese oxyhydroxides. Correlations between elevated arsenic concentrations and low-oxygen to anoxic, low- to neutral-pH conditions, particularly in granitic rocks, suggest release of arsenic by reductive dissolution of iron and manganese oxyhydroxides.

In granitic and metamorphic rocks, high and moderate RCs of uranium were associated with pre-modern and mixed-age groundwater, low-oxygen to anoxic conditions, and location within parts of the Central Sierra and Southern Sierra study units known to have rocks with anomalously high uranium contents compared to other parts of the Sierra Nevada. High and moderate RCs of uranium in sedimentary rocks were associated with pre-modern-age groundwater, oxic and high-pH conditions, low total dissolved solids, and location in the Tahoe Valley South subbasin.

Elevated manganese and iron concentrations were associated with anoxic conditions, older groundwater, and granitic and metamorphic aquifer lithologies. Of the samples with pre-modern ages from wells in granitic rocks, 60% had high RCs of manganese. Most wells in sedimentary and volcanic rocks had oxic groundwater, regardless of age, and approximately 5 and 10%, respectively, of the samples from wells in those rock types had moderate or high RCs of manganese.

Land use within 500 meters of the well and groundwater age were the most significant explanatory factors with potential causative value for the organic constituents. Herbicide detections were most strongly associated with modern- and mixed-age groundwater from wells with any agricultural land use. Trihalomethane detections were most strongly associated with modern- and mixed-age groundwater from wells with >10% urban land use and (or) septic tank

density >7 tanks per square kilometer. Eighty-four percent of the wells with modern- or mixed-age groundwater and 86% of wells with detections of herbicides and (or) THMs had depths to the top of the screened or open interval of <170 feet below land surface. These results suggest that modern (post-1952) groundwater has infiltrated to a depth of approximately 170 feet below land surface. Solvent detections were not significantly related to groundwater age, and only 63% of wells with detections of solvents had depths to the top of the screened or open interval of <170 feet below land surface, suggesting that solvents have different behavior than herbicides and THMs in these aquifer systems.

Moderate RCs of perchlorate and moderate and high RCs of nitrate were detected in the Southern Sierra study unit only. Elevated nitrate concentrations were associated with agricultural land use and detections of herbicides and (or) solvents, suggesting an anthropogenic source for the moderate and high RCs of nitrate. Comparison between observed and predicted detection frequencies of perchlorate suggests that the perchlorate detected at concentrations <1 microgram per liter likely reflects the distribution of perchlorate under natural conditions and that the perchlorate detected at higher concentrations may reflect redistribution of original, natural perchlorate salts by irrigation in the agricultural areas of the Southern Sierra study unit.

Acknowledgments

The authors thank the following cooperators for their support: the State Water Resources Control Board (SWRCB), Lawrence Livermore National Laboratory, California Department of Public Health, and California Department of Water Resources. We especially thank the cooperating well owners and water purveyors for their generosity in allowing the USGS to collect samples from their wells. Funding for this work was provided by State of California bonds authorized by Proposition 50 and administered by the SWRCB. We thank Bryant Jurgens (USGS California Water Science Center) for assistance with the PHREEQC modeling and Tyler Johnson (USGS California Water Science Center) for GIS support. Approximately 30 members of the USGS-GAMA team collected the data presented in this report.

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Appendix A: Selection of CDPH-Grid Wells

Of the 115 grid cells in the three study units, 11 cells did not have a USGS-grid well, 28 cells had a USGS-grid well but no USGS-GAMA data for major ions, trace elements, nutrients, and radioactive constituents, and 49 cells had a USGS-grid well but incomplete USGS-GAMA data for radioactive constituents. The CDPH database was queried to identify wells to provide these missing inorganic data. CDPH wells with data in the most recent 3 years available at the time of sampling were considered. If a well had more than one analysis for a constituent in the 3-year interval, the most recent data were selected. The 3-year intervals were as follows:

Study unit	3-year interval	Number of wells with data
Tahoe-Martis	May 1, 2004–April 30, 2007	157
Central Sierra	June 1, 2003–May 31, 2006	169
Southern Sierra	February 1, 2003–January 31, 2006	205

No quality-control data were available for data stored in the CDPH database. The only measure of data quality available was the cation/anion balance for the major-ion results. We made the broad assumption that if the major-ion data were of acceptable quality, then the data for trace elements, nutrients, and radioactive constituents would also be of acceptable quality ([appendix D](#)). Therefore, to minimize selection of potentially poor-quality data, the algorithm included calculation of the cation/anion balance as a quality-control check for the analyses (Hem, 1989). The total positive charge on dissolved cation species in a water sample must equal the total negative charge on dissolved anion species in the sample. Cation-anion balance was calculated as the absolute value of the difference between the total cations and total anions divided by the average of the total cations and total anions, expressed as a percentage, and acceptable cation-anion balance was defined as >90%:

$$\text{balance} = \left(1 - \frac{|\sum \text{cations} - \sum \text{anions}|}{\frac{\sum \text{cations} + \sum \text{anions}}{2}} \right) * 100,$$

where

\sum cations is the sum of calcium, magnesium, sodium, and potassium in milliequivalents per liter, and

\sum anions is the sum of chloride, fluoride, nitrate, sulfate, bicarbonate, and carbonate in milliequivalents per liter.

A multi-step algorithm was used to select data from the CDPH database to fill in the gaps in the USGS-grid well datasets for these inorganic constituents. The algorithm maintained the principles of spatially distributed, randomized well selection originally used to identify the USGS-grid wells for sampling.

- If the USGS-grid well was a well with data in the CDPH database, then the most recent CDPH data for that well for each missing inorganic constituent was used to supplement the USGS-GAMA data for that cell. The well was given an alphanumeric code name consisting of the same prefix and number as the USGS-well and separated by a second prefix “DG” ([table A1](#)). The “DG” second prefix indicates that the CDPH-grid well and the USGS-grid well are the same well.
- If CDPH “DG” well did not have data for all of the missing inorganic constituents, a second CDPH well could be selected to provide the remainder of the data.
 - The cation/anion balances for the most recent analyses of all the CDPH wells in the cell were calculated. The wells with acceptable cation/anion balances were then divided into priority groups based on the number of missing constituents for which they could provide data. The well with the highest random rank among the wells in the highest priority group was then selected, and the most recent CDPH data from that well for each missing inorganic constituent was used to supplement the USGS-GAMA data for the cell. The random ranks were the same random ranks originally assigned to the CDPH wells during selection of the USGS-grid wells.
 - If no wells in the cell had data in the CDPH database with acceptable cation/anion balances, the wells were divided into priority groups based on the number of missing constituents for which they could provide data. The well with the highest random rank among the wells in the highest priority group was then selected, and the most recent CDPH data from that well for each missing inorganic constituent was used to supplement the USGS-GAMA data for the cell.
 - The well was given a name consisting of the same prefix and number as the USGS-grid well, separated by a second prefix, “DPH” ([table A1](#)). The “DPH” second prefix indicates that the CDPH-grid well and the USGS-grid well in a cell are different wells.

3. If there was no USGS-grid well in the grid cell, a CDPH-grid well was selected as described in step 2. The well was given a name 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 result of this process was selection of one or two CDPH-grid wells per cell. Forty-one “DG” CDPH-grid wells and 34 “DPH” CDPH-grid wells were selected ([figs. A1A,B,C](#); [table A1](#)). Of the 115 cells in the three study units, 44 cells had only USGS-GAMA inorganic data, 31 cells had USGS-GAMA data supplemented by CDPH data, 33 cells had only CDPH inorganic data, and 7 cells had no inorganic data.

Reporting limits used in the CDPH database typically were higher than reporting limits for the same constituents analyzed by USGS-GAMA ([fig. 7](#)). However, for all inorganic constituents, except thallium and antimony, the predominant reporting limit in the CDPH database was lower than half of

the benchmark value, indicating that the moderate and low RCs could be distinguished. If the reporting limit were greater than half of the benchmark value, then a calculated proportion of moderate RC would be only a minimum estimate of the proportion. Calculation of high and moderate aquifer-scale proportions therefore were not affected by differences in reporting limits between USGS-collected and CDPH data. Other comparisons between the USGS-GAMA data and the CDPH data are described in [appendix D](#).

The CDPH database typically did not contain data for all of the missing inorganic constituents at every CDPH-grid well; therefore, the number of wells used for the grid-based assessment was different for different constituents ([table 2](#)). For example, in the Southern Sierra study unit, 37 wells (7 USGS-grid and 30 CDPH-grid) were used for the grid-based assessment of nitrate, but only 15 wells (7 USGS-grid and 8 CDPH-grid) were used for the grid-based assessment of boron.

Table A1. Nomenclature for USGS-grid and CDPH-grid wells used in the status assessments for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[CDPH-grid wells are labeled “DG” if the USGS-grid and CDPH-grid wells are the same well, and are labeled “DPH” if the CDPH-well and USGS-grid well are different wells or if no USGS-grid well exists. Recent data from the CDPH database from CDPH-grid wells provide data for inorganic constituents for grid cells lacking USGS data for inorganic constituents. Identification number prefixes: TMART, Tahoe-Martis study unit, Martis study area grid well; TROCK, Tahoe-Martis study unit, Hard Rock study area grid well; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area grid well; CWISH, Central Sierra study unit, Wishon study area grid well; SOSA, Southern Sierra grid well. **Abbreviations:** CDPH, California Department of Public Health; USGS, U.S. Geological Survey; na, not applicable; –, no well sampled or selected]

Well identification number			Well identification number		
USGS-grid	“DG” CDPH-grid	“DPH” CDPH-grid	USGS-grid	“DG” CDPH-grid	“DPH” CDPH-grid
Tahoe-Martis study unit (45 grid cells)			Central Sierra study unit (30 grid cells)		
TMART-01	–	–	CGOLD-01	–	–
TMART-02	–	–	CGOLD-02	–	–
TMART-03	TMART-DG-03	–	CGOLD-03	–	–
TMART-04	TMART-DG-04	–	CGOLD-04	–	–
TMART-05	TMART-DG-05	–	CGOLD-05	CGOLD-DG-05	–
TMART-06	–	–	CGOLD-06	–	–
TMART-07	–	–	CGOLD-07	–	–
TMART-08	TMART-DG-08	–	CGOLD-08	–	–
TMART-09	–	–	CGOLD-09	–	–
TMART-10	–	–	CGOLD-10	–	–
TMART-11	–	–	CGOLD-11	–	CGOLD-DPH-11
TMART-12	–	–	CGOLD-12	CGOLD-DG-12	–
TMART-13	–	–	CGOLD-13	CGOLD-DG-13	–
TMART-14	–	–	CGOLD-14	–	CGOLD-DPH-14
–	–	–	CGOLD-15	CGOLD-DG-15	–
TROCK-01	–	–	CGOLD-16	–	CGOLD-DPH-16
TROCK-02	–	–	CGOLD-17	–	–
TROCK-03	–	TROCK-DPH-03	CGOLD-18	–	CGOLD-DPH-18
TROCK-04	–	TROCK-DPH-04	–	–	CGOLD-DPH-19
TROCK-05	TROCK-DG-05	–	–	–	–
TROCK-06	TROCK-DG-06	TROCK-DPH-06	CWISH-01	–	–
TROCK-07	TROCK-DG-07	–	CWISH-02	–	–
TROCK-08	–	–	CWISH-03	–	–
TROCK-09	–	–	CWISH-04	–	–
TROCK-10	–	–	CWISH-05	–	–
TROCK-11	–	–	CWISH-06	–	CWISH-DPH-06
TROCK-12	–	TROCK-DPH-12	CWISH-07	–	–
TROCK-13	–	–	CWISH-08	–	–
–	–	–	CWISH-09	–	–
–	–	–	–	–	CWISH-DPH-10
TTAHO-01	–	TTAHO-DPH-01	Southern Sierra study unit (40 grid cells)		
TTAHO-02	–	–	SOSA-01	SOSA-DG-01	–
TTAHO-03	TTAHO-DG-03	–	SOSA-02	SOSA-DG-02	–
TTAHO-04	TTAHO-DG-04	TTAHO-DPH-04	SOSA-03	–	–
TTAHO-05	–	–	SOSA-04	SOSA-DG-04	–
TTAHO-06	–	–	SOSA-05	SOSA-DG-05	–
TTAHO-07	–	TTAHO-DPH-07	SOSA-06	SOSA-DG-06	SOSA-DPH-06
TTAHO-08	TTAHO-DG-08	–	SOSA-07	–	SOSA-DPH-07
TTAHO-09	–	TTAHO-DPH-09	SOSA-08	SOSA-DG-08	SOSA-DPH-08
TTAHO-10	–	–	SOSA-09	SOSA-DG-09	–
TTAHO-11	–	–	SOSA-10	SOSA-DG-10	–
TTAHO-12	TTAHO-DG-12	–	SOSA-11	SOSA-DG-11	SOSA-DPH-11
TTAHO-13	–	–	SOSA-12	–	SOSA-DPH-12
TTAHO-14	TTAHO-DG-14	TTAHO-DPH-14	SOSA-13	–	SOSA-DPH-13
–	–	–			

Table A1. Nomenclature for USGS-grid and CDPH-grid wells used in the status assessments for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[CDPH-grid wells are labeled “DG” if the USGS-grid and CDPH-grid wells are the same well, and are labeled “DPH” if the CDPH-well and USGS-grid well are different wells or if no USGS-grid well exists. Recent data from the CDPH database from CDPH-grid wells provide data for inorganic constituents for grid cells lacking USGS data for inorganic constituents. Identification number prefixes: TMART, Tahoe-Martis study unit, Martis study area grid well; TROCK, Tahoe-Martis study unit, Hard Rock study area grid well; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area grid well; CWISH, Central Sierra study unit, Wishon study area grid well; SOSA, Southern Sierra grid well. **Abbreviations:** CDPH, California Department of Public Health; USGS, U.S. Geological Survey; na, not applicable; –, no well sampled or selected]

Well identification number			Well identification number		
USGS-grid	“DG” CDPH-grid	“DPH” CDPH-grid	USGS-grid	“DG” CDPH-grid	“DPH” CDPH-grid
Southern Sierra study unit (40 grid cells)—Continued			Southern Sierra study unit (40 grid cells)—Continued		
SOSA-14	SOSA-DG-14	–	SOSA-28	–	SOSA-DPH-28
SOSA-15	–	SOSA-DPH-15	SOSA-29	SOSA-DG-29	–
SOSA-16	SOSA-DG-16	–	SOSA-30	SOSA-DG-30	SOSA-DPH-30
SOSA-17	SOSA-DG-17	–	SOSA-31	SOSA-DG-31	SOSA-DPH-31
SOSA-18	SOSA-DG-18	SOSA-DPH-18	SOSA-32	–	SOSA-DPH-32
SOSA-19	SOSA-DG-19	–	SOSA-33	–	SOSA-DPH-33
SOSA-20	SOSA-DG-20	–	SOSA-34	SOSA-DG-34	SOSA-DPH-34
SOSA-21	SOSA-DG-21	SOSA-DPH-21	SOSA-35	–	–
SOSA-22	–	–	–	–	SOSA-DPH-36
SOSA-23	SOSA-DG-23	–	–	–	SOSA-DPH-37
SOSA-24	SOSA-DG-24	–	–	–	SOSA-DPH-38
SOSA-25	SOSA-DG-25	–	–	–	–
SOSA-26	SOSA-DG-26	–	–	–	–
SOSA-27	SOSA-DG-27	–	–	–	–

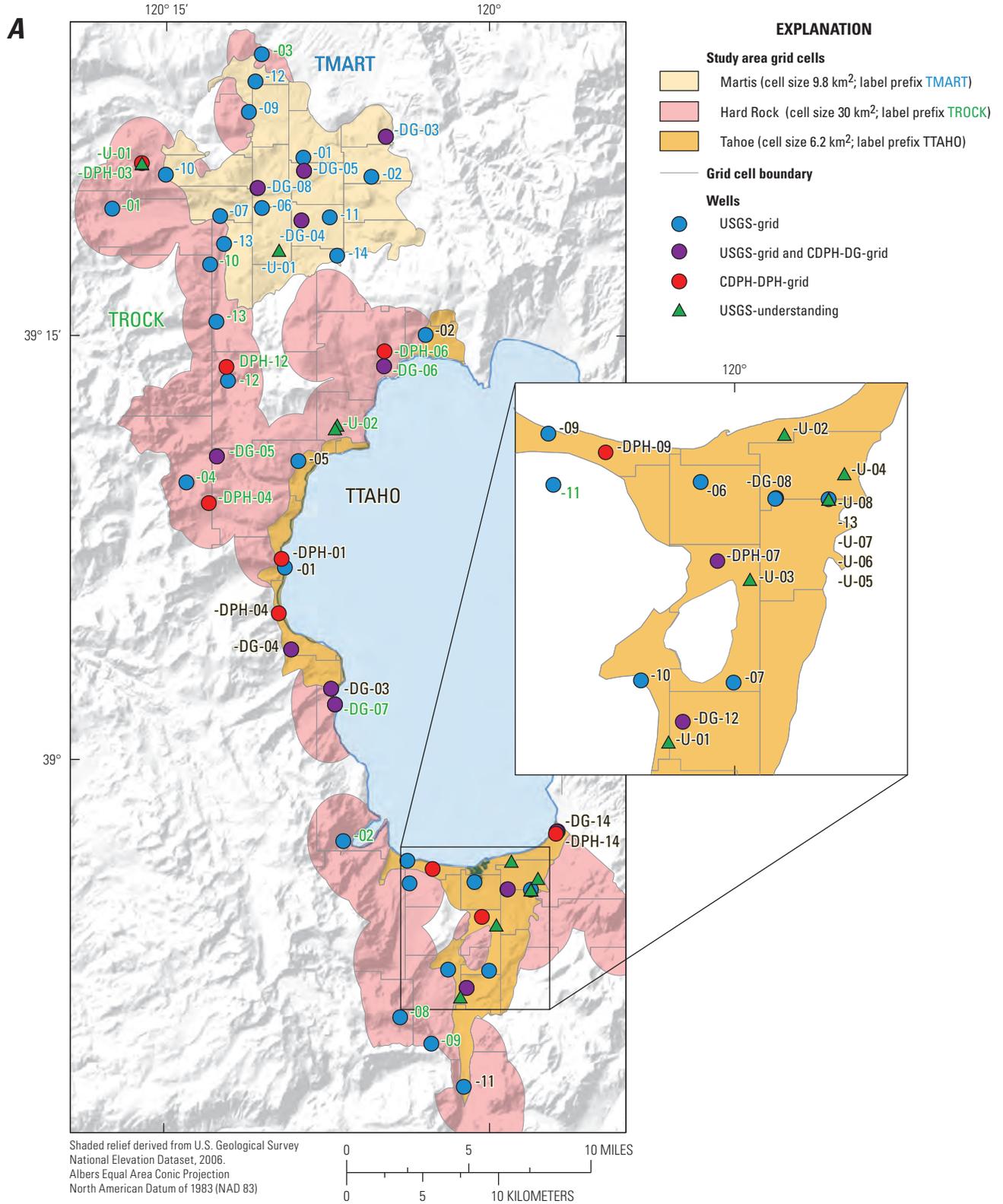


Figure A1. Maps showing locations of grid cells and USGS-grid, CDPH-grid, and USGS-understanding wells in the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

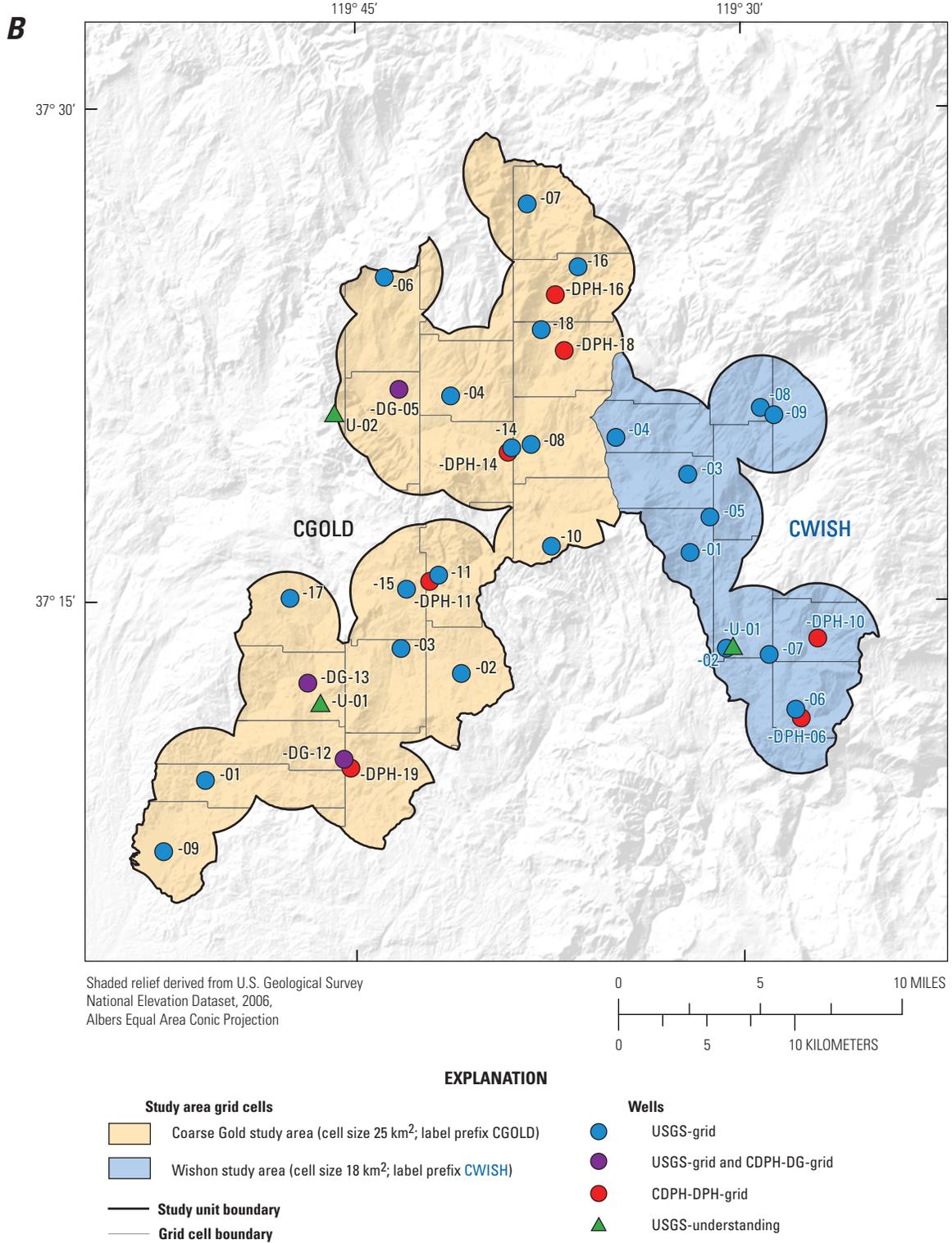


Figure A1.—Continued

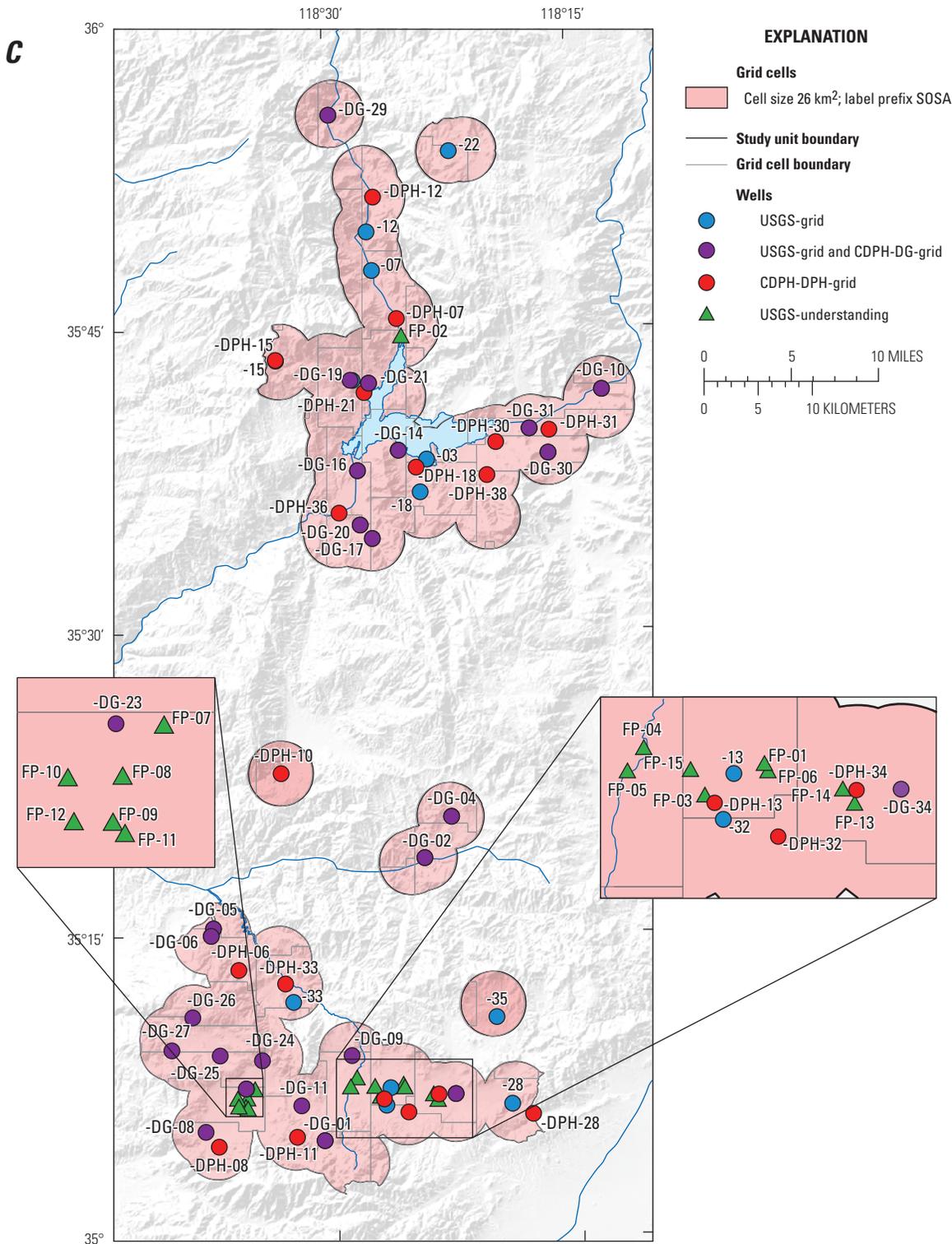


Figure A1.—Continued

Appendix B. Calculation of Aquifer-Scale Proportions

The methods used to calculate aquifer-scale proportions using the grid-based and spatially weighted approaches are described in this appendix.

Grid-Based Calculation

In the grid-based approach, one value per grid cell is used to represent the primary aquifer. A hypothetical example is shown in [figure B1A](#). The proportion of the primary aquifer with high RCs is calculated by dividing the number of cells represented by a high RC for that constituent by the total number of grid cells with data for that constituent. Proportions of moderate and low RCs are calculated similarly. In the example, 1 of the 16 cells with data for constituent A is represented by a high RC, thus the high proportion is 6.25%. Similarly, the moderate proportion for constituent A is 19% (3 of 16 cells are represented by moderate RCs). Only 12 of the cells have data for constituent B; the high proportion for B is 17% (2 of 12 cells), and the moderate proportion is 25% (3 of 12 cells).

The grid-based aquifer-scale proportions for constituent classes also are calculated on a one-value-per-grid-cell basis. A cell with a high RC for any constituent in the class is defined as a high cell, and the high proportion is the number of high cells divided by the number of cells with data for any of the constituents in the class. For the example shown in [figure B1A](#), cells 4 and 11 are defined as high cells, and the high proportion is 12.5% (2 of 16). The moderate proportion for the constituent class is calculated similarly, except that a cell already defined as high cannot also be defined as moderate. A cell with a moderate RC for any constituent in the class that does not also have a high RC for any constituent in the class is defined as moderate. For the example shown in [figure B1A](#), cells 3, 5, 7, and 12 are defined as moderate, and the moderate proportion is 25% (4 of 16).

The Tahoe-Martis and Central Sierra study units were subdivided into study areas, each of which had different sized cells. A hypothetical example of this situation is shown in [figure B1B](#). The study unit is divided into two study areas—SA1, which has 12 equal-area cells, and SA2, which has 9 equal-area cells. SA1 covers 75% of the study unit, and SA2 covers 25%. The cells in SA1 are larger than the cells

in SA2. Now suppose that a constituent has high RCs in one cell of SA1 and in four cells of SA2. The detection frequency of high RCs of the constituent in the grid wells is 24% (5 of 21 wells), but this detection frequency in the grid wells is not equal to the high aquifer-scale proportion for the constituent in the study unit. The proportion for the study unit is determined by calculating the aquifer-scale proportions in each study area separately, and then calculating the area-weighted sum:

$$P_{SU} = \sum P_{SA} F_{SA},$$

where

P_{SU} is the aquifer-scale proportion for the study unit,

P_{SA} is the aquifer-scale proportion for a study area,

and

F_{SA} is the fraction of the total study unit area occupied by the study area.

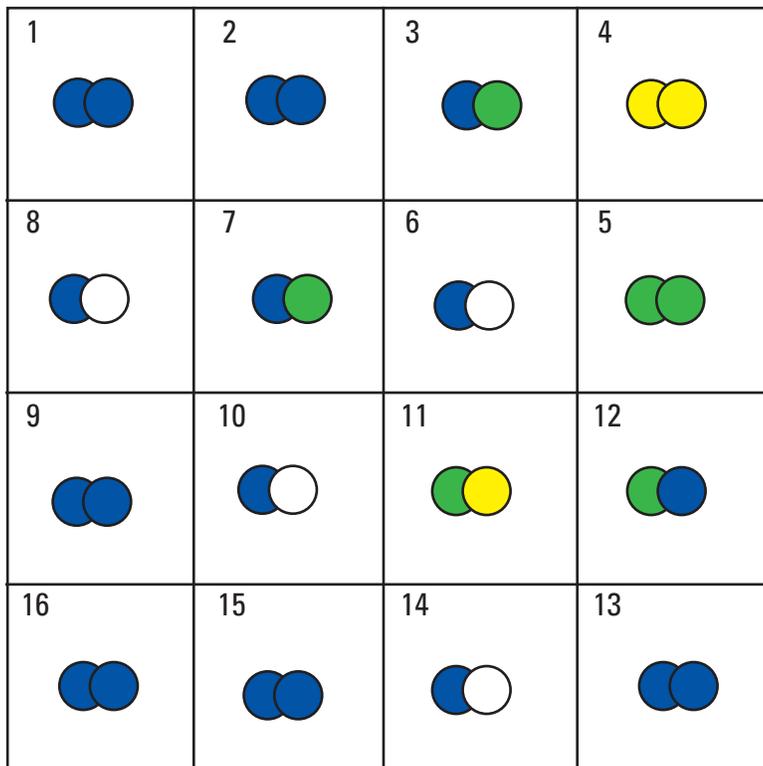
For the example in [figure B1B](#), the study unit aquifer-scale proportion is 17%.

$$0.17 = 0.75 \left(\frac{1}{12} \right) + 0.25 \left(\frac{4}{9} \right).$$

Spatially Weighted Calculation

The spatially weighted calculations of aquifer-scale proportions included all wells in the CDPH database with data in the 3-year interval prior to USGS-GAMA sampling in the study unit, all the USGS-grid wells, and most of the USGS-understanding wells. All of the USGS-understanding wells in the Central Sierra and Southern Sierra study units were included because they were either wells listed in the CDPH database, or were wells with screened or open intervals similar to those of nearby CDPH wells. All of the USGS-understanding wells in the Tahoe-Martis study unit were included, except for four monitoring wells with short screened or open intervals at depths not similar to nearby CDPH wells (TTAHOU-05, -06, -07, and -08).

A

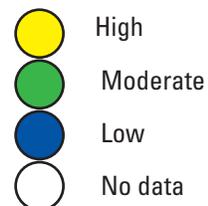


EXPLANATION

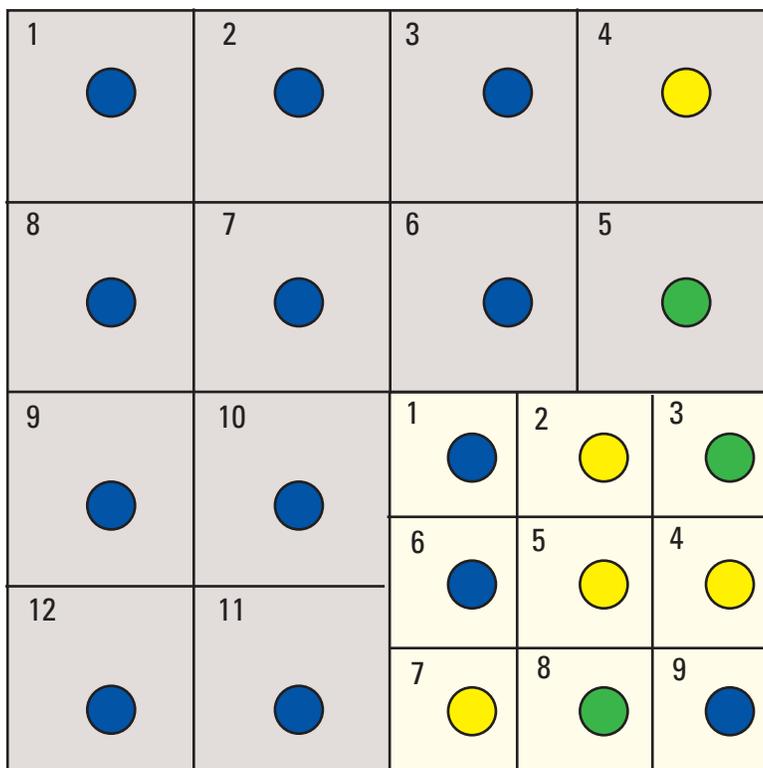
Constituent



Relative-concentration



B



EXPLANATION

Relative-concentration

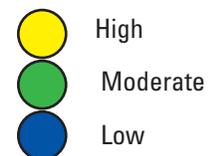


Figure B1. Diagrams demonstrating calculation of aquifer-scale proportions for constituents using the grid-based approach in a study unit with (A) one grid cell size and (B) study areas with different grid cell sizes.

For each constituent, the high aquifer-scale proportion was calculated by (1) computing the proportion of wells having high RCs in each grid cell, and then (2) averaging the grid cell values computed in step (1) (Isaaks and Srivastava, 1989):

$$P_{SU} = \frac{\sum \frac{W_{high}}{W_{total}}}{C},$$

where

P_{SU} is the aquifer-scale proportion for the study unit,

C is the number of cells with data for the constituent,

W_{total} is the number of wells in a given cell, and

W_{high} is the number of wells in a given cell with high RC for the constituent.

The same procedures were used to calculate the proportions of moderate and low concentrations. The resulting proportions are spatially unbiased (Isaaks and Srivastava, 1989).

For the example shown in [figure B2](#), the high aquifer-scale proportion is 14%:

$$0.14 = \frac{\frac{0}{3} + \frac{0}{5} + \frac{1}{3} + \frac{0}{0} + \frac{0}{4} + \frac{0}{1} + \frac{0}{2} + \frac{0}{11} + \frac{9}{11}}{8}.$$

The moderate aquifer-scale proportion is 39%.

Raw Detection Frequencies

The raw detection frequencies of wells with high RCs for constituents were calculated using the same data as used for the spatially weighted approach. However, raw detection frequencies are not spatially unbiased because the wells in the CDPH database are not uniformly distributed. Consequently, high RCs occurring in spatially clustered wells in a particular area representing a small part of the primary aquifer could be given a disproportionately high weight compared to spatially unbiased methods. Raw detection frequencies of high concentrations are provided for reference in this report but were not used to assess aquifer-scale proportions.

For the example shown in [figure B2](#), the raw detection frequencies of high and moderate RCs are both 25% (10 of 40 wells). The raw detection frequency of high RCs is greater than the high aquifer-scale proportion because the wells with high RCs primarily are clustered into one cell. Cell 9 represents one-eighth of the total area of the study unit, and contains 9 of the 10 wells with high concentrations. The raw detection frequency for moderate RCs is less than the moderate aquifer-scale proportion because the wells with moderate RCs are dispersed among multiple cells, each with relatively few wells (cells 2, 5, and 8). Half of the total area of the study unit therefore is characterized by moderate or mostly moderate RCs.

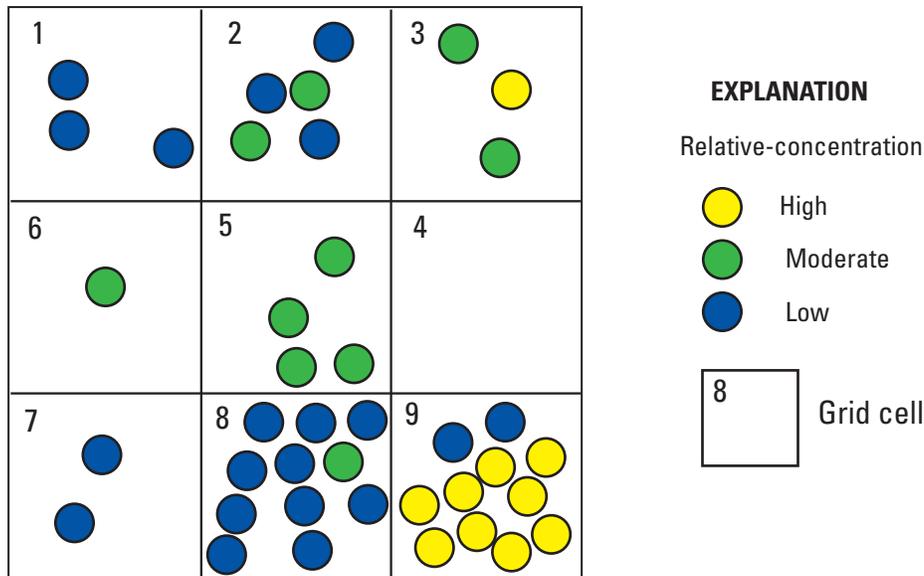


Figure B2. Diagram demonstrating calculation of aquifer-scale proportions for a constituent using the spatially weighted approach.

Study Area Aquifer-Scale Proportion Results

Raw detection frequencies, spatially weighted aquifer-scale proportions, and grid-based aquifer-scale proportions for constituents in the TTAHO, TMART, and TROCK study areas of the Tahoe-Martis study unit are listed in [tables B1A,B,C](#). Each study area had 15 cells, but covered different areal percentages of the total study-unit area: TTAHO 14%, TMART 22%, and TROCK 64%. If the area-weighting calculation had not been done, then TTAHO, and to a lesser extent, TMART, cells would have contributed more to the overall study-unit aquifer-scale proportions than warranted for an equal-area result. Summaries of aquifer-scale proportions for constituent classes by study area are given in [tables B2A,B](#) for inorganic constituent classes and in [table B2C](#) for organic constituent classes.

Groundwater quality differed significantly between the primary aquifers of the three Tahoe-Martis study unit study areas. The only inorganic constituent with a health-based benchmark detected at high RCs in the TMART study area was arsenic ([table B1B](#)). Arsenic also was detected at high RCs in the TROCK and TTAHO study areas ([tables B1A,C](#)). TTAHO was the only study area with radioactive constituents detected at high RCs ([table B1A](#)).

Organic constituents were detected in 36, 8, and 50% of the primary aquifers in the TMART, TROCK, and TTAHO study areas, respectively ([table B2C](#)). Pesticides were only detected in the TMART study area. No organic constituents were detected at moderate or high RCs in the TMART study area ([table B2C](#)). Several solvent constituents were detected at moderate and high RCs in approximately 1% each of the TROCK and TTAHO study areas ([tables B1A,C](#)).

Raw detection frequencies, spatially weighted aquifer-scale proportions, and grid-based aquifer-scale proportions for constituents in the CGOLD and CWISH study areas of the Central Sierra study unit are listed in [tables B1D,E](#). The CGOLD study area has 20 cells and composes 73% of the study unit area; the CWISH study area has 10 cells and composes 27% of the study unit area. If the area-weighting calculation had not been done, then CWISH cells would have contributed more to the overall study unit aquifer-scale proportions than warranted for an equal-area result. Summaries of aquifer-scale proportions for constituent classes by study area are given in [table B2A](#) for organic constituent classes and in [table B2B](#) for inorganic constituent classes.

Groundwater quality differed significantly between the primary aquifers of the two study areas in the Central Sierra study unit. Eighty percent of the primary aquifer in the CWISH study area had high RCs of at least one inorganic constituent with a health-based benchmark, compared to 26% of the primary aquifer in the CGOLD study area ([table B2A](#)). The high aquifer-scale proportions of arsenic, gross alpha particle radiation, and uranium each were $\geq 40\%$ in the CWISH study area ([table B1E](#)). Fluoride, molybdenum, and radon-222 also were present at high RCs. All of the same constituents were present at high RCs in the CGOLD study area, but in lower proportions of the primary aquifer ([table B1D](#)). High RCs of manganese and iron were detected in both study areas; high RCs of TDS were only detected in the CGOLD study area. Organic constituents were detected in 11 and 28% of the primary aquifers in the CWISH and CGOLD study areas, respectively ([table B2C](#)), and both study areas had detections of organic constituents at moderate RCs ([tables B1D,E](#)).

Table B1A. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Tahoe study area, Tahoe-Martis study unit, 2006–2007, California GAMA Priority Basin Project.

[Tahoe study area covers 13.99 percent of the Tahoe-Martis study unit. **Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)		
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high
Trace elements									
Arsenic	45	13	16	14	9.2	15	14	14	14
Boron	22	0	4.5	14	0	7.1	14	0	7.1
Molybdenum	18	5.6	5.6	14	3.6	3.6	14	0	7.1
Strontium	18	0	0	14	0	0	14	0	0
Uranium	18	17	0	14	14	0	14	14	0
Inorganic constituents with SMCL benchmarks									
Iron	43	2.3	9.3	14	1.2	12	14	0	14
Manganese	44	0	6.8	14	0	11	14	0	14
Chloride	44	2.3	0	14	2.4	0	14	7.1	0
Specific conductance	45	0	2.2	14	0	2.4	14	0	7.1
Sulfate	44	0	0	14	0	0	14	0	0
Total dissolved solids (TDS)	45	0	2.2	14	0	2.4	14	0	7.1
Radioactive constituents									
Adjusted gross alpha activity	34	2.9	5.9	13	1.9	3.8	13	7.7	7.7
Gross alpha particle activity	34	21	18	13	14	13	13	15	15
Radium activity	28	3.6	0	11	3.0	0	11	9.1	0
Radon-222 activity	35	8.6	11	14	4.2	6.1	14	7.1	7.1
Uranium activity	42	24	0	14	18	0	14	21	0
Volatile organic compounds - solvents									
Carbon tetrachloride	48	0	0	14	0	0	14	0	0
1,2-Dichloroethane	48	0	2.1	14	0	1.2	14	0	0
Chloroform	48	0	0	14	0	0	14	0	0
Chloromethane	48	0	0	14	0	0	14	0	0
Tetrachloroethylene (PCE)	48	4.2	2.1	14	2.4	1.2	14	0	7.1
Volatile organic compounds - fumigants									
1,2-Dichloropropane	48	0	0	14	0	0	14	0	0
DBCP	36	0	2.8	14	0	1.2	14	0	0

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during May 1, 2004–April 30, 2007, combined with data from U.S. Geological Survey (USGS) grid wells, and selected USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 41 grid wells during June–October 2007.

Table B1B. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Martis study area, Tahoe-Martis study unit, 2006–2007, California GAMA Priority Basin Project.

[Martis study area covers 22.11 percent of the Tahoe-Martis study unit. **Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)		
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high
Trace elements									
Arsenic	16	13	31	14	7.1	32	14	7.1	29
Boron	15	6.7	0	14	7.1	0	14	7.1	0
Molybdenum	15	0	0	14	0	0	14	0	0
Strontium	15	0	0	14	0	0	14	0	0
Uranium	16	0	0	14	0	0	14	0	0
Inorganic constituents with SMCL benchmarks									
Iron	16	0	0	14	0	0	14	0	0
Manganese	16	0	6.3	14	0	7.1	14	0	7.1
Chloride	16	0	0	14	0	0	14	0	0
Specific conductance	16	0	0	14	0	0	14	0	0
Sulfate	16	0	0	14	0	0	14	0	0
Total dissolved solids (TDS)	16	0	0	14	0	0	14	0	0
Radioactive constituents									
Adjusted gross alpha activity	10	0	0	7	0	0	6	0	0
Gross alpha particle activity	10	0	0	7	0	0	6	0	0
Radium activity	3	0	0	3	0	0	2	0	0
Radon-222 activity	15	0	0	14	0	0	14	0	0
Uranium activity	16	0	0	14	0	0	14	0	0
Volatile organic compounds - solvents									
Carbon tetrachloride	16	0	0	14	0	0	14	0	0
1,2-Dichloroethane	16	0	0	14	0	0	14	0	0
Chloroform	16	0	0	14	0	0	14	0	0
Chloromethane	16	0	0	14	0	0	14	0	0
Tetrachloroethylene (PCE)	16	0	0	14	0	0	14	0	0
Volatile organic compounds - fumigants									
1,2-Dichloropropane	16	0	0	14	0	0	14	0	0
DBCP	16	0	0	14	0	0	14	0	0

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during May 1, 2004–April 30, 2007, combined with data from U.S. Geological Survey (USGS) grid wells, and selected USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 41 grid wells during June–October 2007.

Table B1C. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Hard Rock study area, Tahoe-Martis study unit, 2006–2007, California GAMA Priority Basin Project.

[Hard Rock study area covers 63.90 percent of the Tahoe-Martis study unit. **Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)		
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high
Trace elements									
Arsenic	34	0	8.8	13	0	12	13	0	15
Boron	19	0	5.3	13	0	7.7	13	0	7.7
Molybdenum	15	0	6.7	13	0	7.7	13	0	7.7
Strontium	15	0	6.7	13	0	7.7	13	0	7.7
Uranium	15	0	0	13	0	0	13	0	0
Inorganic constituents with SMCL benchmarks									
Iron	36	2.8	8.3	13	0	6.4	13	0	7.7
Manganese	34	0	5.9	13	0	12	13	0	15
Chloride	34	0	0	13	0	0	13	0	0
Specific conductance	34	0	5.7	13	7.7	3.8	13	7.7	7.7
Sulfate	34	0	2.9	13	0	3.8	13	0	7.7
Total dissolved solids (TDS)	35	0	5.7	13	0	12	13	0	15
Radioactive constituents									
Adjusted gross alpha activity	16	0	0	5	0	0	5	0	0
Gross alpha particle activity	16	6.3	0	5	2.5	0	5	0	0
Radium activity	8	0	0	5	0	0	4	0	0
Radon-222 activity	17	12	0	12	17	0	12	17	0
Uranium activity	17	0	0	13	0	0	13	0	0
Volatile organic compounds - solvents									
Carbon tetrachloride	32	0	3.1	13	0	0.7	13	0	0
1,2-Dichloroethane	32	0	0	13	0	0	13	0	0
Chloroform	32	0	0	13	0	0	13	0	0
Chloromethane	32	3.1	0	13	0.7	0	13	0	0
Perchloroethene (PCE)	32	0	0	13	0	0	13	0	0
Volatile organic compounds - fumigants									
1,2-Dichloropropane	32	0	3.1	13	0	0.7	13	0	0
DBCP	20	0	0	13	0	0	13	0	0

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during May 1, 2004–April 30, 2007, combined with data from U.S. Geological Survey (USGS) grid wells, and selected USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 41 grid wells during June–October 2007.

Table B1D. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Coarse Gold study area, Central Sierra study unit, 2006–2007, California Groundwater GAMA Priority Basin Project.

[Course Gold area covers 72.58 percent of the Central Sierra study unit. **Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)		
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high
Nutrients									
Nitrate	129	4.7	0	19	4.2	0	19	0	0
Trace elements									
Arsenic	72	13	18	19	21	17	19	26	5.3
Boron	23	8.7	0	18	5.6	0	18	5.6	0
Chromium	67	0	1.5	19	0	0.6	19	0	0
Fluoride	76	2.6	2.6	19	3.2	6.3	19	5.3	5.3
Lead	71	2.8	0	19	3.2	0	19	0	0
Molybdenum	20	30	10	18	28	8.3	18	28	11
Selenium	67	0	1.5	19	0	0.6	19	0	0
Uranium	41	20	4.9	18	17	2.8	18	17	0
Inorganic constituents with SMCL benchmarks									
Iron	77	2.6	27	19	3.2	23	19	0	16
Manganese	77	7.8	40	19	0	34	19	5.3	37
Zinc	75	2.7	0	19	3.4	0	19	5.3	0
Chloride	76	2.6	3.9	19	1.4	1.8	19	0	0
Specific conductance	76	6.6	3.9	19	4.1	1.8	19	0	0
Total dissolved solids (TDS)	71	5.6	4.2	19	3.0	1.9	19	0	0
Radioactive constituents									
Adjusted gross alpha activity	87	5.7	0	17	3.2	0	17	5.9	0
Gross alpha particle activity	87	16	13	17	15	13	17	24	5.9
Radium activity	9	0	0	10	0	0	10	0	0
Radon-222 activity	9	33	22	9	33	22	9	33	22
Uranium activity	62	16	15	18	12	5.8	18	17	0
Pesticide									
Simazine	75	0	0	19	0	0	19	0	0
Volatile organic compounds									
Benzene	61	1.6	0	18	2.8	0	18	5.6	0
Chloroform	64	1.6	0	18	0.7	0	18	0	0
Perchloroethene (PCE)	61	1.6	0	18	0.7	0	18	0	0
Methyl <i>tert</i> -butyl ether (MTBE)	61	3.3	0	18	2.2	0	18	0	0
1,4-Dichlorobenzene	61	0	0	18	0	0	18	0	0

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during June 1, 2003–May 31, 2006, combined with data from U.S. Geological Survey (USGS) grid wells, and selected USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 27 grid wells during May 2006.

Table B1E. Aquifer-scale proportions calculated using grid-based and spatially weighted methods for those constituents that met criteria for additional evaluation in the status assessment, Wishon study area, Central Sierra study unit, 2006–2007, California GAMA Priority Basin Project.

[Wishon study area covers 27.42 percent of the Central Sierra study unit. **Relative-concentration categories:** high, concentrations greater than water-quality benchmark; moderate, concentrations greater than or equal to 0.1 of benchmark but less than benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark); low, concentrations less than 0.1 of benchmark for organic constituents (threshold for inorganic constituents is 0.5 of benchmark). Benchmark types and values listed in [table 3](#). **Other abbreviations:** SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency ¹ (percent)			Spatially weighted aquifer-scale proportion ¹ (percent)			Grid-based aquifer-scale proportion ² (percent)		
	Number of wells	Percent moderate	Percent high	Number of cells	Proportion moderate	Proportion high	Number of cells	Proportion moderate	Proportion high
Nutrients									
Nitrate	36	0	0	10	0	0	19	0	0
Trace elements									
Arsenic	26	3.8	35	10	0	26	10	0	40
Boron	10	30	0	9	33	0	9	33	0
Chromium	23	0	0	10	0	0	10	0	0
Fluoride	24	17	4.2	10	12	10	10	20	10
Lead	24	4.2	0	10	10	0	10	10	0
Molybdenum	10	40	10	9	33	11	9	33	11
Selenium	23	0	0	10	0	0	10	0	0
Uranium	12	0	58	9	0	50	9	0	56
Inorganic constituents with SMCL benchmarks									
Iron	24	8.3	13	10	5.8	7.9	10	10	0
Manganese	24	4.2	21	10	7.1	15	10	0	20
Zinc	23	4.3	0	10	7.5	0	10	10	0
Chloride	24	0	0	10	0	0	10	0	0
Specific conductance	24	0	0	10	0	0	10	0	0
Total dissolved solids (TDS)	24	0	0	10	0	0	10	0	0
Radioactive constituents									
Adjusted gross alpha activity	24	4.3	8.7	7	2.4	4.8	7	14	14
Gross alpha particle activity	24	17	38	7	16	45	7	29	43
Radium activity	5	20	0	5	20	0	5	20	0
Radon-222 activity	5	0	100	5	0	100	5	0	100
Uranium activity	15	13	47	10	10	52	10	10	50
Pesticide									
Simazine	13	0	0	9	0	0	9	0	0
Volatile organic compounds									
Benzene	23	0	0	9	0	0	9	0	0
Chloroform	23	4.3	0	9	2.2	0	9	0	0
Perchloroethene (PCE)	23	0	0	9	0	0	9	0	0
Methyl <i>tert</i> -butyl ether (MTBE)	23	0	0	9	0	0	9	0	0
1,4-Dichlorobenzene	23	4.3	0	9	1.6	0	9	0	0

¹ Based on most recent analyses for each California Department of Public Health (CDPH) well during June 1, 2003–May 31, 2006, combined with data from U.S. Geological Survey (USGS) grid wells, and selected USGS-understanding wells.

² Grid-based aquifer-scale proportions for organic constituents are based on samples collected by the USGS from 27 grid wells during May 2006.

Table B2A. Summary of aquifer-scale proportions calculated using the grid-based method for study areas for inorganic constituent classes with health-based benchmarks, Tahoe-Martis and Central Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[**Relative-concentration categories:** high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.5 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.5 of benchmark. TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area]

	Number of cells	Aquifer-scale proportion (percent)		
		Detected at low relative-concentration	Detected at moderate relative-concentration	Detected at high relative-concentration
Radioactive constituents¹				
Tahoe-Martis				
TMART	14	100	0	0
TROCK	13	85	15	0
TTAHO	14	64	14	21
Central Sierra				
CGOLD	18	56	28	17
CWISH	10	10	20	70
Nutrients				
Tahoe-Martis				
TMART	14	100	0	0
TROCK	13	100	0	0
TTAHO	14	100	0	0
Central Sierra				
CGOLD	19	96	² 4.2	0
CWISH	10	100	0	0
Trace elements				
Tahoe-Martis				
TMART	14	64	7.1	29
TROCK	13	85	0	15
TTAHO	14	64	14	21
Central Sierra				
CGOLD	19	47	37	16
CWISH	10	30	20	50
All inorganic constituents with health-based benchmarks³				
Tahoe-Martis				
TMART	14	64	7.1	29
TROCK	13	69	15	15
TTAHO	14	57	14	29
Central Sierra				
CGOLD	19	32	42	26
CWISH	10	0	20	80

¹ Aquifer-scale proportions for radioactive constituents were calculated using gross alpha activity. If adjusted gross alpha activity were used instead, the high and moderate aquifer-scale proportions would be as follows: TMART, unchanged; TROCK, unchanged; TTAHO, 14 percent high, 21 percent moderate; CGOLD, 11 percent high, 33 percent moderate; and CWISH, unchanged.

² Based on spatially weighted calculation.

³ Aquifer-scale proportions for all inorganic constituents with health-based benchmarks were calculated using gross alpha activity. If adjusted gross alpha activity were used instead, the high and moderate aquifer-scale proportions would be as follows: TMART, unchanged; TROCK, unchanged; TTAHO, 21 percent high, 21 percent moderate; CGOLD, unchanged; and CWISH, unchanged.

Table B2B. Summary of aquifer-scale proportions calculated using the grid-based method for study areas for inorganic constituent classes with SMCL benchmarks, Tahoe-Martis and Central Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Relative-concentration categories: high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.5 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.5 of benchmark. TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SMCL, secondary maximum contaminant level]

	Number of cells	Aquifer-scale proportion (percent)		
		Detected at low relative-concentration	Detected at moderate relative-concentration	Detected at high relative-concentration
Major ions with SMCL benchmarks¹				
Tahoe-Martis				
TMART	14	100	0	0
TROCK	13	88	0	12
TTAHO	14	98	0	2.4
Central Sierra				
CGOLD	19	93	4.7	2.5
CWISH	10	100	0	0
Trace elements with SMCL benchmarks				
Tahoe-Martis				
TMART	14	93	0	7.1
TROCK	13	85	0	15
TTAHO	14	79	0	21
Central Sierra				
CGOLD	19	58	5.3	37
CWISH	10	60	20	20
All inorganic constituents with SMCL benchmarks				
Tahoe-Martis				
TMART	14	93	0	7.1
TROCK	13	85	0	15
TTAHO	14	79	0	21
Central Sierra				
CGOLD	19	58	5.3	37
CWISH	10	60	20	20

¹ Based on spatially weighted calculation.

Table B2C. Summary of aquifer-scale proportions calculated using the grid-based method for study areas for organic constituent classes with health-based benchmarks, Tahoe-Martis and Central Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[**Relative-concentration categories:** high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than 0.1 of benchmark and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group less than or equal to 0.1 of benchmark. TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area]

	Number of cells	Aquifer-scale proportion (percent)			
		Not detected	Detected at low relative-concentration	Detected at moderate relative-concentration	Detected at high relative-concentration
Volatile organic compounds					
Tahoe-Martis					
TMART	14	71	29	0	0
TROCK	13	92	6.6	¹ 0.7	¹ 0.7
TTAHO	14	50	44	¹ 2.4	¹ 3.6
Central Sierra					
CGOLD	18	72	22	¹ 5.6	0
CWISH	9	89	11	0	0
Pesticides					
Tahoe-Martis					
TMART	14	86	14	0	0
TROCK	13	100	0	0	0
TTAHO	14	100	0	0	0
Central Sierra					
CGOLD	17	76	24	0	0
CWISH	9	100	0	0	0
Any organic constituent					
Tahoe-Martis					
TMART	14	64	36	0	0
TROCK	13	92	6.6	0.7	0.7
TTAHO	14	50	44	2.4	3.6
Central Sierra					
CGOLD	18	67	28	5.6	0
CWISH	9	89	11	0	0

¹ Based on spatially weighted calculation.

Appendix C: Attribution of Potential Explanatory Factors

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 undeveloped. 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 at correlating urban land use with VOC occurrence for the purposes of statistical characterization (Johnson and Belitz, 2009). Land-use data for USGS-grid, CDPH-grid, and USGS-understanding wells are listed in [table C1](#).

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 use includes cultivated crops and land used for pasture or hay. Undeveloped land use includes everything else. In this classification, open-range grazing, such as that practiced on USFS and USBLM lands in the Sierra Nevada, is classified as undeveloped land use, not agricultural land use. 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 (AUM) 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

Septic tank density was determined from housing characteristics data from the 1990 U.S. Census (U.S. Census Bureau, 1990). The density of septic tanks in each housing census block was calculated from the number of tanks and block area. The density of septic tanks around each well was then calculated from the area-weighted mean of the block densities for blocks within a 500-m buffer around the well location. (Tyler Johnson, USGS, written commun., 2009) ([table C1](#)).

Aquifer Lithology

Aquifer lithology was classified into four categories on the basis of lithologic information from driller's logs and on the California State geologic map (Jennings, 1977; Saucedo and others, 2000). The State geologic map shows the lithologic unit exposed at the surface, which may not be the same as the lithologic unit at the depth range over which the well is screened or open. Therefore, if the lithologic category estimated from the geologic map disagreed with the lithology described in the 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; lithologic category for these sites was estimated from the geologic units mapped surrounding the lake. The 132 wells sampled by USGS-GAMA and the 34 "DPH" CDPH-grid wells selected in the three study units were located on areas classified into 8 of the 66 geologic units defined on the California state geologic map (Jennings, 1977; Saucedo and others, 2000). These eight geologic units were grouped into four 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: m).
- Sedimentary deposits: Cenozoic sedimentary deposits, including alluvial, fluvial, lacustrine, and glacial sediments (California State geologic map units: Q, Qg). These Quaternary-age sedimentary deposits are Pleistocene and Holocene in age.
- 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.

The lithologic categories and geologic units assigned to each USGS-grid, USGS-understanding, and CDPH-grid well are listed in [table C1](#).

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 C1. Land-use percentages, septic tank density, and aquifer lithology classification for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Geologic units:** grMz, Mesozoic granitic rocks; m, Paleozoic-Mesozoic metasedimentary and metavolcanic rocks; Ti, Tertiary shallow intrusive rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Qv, Quaternary volcanic rocks; Q, Quaternary non-marine sediment; Qg, Quaternary glacial sediment. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Other abbreviations:** USGS, U.S. Geological Survey; CDPH, California Department of Public Health; na, not available; tanks/km², number of septic tanks per square kilometer]

Well identification number	Land-use percentages ¹			Septic density ²	Aquifer lithology classification	
	Agricultural	Undeveloped ¹	Urban	Tanks/km ²	Geologic unit ³	Aquifer lithology class
Tahoe-Martis study unit USGS-grid wells						
TMART-01	0	94	6	13	Qv ⁸	V ⁸
TMART-02	0	100	0	2	Qv	V
TMART-03	0	100	0	2	Tv	V
TMART-04	0	64	36	3	Qv ⁸	V ⁸
TMART-05	0	100	0	2	Qv ⁸	V ⁸
TMART-06	0	48	52	81	Qv ⁸	V ⁸
TMART-07	0	75	25	3	Qg	S
TMART-08	0	95	5	24	Qv ⁸	V ⁸
TMART-09	0	100	0	0	Qv ⁸	V ⁸
TMART-10	0	13	87	1	Qv	V
TMART-11	0	74	26	2	Qg	S
TMART-12	0	91	9	1	Qv ⁸	V ⁸
TMART-13	0	100	0	7	Qv	V
TMART-14	0	100	0	7	Tv ⁸	V ⁸
TROCK-01	0	64	36	1	grMz	G
TROCK-02	0	100	0	0	grMz	G
TROCK-03	0	100	0	1	Tvp	V
TROCK-04	0	100	0	2	Tvp ⁸	V ⁸
TROCK-05	0	96	4	2	Tvp	V
TROCK-06	0	50	50	0	Qv	V
TROCK-07	0	33	67	0	grMz ⁶	G ⁶
TROCK-08	0	100	0	0	grMz	G
TROCK-09	0	100	0	0	grMz ⁶	G ⁶
TROCK-10	0	88	12	7	Tvp	V
TROCK-11	0	100	0	0	Qg	S
TROCK-12	0	100	0	3	Tvp ⁸	V ⁸
TROCK-13	0	100	0	7	grMz ⁶	G ⁶
TTAHO-01	0	84	16	0	Q	S
TTAHO-02	0	88	12	0	Q	S
TTAHO-03	0	39	61	0	Qg	S
TTAHO-04	0	63	37	0	Qg	S
TTAHO-05	0	92	8	0	Q	S
TTAHO-06	0	9	91	4	Q	S
TTAHO-07	0	92	8	0	Q	S
TTAHO-08	0	21	79	0	Qg	S
TTAHO-09	0	97	3	0	Q	S
TTAHO-10	0	79	21	0	Q	S
TTAHO-11	0	96	4	0	grMz	G
TTAHO-12	0	50	50	0	Q	S
TTAHO-13	0	43	57	0	Qg	S
TTAHO-14	0	45	55	105	Qg	S

Table C1. Land-use percentages, septic tank density, and aquifer lithology classification for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Geologic units:** grMz, Mesozoic granitic rocks; m, Paleozoic-Mesozoic metasedimentary and metavolcanic rocks; Ti, Tertiary shallow intrusive rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Qv, Quaternary volcanic rocks; Q, Quaternary non-marine sediment; Qg, Quaternary glacial sediment. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Other abbreviations:** USGS, U.S. Geological Survey; CDPH, California Department of Public Health; na, not available; tanks/km², number of septic tanks per square kilometer]

Well identification number	Land-use percentages ¹			Septic density ²	Aquifer lithology classification	
	Agricultural	Undeveloped ¹	Urban	Tanks/km ²	Geologic unit ³	Aquifer lithology class
Tahoe-Martis study unit USGS-understanding wells						
TMARTU-01	0	100	0	7	Qv	V
TROCKU-01	0	100	0	1	Tvp	V
TROCKU-02	0	85	15	0	Qv	V
TTAHOU-01	0	61	39	0	Q	S
TTAHOU-02	0	9	91	57	Qg	S
TTAHOU-03	0	26	74	4	Q	S
TTAHOU-04	0	20	80	0	Qg	S
TTAHOU-05	0	43	57	0	Qg	S
TTAHOU-06	0	43	57	0	Qg	S
TTAHOU-07	0	43	57	0	Qg	S
TTAHOU-08	0	43	57	0	Qg	S
Tahoe-Martis study unit CDPH-grid wells						
TROCK-DPH-03	na	na	na	na	Tvp	V
TROCK-DPH-04	na	na	na	na	Qg	S
TROCK-DPH-06	na	na	na	na	Qv	V
TROCK-DPH-12	na	na	na	na	Tv	V
TTAHO-DPH-01	na	na	na	na	Q	S
TTAHO-DPH-04	na	na	na	na	Q	S
TTAHO-DPH-07	na	na	na	na	Qg	S
TTAHO-DPH-09	na	na	na	na	Q	S
TTAHO-DPH-14	na	na	na	na	Qg	S
Central Sierra study unit USGS-grid wells						
CGOLD-01	0	100	0	0	grMz	G
CGOLD-02	0	64	36	6	grMz	G
CGOLD-03	0	100	0	4	grMz	G
CGOLD-04	0	100	0	11	grMz	G
CGOLD-05	0	52	48	18	grMz	G
CGOLD-06	0	100	0	10	grMz	G
CGOLD-07	0	96	4	5	grMz	G
CGOLD-08	0	36	64	34	grMz	G
CGOLD-09	0	100	0	0	grMz	G
CGOLD-10	0	100	0	4	m	M
CGOLD-11	0	86	14	4	m	M
CGOLD-12	0	77	23	14	grMz	G
CGOLD-13	0	87	13	13	grMz	G
CGOLD-14	0	29	71	50	grMz	G
CGOLD-15	0	100	0	4	grMz	G
CGOLD-16	0	100	0	5	grMz ⁴	G ⁴
CGOLD-17	0	100	0	1	grMz	G
CGOLD-18	0	94	6	9	grMz	G
CWISH-01	0	75	25	9	grMz	G
CWISH-02	0	34	66	3	grMz	G

Table C1. Land-use percentages, septic tank density, and aquifer lithology classification for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Geologic units:** grMz, Mesozoic granitic rocks; m, Paleozoic-Mesozoic metasedimentary and metavolcanic rocks; Ti, Tertiary shallow intrusive rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Qv, Quaternary volcanic rocks; Q, Quaternary non-marine sediment; Qg, Quaternary glacial sediment. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Other abbreviations:** USGS, U.S. Geological Survey; CDPH, California Department of Public Health; na, not available; tanks/km², number of septic tanks per square kilometer]

Well identification number	Land-use percentages ¹			Septic density ²	Aquifer lithology classification	
	Agricultural	Undeveloped ¹	Urban	Tanks/km ²	Geologic unit ³	Aquifer lithology class
Central Sierra study unit USGS-grid wells—Continued						
CWISH-03	0	97	3	1	grMz	G
CWISH-04	0	95	5	12	grMz	G
CWISH-05	0	95	5	3	grMz	G
CWISH-06	0	100	0	3	grMz	G
CWISH-07	0	94	6	3	grMz	G
CWISH-08	0	100	0	0	grMz	G
CWISH-09	0	100	0	0	grMz	G
Central Sierra study unit USGS-understanding wells						
CGOLDU-01	0	66	34	14	grMz	G
CGOLDU-02	0	100	0	3	m	M
CWISHU-01	0	48	52	3	grMz	G
Central Sierra study unit CDPH-grid wells						
CGOLD-DPH-11	na	na	na	na	grMz	G
CGOLD-DPH-14	na	na	na	na	grMz	G
CGOLD-DPH-16	na	na	na	na	grMz	G
CGOLD-DPH-18	na	na	na	na	grMz	G
CGOLD-DPH-19	na	na	na	na	grMz	G
CWISH-DPH-06	na	na	na	na	grMz	G
CWISH-DPH-10	na	na	na	na	grMz	G
Southern Sierra study unit USGS-grid wells						
SOSA-01	40	60	0	0	m	M
SOSA-02	0	100	0	0	Ti	V
SOSA-03	45	55	0	17	m ⁵	M ⁵
SOSA-04	0	100	0	0	grMz	G
SOSA-05	0	100	0	5	grMz	G
SOSA-06	0	100	0	5	grMz	G
SOSA-07	0	100	0	0	Q	S
SOSA-08	21	79	0	3	grMz ⁶	G ⁶
SOSA-09	0	95	5	133	m	M
SOSA-10	2	97	0	1	Q	S
SOSA-11	57	43	0	3	Q	S
SOSA-12	0	100	0	0	Q	S
SOSA-13	60	22	18	2	Q	S
SOSA-14	0	98	2	17	m ⁵	M ⁵
SOSA-15	0	100	0	1	grMz	G
SOSA-16	7	44	49	39	Q	S
SOSA-17	0	100	0	36	m	M
SOSA-18	0	96	4	17	Q	S
SOSA-19	0	92	8	23	m	M
SOSA-20	0	87	13	36	m	M
SOSA-21	0	54	46	34	Q	S
SOSA-22	0	100	0	0	grMz	G

Table C1. Land-use percentages, septic tank density, and aquifer lithology classification for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Geologic units:** grMz, Mesozoic granitic rocks; m, Paleozoic-Mesozoic metasedimentary and metavolcanic rocks; Ti, Tertiary shallow intrusive rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Qv, Quaternary volcanic rocks; Q, Quaternary non-marine sediment; Qg, Quaternary glacial sediment. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Other abbreviations:** USGS, U.S. Geological Survey; CDPH, California Department of Public Health; na, not available; tanks/km², number of septic tanks per square kilometer]

Well identification number	Land-use percentages ¹			Septic density ²	Aquifer lithology classification	
	Agricultural	Undeveloped ¹	Urban	Tanks/km ²	Geologic unit ³	Aquifer lithology class
Southern Sierra study unit USGS-grid wells—Continued						
SOSA-23	72	28	0	3	Q	S
SOSA-24	16	84	0	5	grMz ⁶	G ⁶
SOSA-25	26	74	0	5	Q	S
SOSA-26	0	100	0	5	grMz	G
SOSA-27	34	66	0	4	grMz ⁶	G ⁶
SOSA-28	0	95	5	0	Q	S
SOSA-29	0	100	0	0	m	M
SOSA-30	25	75	0	1	grMz ⁶	G ⁶
SOSA-31	89	9	2	1	Q	S
SOSA-32	28	71	1	3	Q	S
SOSA-33	0	100	0	15	grMz	G
SOSA-34	39	60	1	0	Q	S
SOSA-35	0	99	1	0	m ⁹	M ⁹
Southern Sierra study unit USGS-understanding wells						
SOSAFP-01	61	21	18	1	Q	S
SOSAFP-02	1	93	6	33	m ⁵	M ⁵
SOSAFP-03	32	50	19	11	Q	S
SOSAFP-04	7	91	3	138	Q	S
SOSAFP-05	9	76	15	77	Q	S
SOSAFP-06	81	14	5	1	Q	S
SOSAFP-07	79	21	0	1	Q	S
SOSAFP-08	71	29	0	2	Q	S
SOSAFP-09	68	32	0	3	Q	S
SOSAFP-10	86	14	0	3	Q	S
SOSAFP-11	74	26	0	3	Q	S
SOSAFP-12	70	30	0	3	Q	S
SOSAFP-13	39	60	0	0	Q	S
SOSAFP-14	65	34	1	0	Q	S
SOSAFP-15	30	43	27	14	Q	S
Southern Sierra study unit CDPH-grid wells						
SOSA-DPH-06	na	na	na	na	grMz	G
SOSA-DPH-07	na	na	na	na	Q	S
SOSA-DPH-08	na	na	na	na	grMz ⁶	G ⁶
SOSA-DPH-11	na	na	na	na	grMz	G
SOSA-DPH-12	na	na	na	na	m	M
SOSA-DPH-13	na	na	na	na	Q	S
SOSA-DPH-15	na	na	na	na	grMz	G
SOSA-DPH-18	na	na	na	na	Q	S
SOSA-DPH-21	na	na	na	na	grMz ⁷	G ⁷
SOSA-DPH-28	na	na	na	na	m	M
SOSA-DPH-30	na	na	na	na	Q	S

Table C1. Land-use percentages, septic tank density, and aquifer lithology classification for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[**Well identification numbers:** TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Geologic units:** grMz, Mesozoic granitic rocks; m, Paleozoic-Mesozoic metasedimentary and metavolcanic rocks; Ti, Tertiary shallow intrusive rocks; Tv, Tertiary volcanic rocks; Tvp, Tertiary pyroclastic rocks; Qv, Quaternary volcanic rocks; Q, Quaternary non-marine sediment; Qg, Quaternary glacial sediment. **Aquifer lithology class:** G, granitic rocks; M, metamorphic rocks; S, sedimentary deposits; V, volcanic rocks. **Other abbreviations:** USGS, U.S. Geological Survey; CDPH, California Department of Public Health; na, not available; tanks/km², number of septic tanks per square kilometer]

Well identification number	Land-use percentages ¹			Septic density ²	Aquifer lithology classification	
	Agricultural	Undeveloped ¹	Urban	Tanks/km ²	Geologic unit ³	Aquifer lithology class
Southern Sierra study unit CDPH-grid wells—Continued						
SOSA-DPH-31	na	na	na	na	Q	S
SOSA-DPH-32	na	na	na	na	Q	S
SOSA-DPH-33	na	na	na	na	grMz	G
SOSA-DPH-34	na	na	na	na	Q	S
SOSA-DPH-36	na	na	na	na	Q	S
SOSA-DPH-37	na	na	na	na	Q	S
SOSA-DPH-38	na	na	na	na	grMz ⁶	G ⁶

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

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

³ Geologic units from geologic map of California (Jennings, 1977, and Saucedo and others, 2000).

⁴ Geologic unit based on surficial geology was metamorphic; classification changed to granitic based on driller's log.

⁵ Geologic unit based on surficial geology was water; classification changed to metamorphic based on nearest surficial geologic unit.

⁶ Geologic unit based on surficial geology was sedimentary; classification changed to granitic based on driller's log.

⁷ Geologic unit based on surficial geology was water; classification changed to granitic based on nearest surficial geologic unit.

⁸ Geologic unit based on surficial geology was sedimentary; classification changed to volcanic based on driller's log.

⁹ Geologic unit based on surficial geology was volcanic; classification changed to metamorphic based on driller's logs of adjacent wells.

Well Construction Information and Hydrologic Conditions

Well construction data were obtained primarily from driller’s logs. On occasion, well construction data were obtained from ancillary records of well owners or the USGS National Water Information System database. Well identification verification procedures are described by Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009). Well depths and depths to the top and bottom of the screened or open interval for USGS-grid, USGS-understanding, and CDPH-grid wells are listed in [table C2](#). Wells drilled in hard rock commonly do not have casings; the borehole is left open. For these wells, the top of the screened or open interval was defined as the base of the sanitary seal, and the bottom was defined as the depth of the well. Springs were assigned a value of zero for the well depth and depth to top and bottom of the screened or open interval. Wells were classified as production wells, monitoring wells, or springs ([table C2](#)). Production wells have pumps that pump the groundwater from the aquifer to a distribution system. Monitoring wells include short-screened wells installed specifically as monitoring wells and wells that were once production wells, but no longer have pumps. Wells were classified as springs if water could flow from the aquifer into the distribution system without a pump, and if the well was either drilled horizontally or had no borehole.

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

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

Higher values of the index correspond to wetter conditions. Average annual precipitation for each well site was extracted from the PRISM average annual precipitation for 1971–2000 GIS coverage (PRISM Group, Oregon State University, 2007). Average annual evapotranspiration for each well site was extracted from a GIS coverage modified from Flint and Flint (2007). The modification consisted of calibrating the evapotranspiration values to the measured California Irrigation Management Information System reference evapotranspiration values (California Irrigation Management Information System, 2005; Alan Flint, USGS California Water Science Center, oral commun., 2009).

Elevation of the intersection of the well or spring and the land surface was used as a proxy for relative position in the groundwater flow system. All three study units have a large range in elevation of well sites—approximately 2,300 ft, 5,500 ft, and 5,000 ft, for Tahoe-Martis, Central Sierra, and Southern Sierra, respectively. Elevations were obtained from U.S. Geological Survey digital elevation GIS coverage and are reported in feet relative to NAVD 88 ([table C2](#)).

Groundwater Age Classification

Groundwater dating techniques provide a measure of the time since the groundwater was last in contact with the atmosphere. Techniques aimed at estimating groundwater residence times or ‘age’ include those based on tritium (^3H) (for example, Tolstikhin and Kamensky, 1969; Torgersen and others, 1979), carbon-14 (^{14}C) activity (for example, Vogel and Ehhalt, 1963; Plummer and others, 1993), dissolved noble gases, particularly helium-4 (^4He) accumulation (for example, Davis and DeWiest, 1966; Andrews and Lee, 1979; Kulongoski and others, 2008), and tritium in combination with its decay product helium-3 (^3He) (Poreda and others, 1988; Schlosser and others, 1989).

Tritium (^3H) is a short-lived radioactive isotope of hydrogen with a half-life of 12.32 years (Lucas and Unterweger, 2000). Tritium is produced naturally in the atmosphere from the interaction of cosmogenic radiation with nitrogen (Craig and Lal, 1961), by above-ground nuclear weapons testing (peak 1952 to 1963; Michel, 1989), and by the operation of nuclear reactors. Tritium enters the hydrological cycle following oxidation to tritiated water. Consequently, the presence of tritium in groundwater may be used to identify water that has exchanged with the atmosphere in the past 60 years. For the Tahoe-Martis, Central Sierra, and Southern Sierra study units, presence of tritium >0.5 TU (tritium units) was defined as indicating presence of water recharged more recently than 1950. Water recharged since 1950 is defined as “modern” groundwater. Previous investigations have used a range of tritium values from 0.3 to 1.0 TU as thresholds for distinguishing pre-1950 from post-1950 water (Michel, 1989; Plummer and others, 1993; Michel and Schroeder, 1994; Clark and Fritz, 1997; Manning and others, 2005).

Carbon-14 (^{14}C) is a widely used chronometer based on the radiocarbon content of organic and inorganic carbon. Dissolved inorganic carbonate species typically are used for ^{14}C dating of groundwater. Carbon-14 is formed in the atmosphere by the interaction of cosmic-ray neutrons with nitrogen, and to a lesser degree, with oxygen and carbon. Carbon-14 is incorporated into carbon dioxide and mixed throughout the atmosphere. The carbon dioxide dissolves in precipitation which eventually recharges the aquifer. Carbon-14 activity in groundwater, expressed as percent modern carbon (pmc), reflects exposure to the atmospheric ^{14}C source and is governed by the decay constant of ^{14}C (with a half-life of 5,730 yrs). Carbon-14 can be used to estimate groundwater ages ranging from 1,000 to approximately 30,000 years before present because of its half-life. Calculated ^{14}C ages in this study are referred to as “uncorrected” because they have not been adjusted to consider exchanges with sedimentary sources of carbon (Fontes and Garnier, 1979).

Table C2. Hydrologic conditions and well construction information for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Other abbreviations:** na, not available; ft, feet; LSD, land-surface datum]

Well identification number	Hydrologic conditions			Well construction information (feet below LSD)		
	Aridity index ¹	Elevation of LSD (ft above NAVD 88) ²	Well type ³	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD)
Tahoe-Martis study unit USGS-grid wells						
TMART-01	0.65	5,847	Production	1,132	280	1,110
TMART-02	0.82	6,125	Production	690	65	680
TMART-03	0.59	5,596	Production	383	363	383
TMART-04	0.70	5,889	Production	1,026	100	1,026
TMART-05	0.66	5,968	Production	1,370	460	1,360
TMART-06	0.76	5,879	Production	900	40	900
TMART-07	0.80	5,884	Production	106	50	106
TMART-08	0.71	5,973	Production	612	125	612
TMART-09	0.78	5,940	Production	120	70	120
TMART-10	1.02	6,604	Production	600	500	600
TMART-11	0.68	5,914	Production	132	na	na
TMART-12	0.74	5,871	Production	250	175	250
TMART-13	0.87	5,857	Production	175	175	175
TMART-14	0.78	5,840	Production	800	217	800
TROCK-01	0.95	6,044	Production	270	na	na
TROCK-02	1.13	6,584	Spring	0	0	0
TROCK-03	0.73	6,064	Production	292	232	292
TROCK-04	1.58	7,209	Spring	0	0	0
TROCK-05	1.34	6,758	Spring	0	0	0
TROCK-06	0.82	6,314	Production	218	75	218
TROCK-07	0.82	6,319	Production	320	190	320
TROCK-08	1.29	8,107	Spring	0	0	0
TROCK-09	1.00	7,615	Spring	0	0	0
TROCK-10	0.89	6,316	Production	610	na	610
TROCK-11	0.77	6,354	Production	48	na	48
TROCK-12	0.99	6,056	Production	na	na	na
TROCK-13	1.00	5,984	Production	102	93	98
TTAHO-01	0.82	6,232	Production	50	45	50
TTAHO-02	0.79	6,443	Production	880	240	880
TTAHO-03	0.78	6,293	Production	152	124	144
TTAHO-04	0.82	6,405	Production	240	60	210
TTAHO-05	0.79	6,400	Production	482	228	452
TTAHO-06	0.64	6,232	Production	495	138	480
TTAHO-07	0.80	6,309	Production	266	108	160
TTAHO-08	0.58	6,254	Production	156	86	156
TTAHO-09	0.72	6,214	Production	100	70	100
TTAHO-10	0.89	6,319	Production	250	95	245
TTAHO-11	1.05	6,472	Monitoring	200	na	na
TTAHO-12	0.85	6,304	Monitoring	325	106	315
TTAHO-13	0.56	6,281	Monitoring	135	130	135
TTAHO-14	0.48	6,241	Production	250	135	245

Table C2. Hydrologic conditions and well construction information for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Other abbreviations:** na, not available; ft, feet; LSD, land-surface datum]

Well identification number	Hydrologic conditions			Well construction information (feet below LSD)		
	Aridity index ¹	Elevation of LSD (ft above NAVD 88) ²	Well type ³	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD)
Tahoe-Martis study unit USGS-understanding wells						
TMARTU-01	0.81	5,996	Production	900	140	900
TROCKU-01	1.23	6,984	Production	317	285	317
TROCKU-02	0.88	6,645	Production	860	380	800
TTAHOU-01	0.89	6,304	Production	330	130	310
TTAHOU-02	0.55	6,259	Production	418	110	400
TTAHOU-03	0.67	6,284	Production	380	186	366
TTAHOU-04	0.54	6,263	Production	247	152	220
TTAHOU-05	0.56	6,281	Monitoring	335	325	335
TTAHOU-06	0.56	6,281	Monitoring	255	245	255
TTAHOU-07	0.56	6,281	Monitoring	163	158	163
TTAHOU-08	0.56	6,281	Monitoring	93	88	93
Tahoe-Martis study unit CDPH-grid wells						
TROCK-DPH-03	na	7,092	Production	317	285	317
TROCK-DPH-04	na	7,405	Spring	0	0	0
TROCK-DPH-06	na	6,595	Spring	0	0	0
TROCK-DPH-12	na	6,307	Spring	0	0	0
TTAHO-DPH-01	na	6,336	Production	na	na	na
TTAHO-DPH-04	na	6,372	Production	114	49	109
TTAHO-DPH-07	na	6,340	Production	225	55	220
TTAHO-DPH-09	na	6,357	Production	495	110	230
TTAHO-DPH-14	na	6,340	Production	240	136	232
Central Sierra study unit USGS-grid wells						
CGOLD-01	0.29	760	Production	1,007	100	1,007
CGOLD-02	0.54	2,220	Production	750	100	750
CGOLD-03	0.48	1,900	Production	680	50	680
CGOLD-04	0.55	2,300	Production	500	55	500
CGOLD-05	0.51	2,200	Production	na	na	na
CGOLD-06	0.67	3,240	Production	377	60	377
CGOLD-07	0.92	4,400	Production	462	60	462
CGOLD-08	0.55	2,310	Production	225	na	225
CGOLD-09	0.26	660	Production	1,027	70	1,027
CGOLD-10	0.77	3,680	Production	1,025	50	1,025
CGOLD-11	0.58	2,200	Production	na	na	na
CGOLD-12	0.37	1,300	Production	880	100	880
CGOLD-13	0.38	1,090	Production	302	60	302
CGOLD-14	0.55	2,280	Production	na	na	na
CGOLD-15	0.53	2,200	Production	355	50	355
CGOLD-16	0.87	4,800	Production	500	220	500
CGOLD-17	0.40	1,200	Production	300	200	300
CGOLD-18	0.72	3,030	Production	631	56	631
CWISH-01	0.73	3,360	Production	608	52	608
CWISH-02	0.64	2,660	Production	520	66	520
CWISH-03	0.78	3,500	Production	472	50	472

Table C2. Hydrologic conditions and well construction information for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Other abbreviations:** na, not available; ft, feet; LSD, land-surface datum]

Well identification number	Hydrologic conditions			Well construction information (feet below LSD)		
	Aridity index ¹	Elevation of LSD (ft above NAVD 88) ²	Well type ³	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD)
Central Sierra study unit USGS-grid wells—Continued						
CWISH-04	0.76	3,400	Production	700	52	700
CWISH-05	0.72	3,480	Production	202	85	202
CWISH-06	0.61	1,800	Production	900	20	200
CWISH-07	0.65	2,900	Production	900	100	900
CWISH-08	1.19	5,400	Production	925	81	925
CWISH-09	1.24	5,390	Production	700	70	700
Central Sierra study unit USGS-understanding wells						
CGOLDU-01	0.37	1,300	Production	675	20	675
CGOLDU-02	0.53	1,950	Production	100	30	100
CWISHU-01	0.64	2,560	Production	na	na	na
Central Sierra study unit CDPH-grid wells						
CGOLD-DPH-11	na	2,269	Production	na	na	na
CGOLD-DPH-14	na	2,327	Production	780	60	780
CGOLD-DPH-16	na	3,459	Spring	0	0	0
CGOLD-DPH-18	na	3,219	Production	na	na	na
CGOLD-DPH-19	na	1,294	Production	na	na	na
CWISH-DPH-06	na	2,606	Production	125	20	125
CWISH-DPH-10	na	3,803	Production	na	na	na
Southern Sierra study unit USGS-grid wells						
SOSA-01	0.32	5,049	Production	na	na	na
SOSA-02	0.20	2,822	Production	102	54	102
SOSA-03	0.20	2,606	Production	270	130	270
SOSA-04	0.19	3,333	Production	540	300	540
SOSA-05	0.28	2,940	Production	470	370	470
SOSA-06	0.28	3,245	Production	580	300	580
SOSA-07	0.26	2,800	Production	51	21	51
SOSA-08	0.30	3,770	Production	700	300	700
SOSA-09	0.21	3,840	Production	300	60	300
SOSA-10	0.22	2,720	Production	174	90	174
SOSA-11	0.24	4,335	Production	332	50	332
SOSA-12	0.29	3,000	Production	70	25	70
SOSA-13	0.22	4,010	Production	520	280	510
SOSA-14	0.22	2,600	Production	305	150	305
SOSA-15	0.76	5,060	Spring	0	0	0
SOSA-16	0.23	2,549	Production	na	na	na
SOSA-17	0.30	3,330	Production	150	20	150
SOSA-18	0.24	3,025	Production	615	120	615
SOSA-19	0.24	3,045	Production	na	na	na
SOSA-20	0.24	2,964	Production	165	na	165
SOSA-21	0.21	2,671	Production	na	na	na
SOSA-22	0.66	7,200	Spring	0	0	0
SOSA-23	0.26	3,845	Production	460	200	460
SOSA-24	0.26	4,226	Production	350	243	350

Table C2. Hydrologic conditions and well construction information for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Other abbreviations:** na, not available; ft, feet; LSD, land-surface datum]

Well identification number	Hydrologic conditions			Well construction information (feet below LSD)		
	Aridity index ¹	Elevation of LSD (ft above NAVD 88) ²	Well type ³	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD)
Southern Sierra study unit USGS-grid wells—Continued						
SOSA-25	0.30	4,124	Production	180	84	180
SOSA-26	0.27	4,633	Production	490	140	490
SOSA-27	0.28	4,094	Production	600	140	400
SOSA-28	0.25	3,914	Production	200	80	200
SOSA-29	0.37	3,533	Production	42	21	42
SOSA-30	0.23	2,770	Production	375	220	375
SOSA-31	0.20	2,650	Production	120	78	120
SOSA-32	0.25	4,180	Production	400	200	400
SOSA-33	0.23	3,100	Production	195	115	195
SOSA-34	0.23	3,970	Production	180	84	174
SOSA-35	0.22	4,260	Production	na	na	na
Southern Sierra study unit USGS-understanding wells						
SOSAFP-01	0.22	4,029	Production	546	267	546
SOSAFP-02	0.19	2,640	Production	55	10	55
SOSAFP-03	0.23	4,072	Production	604	400	590
SOSAFP-04	0.21	3,940	Production	290	50	285
SOSAFP-05	0.22	4,040	Production	480	180	480
SOSAFP-06	0.22	4,045	Production	420	na	na
SOSAFP-07	0.26	3,862	Production	472	202	472
SOSAFP-08	0.26	3,840	Production	402	54	396
SOSAFP-09	0.26	3,850	Production	300	na	na
SOSAFP-10	0.27	3,820	Production	357	119	na
SOSAFP-11	0.26	3,850	Production	300	na	na
SOSAFP-12	0.27	3,838	Production	550	na	na
SOSAFP-13	0.23	4,060	Production	478	212	478
SOSAFP-14	0.23	4,055	Production	500	180	500
SOSAFP-15	0.22	3,980	Production	294	114	288
Southern Sierra study unit CDPH-grid wells						
SOSA-DPH-06	na	3,324	Production	na	na	na
SOSA-DPH-07	na	2,708	Production	na	na	na
SOSA-DPH-08	na	3,999	Production	340	200	340
SOSA-DPH-11	na	5,378	Production	na	na	na
SOSA-DPH-12	na	3,245	Production	na	na	na
SOSA-DPH-13	na	4,188	Production	604	400	590
SOSA-DPH-15	na	6,044	Spring	0	0	0
SOSA-DPH-18	na	2,735	Production	585	150	270
SOSA-DPH-21	na	2,681	Production	450	220	450
SOSA-DPH-28	na	4,228	Production	130	70	130
SOSA-DPH-30	na	2,705	Production	na	na	na
SOSA-DPH-31	na	2,724	Production	253	121	253

Table C2. Hydrologic conditions and well construction information for USGS-grid, USGS-understanding, and CDPH-grid wells, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Other abbreviations:** na, not available; ft, feet; LSD, land-surface datum]

Well identification number	Hydrologic conditions			Well construction information (feet below LSD)		
	Aridity index ¹	Elevation of LSD (ft above NAVD 88) ²	Well type ³	Well depth (ft below LSD)	Top of screened or open interval (ft below LSD)	Bottom of screened or open interval (ft below LSD)
Southern Sierra study unit CDPH-grid wells—Continued						
SOSA-DPH-32	na	4,256	Production	na	na	na
SOSA-DPH-33	na	2,802	Production	na	na	na
SOSA-DPH-34	na	4,111	Production	na	na	na
SOSA-DPH-36	na	2,553	Production	na	na	na
SOSA-DPH-37	na	3,311	Production	107	47	107
SOSA-DPH-38	na	3,266	Production	665	73	665

¹Aridity index is average annual precipitation divided by average annual evapotranspiration.

² Land-surface datum (LSD) is a datum plane that is approximately at land surface at each well. The elevation of the LSD is described in feet above the North American Vertical Datum 1988 (NAVD 88).

³ Production wells had installed pumps that brought groundwater to the surface; monitoring wells were sampled with monitoring well pumps; springs had groundwater reaching the surface without pumps. Well depth, and depths to top and bottom of screened interval defined as 0 feet for springs for this study.

The ¹⁴C age (residence time) is calculated on the basis of the decrease in ¹⁴C activity because of radioactive decay since groundwater recharge, relative to an assumed initial ¹⁴C concentration (Clark and Fritz, 1997). An average initial ¹⁴C activity of 100 percent modern carbon (pmc) is assumed for this study, with estimated errors on calculated groundwater ages up to ± 20%. Groundwater with a ¹⁴C activity 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 activity in “modern” carbon does not include the excess ¹⁴C produced in the atmosphere by above-ground nuclear weapons testing. For the Tahoe-Martis, Central Sierra, and Southern Sierra study units, ¹⁴C activity <88 pmc was defined as indicative of presence of groundwater recharged before 1950. The threshold value of 88 pmc was selected because all groundwater samples with tritium <0.5 TU also had ¹⁴C <88 pmc.

Helium (He) is a naturally occurring inert gas initially included during accretion of the planet, and later produced by radioactive decay of lithium, uranium, and thorium in the Earth. Helium (³He plus ⁴He) concentrations in groundwater often exceed the expected solubility equilibrium values as a result of air-bubble entrainment, or subsurface production

of both isotopes, and their subsequent release into the groundwater (for example, Morrison and Pine, 1955; Andrews and Lee, 1979; Torgersen, 1980; Torgersen and Clarke, 1985). There are four primary sources of He in groundwater:

$$He_{total} = He_{equil} + He_{exair} + He_{trit} + He_{terr},$$

where

He_{total} is the total amount of helium in the groundwater sample;

He_{equil} is the helium derived from equilibration with the atmosphere at the time of recharge;

He_{exair} is the helium derived from dissolved air bubbles (“excess” air);

He_{trit} is the helium produced by radioactive decay of tritium in the sample, and

He_{terr} is the helium produced by radioactive decay of uranium and thorium in aquifer materials or emanating from deeper in the Earth's crust or mantle.

He_{equil} , He_{exair} , and He_{terr} all consist of helium-3 (³He) and helium-4 (⁴He); however, He_{trit} consists only of ³He.

He_{equil} is a function of temperature at the time of recharge. Recharge temperatures were calculated from dissolved neon, argon, krypton, and xenon using methods described in Aeschbach-Hertig and others (1999, 2000) to model the He_{exair} component. The best model for the He_{exair} component for each groundwater sample was selected by comparing the sums of the weighted squared standard deviations between the modeled and measured noble-gas concentrations (χ^2). The model with the lowest χ^2 value (least amount of deviation between the modeled and measured concentrations) was selected. The χ^2 was compared to the value of a chi-squared distribution with the appropriate number of degrees of freedom for the model and a significance level (α) of 0.01 ($\chi^2_{\alpha=0.01}$). Recharge temperatures were only calculated for groundwater samples for which χ^2 was less than $\chi^2_{\alpha=0.01}$ (Aeschbach-Hertig and others, 2000).

The presence of large concentrations of He_{terr} commonly is indicative of long groundwater residence times. For the purpose of estimating groundwater residence times, the amount of He_{terr} is converted to the parameter % He_{terr-c} , the percent of He_{terr} in He_{total} corrected for excess air:

$$\%He_{terr-c} = \frac{He_{terr}}{He_{total} - He_{exair}} \times 100.$$

(He_{trit} is neglected in calculation of % He_{terr-c} because it typically is very small.) For Tahoe-Martis, Central Sierra, and Southern Sierra study units, values of % $He_{terr-c} > 50\%$ were defined as indicative of the presence of pre-modern groundwater. This threshold of 50% is greater than the thresholds used in other studies (for example, Kulongoski and others, 2010; Landon and others, 2010). A higher threshold was selected to reduce the number of samples for which groundwater age class inferred from % He_{terr-c} disagreed with that inferred on the basis of ^{14}C and tritium data.

By determining the concentrations of tritium and its decay product helium-3 (He_{trit}), the time that the water has resided in the aquifer can be calculated more precisely than using tritium alone for water (for example, Poreda and others, 1988; Schlosser and others, 1989). Tritium-helium ages were computed as described by Schlosser and others (1989). The calculation requires determining how much of the total 3He was contributed from each of the components He_{trit} , He_{terr} , He_{equil} , and He_{exair} . The amounts of 3He in He_{equil} and He_{exair} are determined from equilibrium with atmospheric He and the model used for He_{exair} . The amount of 3He in He_{terr} is determined from the concentration of He_{terr} and the $^3He/^4He$ ratio of the He_{terr} . The remaining 3He is He_{trit} . The uncertainty in this calculation of He_{trit} and therefore the uncertainty in the tritium-helium age, increases as He_{terr} increases.

The $^3He/^4He$ ratio of He_{terr} was determined by the linear regression of He_{terr}/He_{total} and δ^3He [$(\delta^3He = R_{meas}/R_{atm} - 1) \times 100$ percent, where R_{meas}/R_{atm} is the measured $^3He/^4He$ ratio in the sample divided by the $^3He/^4He$ ratio in the atmosphere] for groups of related groundwater samples containing < 1 tritium unit. He_{terr} has two primary sources: He from decay of radioactive isotopes of uranium, thorium, and lithium in the aquifer rocks or sediment (He_{UTh}), and He emanating from the lower crust and mantle below (He_{mant}). He_{UTh} was assumed to have a $^3He/^4He$ ratio of 2.0×10^{-8} ($R_{meas}/R_{atm} = 0.015$) (Andrews, 1985), and He_{mant} was assumed to have a $^3He/^4He$ ratio of 8.3×10^{-6} ($R_{meas}/R_{atm} = 6$), which is the median value measured in continental basalts and mantle xenoliths in the Western United States (Dodson and others, 1998). Samples were divided into four groups—(1) Tahoe-Martis study unit, Martis study area, (2) the rest of the Tahoe-Martis study unit, (3) Central Sierra study unit, and (4) Southern Sierra study unit. For each group, the fraction of He_{mant} in He_{terr} was calculated from the $^3He/^4He$ ratio of He_{terr} determined from the linear regression. The Martis study area was considered separately from the rest of the Tahoe-Martis study unit because the geologic setting (recent volcanic activity and active faulting) suggested that the volume of He_{mant} might be greater than in other regions. He_{trit} was then calculated for groundwater samples containing tritium ≥ 1 TU by mass balance for 3He .

Noble gas concentrations, modeled recharge temperatures, and measured $^3He/^4He$ ratios are reported in [table C3](#), and tritium, modeled $^3H/^3He$ ages, ^{14}C ages, and % He_{terr-c} are reported in [table C4](#). Because of uncertainties in age distributions, particularly the uncertainties caused by mixing of waters of different ages in wells with long screened or open intervals and high withdrawal rates, the uncorrected ^{14}C ages and the ages calculated from He_{terr} accumulation were not specifically used for quantifying the relation between age and water quality in this report. While more sophisticated lumped parameter models for analyzing age distributions that incorporate mixing are available (Cook and Böhlke, 2000), use of these alternative models to understand age mixtures was beyond the scope of this report. Using the data for tritium, ^{14}C , and % He_{terr-c} , the age distribution of groundwater samples was classified as “Modern,” “Mixed,” or “Pre-modern” following the decision-tree shown in [figure C1](#). Classification into modern, mixed, and pre-modern categories was sufficient to provide an appropriate and useful characterization for the purposes of examining groundwater quality.

Table C3. Results for analyses of noble gases in samples collected for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California 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. **GAMA identification numbers:** TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Measurement errors:** Helium-3/helium-4 ratios, and helium-4, neon, and argon concentrations have 2-percent errors; krypton and xenon concentrations have 3-percent errors; errors for modeled recharged temperatures are ≤ 0.3 °C for 90 percent of samples. **Other abbreviations:** cm^3 STP g^{-1} H_2O , cubic centimeters at standard temperature and pressure per gram of water; °C, degrees Celsius; \leq , less than or equal to; na, not available]

GAMA identification number	Helium-3/ Helium-4	Helium-4	Neon	Argon	Krypton	Xenon	Modeled recharge temperature (°C)	
	(atom ratio)	$(\text{cm}^3 \text{ STP/gH}_2\text{O})$						
	(61040)	(85561)	(61046)	(85563)	(85565)	(85567)		
	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-4}$	$\times 10^{-8}$	$\times 10^{-8}$		
Tahoe-Martis study unit USGS-grid wells								
TMART-01	31.57	5.06	1.95	3.54	7.53	1.13	10.3	
TMART-02	14.27	0.64	2.43	3.45	7.45	1.04	11.3	
TMART-03	33.66	4.70	1.90	3.25	7.39	1.06	10.5	
TMART-04	na	na	na	na	na	na	na	
TMART-05	33.50	39.07	9.04	7.22	12.14	1.52	7.5	
TMART-06	26.61	1.22	1.84	3.30	7.72	1.10	8.9	
TMART-07	17.40	0.48	1.73	2.97	6.69	0.98	13.0	
TMART-08	26.04	21.73	1.82	3.23	7.73	1.07	9.4	
TMART-09	15.61	0.45	2.01	3.54	7.77	1.13	9.7	
TMART-10	9.36	0.99	2.14	3.60	8.39	1.18	7.3	
TMART-11	14.15	0.35	1.63	2.94	6.99	0.98	12.2	
TMART-12	14.50	0.48	2.06	3.51	8.14	1.14	8.7	
TMART-13	7.62	40.84	1.50	3.15	7.39	1.08	10.3	
TMART-14	33.06	1.49	1.85	3.09	7.16	1.03	11.5	
TROCK-01	17.64	0.95	3.38	4.68	9.93	1.30	7.5	
TROCK-02	13.71	0.36	1.64	3.03	7.08	1.05	10.1	
TROCK-03	12.69	0.46	1.82	3.24	7.48	1.06	10.4	
TROCK-04	19.50	0.52	2.33	3.67	8.48	1.19	5.7	
TROCK-05	17.67	0.42	1.93	3.44	8.13	1.19	6.2	
TROCK-06	17.88	0.41	1.83	3.28	7.77	1.10	8.4	
TROCK-07	15.96	0.57	1.88	3.30	7.71	1.13	8.2	
TROCK-08	13.69	0.32	1.47	2.90	6.99	1.05	8.9	
TROCK-09	13.62	0.35	1.58	3.27	7.70	1.19	5.4	
TROCK-10	14.88	0.36	1.56	3.06	7.38	1.12	9.2	
TROCK-11	16.58	0.53	2.22	3.64	8.13	1.14	8.7	
TROCK-12	na	na	na	na	na	na	na	
TROCK-13	20.89	21.90	8.42	7.90	14.90	1.79	4.3	
TTAHO-01	25.07	0.47	2.14	3.72	8.69	1.22	6.5	
TTAHO-02	15.81	0.61	2.22	3.47	8.09	1.12	8.2	
TTAHO-03	15.11	0.45	1.90	3.23	7.85	1.12	8.6	
TTAHO-04	15.84	1.08	4.43	5.40	10.66	1.42	5.8	
TTAHO-05	15.35	0.43	1.75	3.27	7.79	1.14	7.6	
TTAHO-06	5.50	2.27	2.19	3.59	8.24	1.14	8.6	
TTAHO-07	10.99	0.83	1.95	3.39	7.78	1.15	7.8	
TTAHO-08	8.25	1.04	1.81	3.28	7.41	1.09	8.9	
TTAHO-09	13.86	0.74	2.98	4.11	8.96	1.22	8.4	
TTAHO-10	4.07	3.19	2.39	3.73	8.48	1.18	8.2	
TTAHO-11	na	na	na	na	na	na	na	
TTAHO-12	14.89	0.53	2.15	3.77	8.08	1.23	7.4	
TTAHO-13	28.59	0.46	1.92	3.57	7.90	1.19	6.5	
TTAHO-14	3.23	2.91	3.04	4.03	8.68	1.19	8.6	

Table C3. Results for analyses of noble gases in samples collected for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California 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. **GAMA identification numbers:** TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Measurement errors:** Helium-3/helium-4 ratios, and helium-4, neon, and argon concentrations have 2-percent errors; krypton and xenon concentrations have 3-percent errors; errors for modeled recharged temperatures are ≤ 0.3 °C for 90 percent of samples. **Other abbreviations:** cm^3 STP g^{-1} H_2O , cubic centimeters at standard temperature and pressure per gram of water; °C, degrees Celsius; \leq , less than or equal to; na, not available]

GAMA identification number	Helium-3/ Helium-4	Helium-4	Neon	Argon	Krypton	Xenon	Modeled recharge temperature (°C)
	(atom ratio)	$(\text{cm}^3 \text{STP/gH}_2\text{O})$					
	(61040)	(85561)	(61046)	(85563)	(85565)	(85567)	
	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-4}$	$\times 10^{-8}$	$\times 10^{-8}$	
Tahoe-Martis study unit USGS-understanding wells							
TMARTU-01	31.94	1.59	1.80	3.24	7.91	1.08	8.9
TROCKU-01	na	na	na	na	na	na	na
TROCKU-02	15.14	0.68	1.84	3.16	7.33	1.05	9.8
TTAHOU-01	5.82	2.32	2.03	3.49	7.85	1.15	7.6
TTAHOU-02	6.32	1.28	2.29	3.53	7.78	1.15	8.4
TTAHOU-03	1.93	10.32	2.22	3.78	7.88	1.14	10.5
TTAHOU-04	11.50	1.00	2.57	3.84	8.31	1.13	10.0
TTAHOU-05	4.14	0.98	1.49	3.06	7.40	1.06	8.2
TTAHOU-06	5.76	1.77	2.41	3.65	8.05	1.16	7.9
TTAHOU-07	13.57	0.67	1.96	3.46	7.97	1.16	7.3
TTAHOU-08	14.93	0.35	1.90	4.39	10.49	1.42	8.2
Central Sierra study unit USGS-grid wells							
CGOLD-01	4.97	4.85	2.03	3.19	7.10	0.97	18.9
CGOLD-02	5.50	1.97	3.35	4.39	8.79	1.11	17.0
CGOLD-03	2.91	4.55	2.42	3.49	7.26	0.97	19.3
CGOLD-04	7.08	1.12	2.27	3.55	7.76	1.05	15.4
CGOLD-05	8.42	38.06	2.51	3.75	8.21	1.12	14.1
CGOLD-06	5.15	1.70	2.32	3.60	8.01	1.08	13.6
CGOLD-07	2.59	23.66	2.30	3.83	8.65	1.22	8.8
CGOLD-08	6.69	2.75	4.26	5.03	10.21	1.30	13.2
CGOLD-09	0.88	23.42	2.52	3.66	7.83	1.05	17.5
CGOLD-10	13.68	0.37	1.71	3.17	7.56	1.08	12.1
CGOLD-11	na	na	na	na	na	na	na
CGOLD-12	4.09	2.84	2.54	3.58	7.75	1.00	18.9
CGOLD-13	6.56	14.17	10.35	8.85	16.20	1.65	19.1
CGOLD-14	4.45	61.71	2.40	3.66	8.00	1.05	15.8
CGOLD-15	3.32	3.72	2.44	3.58	7.66	1.02	16.9
CGOLD-16	15.53	0.39	1.87	3.56	7.92	1.10	11.4
CGOLD-17	na	na	na	na	na	na	na
CGOLD-18	2.63	23.83	1.93	3.33	7.46	1.07	13.1
CWISH-01	4.46	44.27	2.56	3.75	8.25	1.10	13.5
CWISH-02	0.99	65.01	2.39	3.74	8.33	1.16	11.7
CWISH-03	3.07	52.25	3.97	4.78	9.51	1.30	10.0
CWISH-04	14.22	0.42	1.63	3.21	7.56	1.04	13.1
CWISH-05	5.21	3.84	3.10	4.06	8.57	1.14	13.4
CWISH-06	0.20	69.44	2.28	3.69	8.02	1.15	12.5
CWISH-07	0.75	29.09	2.31	3.57	7.83	1.05	15.0
CWISH-08	2.00	3.45	2.12	3.78	8.66	1.26	6.7
CWISH-09	1.71	13.70	1.74	3.42	8.28	1.17	7.1

Table C3. Results for analyses of noble gases in samples collected for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California 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. **GAMA identification numbers:** TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Measurement errors:** Helium-3/helium-4 ratios, and helium-4, neon, and argon concentrations have 2-percent errors; krypton and xenon concentrations have 3-percent errors; errors for modeled recharged temperatures are ≤ 0.3 °C for 90 percent of samples. **Other abbreviations:** cm^3 STP g^{-1} H_2O , cubic centimeters at standard temperature and pressure per gram of water; °C, degrees Celsius; \leq , less than or equal to; na, not available]

GAMA identification number	Helium-3/ Helium-4 (atom ratio) (61040) $\times 10^{-7}$	Helium-4	Neon	Argon	Krypton	Xenon	Modeled recharge temperature (°C)
		(cm ³ STP/gH ₂ O)					
		(85561) $\times 10^{-7}$	(61046) $\times 10^{-7}$	(85563) $\times 10^{-4}$	(85565) $\times 10^{-8}$	(85567) $\times 10^{-8}$	
Central Sierra study unit USGS-understanding wells							
CGOLDU-01	3.00	3.99	3.28	4.21	8.58	1.06	19.0
CGOLDU-02	5.73	1.49	2.06	3.21	7.13	0.95	17.6
CWISHU-01	2.59	14.95	6.85	5.23	9.36	1.17	19.6
Southern Sierra study unit USGS-grid wells							
SOSA-01	11.45	0.72	2.23	3.48	7.83	1.09	11.2
SOSA-02	10.26	0.85	2.51	3.35	6.95	0.90	20.3
SOSA-03	9.93	4.37	3.44	4.50	8.98	1.11	17.6
SOSA-04	1.07	46.74	4.73	5.12	9.87	1.22	13.7
SOSA-05	13.03	0.92	3.84	4.39	9.02	1.12	15.7
SOSA-06	12.72	1.02	3.90	4.74	9.69	1.22	14.0
SOSA-07	6.70	0.93	1.93	3.42	7.84	1.11	12.3
SOSA-08	5.66	1.71	3.07	4.14	8.65	1.11	14.0
SOSA-09	5.79	1.37	3.05	4.19	8.98	1.21	11.1
SOSA-10	7.17	13.54	2.19	3.45	7.80	1.03	15.0
SOSA-11	13.81	3.10	10.07	7.89	14.87	1.54	15.7
SOSA-12	13.37	0.50	2.14	3.36	7.78	1.09	13.1
SOSA-13	11.69	0.76	2.84	3.78	8.03	1.02	16.2
SOSA-14	8.96	1.91	3.51	3.95	7.78	0.95	22.4
SOSA-15	13.89	0.41	1.78	3.35	7.99	1.16	7.4
SOSA-16	3.70	8.61	2.38	3.31	6.97	0.91	20.1
SOSA-17	5.01	1.89	2.54	3.51	7.77	1.02	14.5
SOSA-18	6.78	5.39	3.21	3.63	7.61	1.02	17.2
SOSA-19	8.06	1.09	2.79	3.77	7.88	1.04	16.0
SOSA-20	15.52	0.63	2.67	3.67	7.92	1.09	13.6
SOSA-21	4.82	5.26	4.92	4.77	9.04	1.12	17.1
SOSA-22	na	na	na	na	na	na	na
SOSA-23	11.64	1.85	6.21	5.59	9.82	1.15	18.1
SOSA-24	10.77	1.15	3.86	4.40	8.60	1.07	16.2
SOSA-25	8.64	0.64	1.78	3.20	7.30	0.99	14.9
SOSA-26	10.62	1.16	3.70	4.42	8.97	1.15	13.6
SOSA-27	12.10	1.70	6.09	6.27	11.59	1.36	12.4
SOSA-28	6.48	3.07	3.99	4.15	8.46	1.06	15.1
SOSA-29	13.02	0.54	1.99	3.19	7.11	0.98	15.4
SOSA-30	6.54	8.70	2.67	3.54	7.47	0.96	19.3
SOSA-31	na	na	na	na	na	na	na
SOSA-32	13.41	0.64	2.57	3.51	7.55	1.02	14.6
SOSA-33	5.32	2.21	3.36	4.19	8.79	1.08	16.6
SOSA-34	12.90	1.54	5.58	5.72	10.36	1.18	18.0
SOSA-35	1.74	8.72	2.25	3.48	7.79	1.01	14.3

Table C3. Results for analyses of noble gases in samples collected for the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California 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. **GAMA identification numbers:** TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Measurement errors:** Helium-3/helium-4 ratios, and helium-4, neon, and argon concentrations have 2-percent errors; krypton and xenon concentrations have 3-percent errors; errors for modeled recharged temperatures are ≤ 0.3 °C for 90 percent of samples. **Other abbreviations:** cm^3 STP g^{-1} H_2O , cubic centimeters at standard temperature and pressure per gram of water; °C, degrees Celsius; \leq , less than or equal to; na, not available]

GAMA identification number	Helium-3/ Helium-4	Helium-4	Neon	Argon	Krypton	Xenon	Modeled recharge temperature (°C)	
	(atom ratio)	(cm ³ STP/gH ₂ O)						
	(61040)	(85561)	(61046)	(85563)	(85565)	(85567)		
	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-4}$	$\times 10^{-8}$	$\times 10^{-8}$		
Southern Sierra study unit USGS-understanding wells								
SOSAFP-01	3.04	3.48	2.90	3.84	8.15	1.02	16.1	
SOSAFP-02	3.40	37.92	1.99	3.26	7.24	1.02	15.1	
SOSAFP-03	4.64	2.42	3.43	3.89	8.05	1.04	14.8	
SOSAFP-04	9.56	1.31	3.60	4.14	8.11	1.04	16.7	
SOSAFP-05	3.34	2.12	2.26	3.40	7.36	1.00	15.0	
SOSAFP-06	8.82	1.23	3.30	4.05	8.24	1.02	17.8	
SOSAFP-07	12.70	0.50	2.14	3.70	7.97	1.08	15.4	
SOSAFP-08	7.63	1.28	2.91	3.90	8.20	1.09	13.7	
SOSAFP-09	13.35	0.74	3.55	4.96	9.61	1.14	22.5	
SOSAFP-10	3.71	2.27	2.54	3.55	7.43	0.99	16.5	
SOSAFP-11	8.52	1.16	2.57	3.74	7.92	1.02	16.2	
SOSAFP-12	3.92	2.36	2.60	3.67	8.00	1.03	15.2	
SOSAFP-13	4.71	2.39	3.24	4.07	8.48	1.07	15.9	
SOSAFP-14	12.87	1.26	4.51	4.77	9.21	1.13	18.5	
SOSAFP-15	13.80	0.79	3.25	4.05	8.19	1.04	16.3	

Table C4. Tritium, tritium-helium, terrigenic helium, and carbon-14 data and groundwater age classifications, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Groundwater age classification based on decision tree shown in [figure C1](#). Modern, groundwater recharged since 1952; Pre-modern, groundwater recharged before 1952; Mixed, groundwater containing components recharged before and after 1952. **Errors:** average ^{14}C counting error was 0.36 percent with standard deviation of 0.11 percent; average tritium-helium age error was 6 percent with standard deviation of 3 percent; % $\text{He}_{\text{terr-c}}$ errors less than 4 percent for values greater than 50 percent; average % $\text{He}_{\text{terr-c}}$ error for values less than 50 percent was 5.2 percent with standard deviation of 3.4 percent. **Abbreviations:** $^3\text{He}_{\text{trit}}$, helium-3 formed from decay of tritium; % $\text{He}_{\text{terr-c}}$, concentration of terrigenic helium divided by total helium concentration corrected for helium from excess air; ^{14}C , carbon-14; TU, tritium units; nd, not datable; na, not available; <, less than; >, greater than]

GAMA identification number	Tritium (TU)	$^3\text{He}_{\text{trit}}$ (TU)	Tritium-Helium age (years)	% $\text{He}_{\text{terr-c}}$ (percent)	Percent modern carbon	Uncorrected ^{14}C age (years)	Groundwater age classification ¹
Tahoe-Martis study unit USGS-grid wells							
TMART-01	1.3	nd	nd	92	72	2,580	Mixed
TMART-02	0.5	<1	>50	6	76	2,120	Mixed
TMART-03	0.0	<1	>50	92	30	9,670	Pre-modern
TMART-04	1.1	na	na	na	73	2,430	Mixed
TMART-05	0.3	<1	>50	99	41	7,170	Pre-modern
TMART-06	2.8	nd	nd	68	99	<1,000	Mixed
TMART-07	3.0	nd	nd	16	102	<1,000	Modern
TMART-08	1.0	nd	nd	98	83	1,400	Mixed
TMART-09	4.8	3.4	9.4	0	102	<1,000	Modern
TMART-10	0.1	<1	>50	56	73	2,400	Pre-modern
TMART-11	4.0	0.7	2.7	0	83	1,380	Mixed
TMART-12	0.2	<1	>50	0	86	1,120	Pre-modern
TMART-13	0.0	<1	>50	99	43	6,630	Pre-modern
TMART-14	0.2	<1	>50	74	72	2,510	Pre-modern
TROCK-01	3.9	18.5	31	16	105	<1,000	Modern
TROCK-02	3.5	nd	nd	0	108	<1,000	Modern
TROCK-03	0.1	<1	>50	7	82	1,500	Pre-modern
TROCK-04	2.8	12.2	29.7	0	99	<1,000	Modern
TROCK-05	2.2	6.7	24.9	0	99	<1,000	Modern
TROCK-06	1.6	6.9	29.8	0	99	<1,000	Modern
TROCK-07	3.6	11.4	25.4	25	99	<1,000	Modern
TROCK-08	2.9	0.1	0.3	0	na	na	Modern or Mixed
TROCK-09	2.8	nd	nd	0	113	<1,000	Modern
TROCK-10	2.0	1.7	11	0	89	<1,000	Modern
TROCK-11	3.2	6.1	19.1	0	111	<1,000	Modern
TROCK-12	0.1	na	na	na	2	² 32,080	Pre-modern
TROCK-13	0.1	<1	>50	98	1	² 38,030	Pre-modern
TTAHO-01	3.2	21.5	36.3	0	104	<1,000	Modern
TTAHO-02	0.2	<1	>50	15	83	1,420	Pre-modern
TTAHO-03	5.9	2.5	6.2	0	101	<1,000	Modern
TTAHO-04	4.0	8.8	20.6	0	97	<1,000	Modern
TTAHO-05	2.1	4.3	19.7	7	89	<1,000	Modern
TTAHO-06	0.9	<1	>50	82	84	1,280	Mixed
TTAHO-07	1.1	9.6	40.5	50	92	<1,000	Mixed
TTAHO-08	2.4	8.8	27.3	63	92	<1,000	Mixed
TTAHO-09	0.0	<1	>50	0	77	1,980	Pre-modern
TTAHO-10	0.1	<1	>50	88	69	2,930	Pre-modern
TTAHO-11	1.4	na	na	na	2	² 32,980	Modern or Mixed
TTAHO-12	2.1	3.1	16.1	3	108	<1,000	Modern
TTAHO-13	1.5	<1	>50	2	90	<1,000	Modern
TTAHO-14	0.0	<1	>50	85	85	1,200	Pre-modern

Table C4. Tritium, tritium-helium, terrigenous helium, and carbon-14 data and groundwater age classifications, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Groundwater age classification based on decision tree shown in [figure C1](#). Modern, groundwater recharged since 1952; Pre-modern, groundwater recharged before 1952; Mixed, groundwater containing components recharged before and after 1952. **Errors:** average ^{14}C counting error was 0.36 percent with standard deviation of 0.11 percent; average tritium-helium age error was 6 percent with standard deviation of 3 percent; % $\text{He}_{\text{terr-c}}$ errors less than 4 percent for values greater than 50 percent; average % $\text{He}_{\text{terr-c}}$ error for values less than 50 percent was 5.2 percent with standard deviation of 3.4 percent. **Abbreviations:** $^3\text{He}_{\text{trit}}$, helium-3 formed from decay of tritium; % $\text{He}_{\text{terr-c}}$, concentration of terrigenous helium divided by total helium concentration corrected for helium from excess air; ^{14}C , carbon-14; TU, tritium units; nd, not datable; na, not available; <, less than; >, greater than]

GAMA identification number	Tritium (TU)	$^3\text{He}_{\text{trit}}$ (TU)	Tritium-Helium age (years)	% $\text{He}_{\text{terr-c}}$ (percent)	Percent modern carbon	Uncorrected ^{14}C age (years)	Groundwater age classification ¹
Tahoe-Martis study unit USGS-understanding wells							
TMARTU-01	0.5	<1	>50	76	76	2,170	Mixed
TROCKU-01	1.6	na	na	na	93	<1,000	Modern or Mixed
TROCKU-02	0.2	<1	>50	40	73	2,480	Pre-modern
TTAHOU-01	2.8	20.1	37.2	83	102	<1,000	Mixed
TTAHOU-02	0.7	<1	>50	66	88	<1,000	Mixed
TTAHOU-03	0.0	<1	>50	96	58	4,360	Pre-modern
TTAHOU-04	3.1	9.1	24.3	49	107	<1,000	Mixed
TTAHOU-05	0.0	<1	>50	62	82	1,520	Pre-modern
TTAHOU-06	2.4	3.3	15.2	76	98	<1,000	Mixed
TTAHOU-07	4.1	9.9	21.8	35	88	<1,000	Modern
TTAHOU-08	5.9	1.7	4.6	0	na	na	<u>Modern</u> or Mixed
Central Sierra study unit USGS-grid wells							
CGOLD-01	1.0	<1	>50	91	64	3,530	Mixed
CGOLD-02	1.0	nd	nd	72	87	1,030	Mixed
CGOLD-03	0.1	<1	>50	90	79	1,820	Pre-modern
CGOLD-04	1.8	nd	nd	57	110	<1,000	Mixed
CGOLD-05	0.5	<1	>50	99	79	1,850	Mixed
CGOLD-06	1.9	nd	nd	73	98	<1,000	Mixed
CGOLD-07	-0.1	<1	>50	98	60	4,090	Pre-modern
CGOLD-08	3.0	6.2	19.9	79	109	<1,000	Mixed
CGOLD-09	0.7	<1	>50	98	54	4,840	Mixed
CGOLD-10	3.1	0.1	0.7	0	110	<1,000	Modern
CGOLD-11	2.3	na	na	na	99	<1,000	Modern or Mixed
CGOLD-12	0.2	<1	>50	84	72	2,580	Pre-modern
CGOLD-13	1.6	<1	>50	96	99	<1,000	Mixed
CGOLD-14	2.3	<1	>50	99	84	1,360	Mixed
CGOLD-15	1.8	5.7	25.3	88	94	<1,000	Mixed
CGOLD-16	5.6	2.7	6.9	0	na	na	Modern or <u>Mixed</u>
CGOLD-17	3.4	na	na	na	106	<1,000	Modern or Mixed
CGOLD-18	2.0	<1	>50	98	60	4,080	Mixed
CWISH-01	1.1	<1	>50	99	38	7,750	Mixed
CWISH-02	0.0	<1	>50	99	61	3,820	Pre-modern
CWISH-03	0.0	<1	>50	99	18	13,830	Pre-modern
CWISH-04	3.5	1.9	7.6	4	109	<1,000	Modern
CWISH-05	2.8	26.3	41.5	88	104	<1,000	Mixed
CWISH-06	0.0	<1	>50	99	19	13,350	Pre-modern
CWISH-07	1.1	nd	nd	99	65	3,370	Mixed
CWISH-08	1.4	nd	nd	88	91	<1,000	Mixed
CWISH-09	2.9	29.8	43	97	100	<1,000	Mixed
Central Sierra study unit USGS-understanding wells							
CGOLDU-01	0.7	<1	>50	88	83	1,410	Mixed
CGOLDU-02	3.5	3.4	12	70	115	<1,000	Mixed
CWISHU-01	0.3	<1	>50	97	62	3,800	Pre-modern

Table C4. Tritium, tritium-helium, terrigenic helium, and carbon-14 data and groundwater age classifications, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Groundwater age classification based on decision tree shown in [figure C1](#). Modern, groundwater recharged since 1952; Pre-modern, groundwater recharged before 1952; Mixed, groundwater containing components recharged before and after 1952. **Errors:** average ^{14}C counting error was 0.36 percent with standard deviation of 0.11 percent; average tritium-helium age error was 6 percent with standard deviation of 3 percent; % $\text{He}_{\text{terr-c}}$ errors less than 4 percent for values greater than 50 percent; average % $\text{He}_{\text{terr-c}}$ error for values less than 50 percent was 5.2 percent with standard deviation of 3.4 percent. **Abbreviations:** $^3\text{He}_{\text{trit}}$, helium-3 formed from decay of tritium; % $\text{He}_{\text{terr-c}}$, concentration of terrigenic helium divided by total helium concentration corrected for helium from excess air; ^{14}C , carbon-14; TU, tritium units; nd, not datable; na, not available; <, less than; >, greater than]

GAMA identification number	Tritium (TU)	$^3\text{He}_{\text{trit}}$ (TU)	Tritium-Helium age (years)	% $\text{He}_{\text{terr-c}}$ (percent)	Percent modern carbon	Uncorrected ^{14}C age (years)	Groundwater age classification ¹
Southern Sierra study unit USGS-grid wells							
SOSA-01	0.7	<1	>50	31	na	na	Mixed
SOSA-02	3.4	nd	nd	34	na	na	Modern or Mixed
SOSA-03	3.4	<1	>50	89	73	2,490	Mixed
SOSA-04	0.8	<1	>50	99	na	na	Mixed
SOSA-05	0.6	<1	>50	0	na	na	Mixed
SOSA-06	-0.3	<1	>50	0	60	na	Pre-modern
SOSA-07	2.4	nd	nd	53	92	<1,000	Mixed
SOSA-08	0.5	<1	>50	70	na	na	Mixed
SOSA-09	0.7	<1	>50	59	na	na	Mixed
SOSA-10	2.5	<1	>50	97	51	5,270	Mixed
SOSA-11	0.8	<1	>50	42	na	na	Mixed
SOSA-12	4.1	0.1	0.6	0	na	na	Modern or Mixed
SOSA-13	0.0	<1	>50	5	84	1,320	Pre-modern
SOSA-14	1.0	<1	>50	71	na	na	Mixed
SOSA-15	4.5	0.3	1.2	0	92	<1,000	Modern
SOSA-16	1.4	<1	>50	95	na	na	Mixed
SOSA-17	0.9	<1	>50	76	na	na	Mixed
SOSA-18	1.1	<1	>50	92	na	na	Mixed
SOSA-19	1.8	nd	nd	48	na	na	Mixed
SOSA-20	2.9	5.1	18.1	0	110	na	Modern
SOSA-21	2.2	25.3	45.2	91	na	na	Mixed
SOSA-22	2.8	na	na	na	100	<1,000	Modern or Mixed
SOSA-23	-0.1	<1	>50	27	na	na	Pre-modern
SOSA-24	-0.0	<1	>50	24	na	na	Pre-modern
SOSA-25	0.3	<1	>50	36	na	na	Pre-modern
SOSA-26	1.6	nd	nd	32	na	na	Modern or <u>Mixed</u>
SOSA-27	1.0	nd	nd	9	na	na	Modern or <u>Mixed</u>
SOSA-28	2.3	20.0	40.4	84	na	na	Mixed
SOSA-29	2.6	1.8	9.4	11	na	na	Modern or Mixed
SOSA-30	1.4	<1	>50	95	na	na	Mixed
SOSA-31	3.9	7.9	25.3	45	123	na	Modern
SOSA-32	0.2	<1	>50	0	88	na	Pre-modern
SOSA-33	0.2	<1	>50	77	na	na	Pre-modern
SOSA-34	1.6	nd	nd	2	na	na	Modern or <u>Mixed</u>
SOSA-35	0.1	<1	>50	95	na	na	Pre-modern
Southern Sierra study unit USGS-understanding wells							
SOSAFP-01	0.1	<1	>50	88	66	3,310	Pre-modern
SOSAFP-02	3.2	<1	>50	99	26	10,700	Mixed
SOSAFP-03	-0.1	<1	>50	80	67	3,140	Pre-modern
SOSAFP-04	0.5	<1	>50	47	87	1,080	Mixed
SOSAFP-05	0.2	<1	>50	80	65	3,400	Pre-modern
SOSAFP-06	0.4	<1	>50	48	78	1,870	Pre-modern
SOSAFP-07	1.8	nd	nd	0	106	<1,000	Modern

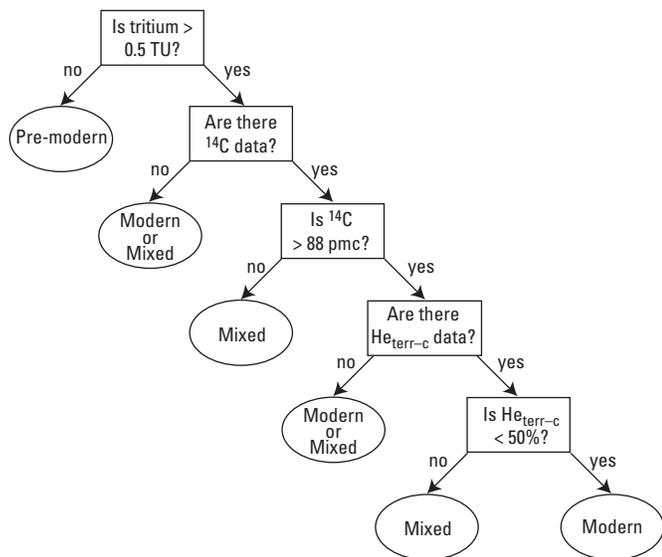
Table C4. Tritium, tritium-helium, terrigenous helium, and carbon-14 data and groundwater age classifications, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Groundwater age classification based on decision tree shown in [figure C1](#). Modern, groundwater recharged since 1952; Pre-modern, groundwater recharged before 1952; Mixed, groundwater containing components recharged before and after 1952. **Errors:** average ¹⁴C counting error was 0.36 percent with standard deviation of 0.11 percent; average tritium-helium age error was 6 percent with standard deviation of 3 percent; %He_{terr-c} errors less than 4 percent for values greater than 50 percent; average %He_{terr-c} error for values less than 50 percent was 5.2 percent with standard deviation of 3.4 percent. **Abbreviations:** ³He_{trit}, helium-3 formed from decay of tritium; %He_{terr-c}, concentration of terrigenous helium divided by total helium concentration corrected for helium from excess air; ¹⁴C, carbon-14; TU, tritium units; nd, not datable; na, not available; <, less than; >, greater than]

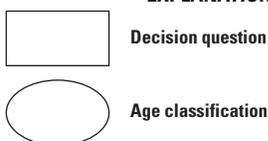
GAMA identification number	Tritium (TU)	³ He _{trit} (TU)	Tritium-Helium age (years)	%He _{terr-c} (percent)	Percent modern carbon	Uncorrected ¹⁴ C age (years)	Groundwater age classification ¹
Southern Sierra study unit USGS-understanding wells—Continued							
SOSAFP-08	0.3	<1	>50	58	85	1,200	Pre-modern
SOSAFP-09	1.0	nd	nd	0	101	<1,000	Modern
SOSAFP-10	-0.1	<1	>50	81	79	1,770	Pre-modern
SOSAFP-11	1.0	3.1	25.2	56	87	1,010	Mixed
SOSAFP-12	0.2	<1	>50	81	na	na	Pre-modern
SOSAFP-13	0.4	<1	>50	80	na	na	Pre-modern
SOSAFP-14	0.6	<1	>50	0	71	2,670	Mixed
SOSAFP-15	1.4	0.2	2.4	0	92	<1,000	Modern

¹ Some samples initially classified as Modern or Mixed based on available groundwater age tracer data were subsequently classified as one or the other (underlined) on the basis of classified well depth.

² Sample oxidation-reduction state was anoxic ([table C6](#)) and stable carbon isotope ratio was between 0 and –10 per mil, suggesting that the carbon isotope composition of the sample may have been altered by methanogenesis. The uncorrected carbon-14 apparent age thus may be too old.



EXPLANATION



Three tracers are used for age classification: Tritium activity, reported in tritium units (TU), Carbon-14 activity (¹⁴C), reported as uncorrected percent modern carbon (pmc), Percent of terrigenous helium in total helium corrected for excess air (He_{terr-c})

Figure C1. Decision tree used for assigning groundwater age classifications on the basis of tritium, carbon-14, and terrigenous helium data, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Geochemical Conditions

Geochemical conditions investigated as potential explanatory factors in this report include oxidation-reduction characteristics and pH. Oxidation-reduction (redox) conditions influence the mobility of many organic and inorganic constituents (McMahon and Chapelle, 2008). Redox conditions along groundwater flow paths commonly proceed along a well-documented sequence of Terminal Electron Acceptor Processes (TEAP), in which a single TEAP typically dominates at a particular time and aquifer location (Chapelle and others, 1995; Chapelle, 2001). The typical TEAP sequence is oxygen reduction (oxic), 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 consequential 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 these inorganic species with oxidation of organic matter to produce energy needed for growth. Groundwater samples may contain chemical species that suggest 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 often are not consistent, indicating electrochemical disequilibrium in groundwater, complicating the assessments of redox conditions (Lindberg and Runnels, 1984; Appelo and Postma, 2005).

In this report, oxidation-reduction conditions were represented in three ways: by DO concentration, by classified oxidation-reduction condition, and by ratios of species of redox-sensitive trace elements. DO concentrations were measured at USGS-grid and USGS-understanding wells (Fram and Belitz, 2007; Ferrari and others, 2008; Fram and others,

2009), but are not reported in the CDPH database (table C5). Oxidation-reduction conditions were classified on the basis of DO, nitrate, manganese, and iron concentrations using a modified version of the classification scheme of McMahon and Chapelle (2008) and Jurgens and others (2009) (table C6). For wells without USGS inorganic constituent data, the most recent data in the CDPH database within the 3-year interval used for the *status assessment* were used.

Arsenic, iron, and chromium 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 C5:

- As^{+5}/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);
- Fe^{+3}/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);
- Cr^{+6}/Cr^{+3} , where Cr^{+6} is the amount of chromium present in the more oxidized +6 oxidation state (chromate) and Cr^{+3} is the amount of chromium present in the more reduced +3 oxidation state (chromite).

Total concentrations of As, Fe, and Cr, and concentrations of As^{+3} , Fe^{+2} , and Cr^{+6} were reported by Fram and Belitz (2007), Ferrari and others (2008), and Fram and others (2009). The concentrations of As^{+5} , Fe^{+3} , Cr^{+3} , Fe(III), As(V), and Cr(III) were calculated by difference. As^{+5}/As^{+3} was reported as >10 if total arsenic was detected and As^{+3} was not detected, and as <0.01 if total arsenic concentration equaled As^{+3} concentration. Similarly, Fe^{+3}/Fe^{+2} was reported as >10 if total iron was detected and Fe^{+2} was not detected, and as <0.01 if total iron concentration equaled Fe^{+2} concentration. Cr^{+6}/Cr^{+3} was reported as >10 if total chromium equaled Cr^{+6} , and as <0.01 if total chromium was detected and Cr^{+6} was not detected.

Table C5. Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic, iron, and chromium, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Oxidation-reduction classification:** NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing; noDO, no dissolved oxygen data available; noMn, no manganese data available. **Ratios of oxidized to reduced species of metals:** 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); 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); Cr⁺⁶/Cr⁺³, ratio of the amount of chromium in the +6 oxidation state (chromate) to the amount in the +3 oxidation state (chromite). **Other abbreviations:** mg/L, milligrams per liter; <, less than; >, greater than; na, not available; –, concentration too low to measure ratio; CDPH, California Department of Public Health; USGS, U.S. Geological Survey]

Well identification number	Source of inorganic data	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification ¹	Ratios of oxidized and reduced species of metals		
					Fe ⁺³ /Fe ⁺²	As ⁺⁵ /As ⁺³	Cr ⁺⁶ /Cr ⁺³
Tahoe-Martis study unit USGS-grid wells							
TMART-01	USGS	8.2	6.5	Oxic	1.0	>10	–
TMART-02	USGS	8.4	6.6	Oxic	–	>10	1.0
TMART-03	USGS	7.9	0.2	Anoxic Mn-red	1.0	3.0	–
TMART-04	USGS	8.0	10.2	Oxic	–	>10	<0.01
TMART-05	USGS	7.9	7.2	Oxic	0.29	>10	–
TMART-06	USGS	7.0	8.6	Oxic	–	>10	–
TMART-07	USGS	6.7	4.1	Oxic	–	–	–
TMART-08	USGS	8.2	6.0	Oxic	>10	>10	–
TMART-09	USGS	6.8	9.6	Oxic	–	–	–
TMART-10	USGS	8.0	6.1	Oxic	–	>10	–
TMART-11	USGS	7.0	9.4	Oxic	0.33	>10	–
TMART-12	USGS	8.1	8.8	Oxic	–	–	–
TMART-13	USGS	8.0	8.9	Oxic	>10	>10	–
TMART-14	USGS	7.5	3.9	Oxic	>10	>10	–
TROCK-01	USGS	7.3	6.2	Oxic	>10	–	–
TROCK-02	USGS	6.0	2.8	Oxic	–	–	–
TROCK-03	USGS	7.6	8.1	Oxic	–	–	–
TROCK-04	USGS	7.3	11.9	Oxic	–	–	–
TROCK-05	USGS	7.2	10.7	Oxic	>10	–	–
TROCK-06	USGS	6.9	9.1	Oxic	>10	–	–
TROCK-07	USGS	6.7	6.8	Oxic	–	>10	–
TROCK-08	USGS	5.5	9.5	Oxic	–	–	–
TROCK-09	USGS	5.9	8.1	Oxic	–	–	–
TROCK-10	USGS	7.4	7.6	Oxic	–	–	–
TROCK-11	USGS	6.5	6.0	Oxic	0.75	>10	–
TROCK-12	USGS	5.8	0.5	Anoxic MnFe-red	<0.01	0.52	–
TROCK-13	USGS	7.3	12.6	Mixed anoxic Mn-red/oxic	>10	>10	–
TTAHO-01	USGS	7.5	4.9	Oxic	3.0	–	–
TTAHO-02	USGS	8.1	7.6	Oxic	–	–	–
TTAHO-03	USGS	6.1	8.8	Oxic	–	–	–
TTAHO-04	USGS	6.7	9.5	Oxic	–	>10	>10
TTAHO-05	USGS	7.6	6.9	Oxic	0.67	0.60	–
TTAHO-06	USGS	8.9	5.2	Oxic	–	>10	–
TTAHO-07	USGS	8.0	8.4	Oxic	–	>10	>10
TTAHO-08	USGS	7.6	4.2	Oxic	–	>10	–
TTAHO-09	USGS	8.1	5.7	Oxic	>10	>10	1.0
TTAHO-10	USGS	8.6	5.3	Oxic	–	>10	–
TTAHO-11	USGS	6.3	0.2	Anoxic MnFe-red	0.01	0.36	–
TTAHO-12	USGS	6.5	4.8	Mixed oxic/Fe-red	0.03	–	–
TTAHO-13	USGS	6.2	0.8	Anoxic Mn-red	0.80	–	–
TTAHO-14	USGS	8.9	9.6	Oxic	–	<0.01	–

Table C5. Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic, iron, and chromium, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Oxidation-reduction classification:** NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing; noDO, no dissolved oxygen data available; noMn, no manganese data available. **Ratios of oxidized to reduced species of metals:** 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); 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); Cr⁺⁶/Cr⁺³, ratio of the amount of chromium in the +6 oxidation state (chromate) to the amount in the +3 oxidation state (chromite). **Other abbreviations:** mg/L, milligrams per liter; <, less than; >, greater than; na, not available; –, concentration too low to measure ratio; CDPH, California Department of Public Health; USGS, U.S. Geological Survey]

Well identification number	Source of inorganic data	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification ¹	Ratios of oxidized and reduced species of metals		
					Fe ⁺³ /Fe ⁺²	As ⁺⁵ /As ⁺³	Cr ⁺⁶ /Cr ⁺³
Tahoe-Martis study unit USGS-understanding wells							
TMARTU-01	USGS	7.9	7.9	Oxic	–	>10	–
TROCKU-01	USGS	7.3	16.2	Oxic	–	–	–
TROCKU-02	USGS	8.0	5.3	Oxic	–	>10	–
TTAHOU-01	USGS	8.8	4.5	Oxic	–	>10	–
TTAHOU-02	USGS	7.4	3.7	Oxic	–	–	–
TTAHOU-03	USGS	9.0	1.2	Oxic	0.67	>10	–
TTAHOU-04	USGS	6.6	9.0	Oxic	–	–	–
TTAHOU-05	USGS	9.2	5.8	Oxic	–	>10	–
TTAHOU-06	USGS	8.4	6.6	Oxic	–	–	–
TTAHOU-07	USGS	7.3	1.6	Oxic	–	>10	–
TTAHOU-08	USGS	6.1	11.4	Oxic	–	–	–
Tahoe-Martis study unit CDPH-grid wells							
TROCK-DPH-03	CDPH	na	na	Oxic (noDO)	na	na	na
TROCK-DPH-04	CDPH	na	na	Oxic (noDO)	na	na	na
TROCK-DPH-06	CDPH	na	na	Oxic (noDO)	na	na	na
TROCK-DPH-12	CDPH	na	na	Oxic (noDO)	na	na	na
TTAHO-DPH-01	CDPH	na	na	Oxic (noDO)	na	na	na
TTAHO-DPH-04	CDPH	na	na	Oxic (noDO)	na	na	na
TTAHO-DPH-07	CDPH	6.3	na	Oxic (noDO) ²	na	na	na
TTAHO-DPH-09	CDPH	7.9	na	Oxic (noDO)	na	na	na
TTAHO-DPH-14	CDPH	9.0	na	Oxic (noDO)	na	na	na
Central Sierra study unit USGS-grid wells							
CGOLD-01	USGS	7.4	0.8	Anoxic NO ₃ -red	>10	>10	–
CGOLD-02	USGS	6.9	0.2	Anoxic MnFe-red	<0.01	>10	–
CGOLD-03	USGS	7.1	0.2	Anoxic MnFe-red	0.03	–	–
CGOLD-04	USGS	6.2	5.4	Oxic	0.27	>10	–
CGOLD-05	USGS	8.0	1.4	Oxic	–	3.8	–
CGOLD-06	USGS	6.4	0.8	Anoxic Mn-red	>10	>10	–
CGOLD-07	USGS	9.4	0.2	Suboxic	–	>10	–
CGOLD-08	USGS	6.0	1.6	Oxic	1.0	–	–
CGOLD-09	USGS	8.7	1.1	Oxic	–	10.0	–
CGOLD-10	USGS	6.0	1.5	Mixed anoxic Mn-red/oxic	2.4	>10	–
CGOLD-11	USGS	6.7	0.2	Anoxic MnFe-red	0.07	>10	–
CGOLD-12	USGS	7.5	0.2	Anoxic Mn-red	0.42	>10	–
CGOLD-13	USGS	7.2	8.4	Mixed anoxic Mn-red/oxic	0.69	>10	–
CGOLD-14	USGS	6.9	1.1	Oxic	0.67	>10	–
CGOLD-15	USGS	7.6	0.2	Suboxic	1.0	>10	–
CGOLD-16	USGS	6.8	9.3	Oxic	0.50	–	–
CGOLD-17	USGS	7.3	2.2	Oxic	>10	>10	–
CGOLD-18	USGS	8.5	3.4	Oxic	>10	3.5	–

Table C5. Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic, iron, and chromium, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Oxidation-reduction classification:** NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing; noDO, no dissolved oxygen data available; noMn, no manganese data available. **Ratios of oxidized to reduced species of metals:** 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); 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); Cr⁺⁶/Cr⁺³, ratio of the amount of chromium in the +6 oxidation state (chromate) to the amount in the +3 oxidation state (chromite). **Other abbreviations:** mg/L, milligrams per liter; <, less than; >, greater than; na, not available; –, concentration too low to measure ratio; CDPH, California Department of Public Health; USGS, U.S. Geological Survey]

Well identification number	Source of inorganic data	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification ¹	Ratios of oxidized and reduced species of metals		
					Fe ⁺³ /Fe ⁺²	As ⁺⁵ /As ⁺³	Cr ⁺⁶ /Cr ⁺³
Central Sierra study unit USGS-grid wells—Continued							
CWISH-01	USGS	6.9	0.4	Anoxic Mn-red	>10	>10	–
CWISH-02	USGS	8.3	0.2	Suboxic	–	0.10	–
CWISH-03	USGS	7.2	0.3	Anoxic Mn-red	2.2	1.6	–
CWISH-04	USGS	5.7	2.2	Mixed oxic/Fe-red	0.0	–	–
CWISH-05	USGS	6.0	1.0	Oxic	1.2	>10	–
CWISH-06	USGS	9.3	na	Oxic (noDO)	–	0.9	–
CWISH-07	USGS	7.8	1.3	Oxic	–	8.4	–
CWISH-08	USGS	6.5	2.1	Oxic	–	–	–
CWISH-09	USGS	5.3	3.2	Oxic	3.5	–	–
Central Sierra study unit USGS-understanding wells							
CGOLDU-01	USGS	7.2	0.2	Anoxic Mn-red	0.30	>10	–
CGOLDU-02	USGS	6.8	6.3	Oxic	–	>10	–
CWISHU-01	USGS	8.3	12.2	Oxic	>10	>10	–
Central Sierra study unit CDPH-grid wells							
CGOLD-DPH-11	CDPH	7.0	na	Anoxic MnFe-red	na	na	na
CGOLD-DPH-14	CDPH	6.0	na	Oxic (noDO) ²	na	na	na
CGOLD-DPH-16	CDPH	6.8	na	Oxic (noDO) ²	na	na	na
CGOLD-DPH-18	CDPH	7.1	na	Oxic (noDO)	na	na	na
CGOLD-DPH-19	CDPH	6.4	na	Oxic (noDO)	na	na	na
CWISH-DPH-06	na	na	na	Insufficient	na	na	na
CWISH-DPH-10	CDPH	7.7	na	Oxic (noDO)	na	na	na
Southern Sierra study unit USGS-grid wells							
SOSA-01	CDPH	na	1.4	Oxic	na	na	–
SOSA-02	CDPH	na	4.3	Oxic (noMn)	na	na	<0.01
SOSA-03	USGS	6.9	11.6	Oxic	na	>10	<0.01
SOSA-04	CDPH	na	2.2	Oxic (noMn)	na	na	–
SOSA-05	CDPH	na	4.7	Oxic	na	na	–
SOSA-06	CDPH	na	0.1	Anoxic Mn-red	na	na	–
SOSA-07	USGS	6.5	0.1	Anoxic Mnfe-red	0.02	1.1	–
SOSA-08	CDPH	na	0.6	Anoxic NO ₃ -red	na	na	–
SOSA-09	CDPH	na	0.6	Suboxic	na	na	–
SOSA-10	USGS	6.0	0.8	Anoxic MnFe-red	0.04	na	–
SOSA-11	CDPH	na	10.5	Oxic (noMn)	na	na	>10
SOSA-12	CDPH	na	2.1	Oxic (noMn)	na	na	5.0
SOSA-13	USGS	7.6	7.0	Oxic	–	na	–
SOSA-14	CDPH	na	6.0	Oxic (noMn)	na	na	–
SOSA-15	USGS	6.8	7.8	Oxic	–	–	–
SOSA-16	CDPH	na	7.0	Oxic	na	na	–
SOSA-17	CDPH	na	1.2	Oxic	na	na	–
SOSA-18	CDPH	na	5.4	Oxic (noMn)	na	na	–

Table C5. Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic, iron, and chromium, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Oxidation-reduction classification:** NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing; noDO, no dissolved oxygen data available; noMn, no manganese data available. **Ratios of oxidized to reduced species of metals:** 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); 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); Cr⁺⁶/Cr⁺³, ratio of the amount of chromium in the +6 oxidation state (chromate) to the amount in the +3 oxidation state (chromite). **Other abbreviations:** mg/L, milligrams per liter; <, less than; >, greater than; na, not available; –, concentration too low to measure ratio; CDPH, California Department of Public Health; USGS, U.S. Geological Survey]

Well identification number	Source of inorganic data	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification ¹	Ratios of oxidized and reduced species of metals		
					Fe ⁺³ /Fe ⁺²	As ⁺⁵ /As ⁺³	Cr ⁺⁶ /Cr ⁺³
Southern Sierra study unit USGS-grid wells—Continued							
SOSA-19	CDPH	na	1.4	Oxic	na	na	–
SOSA-20	CDPH	na	5.1	Oxic	na	na	–
SOSA-21	CDPH	na	1.2	Oxic (noMn)	na	na	–
SOSA-22	USGS	6.1	6.6	Oxic	>10	–	–
SOSA-23	CDPH	na	8.0	Oxic	na	na	2.5
SOSA-24	CDPH	na	0.2	Anoxic Mn-red	na	na	–
SOSA-25	CDPH	na	4.2	Oxic	na	na	>10
SOSA-26	CDPH	na	2.1	Oxic	na	na	–
SOSA-27	CDPH	na	2.0	Mixed anoxic MnFe-red/oxic	na	na	–
SOSA-28	CDPH	na	6.3	Oxic (noMn)	na	na	2.0
SOSA-29	CDPH	na	1.4	Oxic (noMn)	na	na	–
SOSA-30	CDPH	na	6.6	Oxic (noMn)	na	na	–
SOSA-31	CDPH	na	7.8	Oxic (noMn)	na	na	–
SOSA-32	CDPH	7.4	8.4	Oxic (noMn)	na	na	<0.01
SOSA-33	CDPH	7.2	0.1	Suboxic (noMn)	na	na	–
SOSA-34	CDPH	7.2	11.6	Oxic (noMn)	na	na	3.0
SOSA-35	USGS	8.6	0.2	Suboxic	na	na	–
Southern Sierra study unit USGS-understanding wells							
SOSAFP-01	USGS	7.8	5.2	Oxic	–	na	1.3
SOSAFP-02	USGS	6.2	0.1	Anoxic MnFe-red	<0.01	2.0	–
SOSAFP-03	USGS	8.1	3.8	Oxic	>10	>10	3.0
SOSAFP-04	USGS	7.9	8.3	Oxic	–	na	2.0
SOSAFP-05	USGS	7.7	3.5	Oxic	–	>10	1.0
SOSAFP-06	USGS	7.7	7.9	Oxic	>10	>10	5.0
SOSAFP-07	USGS	7.6	8.5	Oxic	na	na	<0.01
SOSAFP-08	USGS	7.4	3.1	Oxic	–	–	3.0
SOSAFP-09	USGS	7.0	12.3	Oxic	–	>10	>10
SOSAFP-10	USGS	7.4	4.0	Oxic	>10	–	4.5
SOSAFP-11	USGS	7.7	5.2	Oxic	>10	>10	>10
SOSAFP-12	USGS	7.3	3.3	Oxic	–	–	>10
SOSAFP-13	USGS	7.8	7.0	Oxic	>10	na	<0.01
SOSAFP-14	USGS	7.7	9.7	Oxic	na	na	<0.01
SOSAFP-15	USGS	7.7	9.4	Oxic	>10	>10	>10
Southern Sierra study unit CDPH-grid wells							
SOSA-DPH-06	CDPH	8.2	na	Anoxic MnFe-red	na	na	na
SOSA-DPH-07	CDPH	7.1	na	Anoxic MnFe-red	na	na	na
SOSA-DPH-08	CDPH	7.6	na	Oxic (noDO)	na	na	na
SOSA-DPH-11	CDPH	8.0	na	Oxic (noDO)	na	na	na
SOSA-DPH-12	CDPH	na	na	Insufficient	na	na	na
SOSA-DPH-13	CDPH	8.1	na	Oxic (noDO)	na	na	na

Table C5. Oxidation-reduction classification, dissolved oxygen concentration, pH, and oxidation-reduction species ratios for arsenic, iron, and chromium, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.—Continued

[Well identification numbers: TMART, Tahoe-Martis study unit, Martis study area; TROCK, Tahoe-Martis study unit, Hard Rock study area; TTAHO, Tahoe-Martis study unit, Tahoe study area; CGOLD, Central Sierra study unit, Coarse Gold study area; CWISH, Central Sierra study unit, Wishon study area; SOSA, Southern Sierra study unit. **Oxidation-reduction classification:** NO₃-red, nitrate-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing; noDO, no dissolved oxygen data available; noMn, no manganese data available. **Ratios of oxidized to reduced species of metals:** 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); 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); Cr⁺⁶/Cr⁺³, ratio of the amount of chromium in the +6 oxidation state (chromate) to the amount in the +3 oxidation state (chromite). **Other abbreviations:** mg/L, milligrams per liter; <, less than; >, greater than; na, not available; –, concentration too low to measure ratio; CDPH, California Department of Public Health; USGS, U.S. Geological Survey]

Well identification number	Source of inorganic data	pH (standard units)	Dissolved oxygen (mg/L)	Oxidation-reduction classification ¹	Ratios of oxidized and reduced species of metals		
					Fe ⁺³ /Fe ⁺²	As ⁺⁵ /As ⁺³	Cr ⁺⁶ /Cr ⁺³
Southern Sierra study unit CDPH-grid wells							
SOSA-DPH-15	CDPH	7.0	na	Oxic (noDO)	na	na	na
SOSA-DPH-18	CDPH	7.2	na	Oxic (noDO)	na	na	na
SOSA-DPH-21	CDPH	7.3	na	Oxic (noDO)	na	na	na
SOSA-DPH-28	CDPH	8.1	na	Oxic (noDO)	na	na	na
SOSA-DPH-30	CDPH	8.2	na	Anoxic MnFe-red	na	na	na
SOSA-DPH-31	CDPH	7.0	na	Oxic (noDO) ²	na	na	na
SOSA-DPH-32	CDPH	na	na	Insufficient	na	na	na
SOSA-DPH-33	CDPH	7.6	na	Anoxic MnFe-red	na	na	na
SOSA-DPH-34	CDPH	8.4	na	Oxic (noDO) ²	na	na	na
SOSA-DPH-36	na	na	na	Insufficient	na	na	na
SOSA-DPH-37	CDPH	na	na	Insufficient	na	na	na
SOSA-DPH-38	CDPH	8.1	na	Oxic (noDO)	na	na	na

¹ Oxidation-reduction classification criteria are given in [table C6](#).

² Iron concentrations from California Department of Public Health (CDPH) database were greater than criteria.

Table C6. Oxidation-reduction classification system applied to samples from the Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[**Oxidation-reduction classes:** noDO, no dissolved oxygen data available; noMn, no manganese data available; NO₃-red, nitrate-reducing; Fe-red, iron-reducing; Mn-red, manganese-reducing; MnFe-red, manganese and iron reducing. **Other abbreviations:** mg/L, milligram per liter; µg/L, microgram per liter; ≥, greater than or equal to; <, less than; –, data not available; any, any concentration]

Oxidation-reduction class	Number of wells	Dissolved oxygen ¹ (mg/L)	Nitrate, as nitrogen (mg/L)	Manganese (µg/L)	Iron ² (µg/L)
Oxic classes					
Oxic	87	≥ 1	Any	< 50	< 200
Oxic (noDO)	1	–	Any	< 50	< 200
Oxic (noMn)	13	≥ 1	Any	–	–
Anoxic classes					
Suboxic	5	< 1	< 0.5	< 50	< 200
Suboxic (noMn)	1	< 1	< 0.5	–	–
Anoxic NO ₃ -red	2	< 1	≥ 0.5	< 50	< 200
Anoxic Mn-red	9	< 1	Any	≥ 50	< 200
Anoxic MnFe-red	8	< 1	Any	≥ 50	≥ 200
Mixed classes					
Mixed anoxic Mn-red/oxic	3	≥ 1	Any	≥ 50	< 200
Mixed oxic/Fe-red ²	2	≥ 1	Any	< 50	≥ 200
Mixed anoxic MnFe-red/oxic	1	≥ 1	Any	≥ 50	≥ 200

¹ Criteria of 1 mg/L of dissolved oxygen used instead of the criteria of 0.5 mg/L used by McMahon and Chapelle (2008) and Jurgens and others (2009) because measurements with values less than 1 mg/L were less precise in this study.

² Criteria of 200 µg/L of iron used instead of the criteria of 100 µg/L used by McMahon and Chapelle (2008) and Jurgens and others (2009) because 200 µg/L sometimes was the reporting limit for iron in the CDPH database.

Appendix D: Comparison of CDPH and USGS-GAMA Data

Data acquired by USGS-GAMA and data from the CDPH database were compared to assess the validity of merging data from these two sources for the *status assessment*. Comparisons were made using wells that were analyzed by USGS-GAMA for inorganic and radioactive constituents and had data in the CDPH database within the 3-year intervals used for the *status assessment*. All data were combined because the number of wells in each study unit with data from both sources was small. Because the number of data pairs for many of the constituents was small, the reported concentrations were converted to RCs by dividing by the appropriate benchmark concentration which permitted combining constituents into constituent classes for the purpose of comparing data from the two sources. Five constituent classes were considered: nutrients, trace elements with health-based benchmarks, radioactive constituents, trace elements with SMCL benchmarks, and salinity indicators with SMCL benchmarks. Constituents with 10 or more data pairs also were examined individually. The data were evaluated in three ways:

- The Wilcoxon signed-rank test was used to determine whether the RCs for a constituent or constituent class were systematically greater in one data source compared to the other. The test evaluates whether the median difference between the two values in each data pair is significantly different from zero (Helsel and Hirsch, 2002).
- The coefficient of determination (R^2) of linear regression of the RCs for a constituent or constituent class from the two data sources was used to evaluate the variance in the data.
- The potential effect on the results of the status assessment of using data from one source or the other was evaluated by comparing the proportions of high and moderate RCs for a constituent or class of constituents calculated by using data from the two sources.

The data for nutrients, many trace elements, and radioactive constituents from both sources included many non-detections. This resulted in five types of data pairs, only two of which were included in the quantitative comparisons.

- Both sources reported a detection of the constituent. Pairs of this type were included in the quantitative comparisons.
- Both sources reported a non-detection of the constituent. Pairs of this type were not included in the quantitative comparisons.
- One source reported a non-detection of the constituent, and the other source reported a detection with concentration greater than the reporting limit for the non-detection. Pairs of this type were included in the quantitative comparisons, and the reporting limit was used as the concentration for the non-detection.
- One source reported a non-detection of the constituent, and the other source reported a detection with concentration less than the reporting limit for the non-detection. USGS-GAMA had lower reporting limits than CDPH for all of the inorganic constituents ([fig. 7](#)); thus, this type of data pair was common. Pairs of this type were not included in the quantitative comparisons.
- USGS-GAMA reports a detection and CDPH reports a non-detection with a value of zero rather than a reporting limit. Pairs of this type were only included in the quantitative comparisons if the concentration reported by USGS-GAMA was greater than one-half of the benchmark value for the constituent.

Among the nutrients, only nitrate had data pairs available for comparison (27 pairs) ([table D1](#)). Nitrate concentrations from the CDPH database were significantly higher than those measured by USGS-GAMA (Wilcoxon signed-rank, $p=0.042$), and data for RCs greater than approximately 0.25 deviated both above and below the 1:1 line ([fig. D1A](#)). However, there were no differences in the proportions of high RCs (0%) or moderate RCs (15%) between data from the two sources ([fig. D2](#)).

Table D1. Results of comparisons between relative-concentrations of constituents in samples from wells with U.S. Geological Survey-Groundwater Ambient Monitoring and Assessment (USGS-GAMA) data and data in the California Department of Public Health (CDPH) database within the 3-year intervals used in the status assessment, Tahoe-Martis, Central Sierra, and Southern Sierra study units, 2006–2007, California GAMA Priority Basin Project.

[Results shown for constituents and constituent classes containing 10 or more data pairs. Relation of median differences between data pairs shown for Wilcoxon signed-rank tests in which the populations were determined to be significantly different (two-sided test) on the basis of p-values (not shown) less than threshold value (α) of 0.05; ns, test indicated no significant differences between the sample groups. R^2 for linear regression between relative-concentrations of USGS-GAMA and CDPH data in data pairs. **Abbreviations:** USGS, U.S. Geological Survey; GAMA, Groundwater Ambient Monitoring and Assessment Program; CDPH, California Department of Public Health; >, greater than]

Constituent or constituent class	Number of data pairs	Significant difference	R^2
Inorganic constituents with health-based benchmarks			
Nitrate	27	CDPH > USGS	0.81
Trace elements ¹	62	ns	0.76
Arsenic	18	ns	0.84
Fluoride	14	ns	0.86
Radioactive constituents ²	36	USGS > CDPH	0.93
Gross alpha particle activity	14	ns	0.98
Inorganic constituents with SMCL benchmarks			
Trace metals ³	22	ns	0.77
Salinity indicators	122	USGS > CDPH	0.91
Specific conductance	44	ns	0.80
Chloride	27	USGS > CDPH	0.83
Sulfate	22	ns	0.98
Total dissolved solids	29	ns	0.93

¹Trace element data pairs: aluminium (2), arsenic (18), barium (5), boron (2), chromium (4), fluoride (14), mercury (1), nickel (1), selenium (4), vanadium (4), uranium (6).

²Radioactive constituent data pairs: gross alpha particle activity (14), gross beta particle activity (1), radium activity (5), radon-222 activity (7), uranium activity (9).

³Trace metal data pairs: iron (6), manganese (7), silver (4), zinc (5).

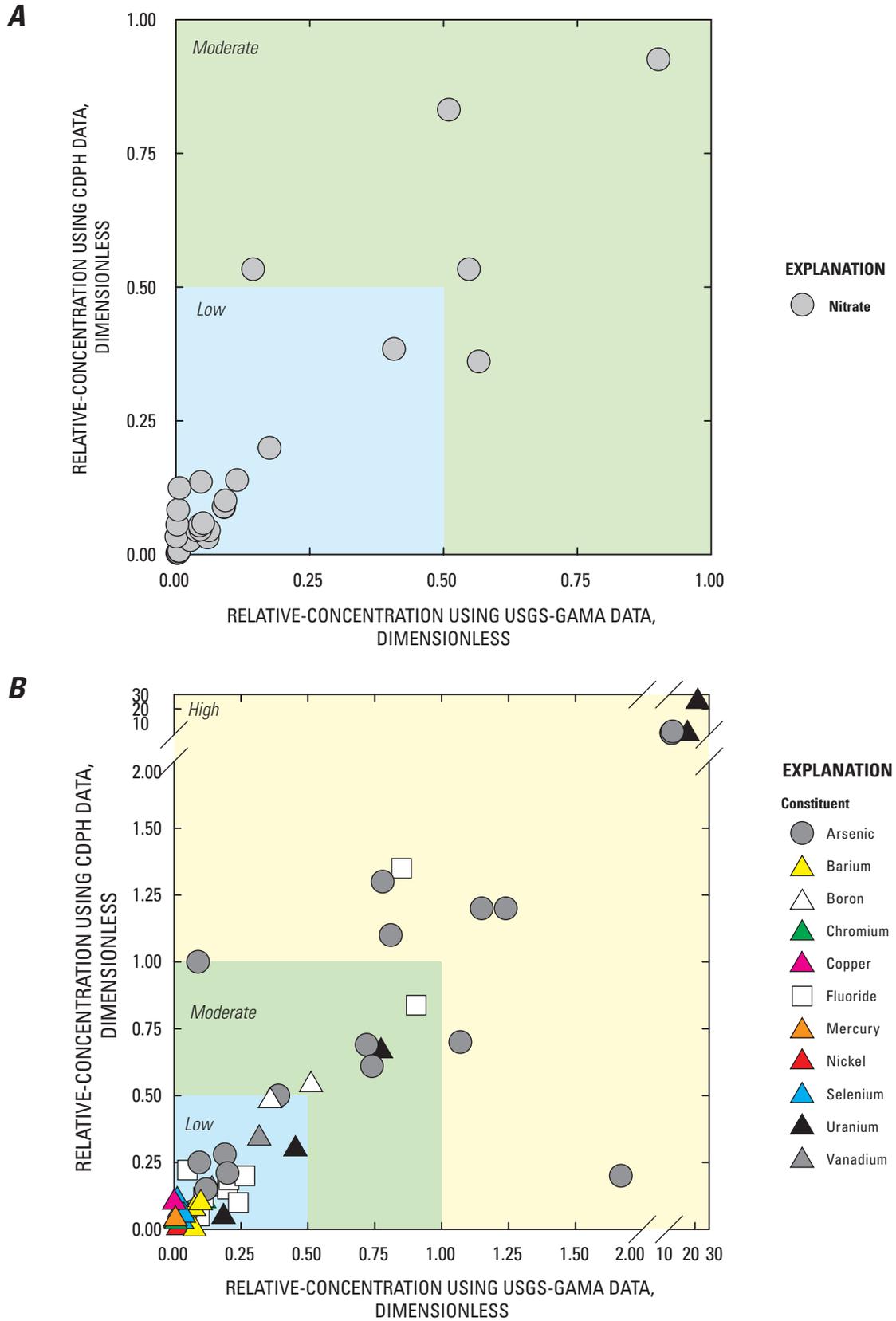
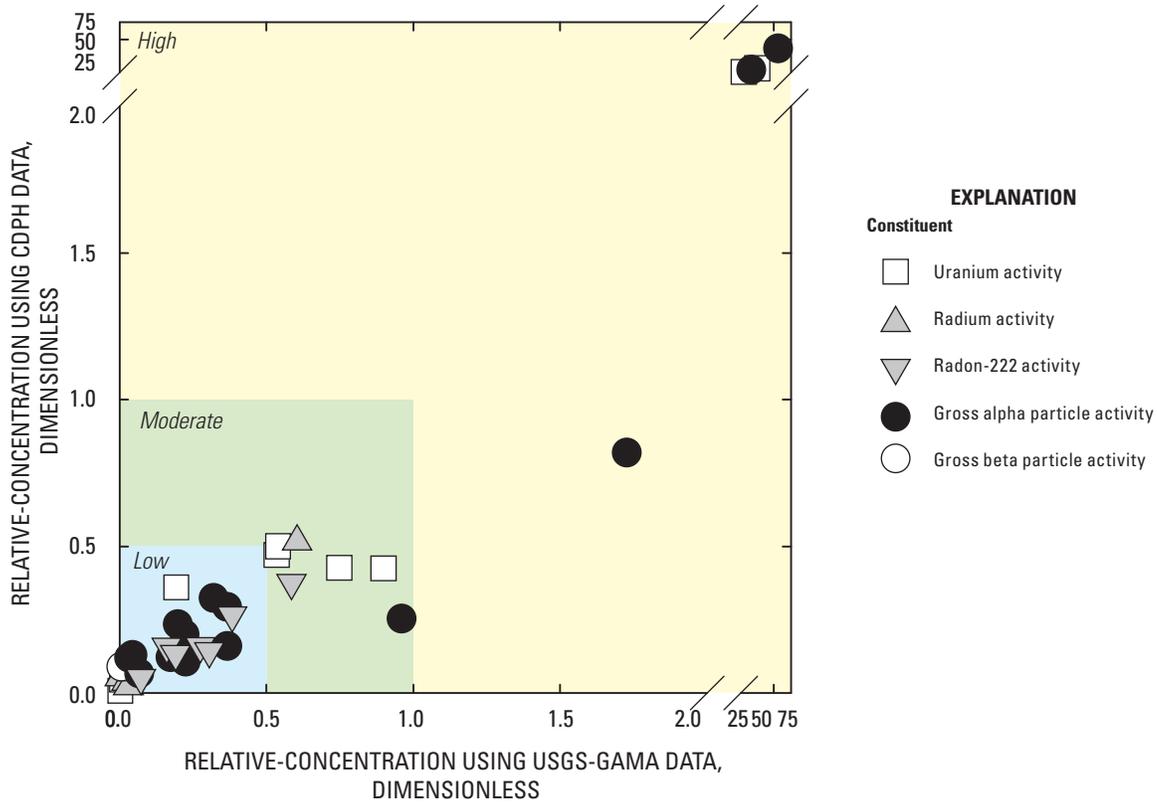


Figure D1. Graphs showing comparisons of relative-concentrations measured by USGS-GAMA and relative-concentrations reported in the CDPH during the 3-year intervals used for the status assessment for wells with data from both sources for (A) nitrate, (B) trace elements with health-based benchmarks, (C) radioactive constituents, (D) metals with SMCL benchmarks, and (E) salinity indicators with SMCL benchmarks, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

C



D

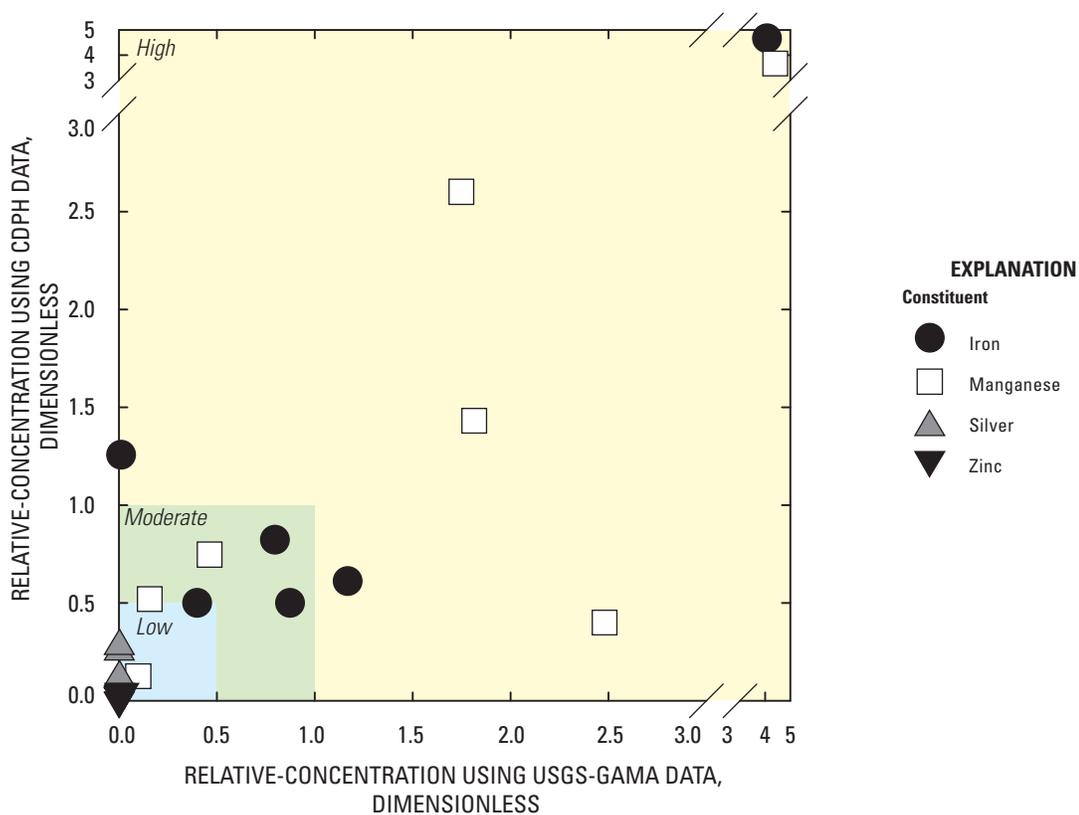


Figure D1.—Continued

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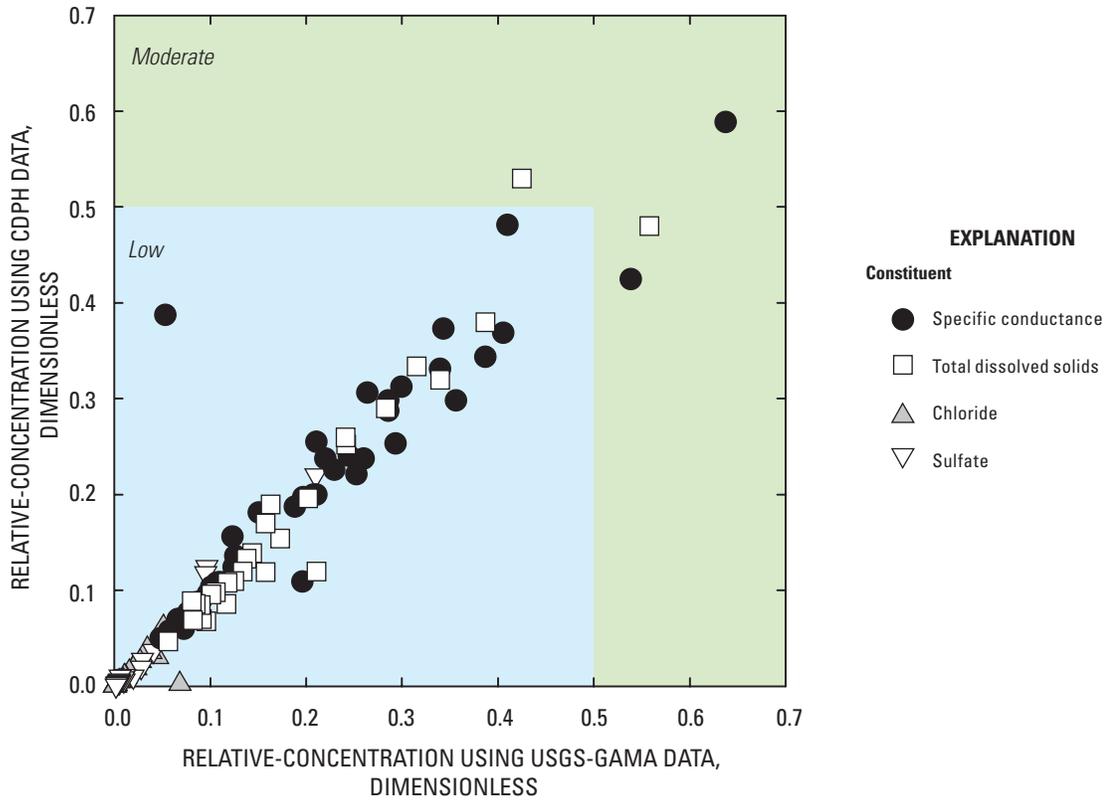
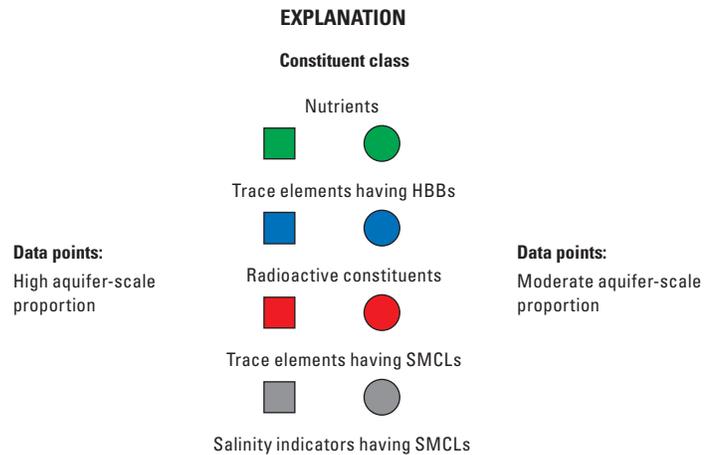
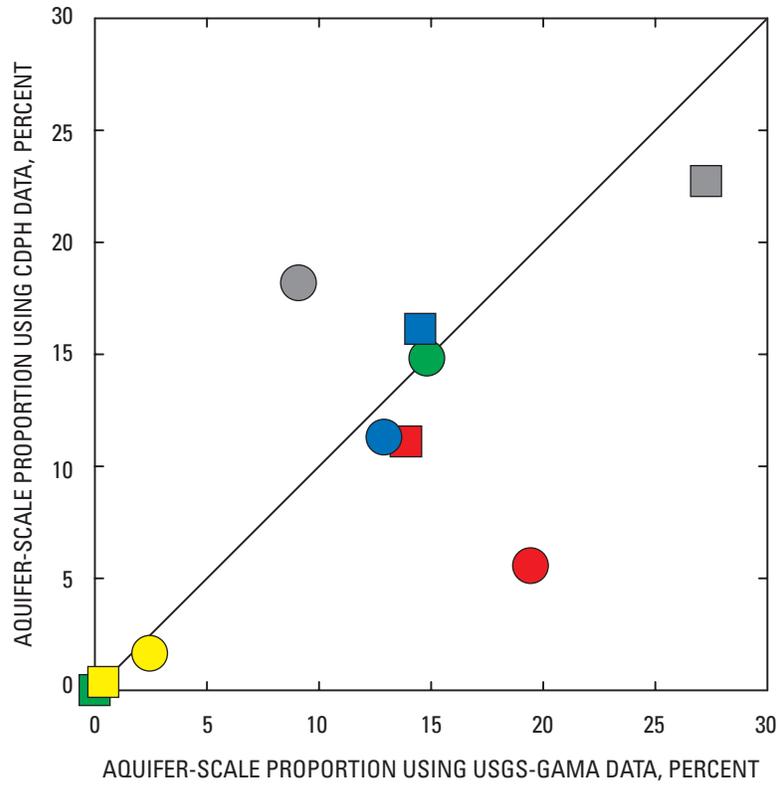


Figure D1.—Continued



HBB, health-based benchmark; SMCL, secondary maximum contaminant level; CDPH, California Department of Public Health; USGS-GAMA, U.S. Geological Survey Groundwater Ambient Monitoring and Assessment Program

Figure D2. Graphs showing comparisons of proportions of high and moderate relative-concentrations for constituent classes in the set of wells with data from the USGS-GAMA and the CDPH database within the 3-year intervals used in the status assessment, Tahoe-Martis, Central Sierra, and Southern Sierra study units, California GAMA Priority Basin Project.

Trace elements with health-based benchmarks had 62 data pairs available for comparison, 32 of which were either pairs of arsenic or fluoride data (table D1). There were no significant differences between USGS-GAMA and CDPH data for trace elements as a class or for arsenic or fluoride individually. Data for RCs greater than approximately 0.25 deviated above and below the 1:1 line, particularly for arsenic (fig. D1B). The relatively high R^2 value for arsenic is strongly controlled by the three data pairs with $RC > 2$; if those three data pairs are excluded, the R^2 value decreases to 0.19. Similarly, the relatively high R^2 value for trace elements as a class is strongly controlled by the five data pairs (three for arsenic and two for uranium) with $RC > 2$; if those five data pairs are excluded, the R^2 value decreases to 0.56. Despite the poor agreement between the USGS-GAMA and CDPH trace element data on a well-by-well basis, the agreement between the aggregate datasets is sufficient for the purposes of the *status assessment*. For trace elements as a class, USGS-GAMA data and CDPH data yielded similar proportions with high and moderate RCs: 15% high and 13% moderate for USGS-GAMA data, and 16% high and 11% moderate for CDPH data (fig. D2). The proportions for arsenic also were similar: 39% high and 28% moderate for USGS-GAMA data, and 39% high and 22% moderate for CDPH data. These results indicate that the agreement between the aggregate datasets is sufficient for calculating aquifer-scale proportions of high, moderate, and low RCs of trace elements, which is the central objective of the *status assessment*.

Radioactive constituents had 36 data pairs available for comparison, 14 of which were gross alpha particle activity (table D1). RCs measured by USGS-GAMA for radioactive constituents were significantly greater than RCs reported in the CDPH database (Wilcoxon signed-rank, $p=0.003$). The relatively high R^2 value for radioactive constituents is strongly controlled by the four data pairs with $RC > 2$ (fig. D1C); if those four data pairs are excluded, the R^2 value decreases to 0.76. Agreement between the aggregate datasets for radioactive constituents was poorer than agreements for nutrients and for trace elements with health-based benchmarks. For radioactive constituents as a class, USGS-GAMA data yielded 14% with high RCs and 19% with moderate RCs; CDPH data yielded 11% with high RCs and 5.6% with moderate RCs (fig. D2). The difference between the proportions with moderate RCs mainly was due to greater proportion of moderate RCs of uranium activity in the USGS-GAMA data. The reason for the systematic discrepancy between USGS-GAMA and CDPH results for radioactive constituents is unknown.

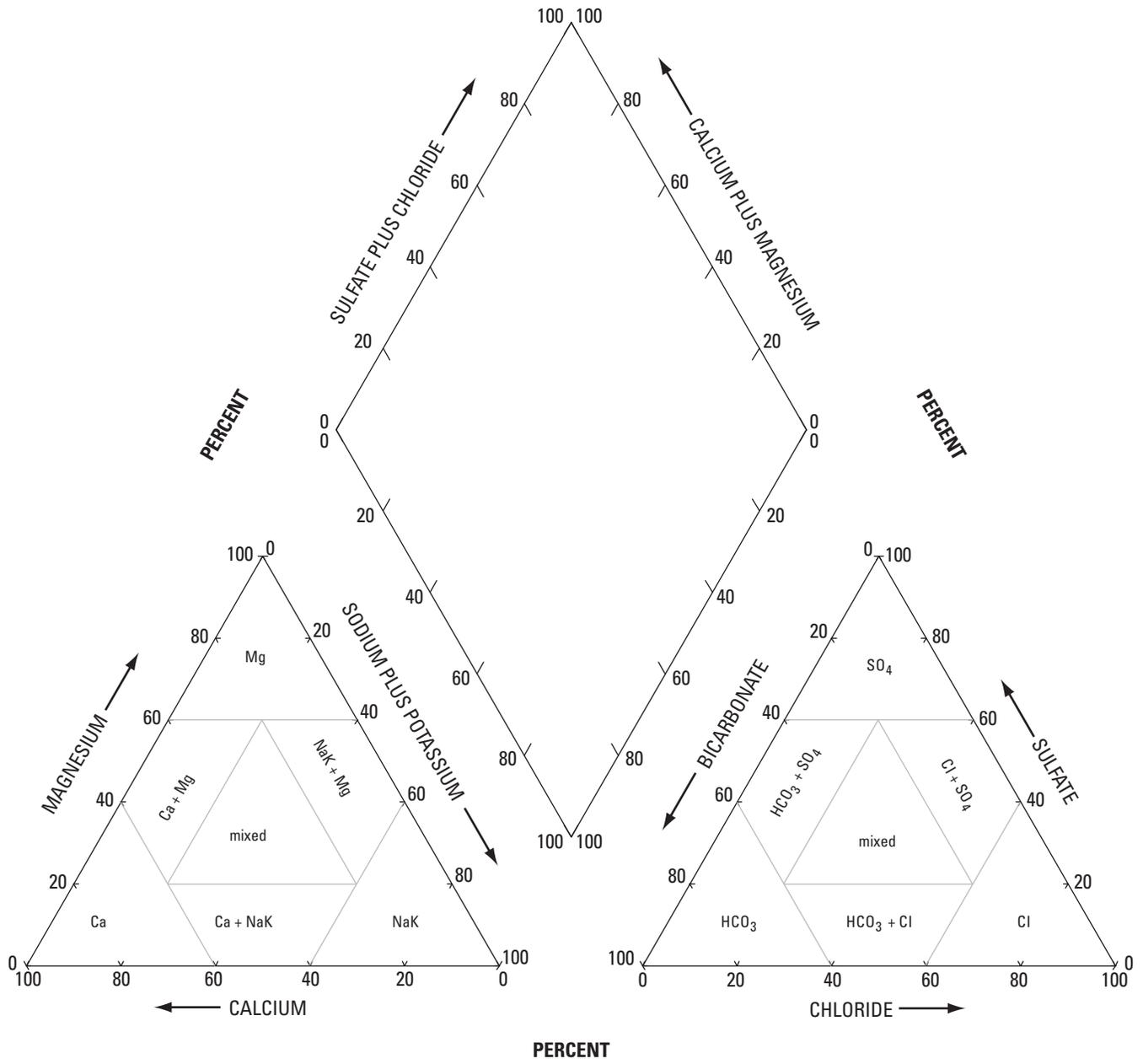
Trace elements with SMCL benchmarks had 22 data pairs available for comparison (table D1). There was no significant difference between RCs measured by USGS-GAMA and RCs

reported by CDPH. The relatively high R^2 value for the class is strongly controlled by the two data pairs with $RCs > 3$; if those two data pairs are excluded, the R^2 value decreases to 0.35 (fig. D1D). Agreement between the aggregate datasets for trace elements with SMCL benchmarks was poorer than agreement for salinity indicators with SMCL benchmarks. For trace elements with SMCL benchmarks as a class, USGS-GAMA data yielded 27% with high RCs and 9.1% with moderate RCs, whereas, CDPH data yielded 23% with high RCs and 18% with moderate RCs (fig. D2).

Salinity indicators with SMCL benchmarks had 122 data pairs available for comparison, and specific conductance, total dissolved solids, chloride, and sulfate each had a sufficient number of data pairs for evaluation as individual constituents (table D1). RCs measured by USGS-GAMA for salinity indicators as a class and for chloride as an individual constituent were significantly greater than RCs reported in the CDPH database (Wilcoxon signed-rank, $p=0.024$ and $p=0.041$, respectively). However, agreement between the aggregate datasets was good: for salinity indicators as a class, USGS-GAMA data yielded 0% high and 2.5% moderate, and CDPH data yielded 0% high and 1.6% moderate (fig. D2).

Major ion data for grid wells in each study unit were compared with major ion data from all wells in the CDPH database for each study unit to evaluate whether the grid wells in each study unit were representative of the range of groundwater types pumped by wells used for municipal and community drinking water supply in that study unit. The CDPH well dataset consisted of all wells with a complete major ion analysis within the 3-year intervals used for the *status assessment*. If there were multiple analyses available, the most recent one with an acceptable cation-anion balance was selected. The datasets were compared using Piper diagrams (Piper, 1944; Hem, 1989). Groundwater types are defined on a Piper diagram according to the cations and anions present in the greatest proportions (fig. D3).

Because Piper diagrams show relative abundances of cations and anions, only major ion analyses with acceptable cation-anion balances were plotted (see appendix A for definition of acceptable cation-anion balance). Calculating cation-anion balance for major ion analyses from the CDPH database occasionally included adjusting the reported alkalinity value. 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 relationship was not consistently observed in the CDPH databases for these study units. In particular, total alkalinity and bicarbonate alkalinity were commonly reported as the same value.



EXPLANATION

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

Figure D3. Piper diagram showing definitions of groundwater types.

Other inconsistencies included total alkalinity greater than bicarbonate alkalinity, which, in the absence of other anions, would indicate significant amounts of non-carbonate alkalinity, and presence of only total alkalinity or bicarbonate alkalinity data, not both. For major ion analyses with cation-anion balance <90%, cation-anion balance was recalculated by substituting total alkalinity values equaling 1.22 or 0.82 times the reported total alkalinity or the reported bicarbonate alkalinity. If any substitution resulted in a cation-anion balance of > 90%, the major ion analysis was used for the Piper diagram with the substituted value.

The range of groundwater types represented by the grid wells was similar to the range of groundwater types with major ion data in the CDPH database in each of the three study units (figs. D4A–C). The anion composition of the majority of CDPH and grid wells from all three study units was classified as bicarbonate-type (HCO_3^-), and most of the remainder was classified as bicarbonate-chloride (HCO_3^- -Cl) (Tahoe-Martis and Central Sierra study units) or as bicarbonate-sulfate (HCO_3^- - SO_4^{2-}) (Southern Sierra study unit). The cation composition of the majority of CDPH and grid wells was classified as calcium-sodium/potassium (Ca-NaK), calcium-magnesium (Ca-Mg), or mixed in the Tahoe-Martis study unit; Ca-NaK, Ca, or mixed in the Central Sierra study unit; and Ca-NaK or mixed in the Southern Sierra study unit. The similarities in the ranges of anion and cation compositions in the CDPH wells and the grid wells in each of the three study units suggest that the grid wells do indeed represent the diversity of groundwater types used for public supply in the three study units.

Several differences in groundwater types between the CDPH wells and grid wells were noted.

Tahoe-Martis study unit: One of the grid wells in the Hard Rock study area had Ca as the major cation and SO_4^{2-} as the major anion (fig. D4A). Ca- and SO_4^{2-} -dominated groundwater was not seen in any other wells from the Tahoe-Martis, Central Sierra, or Southern Sierra study units. The well is listed in the CDPH database; however, major ion data were not available for comparison with the USGS-GAMA data.

Central Sierra study unit: A minority of the CDPH wells had anion compositions classified as Cl or Cl- HCO_3^- groundwater (fig. D4B). The wells with Cl-type groundwater were all located in five adjacent cells around the city of Oakhurst (fig. A1B), and represented one-third of the total number of wells (CDPH plus USGS) in those five cells. The Cl- HCO_3^- -type wells were located in the same five adjacent cells, plus in two other, non-adjacent cells. Together, Cl and Cl- HCO_3^- types accounted for nearly two-thirds of the total number of wells in the seven cells. The grid wells for these seven cells included four Cl- HCO_3^- -type samples, but no Cl-type samples. The Cl and Cl- HCO_3^- -type samples also have a wide range of cation composition, from 14 to 89% NaK; however, the four grid wells had 63 to 87% NaK. Thus, the grid well dataset may not adequately represent the Cl-type groundwater, particularly low-NaK varieties.

Southern Sierra study unit: One CDPH well has markedly higher chloride than all of the other CDPH wells, and this well was selected as a grid well.

A

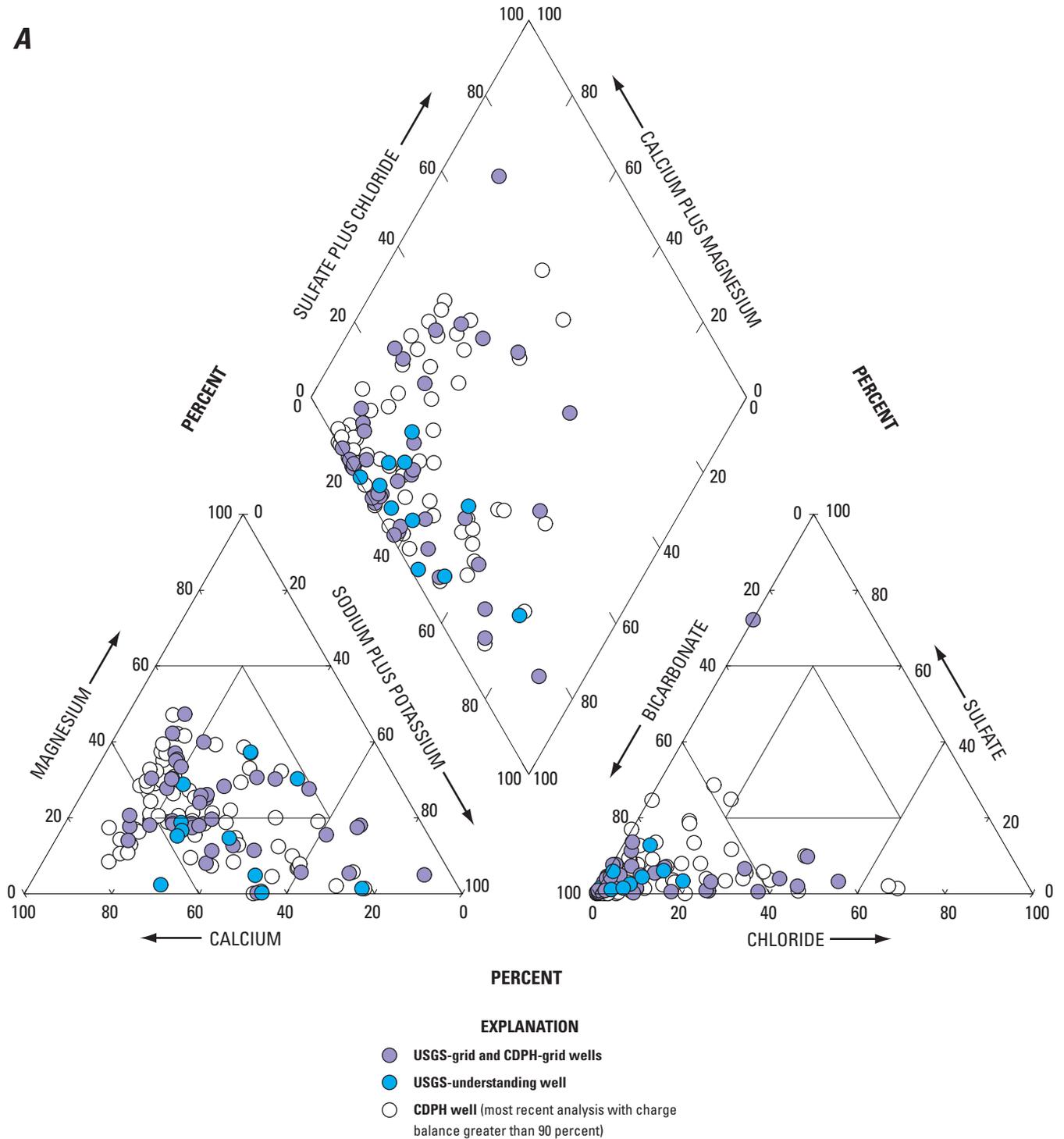


Figure D4. Piper diagram for grid wells, USGS-understanding wells, and all wells in the CDPH database that had major ion data with acceptable charge balances during the 3-year intervals used in the status assessment for the (A) Tahoe-Martis, (B) Central Sierra, and (C) Southern Sierra study units, California GAMA Priority Basin Project.

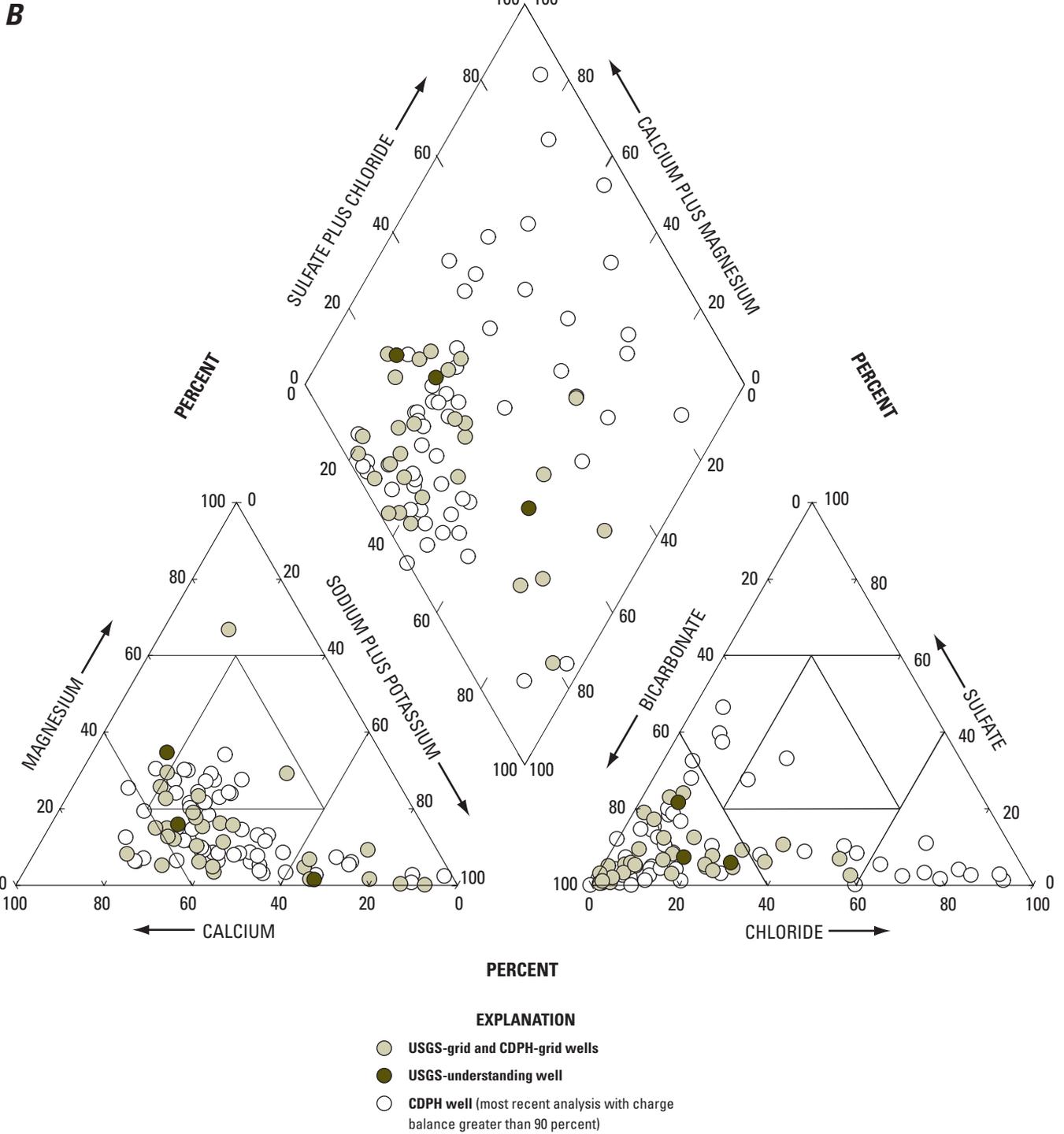


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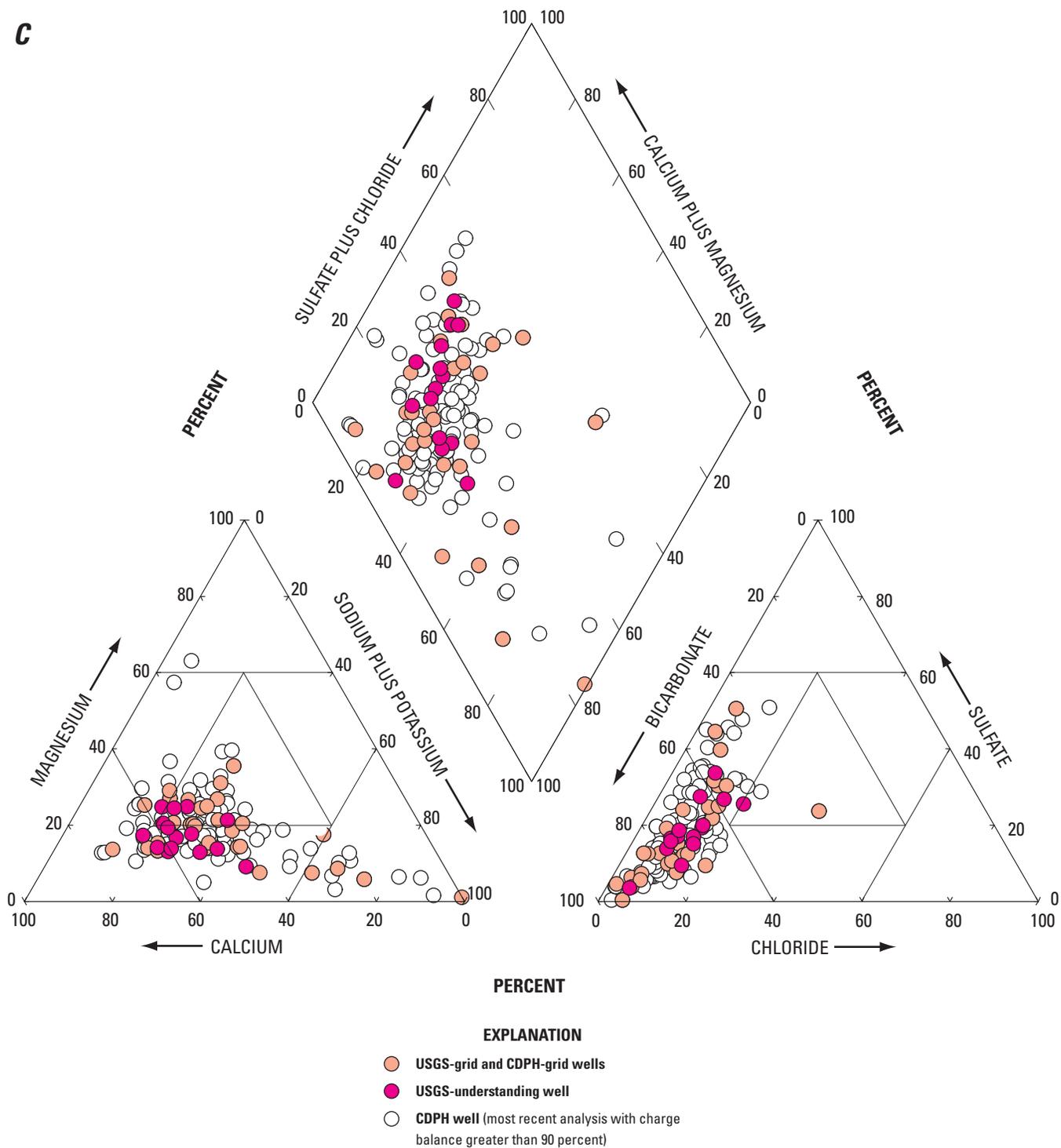


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