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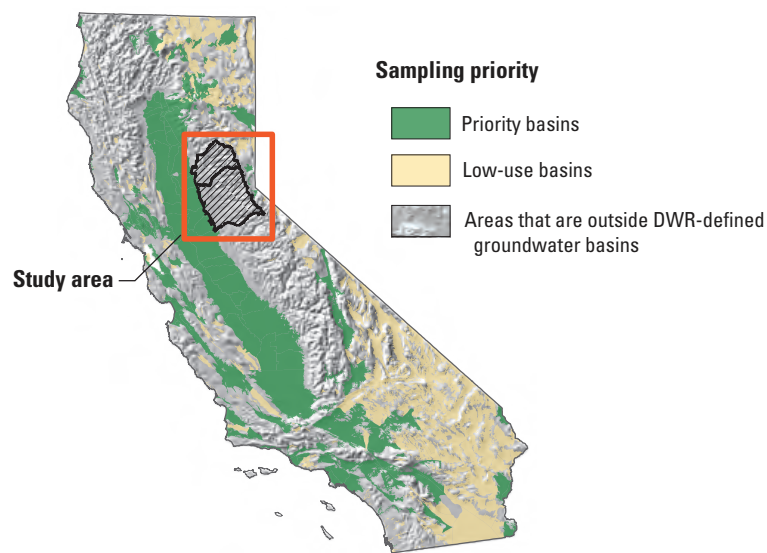
A product of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program

Status and Understanding of Groundwater Quality in the Northern Sierra Nevada Foothills Domestic-Supply Aquifer Study Units, 2015–17: California GAMA Priority Basin Project



Scientific Investigations Report 2021–5019

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



Cover photographs:

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Status and Understanding of Groundwater Quality in the Northern Sierra Nevada Foothills Domestic-Supply Aquifer Study Units, 2015–17: California GAMA Priority Basin Project

By Zeno F. Levy and Miranda S. Fram

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Levy, Z.F., 2020, Potential Explanatory factors for Groundwater Quality in the Northern Sierra Nevada Foothills Domestic-Aquifer Assessment Study Units, 2015–2017: California GAMA Priority Basin Project: U.S. Geological Survey data release, <https://doi.org/10.5066/P9Z30812>.

Levy, Z.F., and Faulkner, K.E., 2019, Dissolved Noble Gas Concentrations and Modeled Recharge Temperatures for Groundwater from Northern Sierra Nevada Foothills Shallow Aquifer Assessment Study Units, 2015–2017: Results from the California GAMA Priority Basin Project: U.S. Geological Survey data release, <https://doi.org/10.5066/P9YETK9P>.

Shelton, J.L., Fram, M.S., Goldrath, D.A., Bennett, G.L., V., and Jasper, M., 2018, Groundwater-quality data in the Mokelumne, Cosumnes, and American River Watersheds Shallow Aquifer Study Unit, 2016–2017: Results from the California GAMA Priority Basin Project: U.S. Geological Survey data release, <https://doi.org/10.5066/F78G8JXP>.

Stork, S.V., McGregor, A.M., Balkan, M., Arroyo-Lopez, J., Borkovich, J.G., Lor, V., Peng, S., and Jasper, M., 2019, Attributed California Water Supply Well Completion Report Data for Selected Areas, Derived from CA WCR OSCWR Data: U.S. Geological Survey data release, <https://doi.org/10.5066/P9R1V41Q>.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Area		
square meter (m ²)	0.0002471	acre
square kilometer (km ²)	247.1	acre
square centimeter (cm ²)	0.001076	square foot (ft ²)
square meter (m ²)	10.76	square foot (ft ²)
square centimeter (cm ²)	0.1550	square inch (in ²)
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
cubic meter (m ³)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)

Multiply	By	To obtain
Volume—Continued		
liter (L)	0.2642	gallon (gal)
cubic meter (m ³)	264.2	gallon (gal)
cubic decimeter (dm ³)	0.2642	gallon (gal)
cubic meter (m ³)	0.0002642	million gallons (Mgal)
cubic centimeter (cm ³)	0.06102	cubic inch (in ³)
liter (L)	61.02	cubic inch (in ³)
cubic meter (m ³)	35.31	cubic foot (ft ³)
cubic meter (m ³)	1.308	cubic yard (yd ³)
cubic meter (m ³)	0.0008107	acre-foot (acre-ft)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

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

Datum

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

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

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

Supplemental Information

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L), micrograms per liter ($\mu\text{g}/\text{L}$), or nanograms per liter (ng/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); 1 nanogram per liter (ng/L) is equivalent to 1 part per trillion (ppt); 1 per mille is equivalent to 1 part per thousand.

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

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

Abbreviations

ACMW	American-Cosumnes-Mokelumne watersheds
AI	aridity index
AL-US	action level (U.S. Environmental Protection Agency)
CDPH	California Department of Public Health
DAA	Domestic-supply Aquifer Assessment
DDW	Division of Drinking Water
<i>d-excess</i>	deuterium excess
DO	dissolved oxygen
DWR	California Department of Water Resources
EC	<i>Escherichia coli</i>
ENT	<i>Enterococci</i>
EPA	U.S. Environmental Protection Agency
GAMA	Groundwater Ambient Monitoring and Assessment program
HAL-US	lifetime health advisory level (U.S. Environmental Protection Agency)
HBSL	health-based screening level (U.S. Geological Survey)
HHBP-US	human-health benchmark for pesticides (U.S. Environmental Protection Agency)
LSI	Langlier saturation index
LUFT	leaking (or formerly leaking) underground fuel tank
MAAT	mean annual air temperature
MAP	mean annual precipitation
MCL-CA	maximum contaminant level (California State Water Resources Control Board)
MCL-US	maximum contaminant level (U.S. Environmental Protection Agency)
MTBE	methyl <i>tert</i> -butyl ether
NAWQA	National Water Quality Assessment (U.S. Geological Survey)
NGRT	noble-gas recharge temperature
NL-CA	notification level (California State Water Resources Control Board)
PBP	Priority Basin Project
PCE	tetrachloroethylene
RC	relative concentration
RL-CA	response level (California State Water Resources Control Board)
RSD5-US	risk-specific dose at risk factor of 10^{-5} (U.S. Environmental Protection Agency)
SI	saturation index
SMCL-CA	secondary maximum contaminant level (California State Water Resources Control Board)

SWRCB	California State Water Resources Control Board
TC	total coliform
TCE	trichloroethylene
THM	trihalomethane
TOP	top of perforated or open interval
TT-CA	treatment technique (California State Water Resources Control Board)
USGS	U.S. Geological Survey
VOC	volatile organic compound
YBW	Yuba-Bear watersheds

Status and Understanding of Groundwater Quality in the Northern Sierra Nevada Foothills Domestic-Supply Aquifer Study Units, 2015–17: California GAMA Priority Basin Project

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Abstract

Groundwater quality in the northern Sierra Nevada foothills region of California was investigated as part of California State Water Resources Control Board (SWRCB) Groundwater Ambient Monitoring Assessment Priority Basin Project (GAMA-PBP). The region was divided into two study units: the Yuba-Bear watersheds (YBW) study unit and the American-Cosumnes-Mokelumne watersheds (ACMW) study unit. The GAMA-PBP made a spatially unbiased assessment of aquifer systems used for domestic drinking-water supply in the study region, which are predominantly composed of fractured, hard-rock aquifers of varying lithology. These assessments characterized the quality of raw groundwater to evaluate ambient conditions in the domestic-supply aquifer and not the quality of treated drinking water.

The study included three components: (1) a *status assessment*, which characterized the quality of groundwater resources used for domestic drinking-water supply in the YBW and ACMW study units; (2) an *understanding assessment*, which evaluated natural and anthropogenic explanatory factors that could potentially affect groundwater quality in the study region; and (3) a *comparative assessment* between the groundwater resources used for domestic and public drinking-water supply in the study region.

The status assessment was based on data collected by the GAMA-PBP from 74 sites in the YBW study unit during 2015–16 and 67 sites in the ACMW study unit from 2016 to 2017. To contextualize water-quality results, concentrations of water-quality constituents in ambient groundwater were compared to regulatory and non-regulatory benchmarks typically used by the State of California and Federal agencies as health-based or aesthetic standards

for public drinking water. The status assessment used a grid-based method to estimate proportions of groundwater resources with concentrations approaching or exceeding benchmark thresholds. This method provides spatially unbiased results and allows inter-comparability with similar groundwater-quality assessments.

Inorganic constituents with health-based benchmarks were present at high relative concentration (RC), meaning they exceeded the benchmark threshold, in 5.4 and 10 percent of domestic-supply aquifer systems in the YBW and ACMW study units, respectively. Inorganic constituents with aesthetic-based benchmarks were detected at high-RCs in 20 and 28 percent of the YBW and ACMW study units, respectively. The inorganic constituents present at high RC were arsenic, barium, boron, molybdenum, strontium, nitrate, adjusted gross-alpha particle activity, chloride, total dissolved solids, specific conductance, iron, manganese, and hardness. Groundwater samples were tested for presence or absence of three microbial indicators (total coliform, *Escherichia coli*, and *Enterococci*). At least one microbial indicator was present in 26 and 28 percent of the YBW and ACMW study units, respectively. At least one organic constituent was detected in 30 and 42 percent of the YBW and ACMW study units, respectively. Organic constituents were not present at high RC, but tetrachloroethene (PCE), trichloroethene (TCE), and toluene were detected in the YBW study unit at moderate RC (between the benchmark concentration and one-tenth of the benchmark concentration). Methyl *tert*-butyl ether (MTBE) and chloroform were present at low RC (less than one-tenth of the benchmark concentration) in the YBW and ACMW study units with detection frequencies greater than 10 percent. Perchlorate, a constituent of special interest, was detected in 31 and 41 percent of the YBW and ACMW study units, respectively, at either low or moderate RCs.

Relations among select water-quality constituents and potential explanatory factors were evaluated using statistical and graphical approaches. Nitrate, microbial indicators, and perchlorate were all correlated to elevation-dependent variables relating to climate, land use, and recharge condition. Isotopic and dissolved noble-gas tracers indicated these water-quality constituents are associated with recharge conditions associated with irrigation during the summer dry-season, which is common in areas of rural-residential or agricultural land uses. Higher concentrations of iron and manganese were primarily associated with anoxic groundwater in aquifers of metasedimentary lithology. Increased hardness was primarily associated with anoxic groundwater in aquifers of mafic-ultramafic or metavolcanics lithologies at lower elevations in the study region in the Melones fault zone. Chloroform and MTBE were associated with shallow groundwater (wells depths less than 130 m) under oxic and anoxic redox conditions, respectively.

The comparative assessment evaluated differences between the aquifer systems used for domestic- and public-supply in study region based on (1) well-construction characteristics, and (2) water quality. Analysis of over 60,000 well-completion reports in the study region showed that although domestic-supply wells span the deepest depth zones in regional aquifers, median depths for public-supply wells were significantly greater than those of domestic-supply wells in both study units. Water-quality data from more than 300 public-supply wells in the study region were assessed using a spatially weighted method for calculation aquifer-scale proportions and compared with the domestic-supply assessment results. Detections of inorganic constituents at high RC and detection frequencies for organic constituents were generally similar between the domestic- and public-supply aquifer systems in both study units, with a few notable exceptions in the ACMW study unit: nitrate was greater for the public- compared to domestic-supply aquifer system and both manganese, hardness, and MTBE were greater in the domestic- compared to public-supply aquifer system. These differences are likely related to contrasting land uses, aquifer lithologies, landscape positions, and depths characterizing domestic- and public-supply wells in the ACMW study unit.

Overall, fewer samples from domestic-supply wells in the northern Sierra Nevada foothills exceeded health-based benchmarks compared to aesthetic-based benchmarks for groundwater quality. Exceedences of health-based benchmarks were primarily caused by nitrate and coliform bacteria, which were associated with recharge from diverted surface water used primarily for irrigation. Exceedences of aesthetic-based benchmarks were primarily caused by iron, manganese, and hardness, which were associated with geologic factors. Regional irrigation practices and aquifer lithology can affect groundwater quality in fractured-rock aquifers in the northern Sierra Nevada foothills used for domestic drinking-water supply.

Introduction

Almost half the residential population of California depends in some part on groundwater for either public or domestic drinking-water supply (Carle, 2016). To assess the quality of ambient groundwater used for drinking-water supply in California and establish a statewide baseline groundwater-monitoring program, the California State Water Resources Control Board (SWRCB), in collaboration with the U.S. Geological Survey (USGS) and Lawrence Livermore National Laboratory, implemented the Groundwater Ambient Monitoring and Assessment (GAMA) program (<http://waterboards.ca.gov/gama/>). The SWRCB first established the GAMA program in 2000 in response to a legislative mandate (State of California, 1999, 2001a).

The statewide GAMA program currently consists of two active projects: (1) the GAMA Groundwater Information System, implemented by the SWRCB (<https://geotracker.waterboards.ca.gov/gama/>), and (2) the GAMA Priority Basin Project (GAMA-PBP), implemented by the USGS (<https://ca.water.usgs.gov/gama/>). The GAMA-PBP was established in response to mandates of the Groundwater Quality Monitoring Act of 2001 “to improve comprehensive groundwater monitoring and increase the availability to the public of information about groundwater contamination” (State of California, 2001b, Sections 10780–10782.3). A monitoring framework was subsequently designed by the USGS in collaboration with the SWRCB to assess groundwater resources used for drinking-water supply throughout California using statistically reliable sampling approaches (Belitz and others, 2003; California State Water Resources Control Board, 2003).

The GAMA-PBP assesses two primary types of groundwater resources: public and domestic drinking-water supplies. The difference between public and domestic water supplies is based on the population served and frequency of use. Public drinking-water systems are defined as providers of water for human consumption through pipes or other constructed conveyances that have 15 or more service connections or regularly serve at least 25 individuals for 60 days or more of the year (State of California, 1995, Section 116275). Public-supply wells, by definition, service larger populations than domestic-supply wells and tend to be drilled deeper into aquifers, have longer screens, and continuously pump for longer time spans (Warner and Ayotte, 2014). The assumption that public-supply wells are open to aquifers at deeper depths than domestic-supply wells in California has been mostly based on analyses of alluvial groundwater basins (Buwow and others, 2013; Voss and others, 2019) and it is unclear as to whether this distinction is also applicable in highland areas, where wells are drilled into fractured bedrock.

The first phase of the GAMA-PBP characterized groundwater resources in California used for public drinking-water supply (Belitz and others, 2003). From 2004 through 2012, the GAMA-PBP assessed groundwater quality

in 87 study areas that were delineated on the basis of common physiographic characteristics and geographically grouped into 35 study units representing more than 95 percent of the groundwater resources used for public supply statewide (Belitz and others, 2015). Groundwater basins composed of unconsolidated sediments and highland areas outside the basins were prioritized for sampling on the basis of well distribution, population served, and vulnerability to contamination (Belitz and others, 2003). Prioritization of study areas and selection of sampling sites were accomplished using the California State database of public-supply wells, which has been maintained by the SWRCB Division of Drinking Water (DDW) since 2014, when DDW assumed regulatory authority over public drinking-water systems in California from the California Department of Public Health (CDPH).

The second phase of the GAMA-PBP has focused on characterizing the quality of groundwater resources used for domestic drinking-water supply (U.S. Geological Survey, 2018). Approximately two million California residents rely on privately owned domestic groundwater wells or small community systems serving fewer than 25 people for their drinking water (California State Water Resources Control Board, 2015). Because drinking water from domestic-supply wells is not regulated under the California Safe Drinking Water Act, which only applies to public drinking-water systems, water-quality monitoring is not required by homeowners for their own private wells, and comparatively little is known regarding the status and vulnerability of domestic groundwater resources statewide. It is a high priority for the SWRCB to understand where communities reliant on domestic-supply wells might be vulnerable to water-quality degradation, because these communities may need to be connected to public-supply systems in the future (California State Water Resources Control Board, 2019a). As an initial step to address this knowledge gap, the SWRCB implemented the GAMA Domestic Well Project between 2002 and 2011 and chose wells for sampling in six counties on a voluntary, first-come-first-served basis (California State Water Resources Control Board, 2005, 2010).

In 2012, the GAMA-PBP began a “domestic-supply aquifer assessment” (DAA) to apply the statistical framework established during the first phase of public-supply aquifer studies to systematically characterize the quality of groundwater resources used for domestic or small-system drinking-water supplies statewide (U.S. Geological Survey, 2018). This phase of the GAMA-PBP necessitated another method of study-area prioritization and site selection because there is no centralized statewide database for domestic well locations. To this end, U.S. Census data were utilized along with water-use and well-location information from a database of well-completion reports maintained by the California Department of Water Resources (DWR). From this analysis, 463 alluvial groundwater basins (previously delineated by California Department of Water Resources, 2003) and 543 highland study areas outside the basins were grouped and prioritized for sampling on the basis of the number and density of households with domestic wells in a given area

(Johnson and Belitz, 2015). Study areas were also spatially grouped to facilitate comparison with prior public-supply aquifer assessments.

For the Sierra Nevada hydrogeologic province of California, defined by Belitz and others (2003), domestic-supply aquifer assessments were completed during 2015–17 in two northern Sierra Nevada foothills region study units: the Yuba-Bear watersheds (YBW) study unit and the American-Cosumnes-Mokelumne watersheds (ACMW) study unit (fig. 1). These two study units contain some of the densest areas of domestic-supply wells in California because of the high degree of dispersed rural development throughout the northern Sierra Nevada foothills and were therefore included in the group of highest priority DAA study units (Johnson and Belitz, 2015). Domestic-supply wells in this region are primarily finished in hard-rock aquifers of varying lithologies.

Sampling in the northern Sierra Nevada foothills was also prioritized to assess the effects of drought on groundwater availability and quality in the region. During 2012–16, California experienced one of its most severe and extended droughts in modern history. A drought-response vulnerability assessment by the DWR found that 77 percent of wells deepened in the State from before through the onset of drought during 2010–14 were domestic wells in fractured bedrock aquifers concentrated in the Sierra Nevada foothills of northern California (California Department of Water Resources, 2014). Sampling of the YBW and ACMW study units during 2015–16 and 2016–17, respectively, was therefore intended to provide assessments of these domestic-supply aquifers following a period of intense hydrologic stress (Levy and others, 2020).

The GAMA-PBP was designed to provide three types of groundwater resource assessments: (1) a *status assessment* that synoptically characterizes the present-day quality of a defined groundwater resource, (2) an *understanding assessment* of the natural and anthropogenic factors that affect groundwater quality, and (3) a *trends assessment* of changes in groundwater quality through time (Belitz and others, 2003; Kent and Landon, 2016). The GAMA-PBP study framework was modeled after the USGS National Water Quality Assessment (NAWQA) Project (Hirsch and others, 1988). Sampling protocols were designed to obtain representative samples of aquifer water. Therefore, groundwater-quality results are indicative of the ambient resource and not finished drinking water, which is often treated for constituents such as bacteria, blended with waters from different sources, or altered by interactions with conveyance systems such as corrosion from lead pipes (Belitz and others, 2003, 2016). The assessments provided by the GAMA-PBP are specific to the depth zones in aquifers that provide drinking-water resources for public or domestic supply. Although domestic-supply wells typically draw from shallower parts of aquifers than do public-supply wells, this is not always the case, particularly in hard rock aquifers where well-production rates are primarily a function of fracture abundance and orientation as opposed to borehole or well screen depths (Page and others, 1984).



Figure 1. Hydrogeologic provinces of California and the location of northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Purpose and Scope

The purposes of this report are to provide (1) descriptions of the hydrogeologic setting of the northern Sierra Nevada foothills DAA study units (YBW and ACMW), (2) a *status assessment* of groundwater resources used for domestic drinking-water supply for both study units, (3) an *understanding assessment* of the natural and anthropogenic factors that affect the quality of groundwater used for domestic supply in the study region, and (4) a *comparative assessment* of the groundwater resources used for domestic and public supply. Temporal trends in groundwater quality are not assessed. This report follows a format similar to previous GAMA-PBP status and understanding assessments available online from the USGS (https://ca.water.usgs.gov/gama/includes/GAMA_publications.html) and the SWRCB (<http://www.swrcb.ca.gov/gama/>). The previous DAA reports also made comparative assessments between groundwater resources used for domestic and public drinking-water supply (Bennett, 2018; Burton and Wright, 2018). The three primary assessment approaches are summarized in the next subsection.

Assessment Approaches Used for this Study

The status assessment was designed to provide a statistically representative characterization of groundwater resources in the study unit during the time of sampling. To prevent skewing assessment results to areas of greater well density, a stratified random sampling design was used to effectively characterize the entire area of the groundwater resource within the study units. The stratified design involved dividing study units into equal-area grid cells, randomly selecting one groundwater well in each cell (herein, “grid site”) to sample, and using the data obtained from those samples to calculate “aquifer-scale proportions” for different water-quality constituents. Aquifer-scale proportion refers to the areal proportion of the groundwater resource having a defined level of quality (Belitz and others, 2010). This method provides a spatially unbiased assessment of groundwater resources for a given study area and allows inter-comparability of GAMA-PBP assessments with other similar groundwater studies over a wide range of spatial scales at different sampling resolutions (Belitz and others, 2015). A total of 74 grid sites were used to assess the groundwater resource used for domestic supply in the YBW study unit during 2015–16 (Jasper and others, 2017). A total of 67 grid sites were used to make a similar assessment of the ACMW study unit during 2016–17 (Shelton and others, 2018).

To define specific classifications for groundwater quality for which to calculate aquifer-scale proportions and contextualize assessment results for a wide variety of organic and inorganic constituents, water-quality measurements were compared to State and Federal benchmarks (both regulatory and non-regulatory). These benchmarks are typically used to evaluate the quality of treated drinking water delivered by public-supply systems in and outside of California. Although domestic groundwater quality is not regulated under the California Safe Drinking Water Act, the benchmarks provide useful metrics for assessing domestic drinking-water resources because they were developed to meet broad health- and aesthetic-based standards for human consumption (Toccalino and Hopple, 2010). Groundwater quality is interpreted in terms of relative concentration (RC), which is the ratio of the measured concentration of a given water-quality constituent to its established benchmark level.

The understanding assessment evaluates natural and anthropogenic factors that could affect groundwater quality for selected water-quality constituents in the northern Sierra Nevada foothills study region. For this assessment, groundwater-quality data were combined for all grid sites from both study units (plus one additional “understanding” well in the ACMW study unit) and evaluated with respect to potential explanatory factors using graphical and statistical methods. These explanatory factors included land use characterized by percentage urban, natural, or agricultural land use; septic tank density; and leaking or formerly leaking underground fuel tank (LUFT) density; hydrologic conditions characterized by aridity index (AI), elevation of land surface, well depth, depth to top of perforated or open interval (TOP); geochemical conditions of pH and dissolved oxygen (DO); groundwater age based on analyses of tritium and carbon-14 activities; aquifer lithology; study unit or area; and recharge conditions based on analyses of stable isotopes of water and dissolved noble gases.

The comparative assessment of domestic- and public-supply aquifer systems includes (1) a well-construction comparison and (2) a water-quality comparison. The well-construction comparison is a broad evaluation of aquifer-depth zones used for public- and domestic-supply in the study region using over 60,000 records from the DWR well-completion report database (Stork and others, 2019). The water-quality comparison is a more focused evaluation of differences between the results of the domestic-supply status assessment and regional data for public-supply wells sourced from both the GAMA-PBP and the SWRCB-DDW. The water-quality comparison in this report differs from those of previous DAA studies that only used data from prior GAMA-PBP assessments to contrast the two resources (Bennett, 2018; Burton and Wright, 2018) because prior GAMA-PBP assessments of public-supply wells in the Sierra Nevada did not provide adequate spatial coverage to

characterize the northern Sierra Nevada foothills study units (Fram and Belitz, 2012, 2014). Water-quality data from the SWRCB-DDW's regulatory-monitoring database (California State Water Resources Control Board, 2019b) were therefore used to expand the otherwise limited coverage of GAMA-PBP data for the study region. Aquifer-scale proportions for water-quality data from the public-supply wells were calculated using the spatially weighted approach described by Belitz and others (2010) and compared to grid-based estimates and confidence intervals used to evaluate water quality in the status assessment on the study-unit scale.

Definitions and Locations of Study Units

The YBW study unit covers an area of 4,426 kilometers squared (km²) and was divided into Yuba (Y) and Bear (B) study areas (fig. 2). Study areas were defined as the regions where the upper Yuba and upper Bear River watersheds overlap with the Sierra Nevada hydrogeologic province as defined by Belitz and others (2003). The Yuba and Bear Rivers

flow into the Sacramento Valley, where they meet the Feather River (not shown on map), which is the largest tributary of the Sacramento River draining the Sierra Nevada. The YBW study unit contains parts of Nevada, Yuba, Sierra, and Placer Counties in California (Jasper and others, 2017).

The ACMW study unit covers an area of 9,095 km² and is divided into North American (NA), South American (SA), Cosumnes (C), and Mokelumne (M) study areas (fig. 2). Study areas were defined as the regions where the North Fork American, South Fork American, upper Cosumnes, and upper Mokelumne River watersheds overlap with the Sierra Nevada hydrogeologic province as defined by Belitz and others (2003). The American River joins the Sacramento River in the Sacramento metropolitan area. The southern part of the study unit drains the Cosumnes and Mokelumne River watersheds, which join the San Joaquin River just upstream from its terminus in the Sacramento–San Joaquin River Delta. The ACMW study unit contains parts of Placer, El Dorado, Amador, and Calaveras Counties in California (Shelton and others, 2018).

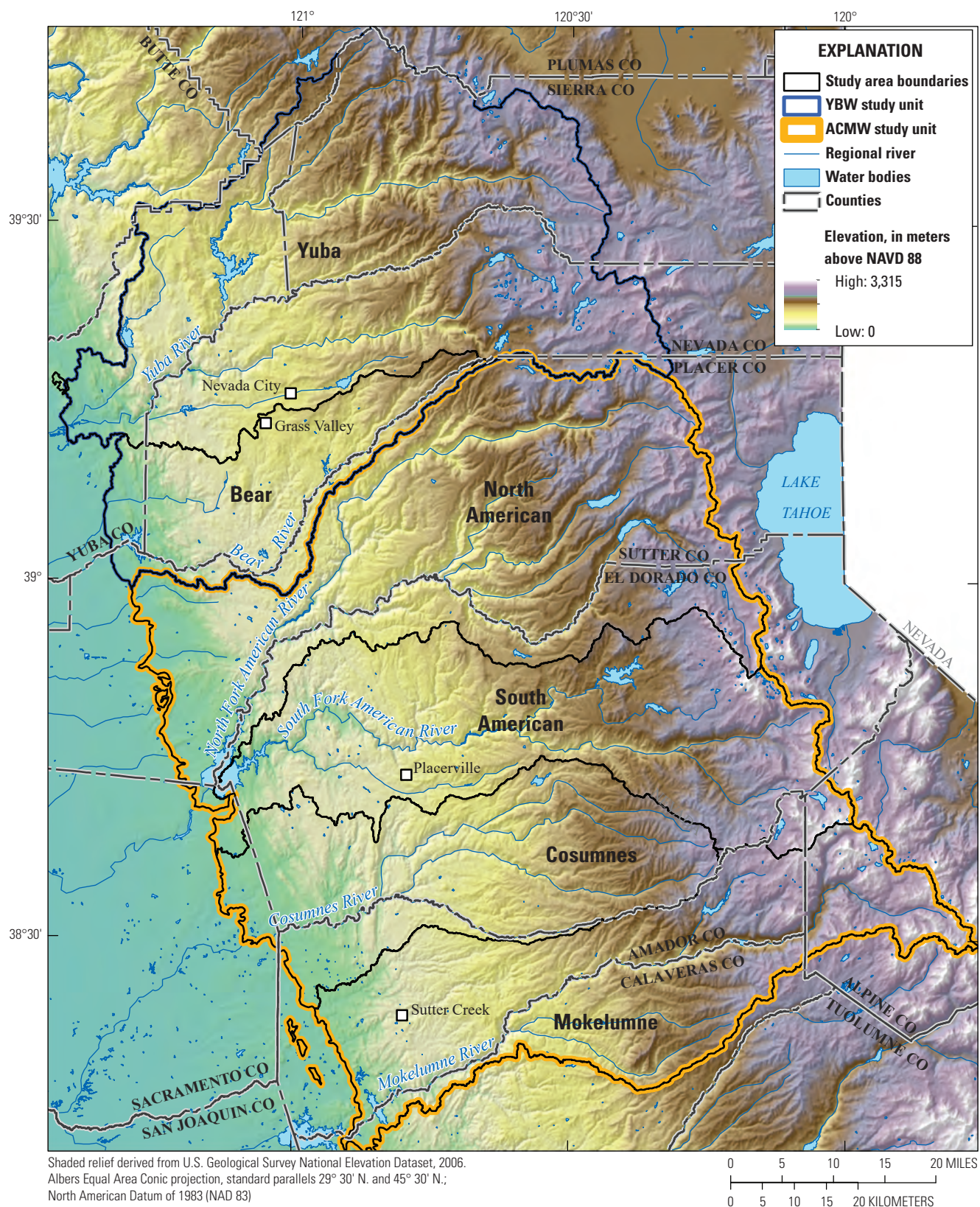


Figure 2. Location and boundaries of Yuba, Bear, North American, South American, Cosumnes, and Mokelumne study areas in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. (ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds).

Hydrogeologic Setting

The Sierra Nevada, a mountain range that extends for more than 600 kilometers (km), is one of California's largest hydrogeologic provinces and is bounded by the Central Valley and Basin and Range provinces to the west and east, respectively (fig. 1). The Sierra Nevada crest decreases in elevation from southern peaks at around 4,000 meters (m) to northern peaks by Lake Tahoe at around 3,200 m. Tilting of the Sierra Nevada fault block during tectonic uplift provided the range with a steep and rugged eastern escarpment and gently inclined western slope that grades into extensive "foothills," which are generally considered to be transitional areas between high-elevation, mountainous terrain and adjacent plains of low relief (Clark, 1960). For the purposes of this report, the northern Sierra Nevada foothills region is defined as the western flank of the Sierra Nevada province north of the 38° N parallel; more specifically, it extends altitudinally from the uppermost elevations of its westward draining watersheds (about 2,000 m) to the eastern extent of Quaternary sediments defining the Central Valley province (about 40 m). The northern Sierra Nevada foothills drain to major tributaries flowing into the Sacramento–San Joaquin River Delta, which are diverted to supply drinking and irrigation water both locally and statewide (Carle, 2016).

The study region has a Mediterranean climate characterized by warm, dry summers and cool, wet winters. The YBW study unit has a mean annual air temperature (MAAT) of 12 degrees Celsius (°C) and mean annual precipitation (MAP) of 1,500 millimeters (mm), and the ACMW study unit has a MAAT of 12 °C and MAP of 1,200 mm (1981–2010 climate normals; PRISM Climate Group, 2015). There is a steep climate-elevation gradient in the study region, such that average MAAT and MAP decrease and increase, respectively, from the Central Valley boundary (16 °C and 150 mm) to upper watershed divides (4 °C and 1,500 mm). Precipitation primarily falls as rain throughout the study region except at elevations above about 1,500 m, where snow falls and accumulates during the winter (Hatchett and others, 2017). Nearly 85 percent of total annual precipitation falls during the "wet season" (November–April). Streamflow is driven by winter rain followed by high-elevation snowmelt later in spring, typically between mid-April and June, and streamflow is low during the "dry season" (June–September), when there is virtually no precipitation (Peterson and others, 2008).

The primary geologic feature of the Sierra Nevada range is the Sierra Nevada batholith, a massive complex of granitic plutons that intruded the North American Plate in the Mesozoic Era during subduction of the Farallon Plate between 80 and 140 mega-annum (Ma, million years ago; Kistler and others, 1971). The northern Sierra Nevada foothills are part of the Western Metamorphic Belt of the Sierra Nevada, a deformed package of metasedimentary and metavolcanic rocks

that accreted onto the western margin of the North American Plate from Paleozoic to Jurassic time during subduction of the Farallon Plate (Day and others, 1985).

The bedrock geology of the study region is dominated by extremely complex assemblages of metavolcanic and metasedimentary rocks, including well-preserved Mesozoic ophiolite sequences of the Smartville complex (after Day and others, 1985) to the north, intruded by granitic plutons (fig. 3A). Plutonic mafic and ultramafic rocks also formed during the Mesozoic Era are mostly elongate bodies within and adjacent to major fault zones and in some areas are highly serpentized (Clark, 1960). Eocene auriferous (gold bearing) sediments and Miocene–Pliocene volcanic deposits cap the ridge tops in upper elevations of the study watersheds. Quaternary sediments deposited during multiple glacial advances in the Pleistocene are present on the eastern flank of the study region (Saucedo and Wagner, 1992).

The "foothills fault system" is characterized by northwest–southeast trending folds and steeply dipping faults (Clark, 1960). The Melones fault zone is a major structural feature that likely demarcates the Mesozoic subduction plate boundary and runs roughly perpendicular to the regional topographic slope through the lower reaches of the study watersheds (fig. 3A; Clark, 1960; Böhlke and Kistler, 1986). Upwelling of deep, saline groundwater along structural features of the Melones fault zone in areas south of the study region has been hypothesized (Mack and Ferrell, 1979; Mack and Schmidt, 1981). Gold-bearing quartz veins of the Mother Lode deposit present along the Melones fault zone were heavily mined during the California Gold Rush of the mid-to-late 1800s (Dodge and Loyd, 1984).

Land use in the northern foothills is predominantly natural (fig. 3B); lower elevation grasslands and oak woodlands transition to conifer forests and sub-alpine meadows in the upper reaches of study watersheds. Approximately 50 percent of the area is public land, including U.S. National Forests. Only a small percentage (about 2 percent) of the total area is used for commercial agriculture, which is mostly limited to lower elevations (fig. 3B; Cosumnes, American, Bear, Yuba Integrated Regional Water Management Group, 2014). Forage pasture managed for cattle grazing is not included in this estimate, however, and can constitute up to 70 percent of the land irrigated by surface-water diversions in parts of the study region (Brown and Caldwell, 2016). A much larger extent of the land within the study area is managed and irrigated than is implied by estimates based on commercial agriculture alone, but the gross acreage and locations of forage pasture are uncertain.

Urban land use constitutes less than 10 percent of the total area and is concentrated at lower elevations in the study region and along major transportation corridors, such as Interstate 80 and U.S. Highway 50 (fig. 3B). Traditional land uses in the region, such as mining, forestry, grazing, and agriculture, have been largely overtaken by rural residential

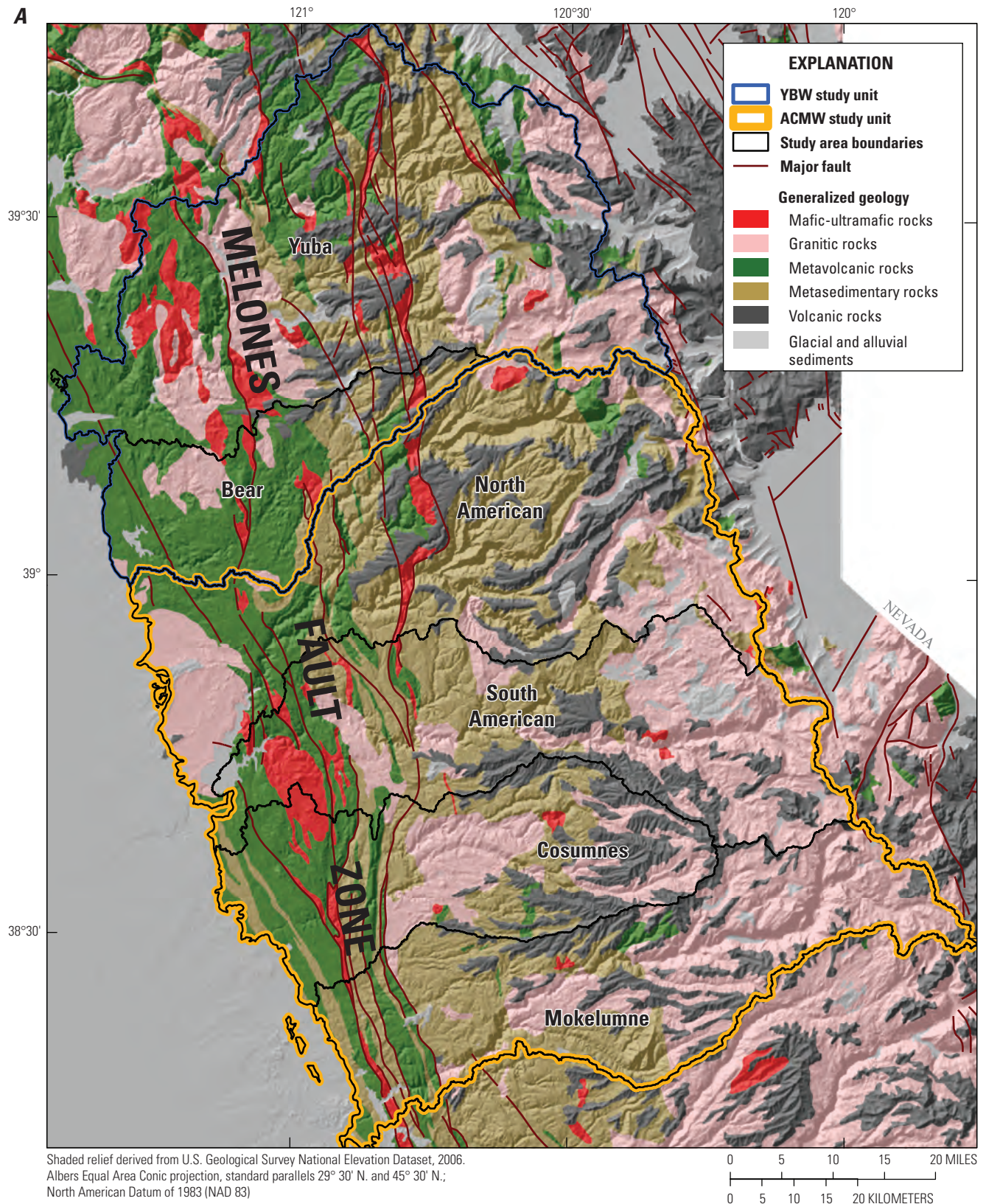


Figure 3. Generalized representations of the northern Sierra Nevada foothills domestic-supply aquifer assessment study units (ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds), 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, aquifer lithology adapted from Saucedo and others (2000); *B*, land use adapted from Jin and others (2013).

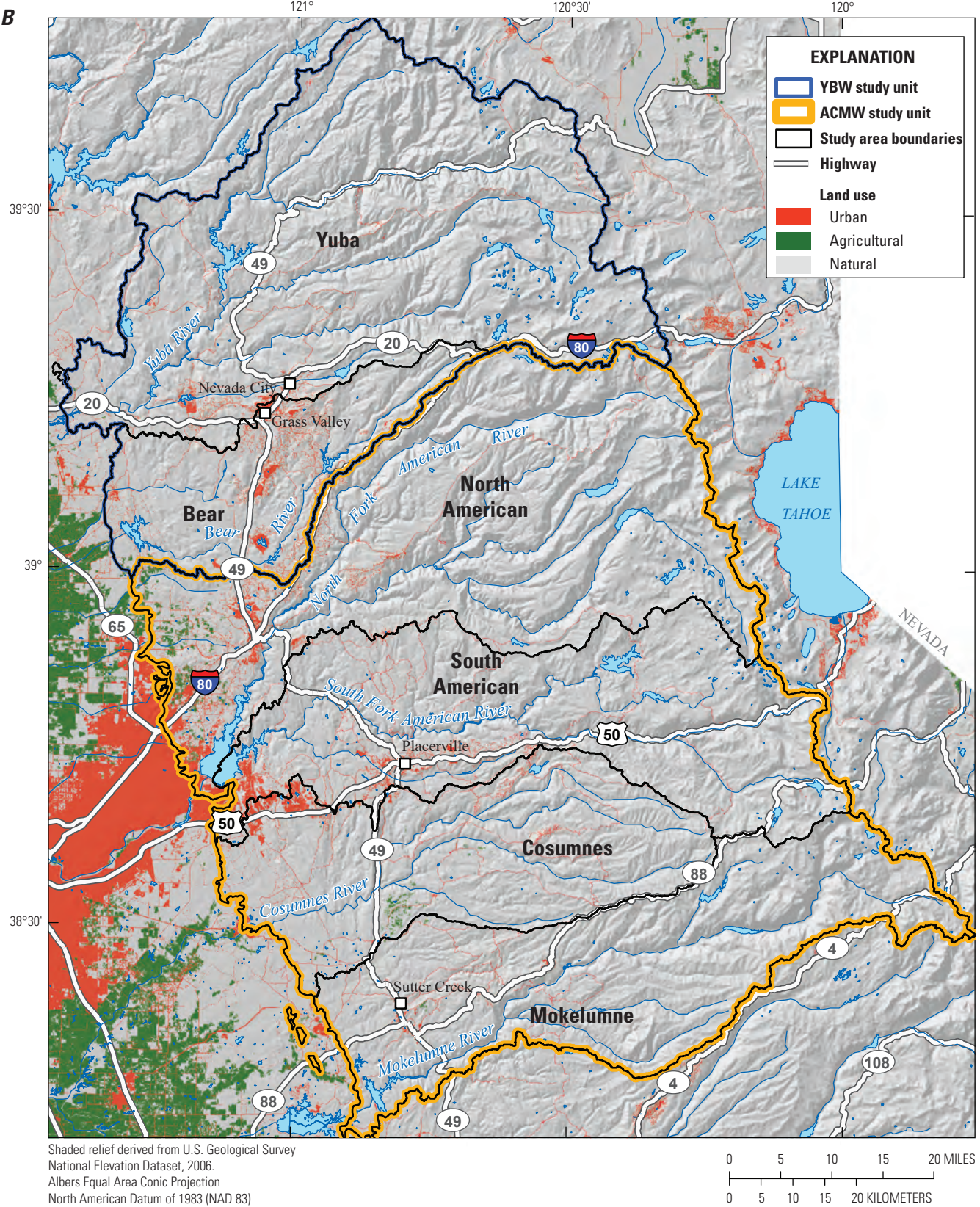


Figure 3.—Continued

development (Walker and others, 2003). This land-use trend is reflected by substantial increases to the unincorporated (rural) population over the past several decades, which grew by 136–485 percent in Nevada, Placer, El Dorado, Amador, and Calaveras Counties between 1970 and 2010 (California Department of Finance, <http://www.dof.ca.gov/>; fig. 4.4). This trend is likely to continue; an overall population increase of 85 percent is projected for the greater Sierra Nevada foothills region between 2010 and 2050 (Cosumnes, American, Bear, Yuba Integrated Regional Water Management Group, 2014).

Surface-water systems in the northern Sierra Nevada foothills have been considerably altered by humans. Hydraulic mining of Eocene gravel exposures during and after the California Gold Rush mobilized more than a half-billion cubic meters of sediment in the Yuba and Bear River watersheds alone, much of it contaminated with mercury used in the gold extraction process (Gilbert, 1917; James, 1989). In subsequent years, extensive water-control infrastructure was developed in the region to control sediment transport, generate hydropower, and supply river water for irrigation and public drinking-water supply. The surface-water distribution infrastructure in the northern foothills comprises more than 1,270 km of canals, 147 dams, 36 powerhouses, and 19 tunnels (Cosumnes, American, Bear, Yuba Integrated Regional Water Management Group, 2014). The Cosumnes River is one of the few California rivers without a major dam, but water is still diverted from the Cosumnes River for local use in the foothills. Numerous water districts in low-elevation areas throughout the study region maintain complex networks of mostly unlined canals and ditches to provide water to local consumers (fig. 5). The largest purveyors of surface-water supply in the study region are the El Dorado Irrigation District, the Georgetown Divide Public Utility District, the Nevada Irrigation District, and the Placer County Water Agency, which collectively distribute more than 0.93 cubic kilometers of water (750,000 acre-feet) per year to lower areas in study

watersheds for public drinking-water supply and irrigation (Cosumnes, American, Bear, Yuba Integrated Regional Water Management Group, 2014). This “re-plumbing” of the natural hydrologic system can increase groundwater recharge in water districts at low elevations, which receive less natural rainfall than higher elevation areas of the study region (Levy and others, 2020).

Groundwater is an important source of drinking water in the study region, especially for rural households not connected to public-water systems. Only about three percent of the Sierra Nevada province consists of DWR-defined groundwater basins, outside of which groundwater wells are drilled directly into hard rock aquifers of mostly granitic and metamorphic lithologies (Fram and Belitz, 2012, 2014). These rock types have extremely low permeability, except where fractured, and yields from hard-rock wells are extremely dependent on fracture density and orientation. Additionally, fracture permeability tends to decrease with depth as a result of increased lithostatic pressure (Ingebritsen and Sanford, 1998). In the northern Sierra Nevada foothills, water-bearing fractures in bedrock tend to be most abundant up to depths of 60 m and predominantly trend to the northwest and southwest (Page and others, 1984).

Depths of domestic-supply wells in hard-rock aquifers have been increasing through time in the study region, however. Median annual driller’s log depths for domestic-supply wells finished in hard-rock aquifers nearly quadrupled between 1964 and 2014 in the study region (fig. 4B; Stork and others, 2019). Rural population growth can put more demand on local hard-rock aquifers, which in turn can decrease water-table elevations and thus increase the depth to which wells need to be drilled to intersect productive bedrock fractures. Increases in well-completion depths through time have been observed in areas where groundwater resources have been depleted by overpumping in the United States (Perrone and Jasechko, 2019).

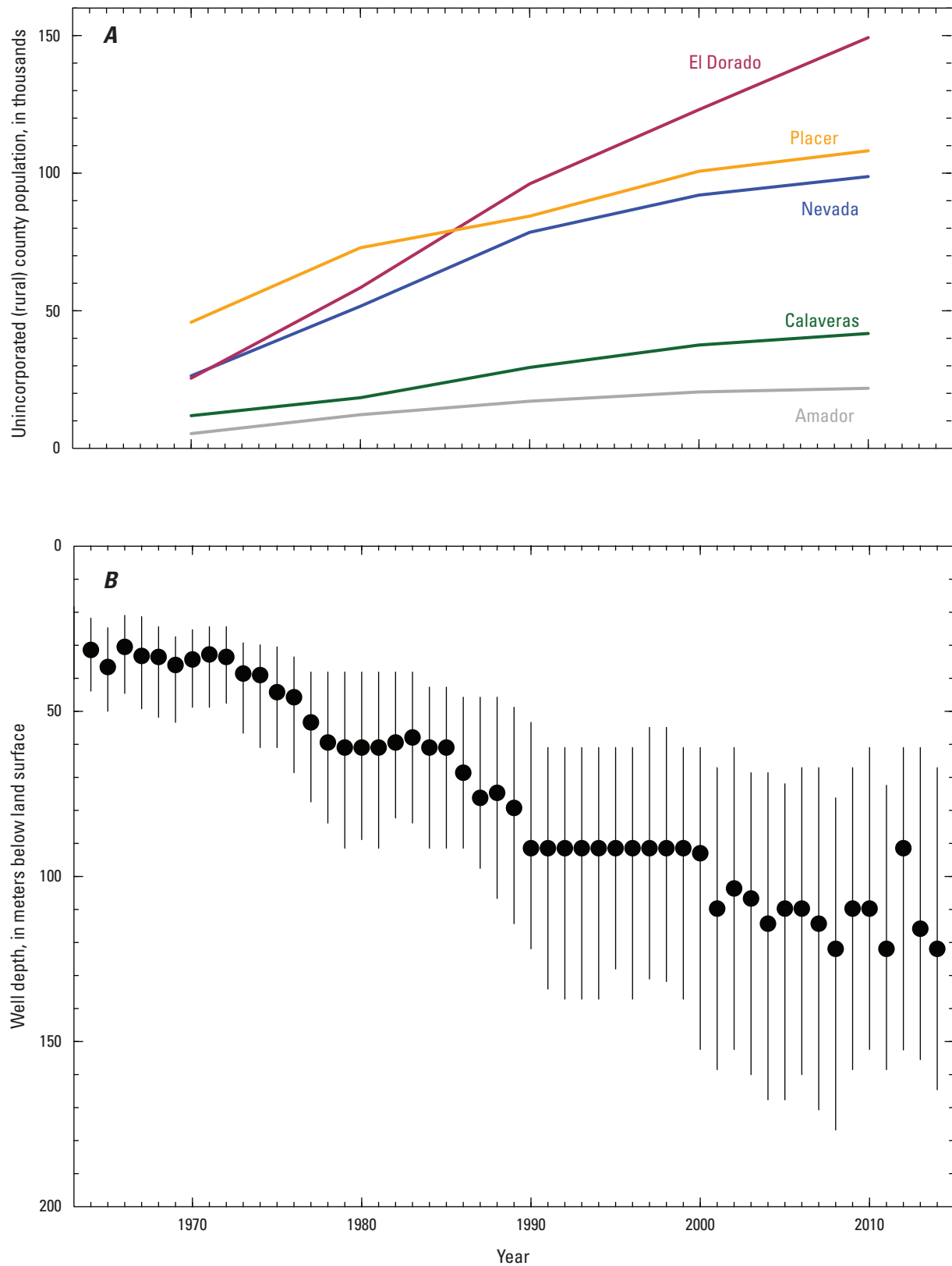


Figure 4. Time series from 1970 to 2010 of *A*, unincorporated (rural) populations of Nevada, Placer, El Dorado, Calaveras, and Amador Counties (California Department of Finance, <http://www.dof.ca.gov/>); *B*, well-completion depths in the study region binned by year; points represent the median of annual data and whiskers span the interquartile range (Stork and others, 2019).

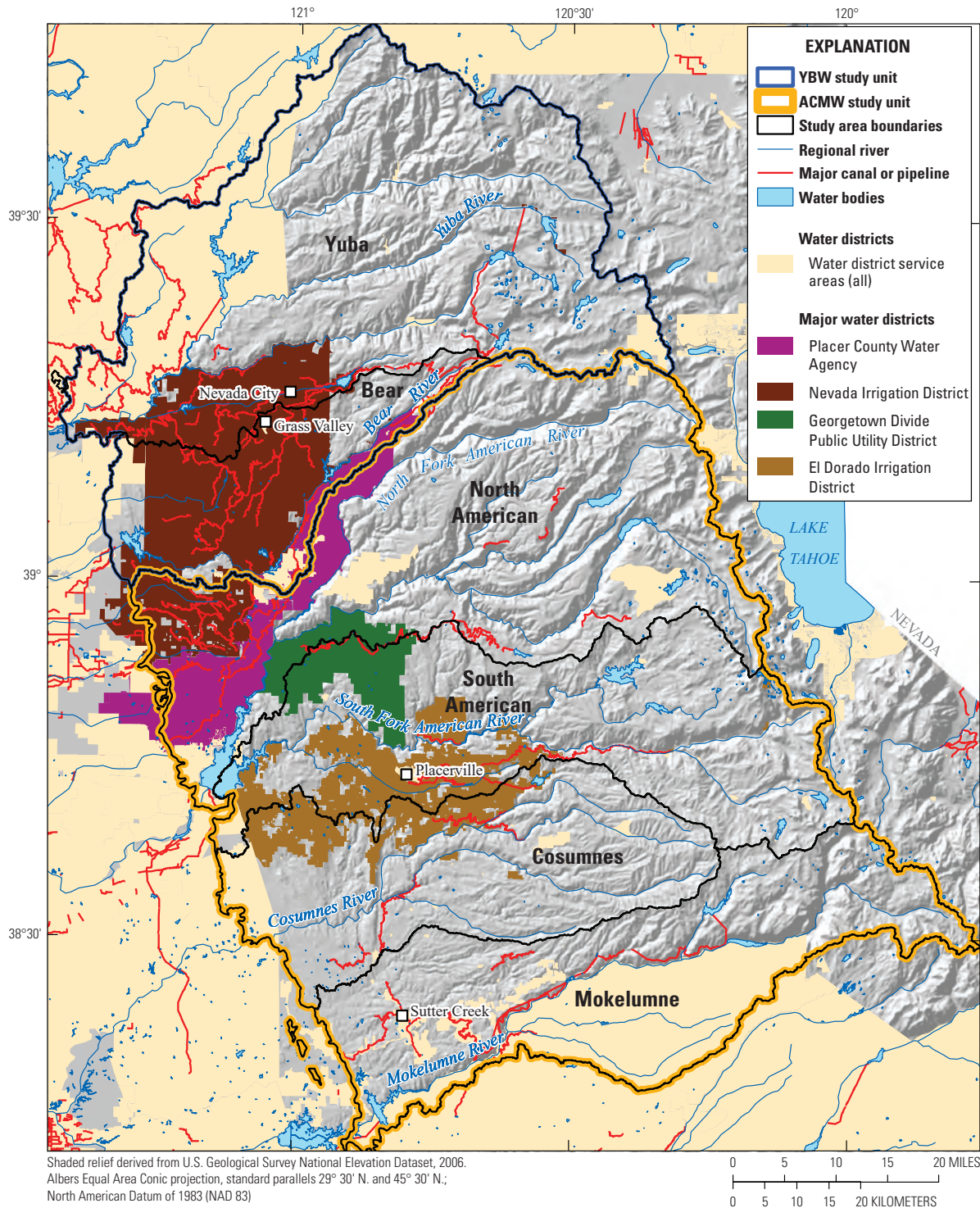


Figure 5. Locations of water districts and major infrastructure for surface-water conveyance in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project (California Department of Water Resources, <https://atlas-dwr.opendata.arcgis.com/>; U.S. Geological Survey, <https://www.usgs.gov/core-science-systems/ngp/national-hydrography>). (ACMW, American-Cosumnes- Mokelumne watersheds; YBW, Yuba-Bear watersheds).

Methods

This section describes methods used for the status and understanding assessments of groundwater resources used for domestic drinking-water supply in the YBW and ACMW study units. Methods used for the comparative assessment of domestic- and public-aquifer systems in the YBW and ACMW study units are also detailed. The methods used to compile data for potential explanatory factors and corresponding data sources are described in appendix 1 and the associated data release of Levy (2020). Methods used to collect and analyze groundwater samples and associated quality-assurance protocols are reported by Jasper and others (2017) for the YBW study unit and Shelton and others (2018) for the ACMW study unit.

Status Assessment

The status assessment was designed to quantify the quality of groundwater used for domestic drinking-water supply in the YBW and ACMW study units using aquifer-scale proportions. This section explains the methods used for (1) defining groundwater quality using established benchmarks, (2) assembling the datasets used for the assessments, (3) selecting constituents for evaluation in the assessments, and (4) calculating aquifer-scale proportions.

Groundwater Quality Defined as Relative Concentrations

In this study, groundwater-quality data were contextualized using relative concentrations (RCs), which are defined as the ratio of a measured constituent's concentration in groundwater to a regulatory or non-regulatory water-quality benchmark. An RC value less than 1.0 indicates a groundwater-quality constituent is less than its benchmark concentration, and an RC value greater than 1.0 indicates the constituent exceeds its benchmark concentration in the sample. Water-quality constituents without benchmarks were not included in the status assessment. Using RCs allows evaluation and inter-comparison of a wide array of organic and inorganic constituents at concentrations that often range several orders of magnitude (Toccalino and others, 2004; Toccalino and Norman, 2006; Rowe and others, 2007).

Regulatory and non-regulatory benchmarks are typically used to evaluate treated drinking water distributed by public-supply systems. Although the State of California does not regulate water quality from domestic wells under the Safe Drinking Water Act of 1974 (amended 1986, 1996), the use of water-quality benchmarks developed to meet the health- and aesthetic-based standards for public-supply sources provides context to evaluate domestic-supply sources for the purposes of this study. The water-quality constituents measured for this study were compared to benchmarks established by the

U.S. Environmental Protection Agency (EPA), California State Water Resources Control Board Division of Drinking Water (SWRCB-DDW), and USGS. For constituents with multiple benchmarks, a primary benchmark was selected in the following order of priority:

1. Regulatory, human-health based levels set by the SWRCB-DDW and EPA (in order of priority): SWRCB-DDW and EPA maximum contaminant levels (MCL-CA and MCL-US, respectively), whichever is lower; U.S. Environmental Protection Agency (EPA) action levels (AL-US); and SWRCB-DDW treatment technique levels (TT-CA; California State Water Resources Control Board, 2019c; U.S. Environmental Protection Agency, 2018).
2. Non-regulatory, aesthetic-based levels set by the SWRCB-DDW: secondary maximum contaminant levels (SMCL-CA; California State Water Resources Control Board, 2019c). Chloride, sulfate, and total dissolved solids (TDS) have recommended and upper SMCL-CA levels, and the upper SMCL-CA values are used as benchmarks for the purposes of this study.
3. Non-regulatory, human-health based levels set by the USGS, EPA, and SWRCB-DDW (in order of priority): EPA lifetime health advisory levels (HAL-US) or SWRCB-DDW response levels (RL-CA), whichever is lower; EPA risk-specific dose for a 1:100,000 risk level (RSD5-US; note, this is the EPA 10^4 Cancer Risk divided by 10); EPA human-health benchmarks for pesticides (HHBP-US); and USGS health-based screening levels (HBSL; Norman and others, 2018; California State Water Resources Control Board, 2019d; U.S. Environmental Protection Agency, 2018, 2019). The HHBP-US and HBSL benchmarks may have both cancer and non-cancer thresholds, and in each case, the lower of the two is used when applicable.

Water hardness (the sum of calcium and magnesium concentrations expressed as milligrams per liter, or mg/L, as calcium carbonate) does not have an official State or Federal benchmark concentration. For the purposes of this study, the level at which a water is generally considered to be “very hard” (180 mg/L; Briggs and Ficke, 1977) was used as a purely “aesthetic” benchmark. Although hardness has an aesthetic effect on water quality, similar to other constituents in the SMCL class including chloride or TDS, it does not have a formal SMCL and was excluded from the calculations of aquifer-scale proportions for the aggregate SMCL class of constituents.

The RCs were classified as low, moderate, or high for calculation of aquifer-scale proportions. Values of RC greater than 1.0 were defined as “high” for all constituents. For inorganic constituents (trace elements, nutrients, radioactive constituents, and inorganic constituents with SMCLs), RC values less than or equal to 1.0 and greater than 0.5 were defined as “moderate,” and RC values less than or equal to

0.5 were defined as “low.” The low-to-moderate RC boundary for hardness was set to 120 mg/L so that concentrations less than this threshold, which are typically considered to be characteristic of “moderately hard” or “soft” water (Briggs and Ficke, 1977), would be considered to have low-RC values.

For organic and special-interest constituents, RC values less than or equal to 1.0 and greater than 0.1 were defined as moderate, and RC values less than or equal to 0.1 were defined as low. Although the high-RC classification indicates concentrations in excess of a benchmark standard for all water-quality constituents, the moderate-RC classification can indicate groundwater that could be vulnerable to developing concentrations in excess of benchmark levels in the future and can be used as an early indicator of potential groundwater contamination. The threshold between low- and moderate-RC is less for organic than for inorganic constituents because organic constituents are unnatural and typically not present in groundwater at high RC. Extending the moderate-RC range to a lower threshold, therefore, effectively draws attention to areas where there has been anthropogenic contamination. Because many inorganic constituents can be present naturally in groundwater systems at RC levels greater than 0.1, an elevated RC threshold of 0.5 was set to focus on inorganic constituents at levels of more immediate concern (Fram and Belitz, 2014).

The “special interest” class of constituents in GAMA-PBP studies has historically included constituents that the State of California was actively considering for an MCL-CA at the time of study or those that do not directly correspond to the other constituent classes. Perchlorate is a trace inorganic compound, and although it does have an MCL-CA, it is typically detected in groundwater at much lower concentrations and with less frequency than many of the inorganic constituents in the trace-element class. Perchlorate, therefore, is considered as a constituent of special interest for the purposes of this study and is evaluated in a manner similar to the organic constituents. This maintains consistency with the evaluation framework for perchlorate in numerous prior GAMA-PBP studies (for example, Bennett, 2018; Burton and Wright, 2018). Perchlorate is the only constituent included in the special interest class in this study.

The SWRCB-DDW “notification level” (NL-CA) is a non-regulatory, health-based advisory level that is associated with the RL-CA (see primary benchmark prioritization framework discussed previously) and functions as an early warning indicator for certain contaminants that do not have regulatory benchmarks (California State Water Resources Control Board, 2019d). The NL-CA can range from 6 to 100 times less than the RL-CA and has a similar function to that of the low-to-moderate boundary in the RC classification system described previously; therefore, if a constituent has an NL-CA, then the value of the NL-CA is taken as the low-to-moderate threshold for the RC classification, instead of the benchmark multiplied by 0.1 (for organic constituents) or 0.5 (for inorganic constituents).

In this study, if the measured constituent concentration was greater than the NL-CA and less than or equal to a corresponding non-regulatory, health-based primary benchmark value (either the RL-CA or HAL-US, whichever is lower), the constituent was considered present at a moderate RC. Boron and vanadium were the only detected constituents with NL-CA values for which RC thresholds were affected by this modification to the RC classification system. For example, although the primary benchmark for boron is the HAL-US of 6,000 micrograms per liter ($\mu\text{g/L}$), the low-to-moderate concentration boundary is the NL-CA of 1,000 $\mu\text{g/L}$ and not 3,000 $\mu\text{g/L}$. Using the NL-CA as the low-to-moderate RC threshold maintains consistency between the interpretation of the moderate-RC classification by the GAMA-PBP and the intended use of the NL-CA benchmark by the SWRCB-DDW as an early-warning indicator of groundwater-quality degradation (California State Water Resources Control Board, 2019d).

Datasets Used for Status Assessment

Groundwater-quality data used in the status assessment of the northern Sierra Nevada foothills study units came from sites sampled by the USGS for the GAMA-PBP using a grid-based sampling approach (fig. 6). Detailed descriptions of grid-cell delineation and well selection are provided for the YBW and ACMW study units by Jasper and others (2017) and Shelton and others (2018), respectively. Briefly, the areal extent of the groundwater resource in each study unit was defined as the aggregate of all 1-square mile Public Land Survey System sections in each study unit containing at least one record for a domestic well in the DWR well-completion report database (Stork and others, 2019). This aggregated area was then subdivided into 75 approximately equal-area grid cells of about 30 km^2 for the YBW study unit and 67 cells of $\sim 60 \text{ km}^2$ for the ACMW study unit, using the algorithm of Scott (1990). In each grid cell, one domestic well or spring was randomly selected from a list of target sites compiled from DWR, USGS, State, or county databases until a suitable site was identified for which permission to sample could be obtained from the well owner.

The USGS sampled 75 grid sites (71 wells and 4 springs) in the YBW study unit and 67 grid sites (66 wells and 1 spring) in the ACMW study unit. All groundwater sampling sites (wells and springs) are referred to as wells in this report unless otherwise noted. The USGS grid sites were labeled with an alphanumeric GAMA identification (GAMA ID), which contains information about the study area and order of sampling. Details on the attribution of GAMA IDs are compiled in the data releases of Jasper and others (2017) and Shelton and others (2018). In this report, groundwater sites are identified using the latter part of the GAMA ID, which is derived from a site’s study area and sampling order. For example, the first and second wells sampled in the Bear study area are referred to as “B01” and “B02,” respectively. A site sampled in the ACMW study unit is referred to as “M10U,”

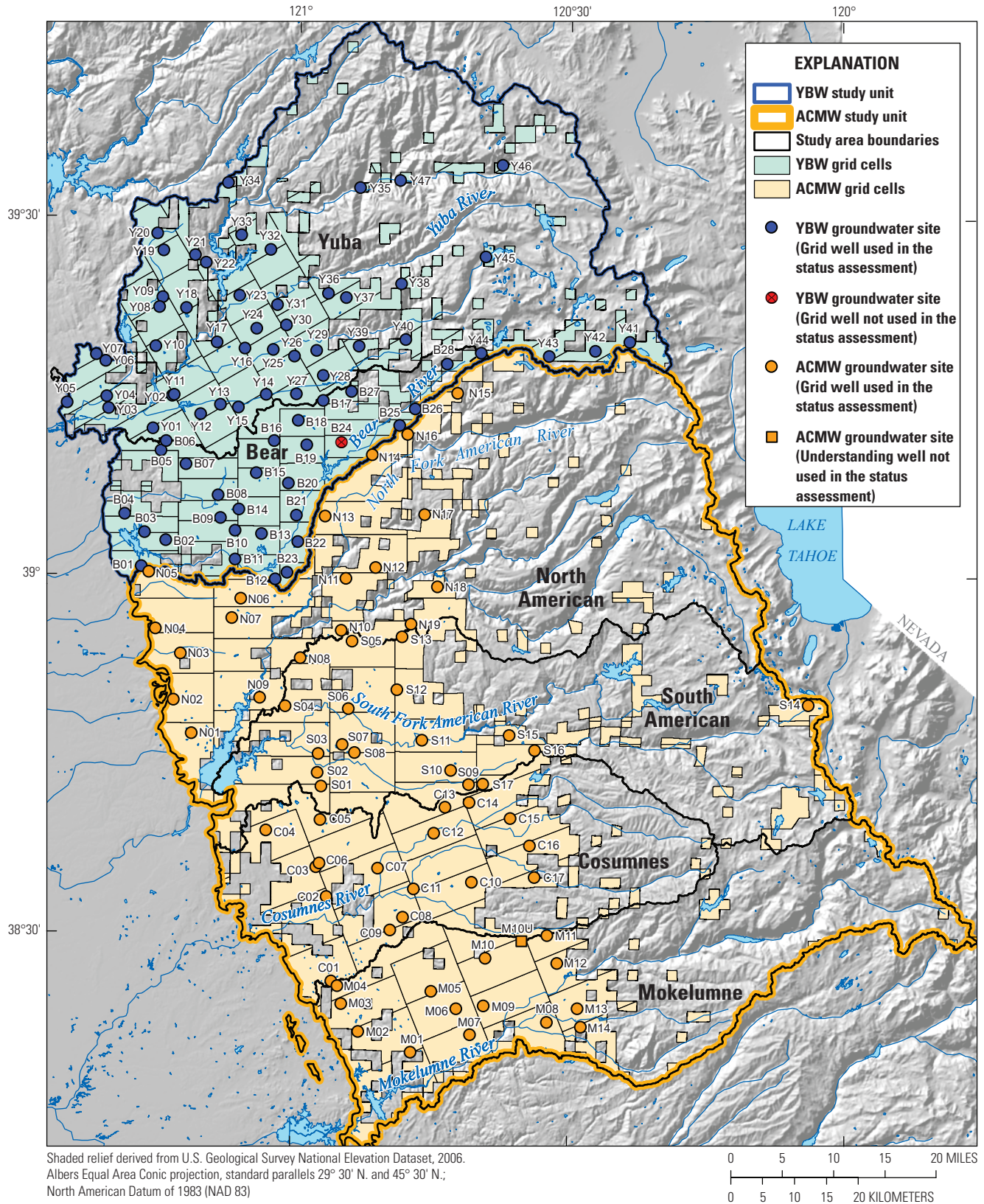


Figure 6. Locations of grid cells, groundwater grid sites, and the understanding site sampled for the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. (ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds).

where the appended “U” signifies an “understanding well” because it was not used to calculate aquifer-scale proportions in the status assessment but was used in statistical calculations relating water-quality constituents to explanatory factors presented in the understanding assessment. The sample from site B24 was determined by graphical analysis to have been treated by a household water-softening system and was not considered to be representative of raw aquifer water. Water-quality results from this site are therefore not included in any of the assessments.

A total of 373 and 372 groundwater constituents were analyzed for all grid sites in the YBW and ACMW study units, respectively (table 1; arsenic [III] was analyzed for the YBW study unit but not the ACMW study unit). The results of these analyses are tabulated in the USGS data releases of Jasper and others (2017), Shelton and others (2018), and Levy and Faulkner (2019), and are also available online from the SWRCB’s GAMA Groundwater Information System (<https://geotracker.waterboards.ca.gov/gama/>) and the USGS publicly available National Water Information System (NWIS; U.S. Geological Survey, 2020).

Selection of Constituents for Additional Evaluation in the Status Assessment

Water-quality constituents were selected for evaluation in the status assessment if they were present at moderate or high RCs in a sample from any grid well or if they were an organic or special interest constituent with a detection frequency in either study unit of 10 percent or greater. Evaluating organic and special-interest constituents both by RC and detection frequency allowed the status assessment to focus both on concentration and frequency of detection for constituents that are not often found at detectable concentrations in natural groundwater samples. Detection frequency was not used as a criterion for evaluation of the inorganic constituents because these are typically detectable at some concentration in most natural groundwater samples. Three microbial indicators (total coliform, TC; *Escherichia coli*, EC; and *Enterococci*, ENT) were only tested for “presence” or “absence” and were included in the status assessment if they were present in at least one well in either study unit.

Twenty-five water-quality constituents were selected for evaluation in the status assessment on the basis of aforementioned criteria (table 2). An additional 30 inorganic constituents and 26 organic constituents were detected that did not have benchmarks or were only present at low RCs for inorganic constituents or were only present at low RCs and had detection frequencies of less than 10 percent for organic constituents (table 3). Aquifer-scale proportions are not presented for water-quality constituents only detected at low-RCs because the proportion of the aquifer having low concentration for those constituents was 100 percent. All geochemical tracers (11 constituents)

and field water-quality indicators (5 constituents) were detected. Of the 373 constituents analyzed for in groundwater samples collected from the two study units, 278 (all organic constituents) were not detected in any of the samples (Jasper and others, 2017; Shelton and others, 2018).

Calculation of Aquifer-Scale Proportions

A grid-based statistical approach was used to calculate the areal proportion of aquifer systems in the northern Sierra Nevada foothills study units having high, moderate, and low RCs for selected water-quality constituents (Belitz and others, 2010). For ease of discussion, these proportions are referred to as “high-RC,” “moderate-RC,” and “low-RC” aquifer-scale proportions. Non-detections were considered to be low RC for inorganic constituents. Because organic and special-interest constituents were often not detected at any concentration, however, low RC was only attributed to detections below the low-to-moderate RC threshold, and a separate aquifer-scale proportion was calculated for non-detections. Aquifer-scale proportions were calculated both for individual water-quality constituents and constituent classes. For a given constituent class, the highest RC value for a constituent belonging to that class at each grid site was used to calculate the aquifer-scale proportions for that class. For example, if a site has groundwater at high RC for boron, a moderate RC for fluoride, and low RCs for the other trace elements, then that site would be considered to have high RC groundwater for the trace-element class because of the high RC of boron. The high-RC aquifer-scale proportion for a constituent class therefore represents the proportion of the groundwater resource having at least one detection at high RC for a constituent within that class. Additionally, aquifer-scale proportions were calculated for presence or absence of microbial indicator species.

Separate aquifer-scale proportions were calculated for each northern Sierra Nevada foothills study unit. High-RC aquifer-scale proportions were calculated as the proportion of grid sites in a study unit having high RC for a given constituent:

$$P_{SU}^{high} = \frac{N_{SU}^{high}}{N_{SU}} \quad (1)$$

where

- P_{SU}^{high} is the high-RC aquifer-scale proportion for the study-unit area,
- N_{SU}^{high} is the number of grid sites in the study unit with a high-RC value for a given water-quality constituent, and
- N_{SU} is the number of grid sites in the study unit that have data for a given water-quality constituent.

Table 1. Summary of groundwater sites, water-quality constituent groups, and numbers of constituents sampled for each constituent group by the U.S. Geological Survey (USGS), northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Unless otherwise noted constituent analysis were made at the USGS National Water Quality Laboratory. **Abbreviations:** C, carbon; H, hydrogen; N, nitrogen, O, oxygen; δ , delta notation: the ratio of the less abundant to more abundant isotope in a sample relative to a reference standard (Clark and Fritz, 1997)]

Category	Study unit	
	Yuba-Bear watersheds (YBW)	American-Cosumnes-Mokelumne watersheds (ACMW)
Site summary		
Total number of sites sampled	75	68
Number of grid sites	75	67
Number of understanding sites	0	1
Constituent	Number of constituents analyzed	
Field water-quality indicators		
Dissolved oxygen, temperature, pH, and specific conductance ¹	4	4
Field alkalinity ²	1	1
Inorganic constituents		
Major and minor ions, silica, trace elements, and total dissolved solids (TDS) ³	36	35
Gross-alpha and gross-beta particle radioactivity ⁴	2	2
Laboratory alkalinity	1	1
Nutrients	5	5
Microbial indicators		
Total coliform, <i>Escherichia coli</i> , <i>Enterococci</i> (presence or absence) ¹	3	3
Organic constituents		
Pesticides and pesticide degradates	225	225
Volatile organic compounds (VOCs) ⁵	84	84
Constituents of special interest		
Perchlorate ⁶	1	1
Tracers		
Carbon-14 and $\delta^{13}\text{C}$ of dissolved inorganic carbon ⁷	2	2
Dissolved noble gases (neon, argon, krypton, xenon) ⁸	4	4
Stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) of water ⁹	2	2
Stable isotopes ($\delta^{15}\text{N}$ and $\delta^{18}\text{O}$) of nitrate ⁹	2	2
Tritium ¹⁰	1	1
Sum	373	372

¹Measured by USGS field staff.

²Measured by USGS field staff; replicate samples only.

³Arsenic(III) was the only constituent in this category analyzed for in the YBW study unit but not the ACMW study unit.

⁴Gross alpha particle and gross beta particle activities were measured after 72-hour and 30-day holding times and data from the 30-day measurements are used in this report; analyzed at ALS Environmental, Fort Collins, Colorado.

⁵Includes 8 constituents classified as fumigants.

⁶Analyzed at Weck Laboratories, Inc., City of Industry, California.

⁷Analyzed at the Woods Hole Oceanographic Institution National Ocean Sciences Accelerator Mass Spectrometer facility, Woods Hole, Massachusetts.

⁸Analyzed at the Lawrence Livermore National Laboratory, Livermore, California.

⁹Analyzed at the USGS Stable Isotope Laboratory, Reston, Virginia.

¹⁰Analyzed at USGS Stable Isotope and Tritium Laboratory, Menlo Park, California.

Table 2. Primary benchmark type and value for constituents present at high or moderate relative concentrations in grid-site samples and for organic or special interest constituents present at detectable concentrations in more than 10 percent of groundwater samples for either study unit, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Relative-concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, $RC > 1.0$ is defined as high and $1 \geq RC > 0.5$ is defined as moderate, unless otherwise noted. For organic constituents, $RC > 1.0$ is defined as high, and $1 \geq RC > 0.1$ is defined as moderate, unless otherwise noted. **Benchmark type:** Regulatory, health-based benchmarks: MCL-US, EPA maximum contaminant level; MCL-CA, SWRCB-DDW maximum contaminant level; HAL-US, EPA lifetime health advisory level; TT-US, EPA treatment technique. **Non-regulatory health-based benchmarks:** HBSL, USGS Health Based Screening Level; NL-CA, SWRCB-DDW notification level. Non-regulatory aesthetic-based benchmarks: SMCL-US, EPA secondary maximum contaminant level; SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units:** mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; $\mu\text{S/cm}$, microsiemens per centimeter; pCi/L, picocuries per liter. **Other abbreviations:** >, greater than; \geq , greater than or equal to; D, detected in study unit; SWRCB-DDW, California State Water Resources Control Board Division of Drinking Water; EPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey]

Constituent	Primary source or typical use	Primary benchmark			Study unit		Included in the understanding assessment?
		Type ¹	Value	Units	Yuba-Bear watersheds	American-Cosumnes-Mokelumne watersheds	
Inorganic constituents with health-based benchmarks							
Trace elements							
Arsenic	Naturally present	MCL-US	10	µg/L	D	D	No
Barium	Naturally present	MCL-CA	1,000	µg/L	D	D	No
Boron	Naturally present	HAL-US ²	6,000	µg/L	D	D	No
Fluoride	Naturally present	MCL-CA	2	mg/L	D	D	No
Molybdenum	Naturally present	HAL-US	40	µg/L	D	D	No
Strontium	Naturally present	HAL-US	4,000	µg/L	D	D	No
Nutrients							
Nitrate, as nitrogen	Natural, fertilizer, sewage	MCL-US	10	mg/L	D	D	Yes
Radioactive constituents							
Adjusted gross-alpha particle radioactivity	Naturally present	MCL-US	15	pCi/L	D	D	No
Gross-beta particle radioactivity	Naturally present	MCL-US (trigger) ³	50	pCi/L	D	D	No
Inorganic constituents with SMCL or aesthetic-based benchmarks							
Chloride	Naturally present	SMCL-CA	500	mg/L	D	D	No
Hardness, as calcium carbonate	Naturally present	Aesthetic ⁴	180	mg/L	D	D	Yes
Manganese	Naturally present	SMCL-CA	50	µg/L	D	D	Yes
Iron	Naturally present	SMCL-CA	300	µg/L	D	D	Yes
Specific conductance	Naturally present	SMCL-CA	1,600	µS/cm	D	D	No
Sulfate	Naturally present	SMCL-CA	500	mg/L	D	D	No
Total dissolved solids (TDS)	Naturally present	SMCL-CA	1,000	mg/L	D	D	No
Microbial indicators							
Total coliform (TC)	Natural, sewage	MCL-CA	Present ⁵	Presence/Absence	D	D	Yes

Table 2. Primary benchmark type and value for constituents present at high or moderate relative concentrations in grid-site samples and for organic or special interest constituents present at detectable concentrations in more than 10 percent of groundwater samples for either study unit, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Relative-concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, $RC > 1.0$ is defined as high and $1 \geq RC > 0.5$ is defined as moderate, unless otherwise noted. For organic constituents, $RC > 1.0$ is defined as high, and $1 \geq RC > 0.1$ is defined as moderate, unless otherwise noted. **Benchmark type:** Regulatory, health-based benchmarks: MCL-US, EPA maximum contaminant level; MCL-CA, SWRCB-DDW maximum contaminant level; HAL-US, EPA lifetime health advisory level; TT-US, EPA treatment technique. **Non-regulatory health-based benchmarks:** HBSL, USGS Health Based Screening Level; NL-CA, SWRCB-DDW notification level. Non-regulatory aesthetic-based benchmarks: SMCL-US, EPA secondary maximum contaminant level; SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units:** mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; $\mu\text{S/cm}$, microsiemens per centimeter; pCi/L, picocuries per liter. **Other abbreviations:** >, greater than; \geq , greater than or equal to; D, detected in study unit; SWRCB-DDW, California State Water Resources Control Board Division of Drinking Water; EPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey]

Constituent	Primary source or typical use	Primary benchmark			Study unit		Included in the understanding assessment?
		Type ¹	Value	Units	Yuba-Bear watersheds	American-Cosumnes-Mokelumne watersheds	
Microbial indicators—Continued							
<i>Escherichia coli</i> (EC)	Natural, sewage	MCL-CA	Present ⁶	Presence/Absence	D	D	Yes
<i>Enterococci</i> (ENT)	Natural, sewage	TT-CA	Present ⁷	Presence/Absence	D	D	Yes
Organic constituents with health-based benchmarks							
Volatile organic compounds							
Trichloromethane (chloroform)	Disinfection byproduct	MCL-US ⁸	80	µg/L	D	D	Yes
Methyl <i>tert</i> -butyl ether (MTBE)	Gasoline oxygenate	MCL-CA	13	µg/L	D	D	Yes
Tetrachloroethylene (PCE)	Solvent	MCL-US	5	µg/L	D	D	No
Toluene	Gasoline hydrocarbon	MCL-CA	150	µg/L	D	D	No
Trichloroethylene (TCE)	Solvent	MCL-US	5	µg/L	D	D	No
Constituents of special interest							
Perchlorate	Natural, fertilizer, industrial	MCL-CA	6	µg/L	D	D	Yes

¹Maximum 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. Secondary contaminant level benchmarks are listed as SMCL-US when the SMCL-US and SMCL-CA are identical, and as SMCL-CA when the SMCL-CA is lower than the SMCL-US or no SMCL-US exists. Sources of benchmarks: HAL-US: U.S. Environmental Protection Agency (2018), MCL-CA: California State Water Resources Control Board (2019c), MCL-US: U.S. Environmental Protection Agency (2018), NL-CA: California State Water Resources Control Board (2019d), SMCL-CA: California State Water Resources Control Board (2019c), TT-US: U.S. Environmental Protection Agency (2018).

²The low-to-moderate concentration boundary for boron is the NL-CA of 1,000 $\mu\text{g/L}$ and not 0.5 times the benchmark value.

³This MCL-US is no longer an official regulatory level, but is still used by the EPA and the SWRCB-DDW as a “trigger level” to determine whether further testing for specific gross-beta particle emitters is necessary (California State Water Resources Control Board, 2019c).

⁴The non-regulatory, aesthetic threshold at which water is considered to be “very hard” (180 mg/L as calcium carbonate) was used as benchmark for this study (Briggs and Ficke, 1977).

⁵MCL violation due to presence of total coliform is based repeat sampling (California State Water Resources Control Board, 2019c).

⁶MCL violation due to presence of *Escherichia coli* is based repeat sampling (California State Water Resources Control Board, 2019c).

⁷Presence of *Enterococci* is considered a violation of treatment technique standards (California State Water Resources Control Board, 2019c).

⁸MCL-US benchmark for trihalomethanes is for the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform (U.S. Environmental Protection Agency, 2018).

Table 3. Primary benchmark type and value for detected constituents lacking benchmarks or present only at low relative concentrations (or present at low relative concentrations with detection frequencies less than 10 percent for organic constituents), northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Relative-concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, $RC > 1.0$ is defined as high and $1 \geq RC > 0.5$ is defined as moderate, unless otherwise noted. For organic constituents, $RC > 1.0$ is defined as high, and $1 \geq RC > 0.1$ is defined as moderate, unless otherwise noted. **Benchmark type: Regulatory, health-based benchmarks:** AL-US, EPA action level; MCL-US, EPA maximum contaminant level; MCL-CA, SWRCB-DDW maximum contaminant level; HAL-US, EPA lifetime health advisory level; HHBP-US, EPA human health benchmark for pesticides. **Non-regulatory health-based benchmarks:** HBSL, USGS health-based screening level; HHBP-US, EPA human-health benchmarks for pesticides, NL-CA, SWRCB-DDW notification level; RL-CA, SWRCB-DDW response level; RSD5, EPA risk-specific doses for a 1:100,000 risk level. **Non-regulatory aesthetic-based benchmarks:** SMCL-US, EPA secondary maximum contaminant level; SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units:** cc/g at STP, cubic centimeters per gram at standard temperature and pressure; mg/L, milligrams per liter; µg/L, micrograms per liter; ng/L, nanograms per liter. **Other Abbreviations:** >, greater than; ≥, greater than or equal to; —, not detected in study unit; D, detected in study unit; NA, not applicable (was not analyzed in study unit), SWRCB-DDW, California State Water Resources Control Board Division of Drinking Water; EPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey]

Constituent	Primary benchmark			Study unit	
	Type ¹	Value	Units	Yuba-Bear watersheds	American-Cosumnes-Mokelumne watersheds
Inorganic constituents with benchmarks					
Aluminum	MCL-CA	1,000	µg/L	D	D
Ammonia	HAL-US ²	24.7	mg/L	D	D
Antimony	MCL-US	6	µg/L	D	D
Beryllium	MCL-US	4	µg/L	D	D
Cadmium	MCL-US	5	µg/L	D	D
Chromium	MCL-CA	50	µg/L	D	D
Chromium (VI)	HBSL	20	µg/L	D	D
Copper	AL-US	1,300	µg/L	D	D
Lead	AL-US	15	µg/L	D	D
Mercury	MCL-US	2	µg/L	D	D
Nickel	MCL-CA	100	µg/L	D	D
Nitrite, as nitrogen	MCL-US	1	mg/L	D	D
Selenium	MCL-US	50	µg/L	D	D
Silver	SMCL-CA	100	µg/L	D	NA
Thallium	MCL-US	2	µg/L	D	D
Uranium	MCL-US	30	µg/L	D	D
Vanadium	RL-CA ³	500	µg/L	D	D
Zinc	SMCL-CA	5,000	µg/L	D	D
Inorganic constituents without benchmarks					
Arsenic (III)	None	None	µg/L	D	NA
Bromide	None	None	mg/L	D	D
Calcium	None	None	mg/L	D	D
Iodide	None	None	mg/L	D	D
Lithium	None	None	µg/L	D	D
Laboratory or field alkalinity (as calcium carbonate)	None	None	mg/L	D	D
Magnesium	None	None	mg/L	D	D
Orthophosphate, as phosphorous	None	None	mg/L	D	D
Potassium	None	None	mg/L	D	D
Silica, as SiO ₂	None	None	mg/L	D	D

Table 3. Primary benchmark type and value for detected constituents lacking benchmarks or present only at low relative concentrations (or present at low relative concentrations with detection frequencies less than 10 percent for organic constituents), northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Relative-concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, $RC > 1.0$ is defined as high and $1 \geq RC > 0.5$ is defined as moderate, unless otherwise noted. For organic constituents, $RC > 1.0$ is defined as high, and $1 \geq RC > 0.1$ is defined as moderate, unless otherwise noted. **Benchmark type: Regulatory, health-based benchmarks:** AL-US, EPA action level; MCL-US, EPA maximum contaminant level; MCL-CA, SWRCB-DDW maximum contaminant level; HAL-US, EPA lifetime health advisory level; HHBP-US, EPA human health benchmark for pesticides. **Non-regulatory health-based benchmarks:** HBSL, USGS health-based screening level; HHBP-US, EPA human-health benchmarks for pesticides, NL-CA, SWRCB-DDW notification level; RL-CA, SWRCB-DDW response level; RSD5, EPA risk-specific doses for a 1:100,000 risk level. **Non-regulatory aesthetic-based benchmarks:** SMCL-US, EPA secondary maximum contaminant level; SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units:** cc/g at STP, cubic centimeters per gram at standard temperature and pressure; mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; ng/L, nanograms per liter. **Other Abbreviations:** >, greater than; \geq , greater than or equal to; —, not detected in study unit; D, detected in study unit; NA, not applicable (was not analyzed in study unit), SWRCB-DDW, California State Water Resources Control Board Division of Drinking Water; EPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey]

Constituent	Primary benchmark			Study unit	
	Type ¹	Value	Units	Yuba-Bear watersheds	American-Cosumnes-Mokelumne watersheds
Inorganic constituents without benchmarks—Continued					
Sodium	None	None	mg/L	D	D
Total nitrogen	None	None	mg/L	D	D
Organic constituents with benchmarks					
1,1,1-Trichloroethane (1,1,1-TCA)	MCL-US	200	$\mu\text{g/L}$	D	—
1,1-Dichloroethene (1,1-DCE)	MCL-CA	6	$\mu\text{g/L}$	—	D
1,4-Dichlorobenzene	MCL-CA	5	$\mu\text{g/L}$	D	—
2-Ethyl-hexanol	HBSL	3,000	$\mu\text{g/L}$	—	D
Bromodichloromethane	MCL-US ⁴	80	$\mu\text{g/L}$	—	D
Bromoform (Tribromomethane)	MCL-US ⁴	80	$\mu\text{g/L}$	—	D
Carbon disulfide	RL-CA	1,600	$\mu\text{g/L}$	—	D
cis-1,2-Dichloroethylene (cis-1,2-DCE)	MCL-CA	6	$\mu\text{g/L}$	D	—
Chlorodiamino-s-triazine (CAAT)	HHBP-US	12,000	$\mu\text{g/L}$	—	D
Cyclohexanone	HBSL	30,000	$\mu\text{g/L}$	D	D
Dibromochloromethane	MCL-US ⁴	80	$\mu\text{g/L}$	—	D
Diuron	RSD5-US	20,000	ng/L	D	D
Hexazinone	HAL-US	400,000	ng/L	D	D
Isopropyl alcohol	HBSL	10,000	$\mu\text{g/L}$	D	—
Malathion	HAL-US	500,000	ng/L	—	D
Methoxyfenozide	HHBP-US	600,000	ng/L	D	D
Methylene chloride (Dichloromethane)	MCL-US	5	$\mu\text{g/L}$	—	D
Propazine	HAL-US	10,000	ng/L	—	D
Tebuthiuron	HAL-US	500,000	ng/L	D	D
Organic constituents without benchmarks					
2-Chloro-4-isopropylamino-6-amino-s-triazine (CIAT)	None	None	ng/L	—	D
2-Chloro-6-ethylamino-4-amino-s-triazine (CEAT)	None	None	ng/L	—	D
Chlorodifluoromethane (HCFC-22)	None	None	$\mu\text{g/L}$	—	D
Demethyl hexazinone B	None	None	ng/L	—	D
Hydroxy monodemethyl fluometuron	None	None	ng/L	—	D

Table 3. Primary benchmark type and value for detected constituents lacking benchmarks or present only at low relative concentrations (or present at low relative concentrations with detection frequencies less than 10 percent for organic constituents), northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Relative-concentration (RC) is defined as the measured value divided by the benchmark value. For inorganic constituents, $RC > 1.0$ is defined as high and $1 \geq RC > 0.5$ is defined as moderate, unless otherwise noted. For organic constituents, $RC > 1.0$ is defined as high, and $1 \geq RC > 0.1$ is defined as moderate, unless otherwise noted. **Benchmark type: Regulatory, health-based benchmarks:** AL-US, EPA action level; MCL-US, EPA maximum contaminant level; MCL-CA, SWRCB-DDW maximum contaminant level; HAL-US, EPA lifetime health advisory level; HHBP-US, EPA human health benchmark for pesticides. **Non-regulatory health-based benchmarks:** HBSL, USGS health-based screening level; HHBP-US, EPA human-health benchmarks for pesticides, NL-CA, SWRCB-DDW notification level; RL-CA, SWRCB-DDW response level; RSD5, EPA risk-specific doses for a 1:100,000 risk level. **Non-regulatory aesthetic-based benchmarks:** SMCL-US, EPA secondary maximum contaminant level; SMCL-CA, SWRCB-DDW secondary maximum contaminant level. **Benchmark units:** cc/g at STP, cubic centimeters per gram at standard temperature and pressure; mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; ng/L, nanograms per liter. **Other Abbreviations:** >, greater than; \geq , greater than or equal to; —, not detected in study unit; D, detected in study unit; NA, not applicable (was not analyzed in study unit), SWRCB-DDW, California State Water Resources Control Board Division of Drinking Water; EPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey]

Constituent	Primary benchmark			Study unit	
	Type ¹	Value	Units	Yuba-Bear watersheds	American-Cosumnes-Mokelumne watersheds
Organic constituents without benchmarks—Continued					
N-(3,4-Dichlorophenyl)-N'-methylurea (DCPMU)	None	None	ng/L	D	D
Tebuthiuron Transformation Product el108	None	None	ng/L	D	D

¹Maximum 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. Secondary contaminant level benchmarks are listed as SMCL-CA when the SMCL-US and SMCL-CA are identical, and as SMCL-CA when the SMCL-CA is lower than the SMCL-US or no SMCL-US exists. Sources of benchmarks: HAL-US: U.S. Environmental Protection Agency (2018), HBSL: Norman and others (2018), HHBP-US: U.S. Environmental Protection Agency (2019), MCL-CA: California State Water Resources Control Board (2019c), MCL-US: U.S. Environmental Protection Agency (2018), NL-CA: California State Water Resources Control Board (2019d), RL-CA: California State Water Resources Control Board (2019d), RSD5-US: U.S. Environmental Protection Agency (2018), SMCL-CA: California State Water Resources Control Board (2019c).

²The HAL-US benchmark is 30 mg/L “as ammonia.” To facilitate comparison to the analytical results, we have converted and reported this HAL-US as 24.7 mg/L “as nitrogen.”

³The low-to-moderate concentration boundary for vanadium is the NL-CA of 50 $\mu\text{g/L}$ and not 0.5 times the benchmark value.

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

Aquifer-scale proportions for moderate and low RCs, non-detections for organic and special-interest constituents, and presence or absence of microbial indicators were calculated similarly by replacing terms using the superscript “high” in [equation 1](#) with terms using the superscripts “moderate,” “low,” “non-detection,” “present,” or “absent,” respectively. Confidence intervals for aquifer-scale proportions were calculated using the Jeffreys interval for the binomial distribution (Brown and others, 2001; Belitz and others, 2010).

Understanding Assessment

The purpose of the understanding assessment was to determine the major natural and anthropogenic factors that affect groundwater quality in the northern

Sierra Nevada foothills study region. The GAMA-PBP uses statistical and graphical methods to evaluate relations among potential explanatory factors and groundwater-quality measurements. Methods for the understanding assessment included (1) selection of constituents for additional evaluation in the understanding assessment and (2) statistical analyses of relations among potential explanatory variables and selected water-quality constituents. The same datasets for water-quality constituents used in the status assessment were used for the understanding assessment (grid sites from the YBW and ACMW study units) with the addition of one extra “understanding” site sampled in the ACMW study unit (M10U).

Selection of Constituents for Additional Evaluation in the Understanding Assessment

A subset of constituents evaluated in the status assessment was selected for further evaluation in the understanding assessment (table 2). Constituents were selected for evaluation in the understanding assessment if they either (1) had high-RC (or microbial indicators were present) at aquifer-scale proportions greater than 2 percent in either study unit or (2) had detection frequencies greater than 10 percent for organic or special-interest constituents in either study unit. These criteria resulted in the selection of four inorganic constituents, three microbial indicators, two organic constituents, and one constituent of special interest for evaluation in the understanding assessment (table 2).

Statistical Analysis

Non-parametric statistical tests were used to quantify associations among water-quality constituents and potential explanatory factors. Non-parametric statistics are rank-based and robust to the effects of non-normality and outliers, which are commonly observed in groundwater-quality data (Helsel and others, 2020). Unless otherwise specified, significance levels (p) for statistical hypothesis tests were evaluated using a critical level (α) of 5 percent ($\alpha = 0.05$), where p values less than or equal to α resulted in rejection of the null hypothesis.

Three types of statistical analyses were used because water-quality constituents and explanatory factors contained continuous and categorical variables. Concentrations of water-quality constituents were treated as continuous variables for which zeros were substituted for non-detections. Substitution is acceptable at a single concentration level for rank-based statistical analyses (Helsel, 2012). Presence or absence of microbial indicators was treated as categorical variables. For the potential explanatory variables, land-use percentages (agricultural, natural, urban), septic tank density, LUFT density, AI, site elevation, well depth, depth to TOP, pH, DO, normalized recharge temperature, and *d-excess* were treated as continuous variables. Groundwater-age class (pre-modern, mixed age, and modern), redox class (anoxic, mixed redox, and oxic), aquifer lithology (mafic-ultramafic, granitic, metavolcanic, metasedimentary, and volcanic), depth class (shallow, mixed depth, and deep), study unit (YBW and ACMW), and study area (Y, B, NA, SA, C, and M) were treated as categorical variables. Detailed explanations of potential explanatory variable selection and classification are provided in appendix 1 and the data release by Levy (2020).

Three classes of statistical analyses were used to test for associations among water-quality constituents and potential explanatory variables:

1. Monotonic correlations among all possible pairs of continuous variables were evaluated using the Spearman's rank-correlation test (Harrell and others, 2018). Rank-order correlation coefficients (ρ , or rho) were calculated for all tests with a statistically significant correlation (p less than or equal to α allowed rejection of null hypothesis of "not correlated"). Spearman's rho values range from -1.0 to 1.0 , with positive values indicating direct correlation, negative values indicating inverse correlation, and the absolute value of rho indicating the degree or strength of the correlation.
2. Differences between groups (based on categorical variables) in terms of continuous variables were evaluated using Kruskal-Wallis and post hoc Dunn rank sum tests (Pohlert, 2014). The null hypothesis for these tests is that the median values of the continuous variable do not differ among the groups. The Kruskal-Wallis test was used initially to assess the difference among the groups. If the Kruskal-Wallis test showed significant difference among three or more groups, the post hoc Dunn test was used for all possible pairwise combinations of the different groups using p values adjusted with the Benjamini-Hochberg correction (Helsel and others, 2020).
3. Relations among categorical variables were evaluated using contingency tables (R Core Team, 2018). For contingency tables, data are tabulated as a matrix of counts with categories of one categorical variable assigned to the rows and categories of another to the columns. The chi-square test for independence compares observed counts under the different row and column headings to the expected counts if the two variables were independent. The resultant test statistic is compared to the quantiles of the chi-square distribution (Helsel and others, 2020). For tests indicating a significant difference between observed and expected distributions of the two categorical variables, the factors contributing most to the difference were identified by comparing the magnitude of the matrix components of the test statistic.

Comparative Assessment

This report makes two distinct comparisons of the aquifer systems used for domestic- and public-supply in the study region. The first comparison ("well-construction comparison") broadly assessed aquifer-depth zones used for public- and domestic-supply in the study region using over 60,000 records compiled from the DWR well-completion report database by Stork and others (2019). The second

comparison (“water-quality comparison”) was a more focused evaluation of water-quality differences between domestic- and public-supply aquifers in the study region using data from the 141 domestic-supply wells sampled for the status assessment and 306 public-supply wells from a prior GAMA-PBP study (Fram and Belitz, 2014) and the SWRCB-DDW regulatory-monitoring database (formerly maintained by the California Department of Public Health and referred to as CDPH database in prior GAMA-PBP assessments; California State Water Resources Control Board, 2019b). Selected explanatory factors (land use, elevation, and aquifer lithology) were attributed to the public-supply wells to help understand differences in groundwater-quality data between the two different resources.

Well-Construction Comparison

To evaluate differences between aquifer system depth zones used for domestic and public drinking-water supply, this report used a geospatial dataset that indexes a subset of records available through the DWR Online System for Well Completion Reports (OSWCR) database for Amador, Calaveras, El Dorado, Nevada, and Placer Counties (Stork and others, 2019). A total of 60,605 well-completion report records were identified for the study region (26,002 from the YBW study unit and 34,603 from the ACMW study unit). Only wells for which “planned use” for the well was explicitly defined as “domestic” or “public” on the well-completion report itself, as reported by Stork and others (2019), were used to evaluate differences in the respective aquifer systems. Because there are no consistent standards by which generalized aquifer lithology was determined on well-completion reports, reported lithologies were broadly categorized in three groups: hard rock (reported as hard rock, granitic, limestone, metamorphic, or volcanic), alluvial (reported as alluvial), and not reported. Regional differences between domestic and public aquifer system depth zones were evaluated using reported well depths and depth to TOP (both reported as depths below the land surface). Statistical differences between well construction characteristics for public and domestic supply wells in both study units were determined using the Kruskal-Wallis and Dunn rank-sum tests, as described in the “Statistical Analysis” section of this report.

Water-Quality Comparison

This report compares water-quality between aquifer systems used for domestic and public drinking-water supply for those constituents selected for evaluation in the status assessment for which there were sufficient public-supply data. Prior GAMA-PBP studies made comparisons between domestic- and public-supply aquifers that roughly overlapped in space with comparable grid-cell resolutions (Bennett, 2018; Burton and Wright, 2018). The only previous GAMA-PBP assessment of public-supply wells that spatially overlapped with the northern Sierra Nevada foothills study units,

however, was a regional study of the entire Sierra Nevada province, which used a sampling grid of much coarser spatial resolution (2,200 km² grid cells; Fram and Belitz, 2014). Only 15 public-supply wells sampled by GAMA-PBP in 2008 for the regional Sierra Nevada study overlapped the sampling grid for the YBW and ACMW study units. To supplement these data, the SWRCB-DDW dataset was queried for all available water-quality analyses on record (from June 19, 1978, to October 23, 2018) for raw, untreated groundwater samples from public-supply wells in the YBW and ACMW study unit grids.

A complete water-quality assessment of public-supply aquifer systems in the study region was outside the scope of this report and only water-quality constituents evaluated in the status assessment of the domestic-supply aquifer system were included in the comparative assessment. Of the 332 public-supply wells with available groundwater-quality records, 306 had at least one measurement of a water-quality constituent that had been selected for evaluation in the status assessment (fig. 7). Of the selected water-quality constituents, 96 wells had data for only one (typically nitrate), and 137 had data for 10 or more, with no apparent spatial bias between data-rich and data-poor wells (fig. 7). Results reported for regulatory compliance monitoring in the SWRCB-DDW database are typically for unfiltered samples, whereas samples analyzed for metals and pesticides by the GAMA-PBP are passed through 0.45 and 0.70 µm filters, respectively (Jasper and others, 2017; Shelton and others, 2018). Analysis of unfiltered samples can result in higher reported values for certain metals in the SWRCB-DDW database, a consideration discussed later in this report.

Aquifer-scale proportions for the public-supply aquifer system were determined for the selected constituents and constituent classes using spatially weighted calculations (Belitz and others, 2010). The spatially weighted method for calculating aquifer-scale proportions is used to avoid bias due to spatial clustering of wells in the study unit. Calculating high-RC aquifer-scale proportions using the spatially weighted method removes spatial bias by averaging the results of multiple wells by cell in the grid-cell network:

$$P_{SU}^{high} = \frac{\sum_{n=1}^n \frac{W_n^{high}}{W_n}}{N_{SU}} \quad (2)$$

where

- P_{SU}^{high} is the high-RC aquifer-scale proportion for the study-unit area,
- N_{SU} is the number of grid sites in the study unit that have data for a given water-quality constituent,
- W_n^{high} is the number of wells in cell n of the study unit with a high-RC value for a given water-quality constituent, and
- W_n is the number of wells in cell n of the study unit with data for a given water-quality constituent.

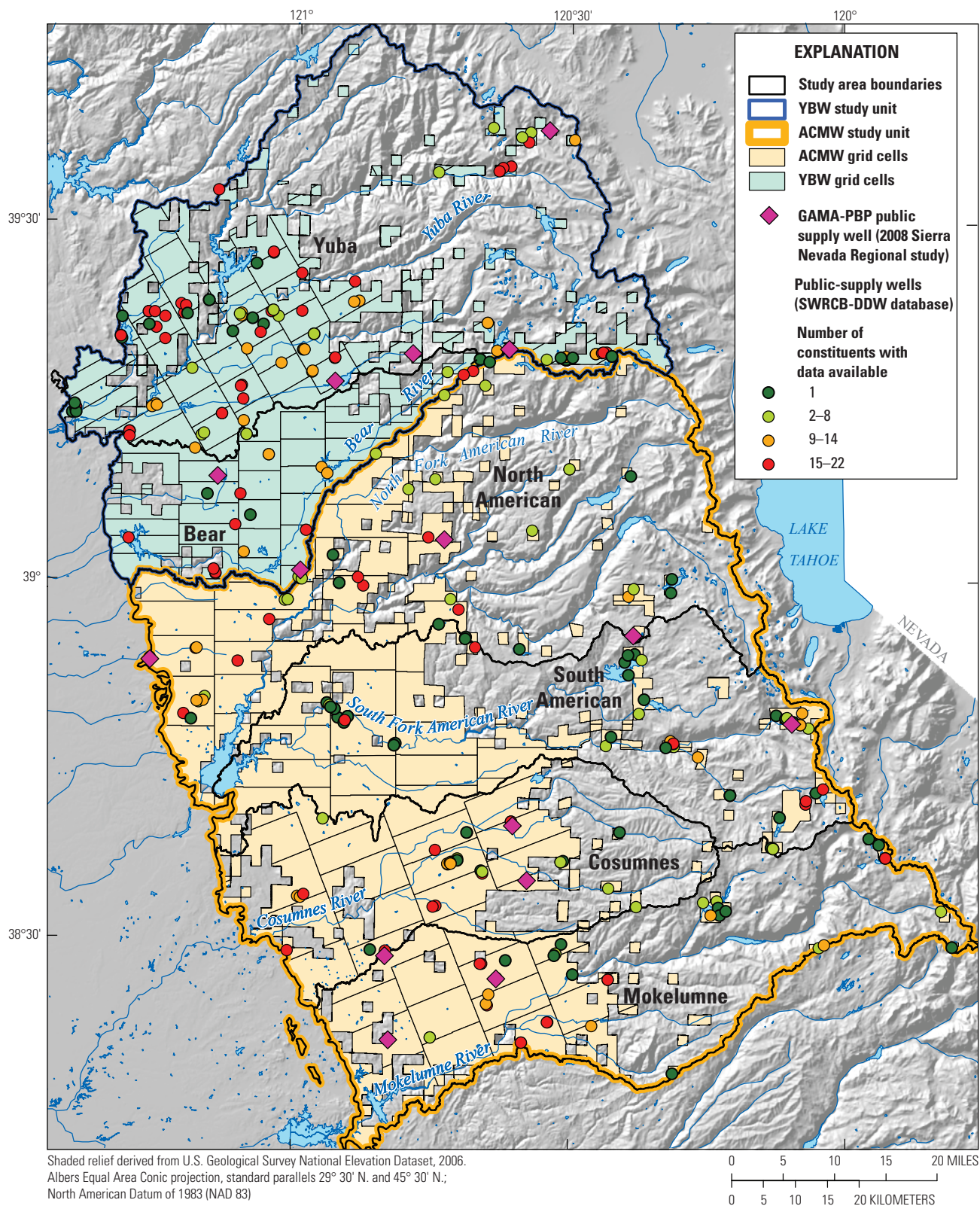


Figure 7. Locations of grid cells for the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project; public-supply wells used for the comparative assessment of domestic wells with public-supply wells from the Sierra Nevada Regional GAMA assessment (Fram and Belitz, 2014); and wells from the State Water Resources Control Board Division of Drinking Water database showing the number of assessed constituents with data available (California State Water Resources Control Board, 2019b).

This approach calculates the proportion of wells in each grid cell with high-RC groundwater for a given water-quality constituent and then averages these proportions across all cells with data in the study-unit grid network. Spatially weighted aquifer-scale proportions for moderate and low RCs and detection frequencies for organic and special interest constituents were calculated similarly.

The spatially weighted calculation requires no more than one measurement per water-quality constituent for each well. The water-quality measurement for a given well and constituent used, therefore, was that made closest to the midpoint of the sampling period for the corresponding domestic-supply assessment (that is, midpoint of October 3, 2015, for YBW and of October 29, 2016, for ACMW). This method prioritized selection of samples measured as close in time as possible to the domestic-supply assessments, without excluding wells for which only considerably older or more recent data were available.

Of the 25 constituents selected for evaluation in the status assessment, 19 had sufficient data to calculate aquifer-scale proportions for the comparative assessment. There were insufficient data for microbial indicators in the comparative assessment because the measurements in the public-supply database are typically made post-treatment for regulatory compliance monitoring and are therefore not comparable to the raw groundwater samples tested for microbial indicators in the status assessment. Additionally, there were minimal data for molybdenum, strontium, and gross-beta particle radioactivity in the SWRCB-DDW database to provide adequate cell coverage for calculation of aquifer-scale proportions (less than 10 and 14 percent of grid cells contained sites with water-quality data for these constituents in YBW and ACMW study units, respectively). For the remaining water-quality constituents, there were data for 35 to 63 percent of the grid cells in either study unit with a relatively even spatial distribution of data-rich grid cells throughout the region (fig. 7; appendix 2). Between 13 and 97 percent of samples used to calculate aquifer-scale proportions for a given constituent in each study unit were collected within three years of October 3, 2015, for YBW study unit or October 29, 2016, for ACMW study unit (appendix table 2.1).

The GAMA-PBP results for organic and special-interest constituents had to be recensored at elevated censoring thresholds because GAMA-PBP reporting levels for these constituents are much less than those in the SWRCB-DDW database (Fram and Belitz, 2012). All GAMA-PBP data used in the comparative assessment were recensored at the most common reporting level in the SWRCB-DDW database for the selected organic constituents (0.5 µg/L) and perchlorate (4 µg/L). Thus, any detection for the selected organic and special-interest constituents in GAMA-PBP data that was less than the recensoring thresholds was considered a non-detection for the purposes of the comparative assessment. Samples in the SWRCB-DDW database that were denoted

as non-detections and had reporting levels greater than their respective recensoring threshold were removed from the comparative analysis because it is impossible to know whether these samples might have had concentrations between the recensoring threshold and the reporting level.

Differences between the overall water quality of public- and domestic-supply aquifer systems were evaluated by comparing high-RC aquifer-scale proportions for the selected inorganic constituents. Alternately, spatially weighted detection frequencies were compared for the selected organic and special-interest constituents because they were not detected at high RCs in samples from either aquifer system and had minimal detections at moderate RCs. Statistical difference between aquifer-scale proportions for comparative assessment was significant if the spatially weighted proportion (public supply) was outside of the 90 percent confidence interval for the grid-based proportion (domestic supply) by more than 1 percent (to account for rounding error). Confidence intervals were not directly assessed for the spatially weighted aquifer-scale proportions because of uncertainties regarding within-cell data clustering (Belitz and others, 2010).

Evaluation of Potential Explanatory Factors

Potential explanatory factors describing the hydrogeologic setting of groundwater sites were compiled for the northern Sierra Nevada foothills study units (appendix 1; Levy, 2020). Specific features of individual hard-rock aquifers are not discussed. Geology, land-use patterns, hydrology, geochemical conditions, and recharge conditions are summarized for the combined study units, and differences among the different study units and study areas are also assessed. Explanatory factors were compiled for the 74 grid sites in the YBW study unit and for the 67 grid sites plus one additional understanding site in the ACMW study unit. Although this study uses explanatory factors to assess patterns in groundwater quality, correlations among the different explanatory factors may result in spurious correlations to water quality; therefore, statistical relations among the different explanatory factors are assessed in this section.

Many of the potential explanatory factors were statistically significantly correlated (tables 4, 5). For example, groundwater-site elevations in the study region span a broad range (77–2,158 m) and had significant associations with other important explanatory variables relating to climate (aridity index [AI]), land use (septic tank density), and aquifer lithology (fig. 8). Water-quality constituents with significant correlations to elevation may therefore be explained by any one or combination of elevation-dependent variables.

Table 4. Results of Kruskal-Wallis and posthoc Dunn tests for differences in values of land-use factors, hydrologic conditions, geochemical conditions, and recharge conditions among samples classified in groups by age class, redox class, aquifer lithology class, well depth class, study area, or study unit, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for significant differences. “V > G, MU, MV, MS; G, MS > MV” for aridity index means the following: The aridity index values for sites with volcanic lithologies are significantly greater than aridity index values for sites with granitic, mafic-ultramafic, metavolcanic, or metasedimentary lithologies and aridity index values for sites with granitic or metasedimentary lithologies are significantly greater than aridity index values for sites with metavolcanic lithologies. Relation of median values in sample groups tested shown for Kruskal-Wallis and posthoc Dunn tests if they 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. Test p-values were calculated using the Kruskal-Wallis test; if significant, then pairwise Dunn tests among the were used to determine which differences were significant among the different groups. **Age class:** Mod, modern; Mix, mixed age (modern and pre-modern); Pre, pre-modern. **Aquifer lithology class:** G, granitic; MU, mafic-ultramafic; MV, metavolcanic; MS, metasedimentary; V, volcanic. **Study unit:** ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds. **Study area:** B, Bear; C, Cosumnes; M, Mokelumne; NA, North American; SA, South American; Y, Yuba. **Other abbreviations:** >, greater than; d-excess, deuterium excess; LUFT, leaking (or formerly leaking) underground fuel tank; MAAT, mean annual air temperature; NGRT, noble-gas recharge temperature; NS, not significant (statistical test indicated no significant differences among the sample groups).]

Explanatory factors	Groundwater-age class	Groundwater-redox class	Aquifer-lithology class	Well-depth class	Study unit	Study area
Land use						
Percent agricultural land use	NS	NS	NS	NS	ACMW > YBW	NA > B, Y, SA
Percent natural land use	NS	NS	NS	NS	NS	NS
Percent urban land use	NS	NS	NS	NS	NS	NS
Septic tank density	Mod, Mix > Pre	NS	NS	NS	ACMW > YBW	B, SA > Y; SA > C, M
LUFT density	NS	NS	NS	NS	NS	B > Y, C; NA, SA > C
Hydrologic conditions						
Aridity index	NS	NS	V > G, MU, MV, MS; G, MS > MV	Shallow > Deep, Mixed	YBW > ACMW	Y > B, NA, SA, C, M
Elevation of land-surface datum	NS	NS	V > G, MU, MV, MS; G, MS > MV	Shallow > Mixed	NS	NS
Well depth	Mix, Pre > Mod	NS	NS	Deep, Mixed > Shallow	NS	NS
Depth to top of screened or open interval	NS	NS	NS	Deep > Shallow, Mixed	NS	NS
Geochemical conditions						
pH	Mix, Pre > Mod	Anoxic > Oxidic, Mixed	MU, G, MV > V; MU, MV > MS	Deep, Mixed > Shallow	NS	NS
Dissolved oxygen (DO)	Mod > Mix	Oxidic, Mixed > Anoxic; Oxidic > Mixed	V > G, MU, MV, MS	Shallow > Mixed	NS	NS
Recharge conditions						
Normalized recharge temperature (NGRT - MAAT)	NS	NS	G, MV > V	NS	ACMW > YBW	C, M > Y
d-excess	NS	NS	MS, V > G; V > MU, MV; MS > MV	Shallow > Mixed	NS	NS

[p values are shown for tests in which the variables were determined to be significantly correlated on the basis of p values (not shown) being less than the critical level (α) of 0.05; **blue text**, significant positive correlation; **red text**, significant negative correlation; **bold and underlined text** signifies absolute p value greater than or equal to 0.30. **Abbreviations:** d-excess, deuterium excess, LUFT, leaking (or formerly leaking) underground fuel tank; NGRT, noble-gas recharge temperature; MAAT, mean annual air temperature, NS, not significant (statistical test indicates no correlation between explanatory factors)]

[illegible]

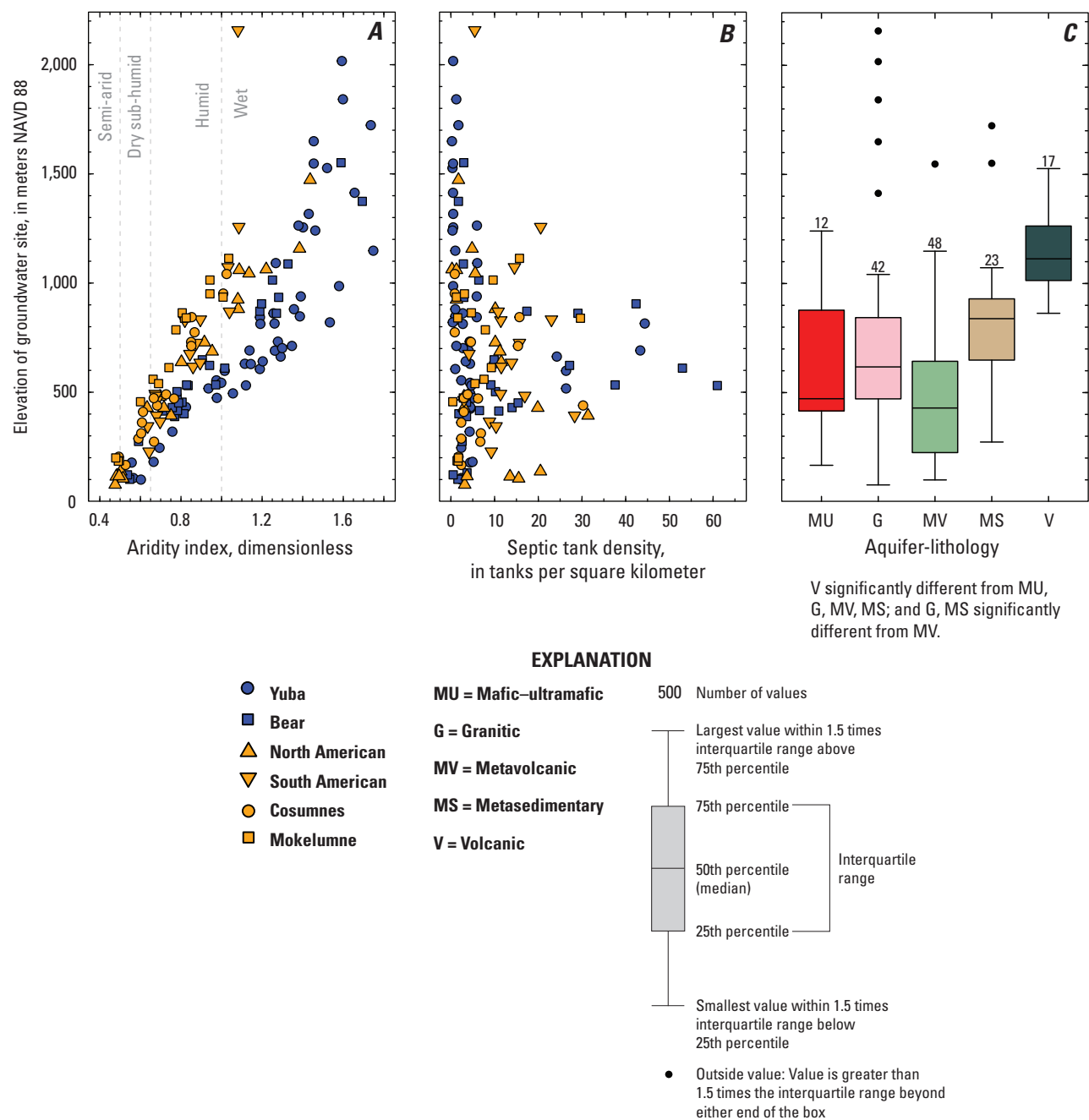


Figure 8. Relations for domestic wells in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project between wellhead elevation and A, aridity index; B, septic tank density; and C, aquifer lithology.

Land Use

Land use in the study region was categorized as “natural,” “urban,” or “agricultural” using satellite imagery (fig. 3B; appendix 1; Levy, 2020). Land use throughout the study region is predominantly natural, which includes grasslands, forests, wetlands, barren land, and other areas where the effects of human development on the land-surface are not easily detectable by satellite imagery. Land use in YBW study unit was only 3 percent urban and less than 1 percent agricultural. Land use in the ACMW study unit was

8 percent urban and less than 1 percent agricultural. To gain a better understanding of the effect of land use on groundwater chemistry, land-use percentages within a 500-m buffer radius from each groundwater site were calculated (Johnson and Belitz, 2009). Land use around individual groundwater sites was mostly dominated by natural land use, with urban land use ranging from less than 1 to 50 percent (fig. 9A). Agricultural land use was minimal around the groundwater sites, except for three sites in the North American study area, three sites in the Cosumnes study area, and one site in the Bear study area where agricultural land use ranged from 10 to 30 percent.

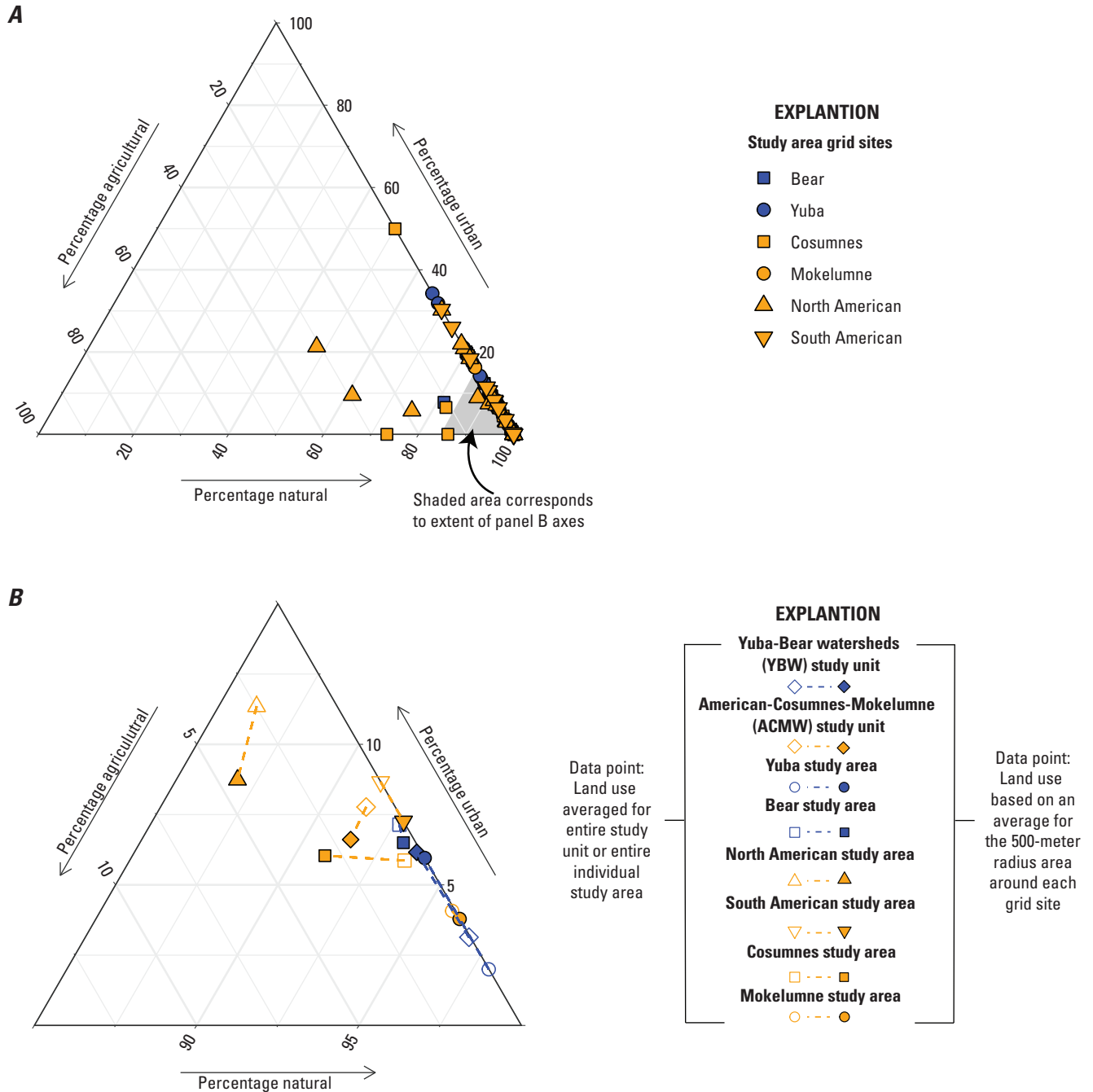


Figure 9. Land use of the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment Program Priority Basin Project: *A*, percentages of urban, agricultural, and natural land use within 500-meter buffer surrounding individual U.S. Geological Survey grid sites and understanding site, and *B*, average land-use composition of the study units and study areas.

Averaging land use around grid sites by study area or unit and comparing to corresponding total study area or unit land use showed that grid sites in the YBW study unit tended to have a greater percentage of urban land use than that of the entire study area or unit (fig. 9B). This was not true, however, for grid sites in the ACMW, which tended to have less urban land use and more agricultural land use within 500 m around wells than in their respective study areas. Using the average land

use characteristics for the entire study unit or area, therefore, could underrepresent land-use influences on groundwater chemistry in individual study areas or grid sites. Agricultural land use was significantly greater around groundwater sites in the ACMW study unit than in the YBW study unit (table 4). Agricultural land use was negatively correlated to elevation (table 5) and was mostly at lower elevations (less than 500 m) in the western part of the study region (fig. 3B).

The satellite data used to quantify land use in this report do not fully capture the complexities of land use in the foothills. Rural-residential land use that is predominant at lower elevations throughout the region can be mistaken as natural use, especially in forested areas. Additionally, large areas of irrigated land used for forage pasture also can be mistaken as natural use because the satellite-based classification scheme used for this report does not distinguish between natural and managed grasslands ([appendix 1](#); Levy, 2020). As a result, human activity in areas dominated by rural-residential development and forage pasture could be underestimated in the land-use results system presented in this report. Consequently, although the land-use data are useful for interpreting water-quality results, they should be evaluated with the aforementioned considerations in mind.

Other land-use metrics can be useful to characterize potential sources of anthropogenic contamination in the study region. Septic-tank and LUFT density were calculated using a Thiessen polygon method and can indicate which sites could be more susceptible to contamination from rural-residential or urban and industrial land uses. Septic tank density ranged from 0.2 to 61 tanks/km² ([fig. 8B](#)) and was greatest in the Bear and South American study areas, although the ACMW study unit had a median density greater than that of the YBW study unit ([table 4](#)). Septic tank density was greatest around sites at elevations between 400 and 1,250 m in suburban (development just beyond urban limits) and exurban (development farther from urban limits than suburban) areas around Nevada City, Grass Valley, and Placerville, where the rural-residential population has greatly expanded in the past 50 years ([fig. 4A](#)). Septic tank density was also positively correlated to urban land use and LUFT density, the latter of which ranged from around 0 to 0.7 tanks/km² ([table 5](#)) and followed elevational patterns similar to that of septic tank density. The LUFT density was greatest in the Bear, North American, and South American study areas ([table 4](#)).

Aquifer Lithology

The bedrock lithology of the northern Sierra Nevada foothills region is complex. To facilitate comparisons among site lithology and water quality, geologic units in the study area, as represented on the California State Geologic Map

(Saucedo and others, 2000) and finer-scale local geologic maps (Saucedo and Wagner, 1992), were grouped into six broad categories:

- Granitic (G): Plutonic, granitic rocks (Mesozoic)
- Mafic-ultramafic (MU): Plutonic, mafic and ultramafic rocks (Mesozoic)
- Metavolcanic (MV): Metamorphosed volcanic rocks (Paleozoic and Mesozoic)
- Metasedimentary (MS): Metamorphosed sedimentary rocks (Paleozoic and Mesozoic)
- Volcanic (V): Volcanic and volcanoclastic rocks (Cenozoic)
- Alluvial and glacial (A): Glacial, alluvial, fluvial, and lacustrine sediments (Cenozoic)

Intrusive plutonic rocks are subdivided into felsic granitic rocks (G; for example, granite and granodiorite) and mafic-ultramafic rocks (MU; for example, gabbro and serpentinite) because the chemical compositions of these igneous rock types differ. Metamorphic rocks are subdivided into metavolcanic (MV) and metasedimentary (MS) groups to differentiate heterogeneous assemblages of metamorphosed volcanic rocks of marine origin (for example, greenstones and ophiolites with abundant peridotite) from variably metamorphosed marine sediments (for example, slates and shales).

Sites with granitic and volcanic lithologies were fairly evenly dispersed throughout the study region and respectively composed approximately 30 and 12 percent of sites in either of the two study units, respectively ([figs. 3A, 10](#)). The YBW study unit had a significantly greater percentage of sites with metavolcanic lithology (43 percent) than the ACMW study unit (24 percent); however, the ACMW study unit had a significantly greater percentage of sites with mafic-ultramafic and metasedimentary lithology (12 and 24 percent, respectively) than the YBW study unit (5 and 10 percent, respectively; [table 6](#); [fig. 10](#)). Sites with volcanic lithology were at significantly higher elevations than the other lithologies, and sites with granitic and metasedimentary lithologies were at higher elevations than those with metavolcanic lithologies ([fig. 8C](#); [table 4](#)). None of the domestic-supply wells sampled for this study were completed in alluvial or glacial sediments ([appendix 1](#); Levy, 2020).

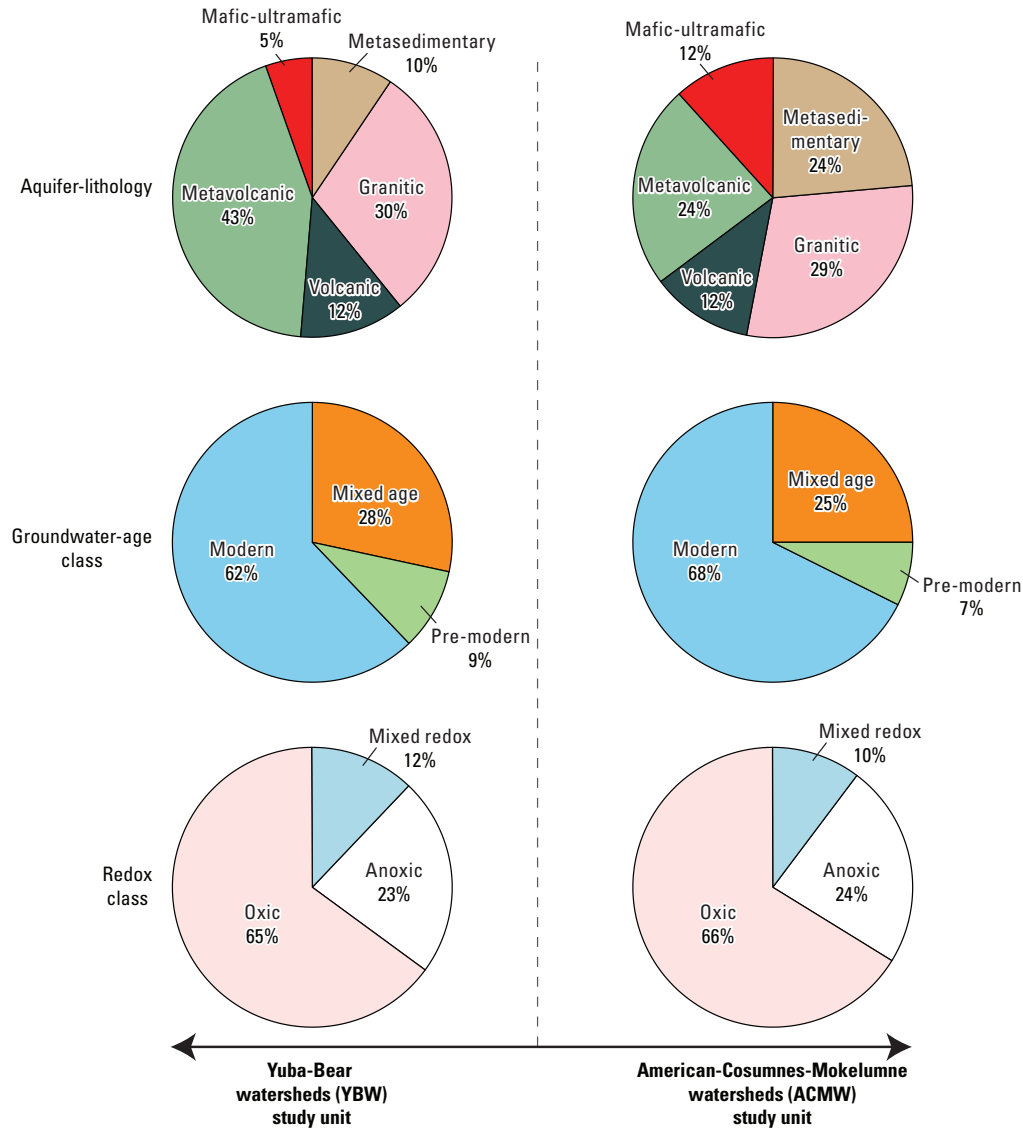


Figure 10. Aquifer lithology, groundwater-age classification, and redox classification for grid sites and understanding site in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. [%, percent]

Hydrologic Conditions

Hydrologic conditions at groundwater sites were summarized by land-surface elevation and AI, the latter of which is a generalized metric of climate defined as the ratio of average potential evapotranspiration to average precipitation (appendix 1; Levy, 2020). Greater values of AI indicate cooler and wetter conditions. The AI was strongly correlated to site elevation because precipitation and temperature increase and decrease, respectively, with land-surface elevation in

the foothills (fig. 8.4; table 5). Sites in the ACMW study unit tended to have lesser AI values than sites at similar elevations in the YBW study unit because there is also a north–south climate gradient in the study region; areas to the south are warmer and drier than areas to the north (fig. 8.4). Sites in the YBW study unit had significantly greater AI values than those in the ACMW study unit, not only because of the north–south climate gradient but also because the Yuba study area contained the highest elevation sites in the study region (fig. 8.4).

Table 6. Results of contingency table tests for associations among groundwater-redox class, groundwater-age class, aquifer lithology, well-depth classification, study unit, and study area, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for factors with significant associations: Groundwater-age class and well depth class are significantly associated. The most important combinations of classes contributing to the significance of the association are *A*, pre-modern groundwater is associated with deep wells; *B*, modern water is associated with shallow wells; and *C*, mixed age water is not associated with shallow wells. Factors determined to be significantly associated on the basis of p-values (not shown) less than a critical value (α) of 0.05 for contingency table test. For factors with a significant association, combinations of classes contributing with the highest percent contributions to the test statistic are listed; **blue text**, classes are associated; **red text**, classes are not associated. **Aquifer lithology class:** G, granitic; MU, mafic-ultramafic; MV, metavolcanic; MS, metasedimentary; V, volcanic. Study unit: ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds. **Study area:** B, Bear; C, Cosumnes; M, Mokelumne; NA, North American; SA, South American; Y, Yuba. **Other abbreviations:** NS, not significant (test indicated no significant association among factors)]

Category	Groundwater-redox class	Aquifer-lithology class	Well-depth class	Study unit	Study area
Groundwater-age class	Anoxic + Mixed age; Anoxic + Pre-modern; Oxic + Modern; Anoxic – Modern; Oxic – Mixed age; Oxic – Pre-modern	NS	Deep + Pre-modern; Shallow + Modern; Shallow – Mixed age	NS	NS
Groundwater-redox class		G + Anoxic; MS + Mixed; V + Oxic; V – Anoxic	NS	NS	NS
Aquifer-lithology class			NS	YBW + MV; ACMW + MS; ACMW + MU; YBW – MS; YBW – MU; ACMW – MV	B + MV; M + MS; SA + MS; B – G; SA – MV
Well-depth class				NS	NS

Well Depth and Groundwater Age

Well-construction information was compiled from well-completion reports for each site to help ascertain depth zones defining domestic-supply aquifer systems in the study region. The four springs in YBW study unit and one spring in ACMW study unit did not have depth-related data because springs emerge at the land surface and do not require drilling to develop. There were construction data for depth to the TOP and well depth for 69 and 70 sites, respectively, in the YBW study unit and for 65 and 67 sites, respectively, in the ACMW study unit. The depth to TOP ranged from 6 to 122 m (median of 21 m) in the YBW study unit and from 3 to 189 m (median of 18 m) in the ACMW study unit (fig. 11A). Well depths ranged from 18 to 229 m (median of 65 m) in the YBW study unit and from 23 to 305 m (median of 85 m) in the ACMW study unit (fig. 11B). There were no significant differences for well depth or depth

to the TOP among the different study areas or study units (table 4). There was a negative correlation of well depth to site elevation (table 5), indicating that deeper wells tended to be at lower elevations, where expansion of the rural-residential population has been concentrated in recent years (figs. 3, 7B; Levy and others, 2020). Lower elevations in the study region tend to have a drier climate, which could cause depths to the water table to be deeper in those areas (fig. 8A). The correlation between elevation and well depth was not extremely strong (Spearman's $\rho = -0.20$), however, and there are likely to be multiple competing factors relating to climate, lithology, and land use that affect this relation (fig. 8). Well depth and depth to the TOP were used to classify wells in aquifer-depth zones (shallow, mixed depth, deep) by choosing a “critical depth,” which was determined by considering groundwater age. After a brief discussion of the groundwater-age classification process, aquifer-depth zone classifications are discussed.

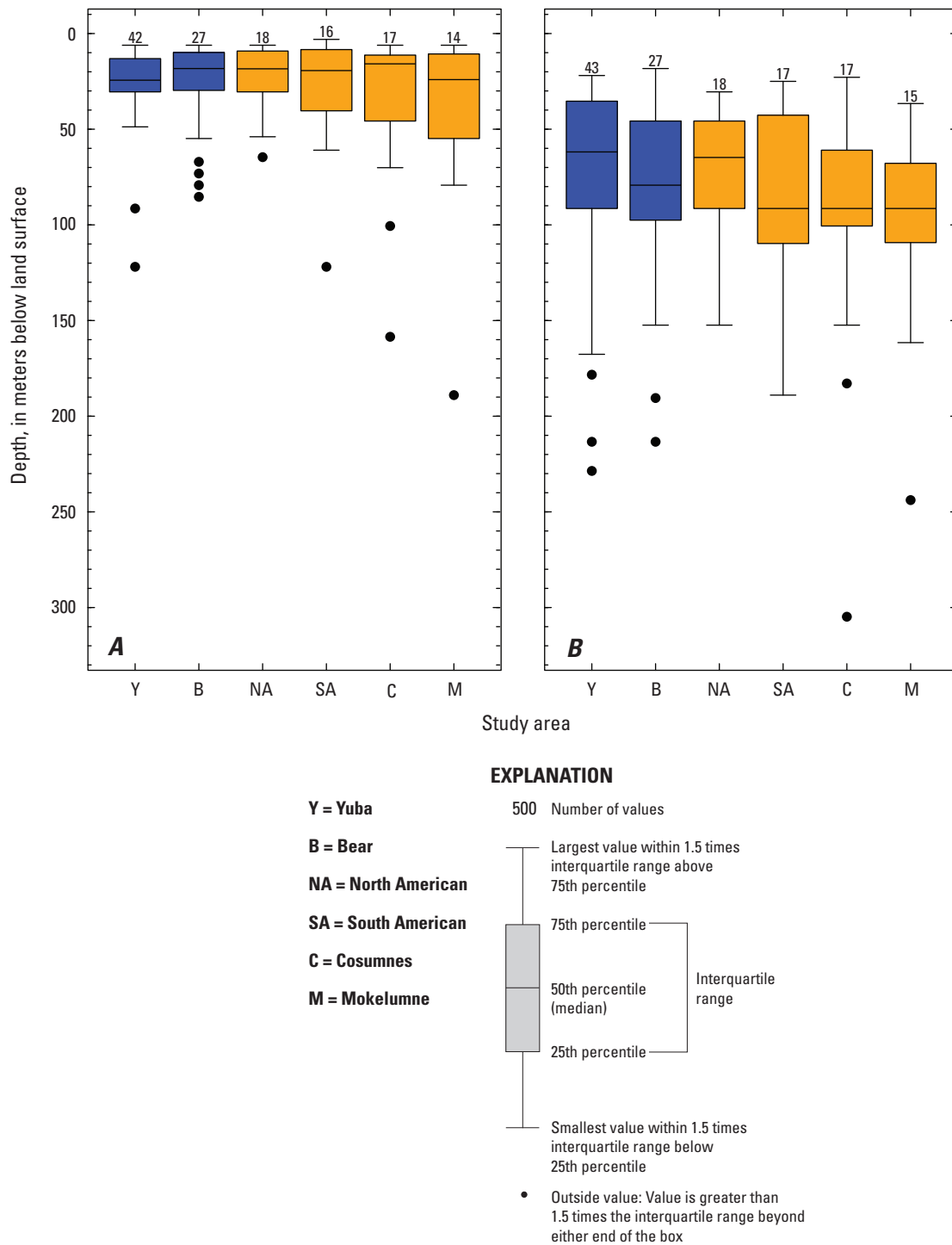


Figure 11. Depths of U.S. Geological Survey sampled grid wells and understanding well by study area in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, to the top of open or perforated interval; and *B*, to completion.

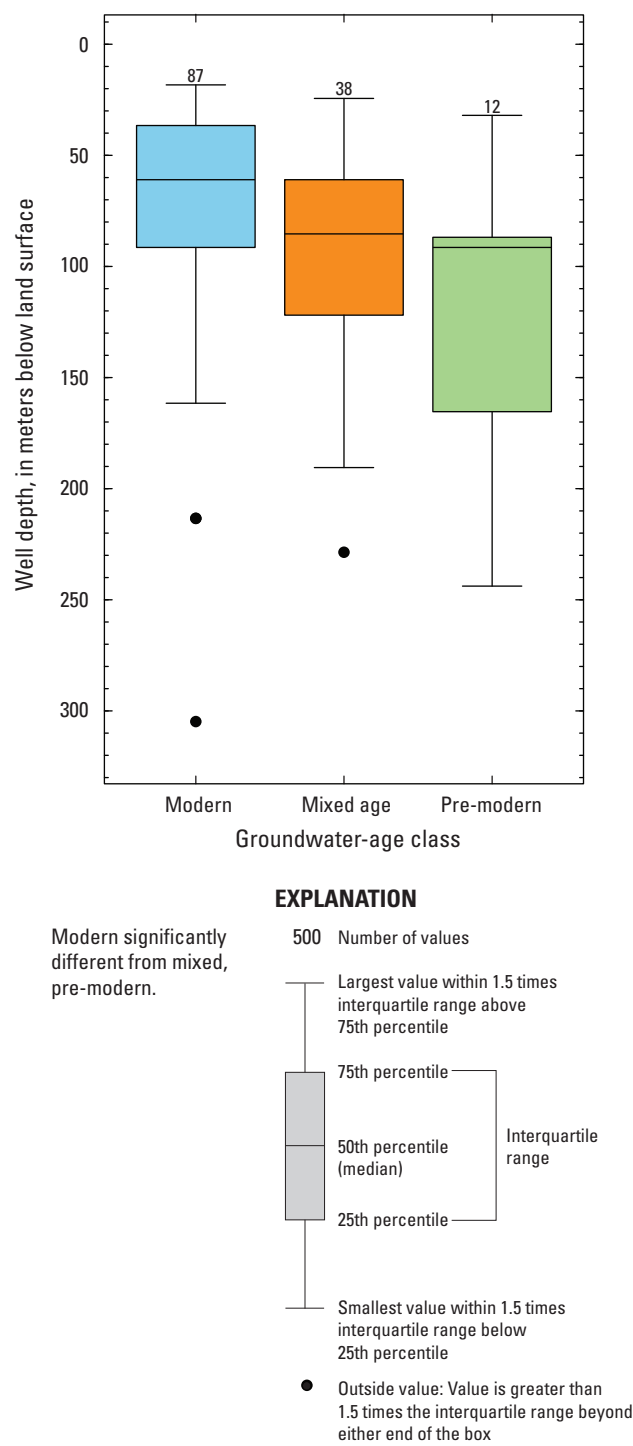


Figure 12. Well depths for U.S. Geological Survey sampled grid wells and understanding well by study groundwater-age classification in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Groundwater age refers to the duration of time that a parcel of water has been in the aquifer system and can be an important indicator of the susceptibility of groundwater to different types of contamination. Younger groundwater tends to be more susceptible to anthropogenic contamination associated with modern land use. Older groundwater can contain higher levels of geogenic contaminants from longer residence times in aquifer systems that can result in more water-rock interactions (Appelo and Postma, 2005). Groundwater samples were assigned groundwater-age classes on the basis of tritium and carbon-14 activities (appendix 1; Levy, 2020). Groundwater classified as “modern” or “pre-modern” recharged the aquifer after or before 1952, respectively, with “mixed” age groundwater representing a mixture of old and young recharge. Regionally, 65, 27, 8 percent of groundwater samples were assigned modern, mixed, and pre-modern age classifications, respectively, with a relatively similar distribution of these groups in the two study units (fig. 10). Sites with mixed and pre-modern age groundwater had deeper wells than those with modern groundwater (fig. 12; table 4), but there was no significant correlation between groundwater age and depth to TOP (table 4). Sites with modern and mixed-age groundwater had higher septic-tank densities than those with pre-modern groundwater (table 4). The latter relation could indicate return flows from rural-residential land uses affect aquifer-recharge dynamics, but this inference was not corroborated by any additional relations among explanatory factors and is a potentially spurious artifact of the small number of groundwater samples of pre-modern age.

Wells were classified in three different depth zones based on the extent of the well’s open interval and groundwater-age classification (Fram and Belitz, 2012). Springs were not assigned depth classes because they did not have construction information from which to attribute aquifer-depth zone information. A critical depth of 40 m was used to define a three-factor depth classification: wells with open intervals above 40 m were considered “shallow,” wells with depths to TOP below 40 m were considered “deep,” and wells with depths to TOP that were above 40 m and total well depths below 40 m were considered “mixed depth” (fig. 13). Fram and Belitz (2012) used a similar critical depth of 52 m. The critical depth of 40 m was chosen for this study to maximize differences in the age distributions among the three depth classes (fig. 13). Because deeper groundwater tends to be older than shallow groundwater, this method helped to identify functional depth zones in the study region where modern, mixed, or pre-modern water are dominant. This resulted in 21, 60, and 19 percent of groundwater sites classified as shallow, mixed depth, and deep, respectively.

Sites with shallow wells were at higher elevations than those with mixed-depth wells, as discussed previously (table 4). Relatedly, sites with shallow wells had greater AI values than those with mixed-depth and deep wells, as discussed previously (table 4). As expected, shallow and deep wells were significantly correlated to modern and pre-modern groundwaters, respectively (table 6).

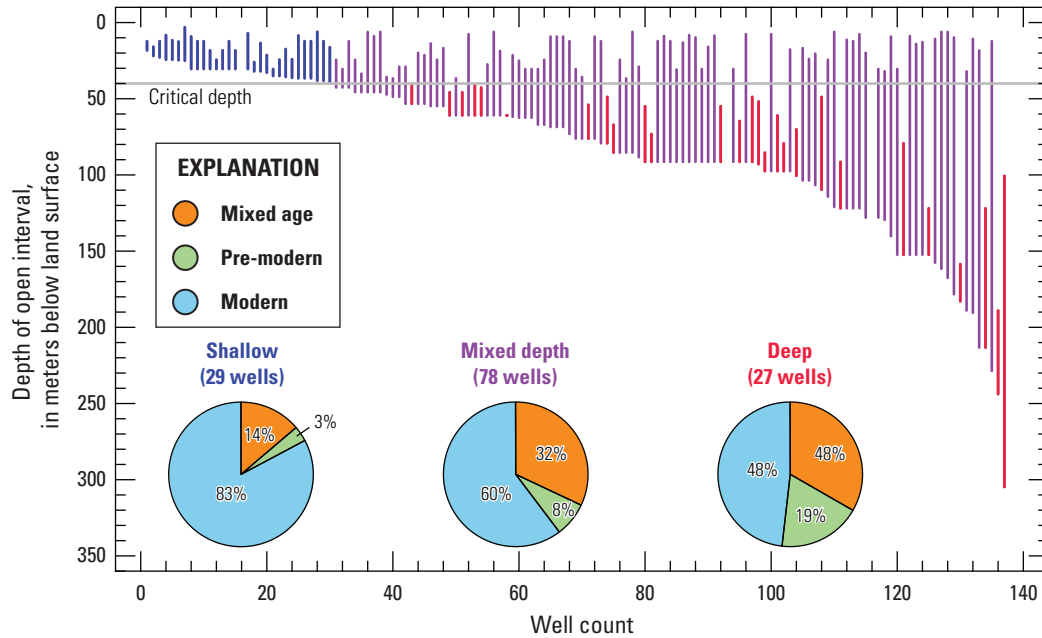


Figure 13. Open intervals for U.S. Geological Survey sampled grid wells and understanding well ranked by well depth and colored by depth classification with inset pie charts showing proportions of groundwater-age classifications for each depth class in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. [%, percent].

Geochemical Conditions

Geochemical conditions in groundwater systems are often characterized by variables such as pH and DO, which influence the fate and transport of many different water-quality constituents in the subsurface (Appelo and Postma, 2005). Oxidation-reduction (redox) conditions for samples from groundwater sites were classified as oxic, anoxic, or mixed (appendix 1; Levy, 2020) using the framework of McMahon and Chapelle (2008) and Jurgens and others (2009). Regionally, 66, 23, 11 percent of groundwater samples were assigned oxic, anoxic, and mixed redox classifications, respectively, with a similar distribution of these groups in the two study units (fig. 10).

Groundwater DO ranged from less than 0.2 to 10.5 mg/L and had strong positive and negative correlations to elevation and pH, respectively, and was also negatively correlated to a lesser degree with well depth (figs. 14A–B, 15A; table 5). Groundwater DO was positively correlated to elevation because volcanic lithologies had higher DO and were at higher elevations than the other lithologies (fig. 8C; table 4). Excluding wells with volcanic lithology from the correlation test resulted in a non-significant correlation between elevation and DO ($p=0.094$). The regional relation of DO to elevation and other elevation-dependent explanatory variables (for example, AI) is therefore spurious; it is primarily driven by the fact that volcanic lithologies with oxic groundwater tended to be at high elevations in the study region.

Volcanic deposits could have groundwater with more DO than do the other lithologies because of complex and interrelated factors. Tertiary volcanic deposits in the study region are mostly pyroclastic and can be highly porous and permeable (Saucedo and Wagner, 1992; John and others, 2012), which could promote infiltration of oxygen-saturated recharge to the subsurface. Additionally, the volcanic deposits tend to be at ridgetops (fig. 3A) and could function as groundwater recharge areas reflecting the composition of downwelling meteoric waters as opposed to deeper, upwelling of groundwater discharge. The median DO concentration for groundwater from volcanic lithologies was 7.7 mg/L, only slightly less than the range that would be expected for oxygen-saturated meteoric water at those sites (9–11 mg/L; Levy and Faulkner, 2019), indicating minimal alteration of recharge by oxygen-consuming redox reactions in the subsurface.

Relations of groundwater DO to well depth and pH are most likely related to differences in groundwater age. Oxic samples were significantly associated with modern groundwater, and anoxic samples were significantly associated with pre-modern and mixed-age groundwater (table 6). Older groundwater tends to be in deeper wells and can have lower DO and higher pH than younger, shallower water because of chemical reactions with organic matter and aquifer minerals that consume oxygen and produce alkalinity as groundwater moves along flowpaths from recharge to discharge zones (Appelo and Postma, 2005).

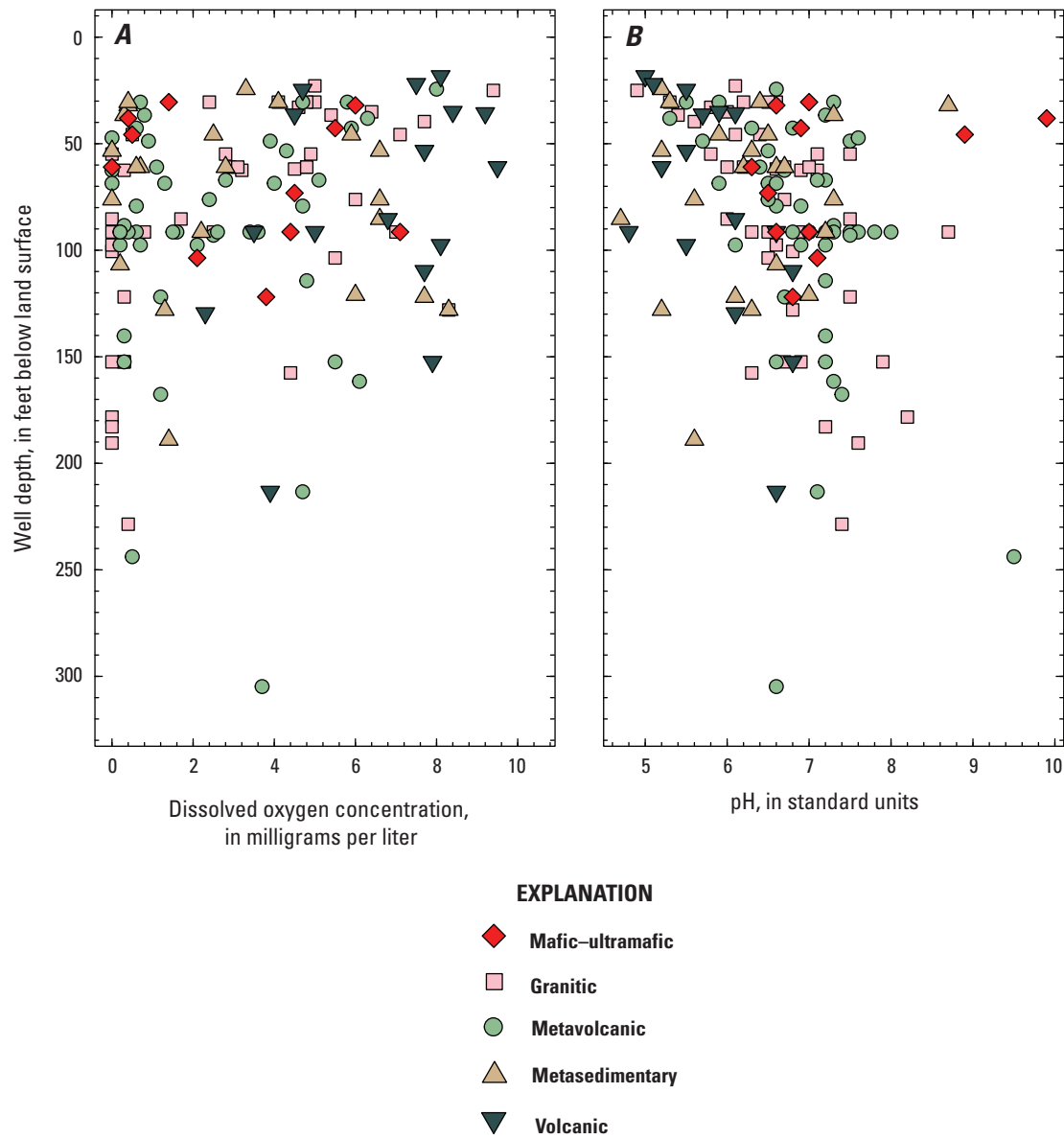


Figure 14. Relations of well depth for U.S. Geological Survey sampled grid wells and understanding well by aquifer lithology in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project to A, dissolved oxygen concentration; and B, pH.

Groundwater pH ranged from 4.7 to 9.9 and had a strong positive correlation to well depth and negative correlations to elevation and DO (fig. 14B; table 5). As discussed previously, higher pH water at deeper well depths with lower DO is likely a function of groundwater age. Groundwater pH was significantly higher in mixed and pre-modern age groundwater than in modern groundwater and was also greater for deep and mixed depth wells than for shallow wells (table 4). The groundwater pH of aquifers with volcanic lithologies was significantly less than those of granitic, mafic-ultramafic, and metavolcanics lithologies (fig. 15B; table 4). Groundwater in the volcanic aquifers had a median pH value of 5.7, similar to what would be expected for rainwater at equilibrium

with the atmosphere (about 5.5; Appelo and Postma, 2005). Similarity between the pH of volcanic groundwater and that of precipitation supports the hypothesis that meteoric recharge with little alteration from water-rock interactions is pervasive in the volcanic deposits, as is also evidenced by the high DO concentrations discussed previously. There was still a significant negative correlation between pH and elevation after excluding the volcanic lithologies from the correlation test (p less than 0.001), however, indicating a broader association between groundwater pH and elevation in the study region that is not exclusively driven by high-elevation sites with volcanic lithology.

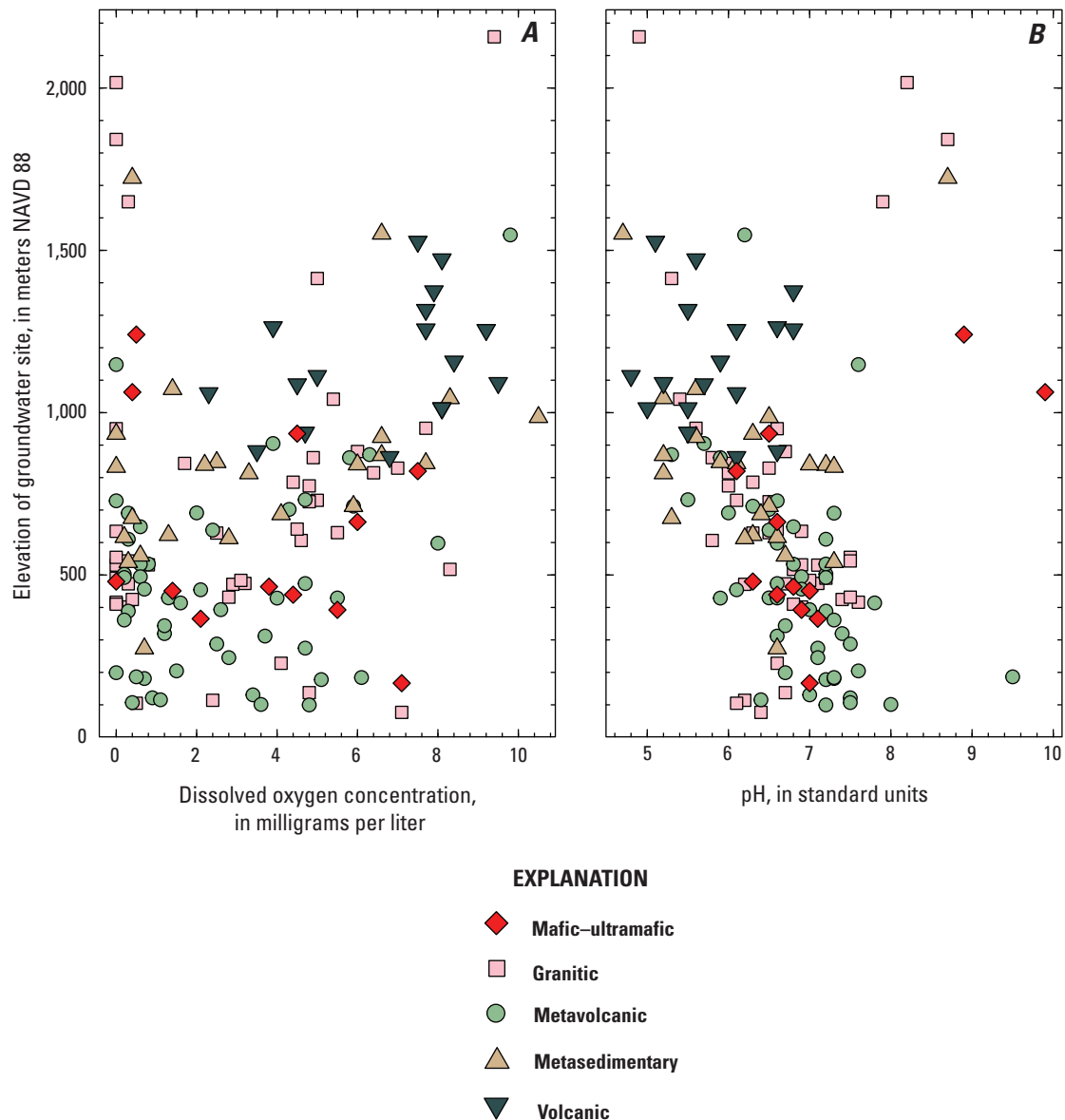


Figure 15. Relations of wellhead elevation for U.S. Geological Survey sampled grid wells and understanding well by aquifer lithology in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project to A, dissolved oxygen concentration; and B, pH.

A number of factors could contribute to the higher pH of groundwater at lower elevations in the study region. As discussed previously, wells in the study region tended to be deeper at lower elevations (table 5). Additionally, changes in geology with elevation in the foothills could also affect groundwater geochemistry (figs. 7C, 15B). For example, metavolcanic and mafic-ultramafic rock types are more prevalent at lower elevations and consist of heterogeneous assemblages of greenstone and serpentized rocks, including ophiolite sequences containing abundant peridotite (Day and

others, 1985). Aquifers with abundant serpentized mafic and ultramafic rocks, particularly peridotite, can develop extremely alkaline groundwater (Chavagnac and others, 2013; Twing and others, 2017; Giampouras and others, 2019). Additionally, lower elevations of the study area fall within the Melones fault zone (fig. 3A; Clark, 1960). Major faults in this area could provide structural pathways for upwelling of deep, alkaline groundwater, as has been observed elsewhere in the Sierra Nevada foothills (Mack and Ferrell, 1979; Mack and Schmidt, 1981).

Recharge Conditions

The process by which water infiltrates the unsaturated zone and enters aquifers is called recharge. Understanding hydrologic processes that affect sources and seasonality of recharge can help to understand where groundwater quality might be more vulnerable to degradation from contaminants originating at the land surface. This report uses two different metrics to understand sources and seasonality of recharge: deuterium excess (*d-excess*) and noble-gas recharge temperature (NGRT; Levy and others, 2020).

The *d-excess* parameter is derived from measurements of the stable isotopes of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$; appendix 1; Levy, 2020) and provides a unique fingerprint for water molecules

derived from local precipitation inputs. Values of *d-excess* are reported in parts per thousand (per mille) and can help to distinguish groundwater recharge from local precipitation (about 12.6 per mille) and recharge from surface water, which tends to be less than the global average for precipitation (less than 10 per mille) in the northern Sierra Nevada foothills (Levy and others, 2020). Surface water in the foothills is diverted for local use to lower elevation (less than 1,000 m) parts of the study watersheds and can recharge aquifers as irrigation return flow or direct seepage from unlined canals and ditches (fig. 5). Groundwater *d-excess* values less than 10 per mille can therefore indicate mixing with recharge from surface-water sources used extensively for irrigation and drinking-water supply in the study region.

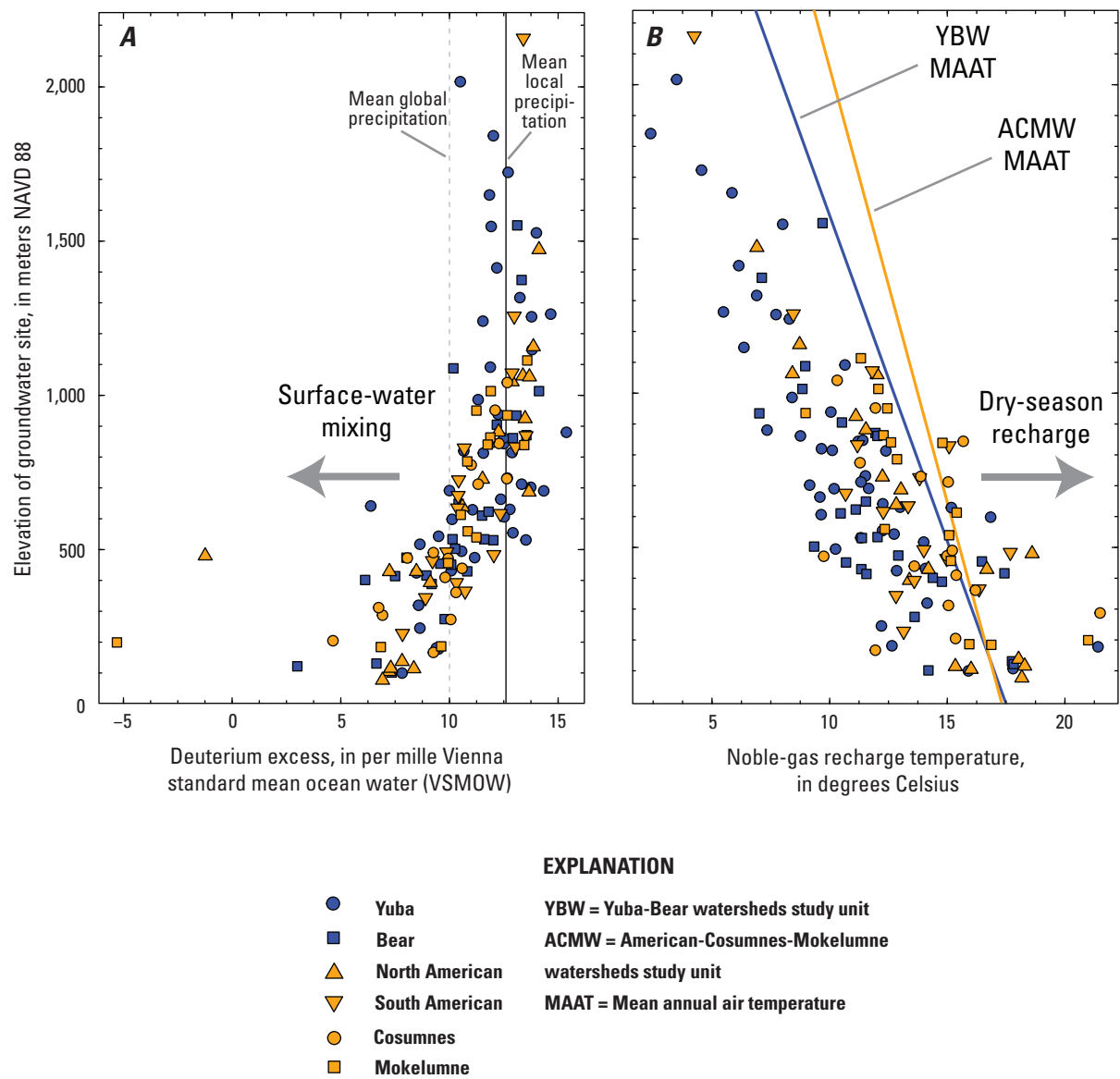


Figure 16. Relations of wellhead elevation for U.S. Geological Survey sampled grid wells and understanding well by study area in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project to A, deuterium excess; and B, noble-gas recharge temperature.

Groundwater *d-excess* ranged from -5.3 to 15.4 per mille and had strong, positive correlations to elevation and AI (also strongly correlated with elevation; [table 5](#)). Wells below an elevation of 700 m showed evidence of mixing with recharge derived from surface water ([fig. 16A](#)). The relations of *d-excess* to elevation and AI most likely arise because irrigation districts divert surface water for local use to serve irrigators predominantly at lower elevations in the study region ([fig. 4](#)) and annual rainfall decreases progressively at lower elevations ([fig. 8A](#)). The effects of recharge from surface water can have a more pronounced effect on groundwater *d-excess* in areas where precipitation is less and return flows from surface sources can make up a more substantial fraction of the annual recharge budget (Levy and others, 2020). Lower values of groundwater *d-excess* were also associated with areas of greater agricultural land use, supporting the hypothesis that irrigation is an important source of surface-water recharge ([table 5](#)). Respective positive and negative correlations of *d-excess* to DO and pH are potentially spurious and more likely reflect the geological factors discussed previously that control geochemical conditions across the elevation gradient of the study region ([table 5](#)).

The solubility of noble gases (neon, argon, krypton, and xenon) in water is temperature dependent, and measurements of noble gases dissolved in groundwater can be used to back-calculate the temperature of recharge water when it initially entered the aquifer system (Stute and Schlosser, 2000). Groundwater NGRT can be used to infer the seasonality of recharge to fractured bedrock aquifers where recharge is rapid and does not have time to equilibrate to the ground temperature in the unsaturated zone (Plummer and others, 2001). Values of NGRT exceeding local mean annual air temperatures (MAATs) are indicative of recharge during the dry season in the northern Sierra Nevada foothills from irrigation or seepage from extensive water-distribution infrastructure (Levy and others, 2020).

Values for NGRT were calculated for 136 groundwater sites for which there were noble-gas measurements and adequate model fits ([appendix 1](#); Levy and Faulkner, 2019; Levy, 2020). Groundwater NGRTs ranged from

2.4 to 21.5 °C and decreased with elevation largely because of regional climate gradients ([fig. 16B](#)). For comparative purposes, MAATs were obtained for individual study sites (1981–2010 climate normals; PRISM Climate Group, 2015) and used to define local temperature–elevation lapse rates on the study-unit scale. Groundwater NGRT typically was less than atmospheric MAATs throughout both study units ([fig. 16B](#)), because groundwater recharge in the northern Sierra Nevada foothills is relatively rapid and derives from winter rainstorms when air temperatures are cooler than the annual average (Levy and others, 2020). At lower elevations (less than 700 m), however, some NGRT values substantially exceeded site MAATs, indicating recharge during the summer dry season when there is virtually no rainfall in the foothills. High NGRTs can serve as another independent indicator of recharge derived from diverted surface-water flows, which increase in response to peak water demand during the dry season (Levy and others, 2020).

To account for the effects of the regional climate–elevation gradient, NGRT values were normalized by subtracting the site MAAT. The normalized NGRT is therefore a measure of how much warmer or colder the NGRT is than the local atmospheric average, with positive and negative values indicating preferential recharge during the summer and winter, respectively. Normalized NGRT ranged from -6.4 °C (below the MAAT) to 5.3 °C (above the MAAT) and was negatively correlated to elevation because NGRT values exceeded local MAATs exclusively at lower elevations (less than 700 m; [fig. 16B](#); [table 5](#)). Normalized NGRTs also correlated to agricultural land use and were greater in the ACMW study unit than the YBW study unit ([tables 4, 5](#)). This is likely due to irrigation during the summer dry season and the fact that the ACMW study unit has more agricultural land use than the YBW study unit ([table 4](#)). Normalized NGRT was also negatively correlated to *d-excess* ([fig. 17](#); [table 5](#)). This supports the interpretation that recharge from surface water (indicated by lesser *d-excess* values) is related to dry-season recharge from regional rivers diverted for human use in the lower elevations of the study region ([fig. 5](#)).

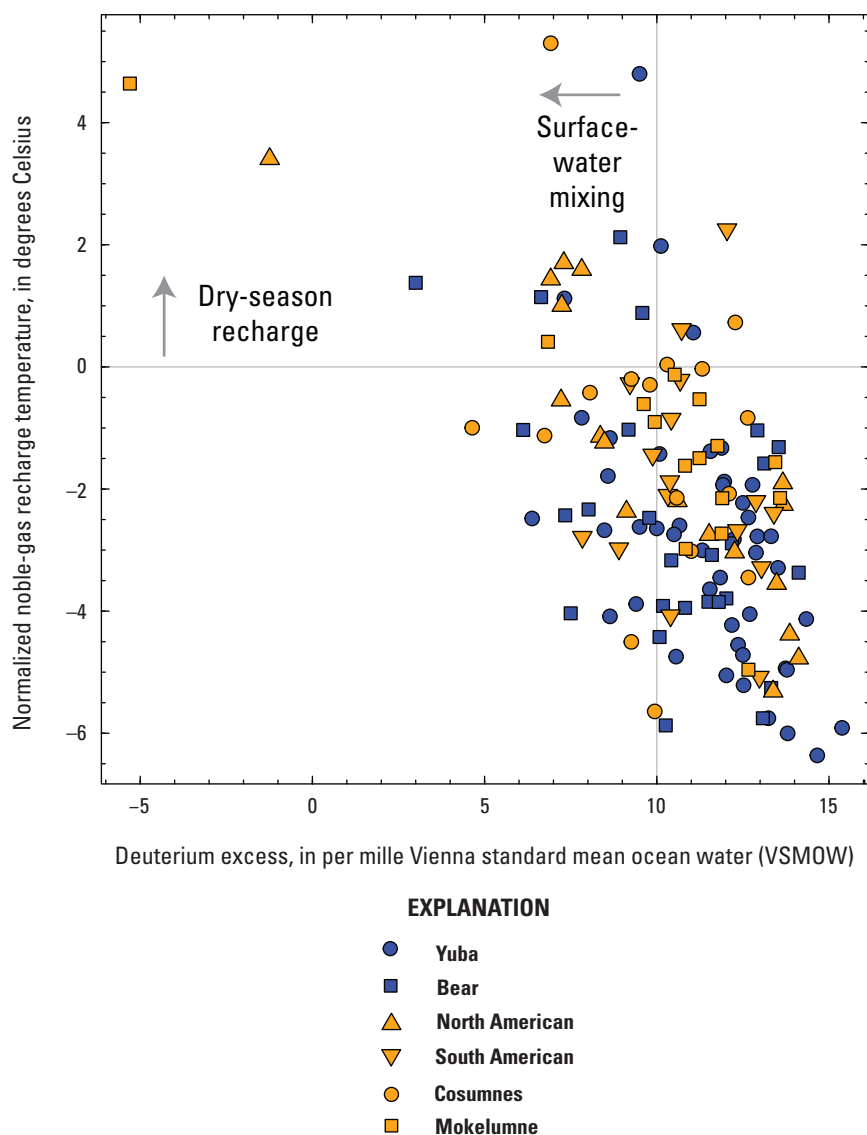


Figure 17. Relations of groundwater deuterium excess to normalized noble-gas recharge temperature for U.S. Geological Survey sampled grid wells and understanding well, by study area, in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Status and Understanding of Groundwater Quality in Aquifers Used for Domestic Drinking-Water Supply

The discussion of the status and understanding assessments for groundwater quality in the northern Sierra Nevada foothills study units is divided into three parts: (1) inorganic constituents, (2) microbial indicators, (3) organic and special-interest constituents. Each part begins with a survey of the constituents that were detected and includes a graphical summary of the constituents with benchmarks that were detected at grid sites. Results for aquifer-scale proportion calculations are presented for individual

constituents and constituent classes that were detected in a grid well at moderate or high RCs or had study unit-scale detection frequencies greater than 10 percent for organic and special-interest constituents. Results of statistical tests and graphical analyses evaluating the effects of potential explanatory factors on regional groundwater quality are then presented for constituents that met the criteria for further evaluation in the understanding assessment (any constituent present at high RC in greater than 2 percent of the aquifer system or with study-unit scale detection frequencies of greater than 10 percent in grid wells for organic and special-interest constituents). Summary statistics for aquifer-scale proportions of inorganic and organic constituents are presented in [tables 7–9](#).

Table 7. Summary of aquifer-scale proportions for inorganic constituent classes with health-based benchmarks, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.5 times the benchmark unless otherwise noted in [table 2](#). **Abbreviations:** YBW, Yuba-Bear watersheds; ACMW, American-Cosumnes-Mokelumne watersheds]

Study unit	Aquifer-scale proportion (percent)		
	Low RC	Moderate RC	High RC
Radioactive constituents with health-based benchmarks			
YBW	96	2.7	1.4
ACMW	99	1.5	0
Nutrients with health-based benchmarks ¹			
YBW	99	1.4	0
ACMW	91	1.5	7.5
Trace elements with health-based benchmarks			
YBW	89	6.8	4.1
ACMW	93	3.0	4.5
All inorganic constituents with health-based benchmarks ²			
YBW	85	9.5	5.4
ACMW	84	6.0	10

¹Nitrate is the only constituent in this category.

²Perchlorate is considered an inorganic constituent of special interest and is not included in this category because it is evaluated in a similar manner to organic constituents to maintain consistency with prior GAMA-PBP assessments.

Inorganic Constituents

Inorganic constituents are naturally present in groundwater as a result of water-rock interactions but can also be affected by anthropogenic factors (Appelo and Postma, 2005). All 45 inorganic constituents analyzed by the GAMA-PBP for the YBW study unit were detected (Jasper and others, 2017). All 44 inorganic constituents analyzed by the GAMA-PBP for the ACMW study unit were detected except for silver (Shelton and others, 2018). The inorganic constituents without benchmarks include major and minor ions that are ubiquitous in most aquifer systems ([table 3](#)). Although perchlorate is technically a trace inorganic compound, it is considered a constituent of special interest and is evaluated in a similar manner to the organic constituents in the “[Organic and Special-Interest Constituents](#)” section of this report.

The maximum RC (highest measured concentration of a water-quality constituent divided by its benchmark) was used to summarize inorganic constituents chosen for evaluation in the status assessment; graphs show the maximum RCs

in both of the northern foothills study units ([figs. 18A–B](#)). Any inorganic constituent detected at a moderate or high maximum RC value was selected for further evaluation in the status assessment. Of the 34 inorganic constituents with benchmarks (not counting perchlorate), 16 were detected at moderate or high RCs at grid sites: the trace elements with health-based benchmarks arsenic, barium, boron, fluoride, molybdenum, and strontium; the nutrient nitrate; radioactive constituents adjusted gross-alpha particle radioactivity (30-day count; [appendix 3](#)), gross-beta particle radioactivity (30-day count; [appendix 3](#)); and the inorganic constituents with aesthetic-based standards or secondary maximum contaminant level (SMCL) benchmarks chloride, hardness, manganese, iron, specific conductance, sulfate, total dissolved solids (TDS; [table 2](#); [figs. 18A–B, 19A–E](#)). Four inorganic constituents were present at high RCs in greater than 2 percent of the aquifer system (in either study unit). Four were selected for further evaluation in the understanding assessment: nitrate, iron, manganese, and hardness.

Table 8. Summary of aquifer-scale proportions for inorganic constituent classes with secondary maximum contaminant level (SMCL) benchmarks, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.5 times the benchmark unless otherwise noted in [table 2](#). **Abbreviations:** ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds]

Study unit	Aquifer-scale proportion (percent)		
	Low RC	Moderate RC	High RC
Salinity indicators with SMCL benchmarks ¹			
YBW	99	1.4	0
ACMW	97	1.5	1.5
Trace elements with SMCL benchmarks ²			
YBW	73	6.8	20
ACMW	66	7.5	27
All constituents with SMCL benchmarks ¹			
YBW	73	6.8	20
ACMW	63	9.0	28

¹Hardness is not included in this constituent class because it does not have an official state or federal SMCL benchmark.
²Iron and manganese are the only constituents in this category.

As a class, inorganic constituents with human-health benchmarks (trace elements, nutrients, and radioactive constituents) were at high RCs in 5.4 and 10 percent of the domestic-supply aquifer system in the YBW and ACMW study units, respectively, and at moderate RCs in 9.5 and 6.0 percent ([table 7](#)). Inorganic constituents having SMCL benchmarks (major ions and trace elements with benchmarks) as a class were at high RCs in 20 and 28 percent of the domestic-supply aquifer system in the YBW and ACMW study units, respectively, and at moderate RCs in 6.8 and 9.0 percent ([table 8](#)). Hardness is not included in the SMCL class and sub-class summary results presented in [table 8](#) because it has no official State or Federal SMCL benchmark. For the purposes of this report, however, hardness is evaluated and discussed in status and understanding assessments alongside constituents with SMCL benchmarks because it has similar aesthetic effects on water quality.

Table 9. Summary of aquifer-scale proportions for organic constituent classes with health-based benchmarks and constituents of special interest, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

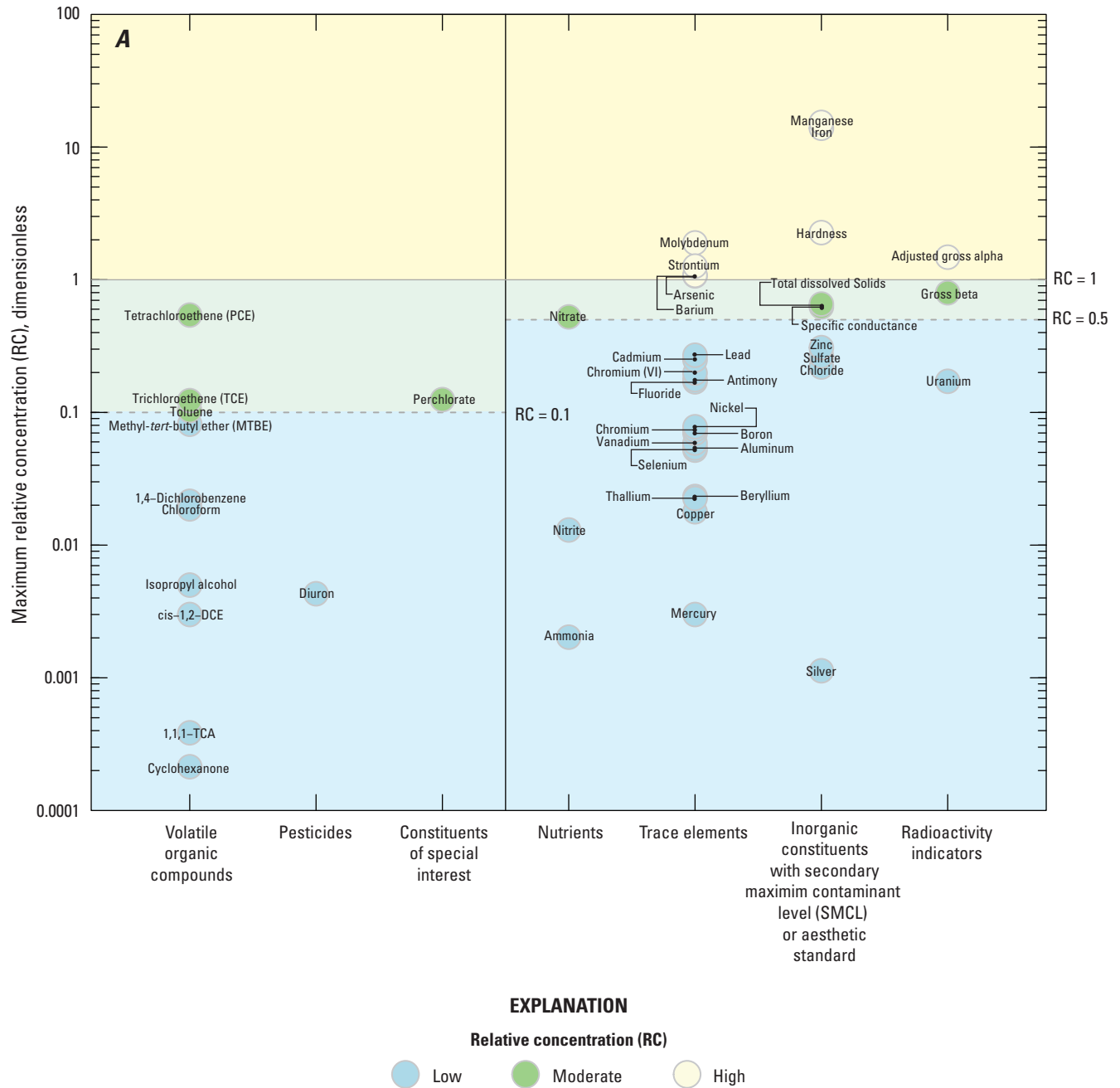
[**Relative-concentration (RC) categories:** high, concentration of at least one constituent in group greater than water-quality benchmark; moderate, concentration of at least one constituent in group greater than low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.1 times the benchmark unless otherwise noted in [table 2](#). **Abbreviations:** ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds]

Study unit	Aquifer-scale proportion (percent)			
	Not detected	Low RC	Moderate RC	High RC
Volatile organic compounds				
YBW	73	24	2.7	0
ACMW	66	34	0	0
Pesticides				
YBW	95	5.5	0	0
ACMW	89	11	0	0
Any organic constituent				
YBW	70	27	2.7	0
ACMW	58	42	0	0
Constituents of special interest ¹				
YBW	69	30	1.4	0
ACMW	59	39	1.5	0

¹Perchlorate is the only constituent in this category.

Trace Elements

As a class, trace elements with health-based benchmarks were at high RCs in 4.1 and 4.5 percent of the domestic-supply aquifer systems in YBW and ACMW study units, respectively, and at moderate RCs in 6.8 and 3.0 percent ([table 7](#)). Arsenic, barium, molybdenum, and strontium were present at high or moderate RCs in the YBW study unit ([fig. 19A](#); [table 10](#)). Arsenic, boron, fluoride, and molybdenum were present at high or moderate RCs in the ACMW study unit ([fig. 19A](#); [table 10](#)). No trace elements with health-based benchmarks were present at high RCs in more than 2 percent of the primary-aquifer system in either study unit. Although there is a history of mercury contamination in river sediments that is related gold mining operations in the study region, mercury was not present at high or moderate RCs in any of the groundwater sampled in this study. Mercury was only detected in groundwater from 4 out of the 142 wells at concentrations ranging from 0.005 to 0.039 µg/L, much less than the MCL-US of 2 µg/L ([table 3](#)).



Two pesticides (tebuthiuron and methoxyfenozide) were detected at relative concentrations (RC) less than 0.0001

Figure 18. Maximum relative concentrations of constituents detected in grid wells by constituent class, 2015–16, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, for the A, Yuba-Bear watersheds study unit; B, American-Cosumnes-Mokelumne watersheds study unit.

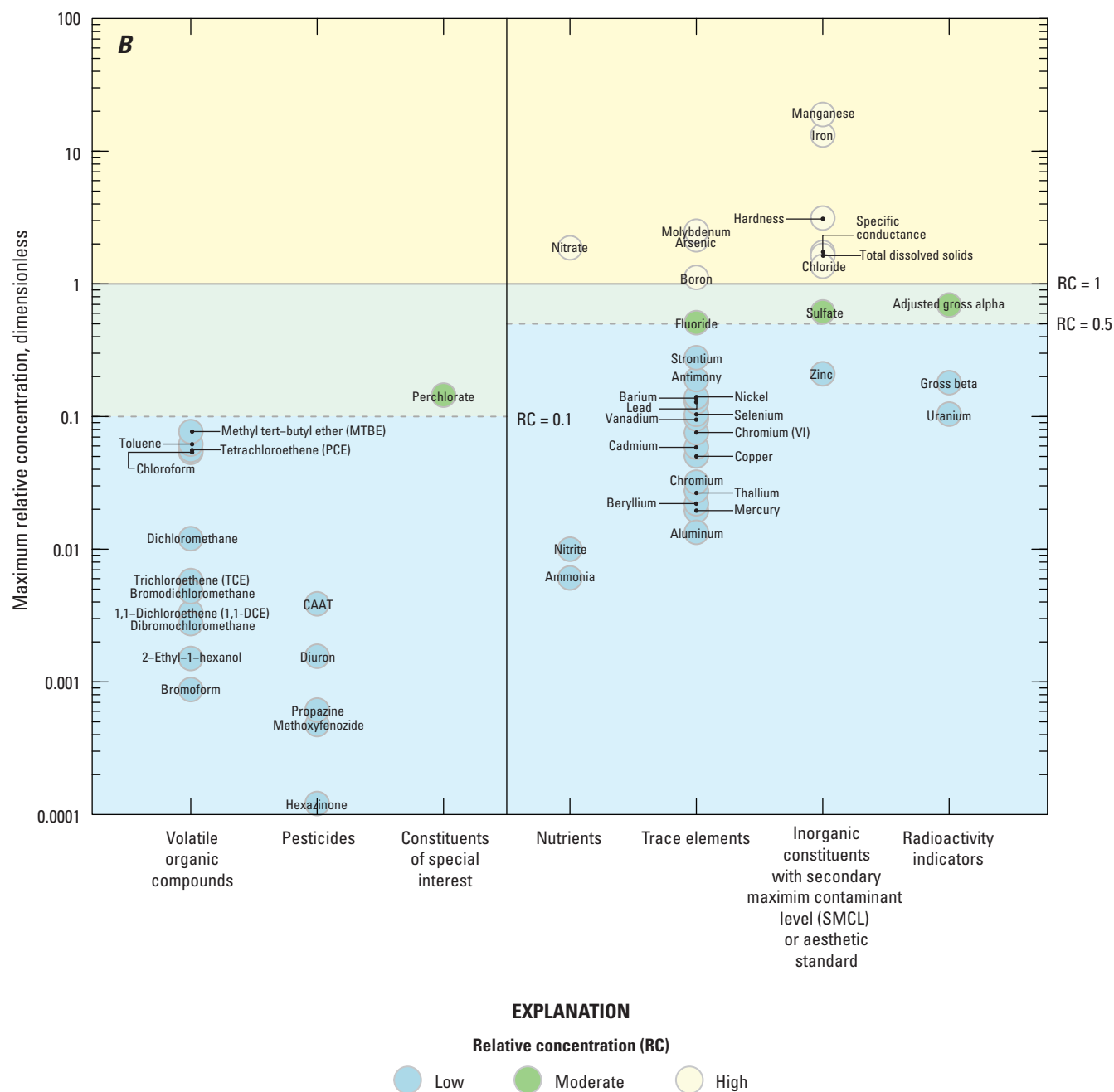


Figure 18.—Continued

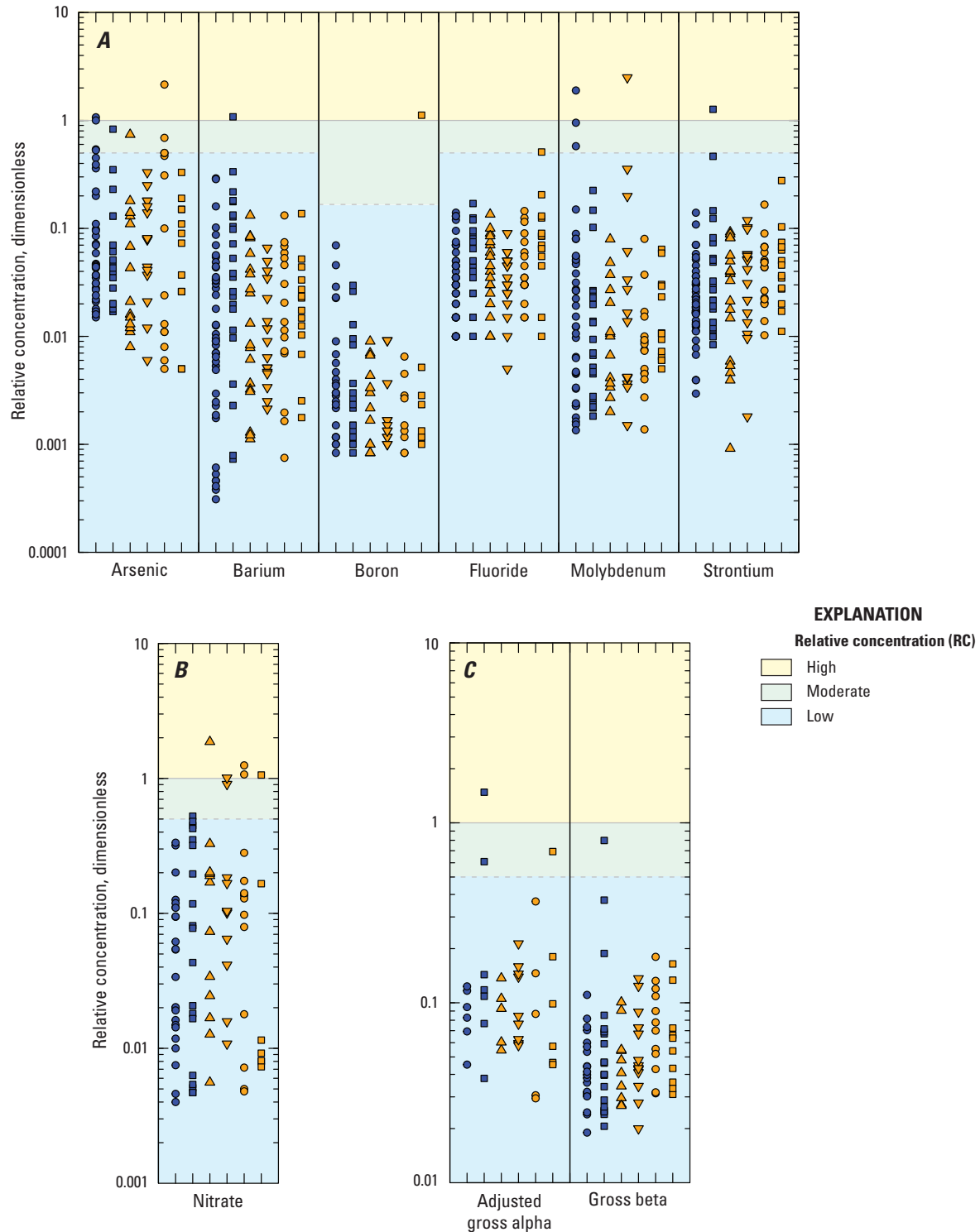


Figure 19. Relative concentrations detected in grid wells in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, for selected *A*, trace elements with regulatory and non-regulatory health-based benchmarks; *B*, nutrients with regulatory health-based benchmarks; *C*, radioactivity indicators with regulatory health-based benchmarks; *D*, major ionic constituents with non-regulatory, aesthetic-based benchmarks; and *E*, trace elements with non-regulatory, aesthetic-based benchmarks.

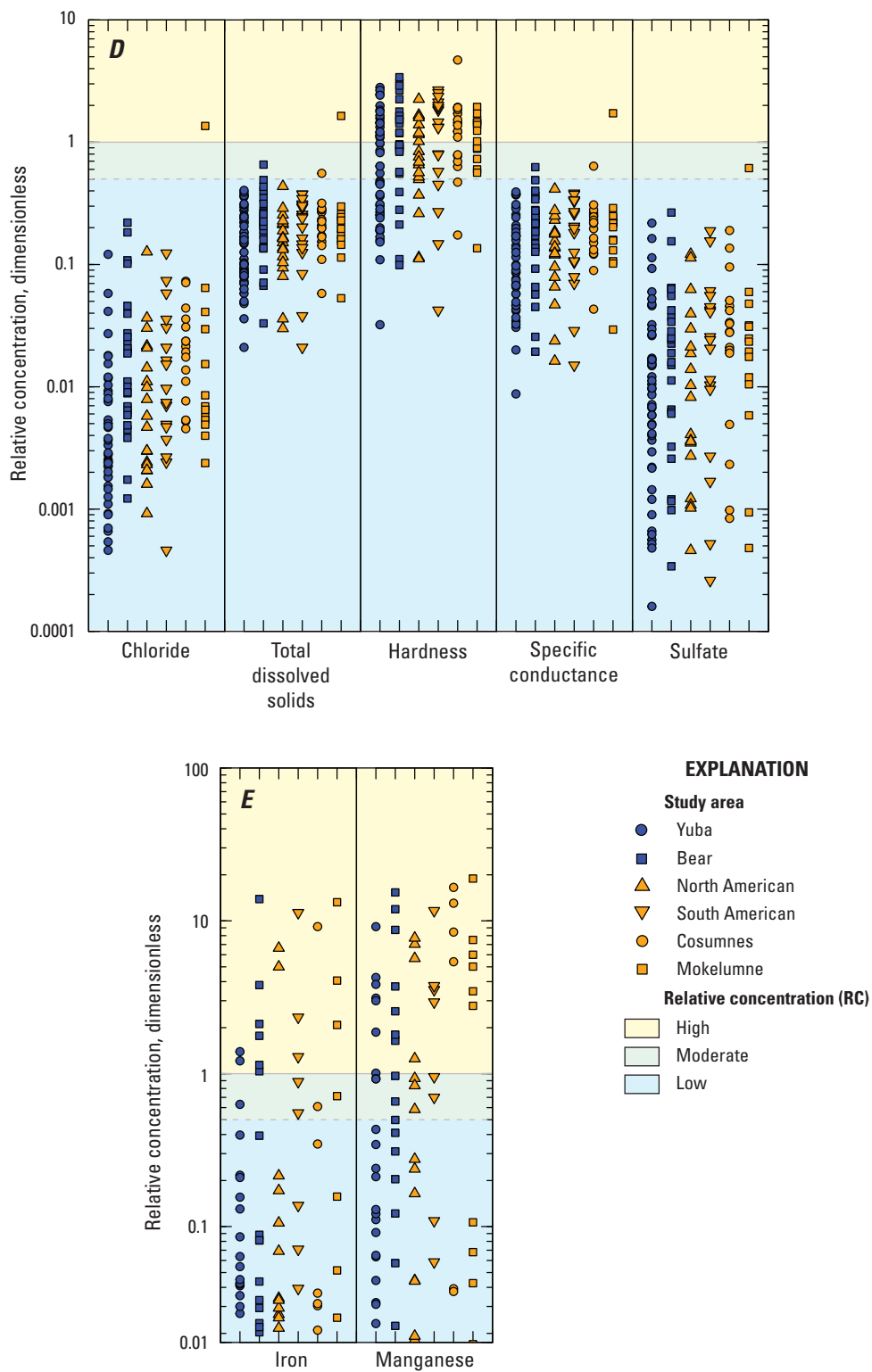


Figure 19.—Continued

Table 10. Aquifer-scale proportions calculated using the grid-based method for constituents that met criteria for additional evaluation in the status assessment, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Grid-based aquifer-scale proportions for the Yuba-Bear watersheds study unit are based on samples collected by the U.S. Geological Survey from 74 of 75 sampled grid sites (one sample per grid cell) from November 2015 to May 2016; the one grid sample that was not used was determined to have been treated by water softeners prior to sampling and is not representative of raw aquifer water. Grid-based aquifer-scale proportions for the American-Cosumnes-Mokelumne watersheds study unit are based on samples collected by the U.S. Geological Survey from 67 sampled grid sites from August 2016 to January 2017. **Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.5 times the benchmark for inorganic constituents and 0.1 times the benchmark for organic constituents unless otherwise noted in table 2. Confidence intervals are given as lower limit and upper limit. **Abbreviations:** %, percentage; NA, not applicable; SMCL, secondary maximum contaminant level.]

Constituent	Yuba-Bear watersheds (YBW) study unit				American-Cosumnes-Mokelumne watersheds (ACMW) study unit			
	Organic constituent detection frequency, in percent	Aquifer-scale proportion, in percent	Moderate RC	High RC	90% confidence interval (lower and upper limit) for grid-based high proportion, in percent ¹	Organic constituent detection frequency, in percent	Aquifer-scale proportion, in percent	90% confidence interval (lower and upper limit) for grid-based high proportion, in percent ¹
Inorganic constituents with health-based benchmarks								
Trace elements								
Arsenic	NA	5.4	1.4	0.2–5.2	NA	3.0	1.5	0.3–5.7
Barium	NA	0	1.4	0.2–5.2	NA	0	0	0–2.0
Boron	NA	0	0	0–1.8	NA	0	1.5	0.3–5.7
Fluoride	NA	0	0	0–1.8	NA	1.5	0	0–2.0
Molybdenum	NA	2.7	1.4	0.2–5.2	NA	0.0	1.5	0.3–5.7
Strontium	NA	0.0	1.4	0.2–5.2	NA	0.0	0	0–2.0
Nutrients								
Nitrate, as nitrogen	NA	1.4	0	0–1.8	NA	1.5	7.5	3.4–14
Radioactive constituents								
Adjusted gross-alpha particle radioactivity	NA	1.4	1.4	0.2–5.3	NA	1.5	0	0–2.1
Gross-beta particle radioactivity	NA	1.4	0	0–1.8	NA	0	0	0–2.0
Inorganic constituents with SMCL or aesthetic-based benchmarks								
Chloride	NA	0	0	0–1.8	NA	0	1.5	0.3–5.7
Hardness, as calcium carbonate	NA	18	24	17–33	NA	25	30	21–40
Iron	NA	1.4	11	6.0–18	NA	6.0	13	7.8–21
Manganese	NA	5.4	19	12–27	NA	7.5	27	19–36
Specific conductance	NA	1.4	0	0–1.8	NA	1.5	1.5	0.3–5.7
Sulfate	NA	0	0	0–1.8	NA	1.5	0	0–2.0
Total dissolved solids (TDS)	NA	1.4	0	0–1.8	NA	1.5	1.5	0.3–5.7

Table 10. Aquifer-scale proportions calculated using the grid-based method for constituents that met criteria for additional evaluation in the status assessment, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[Grid-based aquifer-scale proportions for the Yuba-Bear watersheds study unit are based on samples collected by the U.S. Geological Survey from 74 of 75 sampled grid sites (one sample per grid cell) from November 2015 to May 2016; the one grid sample that was not used was determined to have been treated by water softeners prior to sampling and is not representative of raw aquifer water. Grid-based aquifer-scale proportions for the American-Cosumnes-Mokelumne watersheds study unit are based on samples collected by the U.S. Geological Survey from 67 sampled grid sites from August 2016 to January 2017. **Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.5 times the benchmark for inorganic constituents and 0.1 times the benchmark for organic constituents unless otherwise noted in table 2. Confidence intervals are given as lower limit and upper limit. **Abbreviations:** %, percentage; NA, not applicable; SMCL, secondary maximum contaminant level.]

Constituent	Yuba-Bear watersheds (YBW) study unit			American-Cosumnes-Mokelumne watersheds (ACMW) study unit		
	Organic constituent detection frequency, in percent	Aquifer-scale proportion, in percent	90% confidence interval (lower and upper limit) for grid-based high proportion, in percent ¹	Organic constituent detection frequency, in percent	Aquifer-scale proportion, in percent	90% confidence interval (lower and upper limit) for grid-based high proportion, in percent ¹
Organic constituents with health-based benchmarks						
Volatile organic compounds						
Trichloromethane (chloroform)	14	0	0–1.8	15	0	0–2.0
Methyl <i>tert</i> -butyl ether (MTBE)	15	0	0–1.8	13	0	0–2.0
Tetrachloroethylene (PCE)	9.5	1.4	0–1.8	3.0	0	0–2.0
Toluene	1.4	1.4	0–1.8	1.5	0	0–2.0
Trichloroethylene (TCE)	1.4	1.4	0–1.8	1.5	0	0–2.0
Constituents of special interest						
Perchlorate	31	1.4	0–1.8	41	1.5	0–2.0

¹Based on Jeffreys interval for the binomial distribution; for non-zero proportions, the confidence interval is calculated as a two-sided interval, and for zero, a one-sided interval is computed (Brown and others, 2001; Belitz and others, 2010).

Nutrients

Nitrate was the only nutrient detected at moderate or high RCs in either study unit (fig. 19B; tables 3, 10). Nitrate was only present at moderate RCs in 1.4 percent of the YBW study unit (table 10). Nitrate was present at moderate RCs in 1.5 percent and at high RCs in 7.5 percent of the ACMW study unit (table 10).

Factors Affecting Nitrate

Nitrate is a nutrient that is ubiquitous in natural systems and concentrated in wastewaters (for example, septic-system leachate and effluent from wastewater-treatment plants) as well as natural and synthetic fertilizers (Kendall, 1988). Although nitrate is commonly present at low-concentrations in groundwater, concentrations greater than 1 milligram as nitrogen per liter (mg-N/L) typically indicate anthropogenic sources of contamination (Burow and others, 2010). High concentrations of nitrate in drinking water can be fatal to infants and can cause a variety of ill-health effects in adults. The EPA established an MCL-US for nitrate in drinking water of 10 mg-N/L in 1975 (U.S. Environmental Protection Agency, 2018).

Groundwater nitrate concentrations ranged from non-detection (less than 0.04 mg-N/L) to 18.7 mg-N/L in the study region. Wells with moderate and high RCs of nitrate were located at lower elevations (less than 500 m) where urban and agricultural land uses are more prominent in the study region (fig. 20). Groundwater nitrate increased significantly with decreasing elevation (table 11), and there were no detections of nitrate greater than what would be expected for natural “background” concentrations (1 mg N/L) at elevations above 1,100 m (fig. 21). This is largely due to changes in land use from higher to lower elevation, evidenced by significant correlations to agricultural and urban land uses as well as septic-tank density (table 11). These correlations were not strong (Spearman’s rho less than 0.30), however, and do not fully explain trends in nitrate concentration, most likely because rural-residential and forage-pasture land uses are not recognized as urban or agricultural land uses in the land-use classification framework used in this report (appendix 1; Levy, 2020). Lands developed for rural-residential use and forage pasture can be major sources of nitrate to groundwater recharge from natural and synthetic fertilizer applications, livestock manure, and septic-system leachate (Levy and others, 2020).

Geochemical conditions and groundwater age can help to further characterize the vulnerability of different wells to nitrate contamination. Groundwater with nitrate concentrations higher than natural background levels was overwhelmingly of modern age and oxic redox classifications (figs. 22A–B; table 12), which indicates that nitrate has been introduced to the groundwater by recharge after the 1950s. Additionally, this modern recharge is mostly oxic and does not have a substantial attenuation capacity for nitrate. Alternately, nitrate

can be transformed to nitrogen gas by microbial reduction (denitrification) in anoxic groundwater, which is relatively inert and does not contribute to degradation of drinking-water supply (Burow and others, 2010).

Indicators of groundwater recharge condition can help elucidate sources and pathways of nitrate to groundwater aquifers. Groundwater nitrate had a significant negative correlation to *d-excess* and a significant positive correlation to normalized recharge temperature (NGRT-MAAT; table 11), indicating higher concentrations could be related in part to irrigation recharge, which peaks during the summer dry-season. These regional results are consistent with the finding that groundwater *d-excess* values less than 10 per mille are indicative of mixing with surface waters typically used for irrigation in the YBW study unit (fig. 23; Levy and others, 2020). Additionally, nitrate was significantly correlated to perchlorate (table 13), which is natural in soils and can be flushed from soil zones to drinking-supply aquifers by irrigation water (further discussed in the “Factors Affecting Perchlorate” section of this report). Although the upper range of nitrate concentrations was greater in the ACMW study unit than in the YBW study unit, median concentrations were not significantly different between the two study units. High nitrate concentrations in the ACMW study unit could be an effect of more agricultural land use in that area (table 4). The combined irrigation return flows are an important pathway of nitrate to domestic-supply aquifers in the study region.

Isotopes of nitrogen and oxygen in the nitrate molecule ($\delta^{15}\text{N-NO}_3$, $\delta^{18}\text{O-NO}_3$) can be used to further parse sources of nitrate in groundwater systems. Isotopes of nitrate were measured for 84 samples with sufficient nitrate concentrations for isotopic analyses (Jasper and others, 2017; Shelton and others, 2018). Values of $\delta^{18}\text{O-NO}_3$ ranged from -6.7 to $+12.0$ per mille, which is a typical range for most groundwater nitrate. There was no evidence of mixing with synthetic nitrate fertilizers, which are typically synthesized from atmospheric oxygen and have distinctively high $\delta^{18}\text{O-NO}_3$ values ($+18$ to $+22$ per mille; Kendall, 1988). Values for $\delta^{15}\text{N-NO}_3$ ranged from $+0.6$ to $+24.0$ per mille and could be derived from multiple nitrate sources (fig. 24). Microbial oxidation of ammonium ions derived from fertilizers or rain results in $\delta^{15}\text{N-NO}_3$ values 0 to $+5$ per mille, soil nitrate typically ranges from $+3$ to $+8$ per mille, septic leachate can range from $+5$ to $+20$ per mille, and manure and human waste typically are the most enriched and range from $+10$ to $+25$ per mille (Kendall, 1988; Katz and others, 2011). Microbial denitrification processes enrich $\delta^{15}\text{N-NO}_3$ and $\delta^{18}\text{O-NO}_3$ together causing linear departures from source compositions on cross-plots of the two respective species with slopes ranging from 1 to 2 in δ -space (Kendall, 1988). There was little evidence that denitrification substantially affected the detected concentrations of nitrate in this study, except in one anoxic sample (fig. 24). The only other sample with high $\delta^{15}\text{N-NO}_3$ greater than $+22$ per mille was oxic and had a lower value for $\delta^{18}\text{O-NO}_3$, which could have been caused by mixing with nitrate originating from human or animal waste (fig. 24).

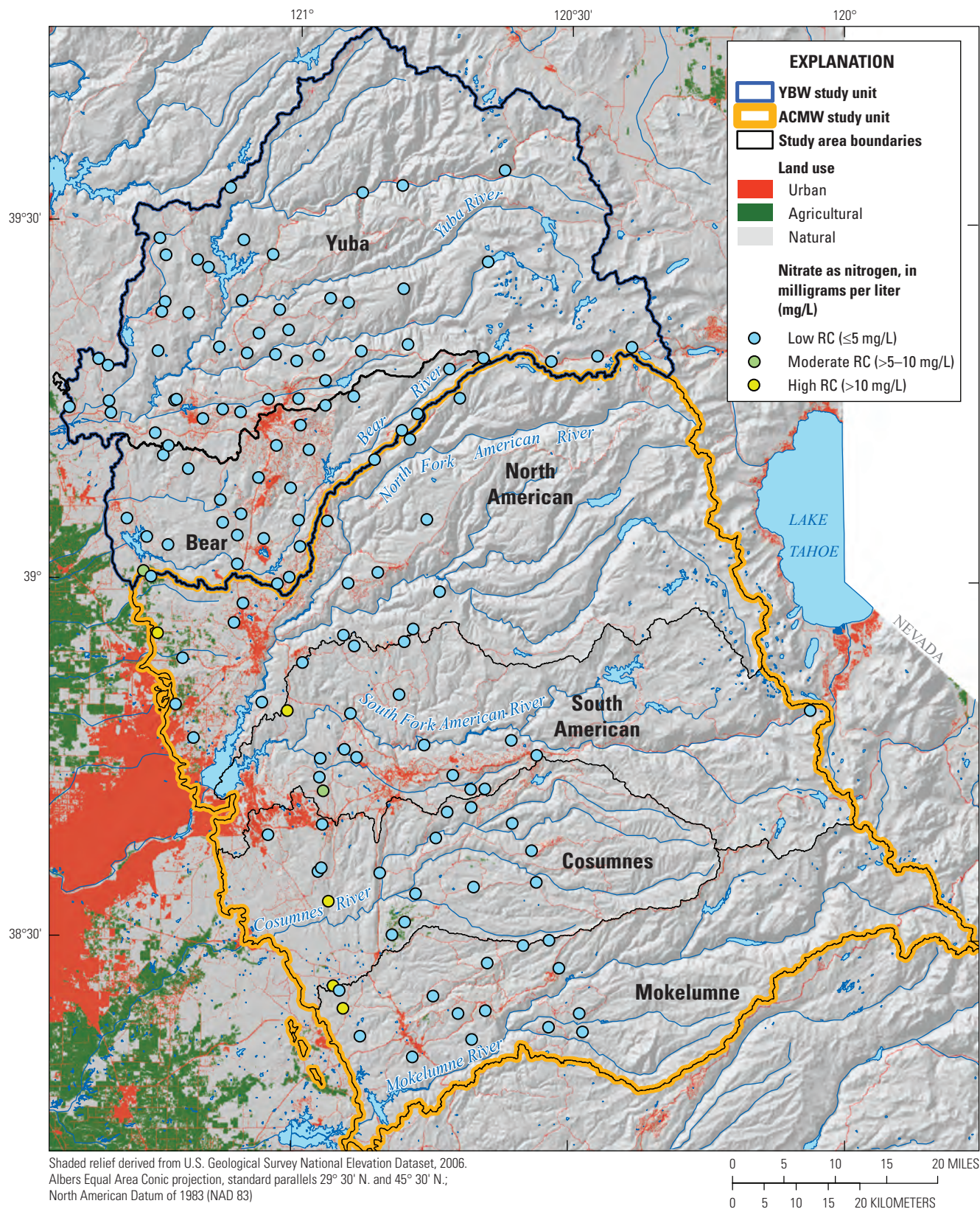


Figure 20. Relative concentrations (RC) of nitrate in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Table 11. Results of Spearman's rho tests for correlation of potential explanatory factors to selected water-quality constituents, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[p values are shown for tests in which the variables were determined to be significantly correlated on the basis of p values (not shown) being less than the critical level (α) of 0.05; **blue text**, significant positive correlation; **red text**, significant negative correlation; **bold and underlined text** signifies absolute p value greater than or equal to 0.30. Abbreviations: d-excess, deuterium excess; LUFT, leaking (or formerly leaking) underground fuel tank; MAAT, mean annual air temperature; NGRT, noble-gas recharge temperature; NS, not significant (statistical test indicated no correlation between water-quality constituent and explanatory factor); SMCL, secondary maximum contaminant level]

Constituent	Land use (percent)			Density of septic tanks	Density of LUFTs	Aridity index	Elevation	Well depth	Depth to top of open interval	pH	Dissolved oxygen	Normalized recharge temperature (NGRT - MAAT)	d-excess
	Agricultural	Natural	Urban										
Inorganic constituents with health-based benchmarks													
Trace elements													
Arsenic	NS	NS	0.07	NS	NS	-0.29	-0.30	0.32	NS	0.50	-0.30	0.09	-0.32
Barium	0.19	-0.08	0.06	0.20	0.16	0.11	0.18	-0.13	0.09	-0.26	NS	-0.19	0.19
Boron	0.17	-0.19	0.16	NS	NS	-0.34	-0.44	0.17	NS	0.55	-0.49	NS	-0.43
Fluoride	0.19	-0.09	NS	0.17	0.22	-0.55	-0.51	0.28	NS	0.51	-0.54	0.28	-0.47
Molybdenum	-0.11	NS	NS	NS	0.11	-0.21	-0.24	0.30	0.08	0.57	-0.50	NS	-0.26
Strontium	0.16	-0.14	0.11	0.27	0.23	-0.26	-0.17	0.12	NS	0.17	-0.18	NS	-0.08
Nutrients													
Nitrate, as nitrogen	0.17	-0.11	0.10	0.23	NS	-0.39	-0.39	-0.07	-0.19	-0.09	0.27	0.35	-0.30
Radioactive constituents													
Adjusted gross-alpha particle radioactivity	NS	-0.06	0.08	0.12	NS	NS	NS	0.09	NS	NS	-0.17	NS	NS
Gross-beta particle radioactivity	0.13	NS	-0.08	0.13	NS	0.07	0.23	0.08	NS	-0.16	NS	-0.06	0.14
Inorganic constituents with SMCL or aesthetic-based benchmarks													
Chloride	0.20	-0.07	NS	0.29	0.18	-0.74	-0.74	0.21	-0.18	0.36	-0.33	0.43	-0.61
Hardness, as calcium carbonate	NS	NS	NS	0.17	0.11	-0.64	-0.67	0.33	-0.09	0.63	-0.45	0.25	-0.52
Manganese	NS	NS	-0.09	0.07	NS	NS	NS	NS	NS	NS	-0.38	-0.10	0.07
Iron	0.07	NS	-0.08	NS	NS	NS	0.07	0.09	NS	0.06	-0.47	-0.06	0.07
Specific conductance	0.09	NS	NS	0.15	0.13	-0.69	-0.73	0.36	-0.08	0.66	-0.46	0.30	-0.57
Sulfate	0.11	NS	NS	0.09	0.09	-0.59	-0.62	0.31	-0.10	0.56	-0.55	0.27	-0.56
Total dissolved solids (TDS)	0.10	NS	NS	0.20	0.18	-0.69	-0.73	0.36	NS	0.63	-0.43	0.31	-0.56

p values are shown for tests in which the variables were determined to be significantly correlated on the basis of p values (not shown) being less than the critical level (α) of 0.05; [blue text](#), significant positive correlation; [red text](#), significant negative correlation; **bold and underlined text** signifies absolute p value greater than or equal to 0.30. Abbreviations: d-excess, deuterium excess; LUFT, leaking (or formerly leaking) underground fuel tank; MAAT, mean annual air temperature; NGRT, noble-gas recharge temperature; NS, not significant (statistical test indicated no correlation between water-quality constituent and explanatory factor); SMCL, secondary maximum contaminant level]

Constituent	Land use (percent)			Density of septic tanks	Density of LUFTs	Aridity index	Elevation	Well depth	Depth to top of open interval	pH	Dissolved oxygen	Normalized recharge temperature (NGRT - MAAT)	d-excess
	Agricultural	Natural	Urban										
Organic constituents with health-based benchmarks													
Volatile organic compounds													
Trichloromethane (chloroform)	NS	-0.09	0.12	0.16	0.13	0.13	0.10	-0.07	NS	-0.21	0.14	NS	0.09
Methyl <i>tert</i> -butyl ether (MTBE)	NS	-0.11	0.11	0.13	0.15	NS	NS	NS	NS	NS	-0.13	-0.07	NS
Tetrachloroethylene (PCE)	0.13	-0.11	0.10	NS	-0.07	NS	NS	NS	NS	-0.10	NS	0.09	-0.07
Toluene	NS	NS	NS	NS	NS	NS	NS	-0.07	-0.07	-0.08	NS	0.14	NS
Trichloroethylene (TCE)	0.19	NS	NS	-0.07	NS	-0.19	-0.20	NS	-0.14	NS	NS	0.18	-0.17
Constituents of special interest													
Perchlorate	0.24	-0.20	0.19	0.18	NS	-0.30	-0.29	-0.10	-0.14	-0.08	0.25	0.38	-0.21

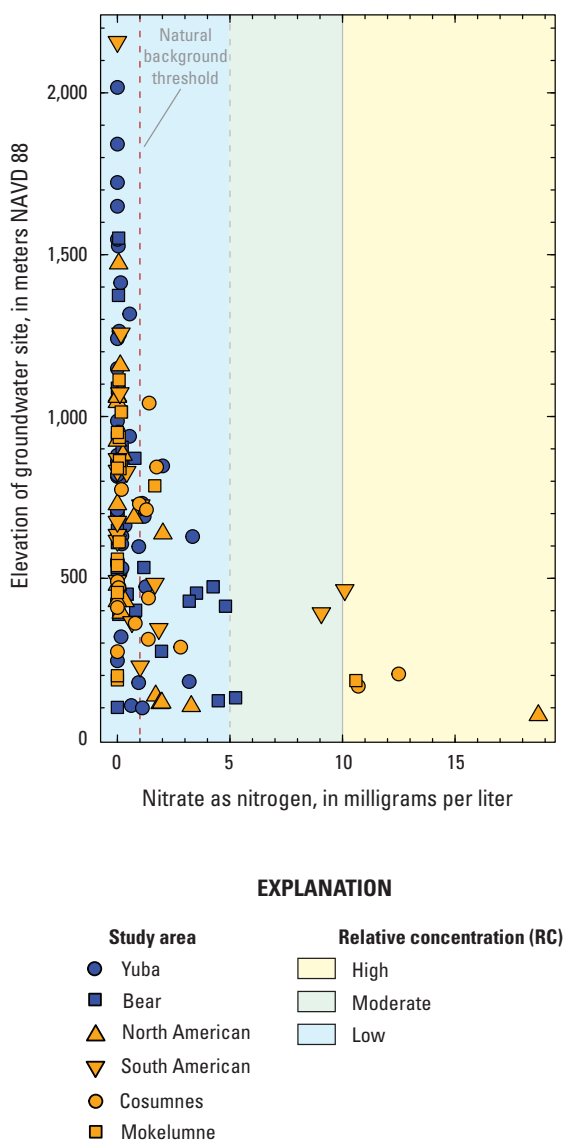


Figure 21. Relation of groundwater nitrate concentration (non-detections for nitrate, that is less than 0.04 mg/L, are plotted at zero) to wellhead elevation by study area from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Nitrate concentrations greater than or equal to 10 mg/L fell into roughly two distinct ranges of $\delta^{15}\text{N-NO}_3$: a “depleted” range between +2 and +7 per mille and an “enriched” range between +10 and +15 per mille (fig. 24). These two ranges

have overlapping and distinct potential nitrate sources. The depleted range likely represents the nitrification of ammonium from soil, surface water, and ammonium-based fertilizers. The enriched range likely represents human and animal waste sources, such as septic leachate or runoff from grazed forage pasture. The most substantial deliveries of irrigation water by acreage in the Nevada Irrigation District (servicing parts of Nevada and Placer Counties) are for forage pasture (69 percent) and family garden and orchard (21 percent; Brown and Caldwell, 2016), both of which could be sources of the elevated nitrate concentrations observed in groundwater in the study region. The nitrate-isotope data support the hypothesis that irrigation water is an important pathway of nitrate to the subsurface and indicate synthetic nitrate-based fertilizers are an unlikely principle source of the elevated nitrate concentrations observed in this study.

Radioactivity Indicators

As a class, radioactivity indicators were present at moderate and high RC in 2.7 percent and 1.5 percent, respectively, of the YBW study unit and were only detected at moderate RC in 1.5 percent of the ACMW study unit (table 7). Adjusted gross-alpha (30-day measurement; appendix 3) was present at high RC in only one groundwater sample in the study region (in the YBW study unit) and at moderate RC in two groundwater samples (one in the YBW study unit and one in the ACMW study unit; table 10; fig. 19C). Gross-beta particle activity (30-day measurement; appendix 3) was not present at high RC in either study unit, but was present at moderate RC in one groundwater sample (in the YBW study unit; table 10; fig. 19C).

Constituents with Secondary Maximum Contaminant Level Benchmarks

As a class, constituents with aesthetic-based benchmarks (SMCLs; excluding hardness, which does not have a formal State or Federal benchmark) were present at moderate and high RCs in 6.8 and 20 percent of the YBW study unit, respectively, and 9.0 and 28 percent of the ACMW study unit, respectively (table 8). Salinity indicators with SMCLs (chloride, specific conductance, sulfate, and total dissolved solids), as a class (table 8) and individually (table 10), were not present at high RC in greater than 2 percent of either study unit and are therefore not discussed in the understanding assessment. Trace elements with SMCLs (iron and manganese) were present at moderate and high RCs in 6.8 and 20 percent of the YBW study unit, respectively, and 7.5 and 27 percent of the ACMW study unit, respectively.

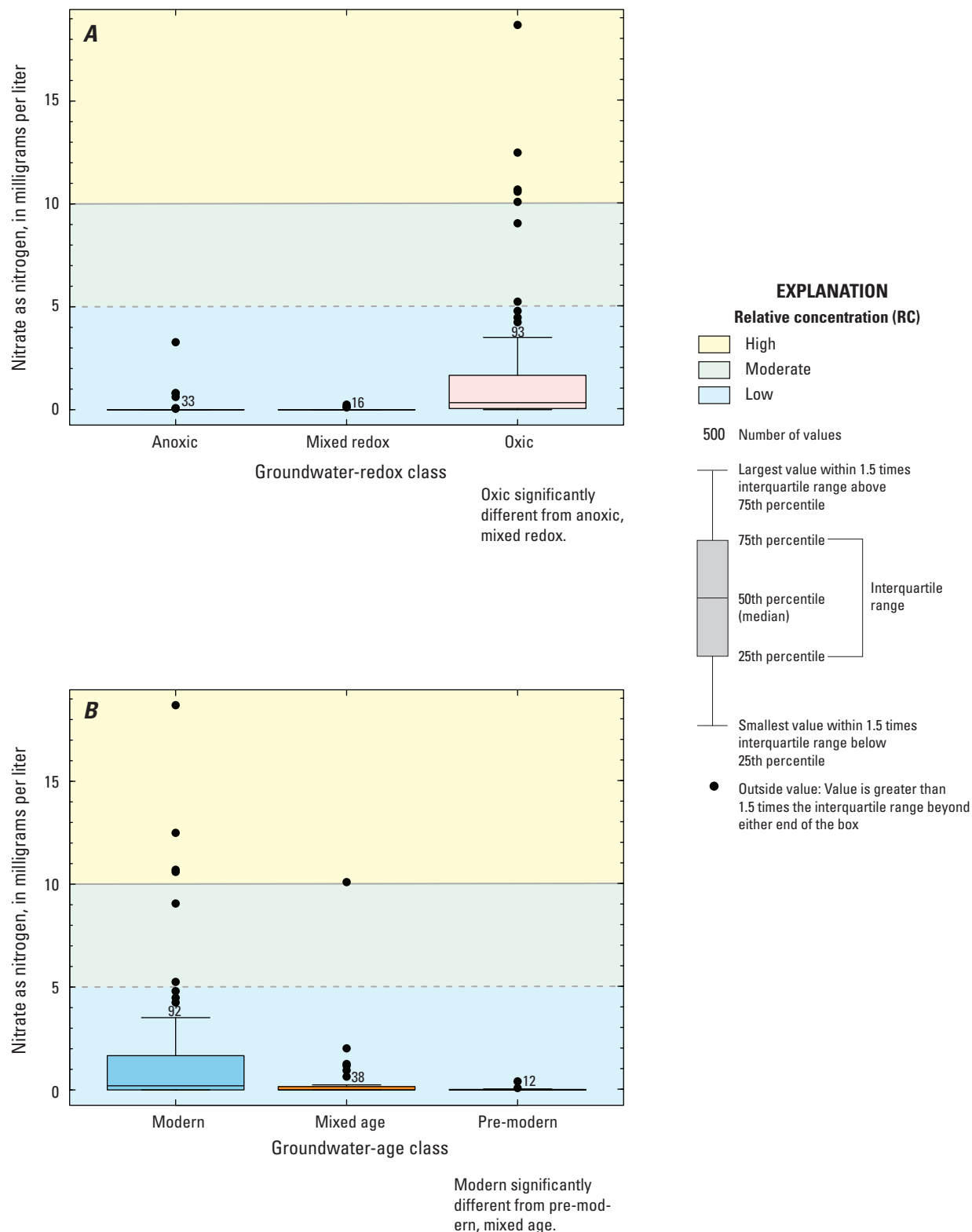


Figure 22. Groundwater nitrate concentration (non-detections for nitrate, that is less than 0.04 mg/L, are plotted at zero) for U.S. Geological Survey sampled grid and understanding wells in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, by *A*, groundwater-redox classification; *B*, groundwater-age classification.

Table 12. Results of Kruskal-Wallis and posthoc Dunn rank-sum tests for differences in values of selected water quality constituents among samples classified into groups by age class, redox class, aquifer lithology class, well depth class, study area, or study unit, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for significant differences. “MV, MS > V” for boron means the following: The boron concentrations for sites with metavolcanic or metasedimentary lithologies are significantly greater than boron concentrations for sites with volcanic lithology. Relation of median values in sample groups tested shown for Kruskal-Wallis and posthoc Dunn tests if they 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. Test p-values were calculated using the Kruskal-Wallis test; if significant, then pairwise Dunn tests among the were used to determine which differences were significant among the different groups. **Age class:** Mod, modern; Mix, mixed (modern and pre-modern); Pre, pre-modern. **Aquifer lithology class:** G, granitic; MU, mafic-ultramafic; MV, metavolcanic; MS, metasedimentary; V, volcanic. **Study unit:** ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds. **Study area:** B, Bear; C, Cosumnes; M, Mokelumne; NA, North American; SA, South American; Y, Yuba. **Other abbreviations:** NS, not significant (statistical test indicated no significant differences among the sample groups); >, greater than; SMCL, secondary maximum contaminant level.]

Constituent	Groundwater-age class	Groundwater-redox class	Aquifer-lithology class	Well-depth class	Study unit	Study area
Inorganic constituents with health-based benchmarks						
Trace elements						
Arsenic	NS	Anoxic > Oxidic	NS	Deep, Mixed > Shallow	NS	NS
Barium	NS	NS	G, MS, V > MU, MV	NS	NS	NS
Boron	Pre > Mod	Anoxic > Oxidic	MV > MS, V	NS	NS	NS
Fluoride	Mix > Mod	Anoxic > Oxidic	G, MV, MS > MU, V	Deep, Mixed > Shallow	NS	M > Y
Molybdenum	Mix, Pre > Mod	Anoxic > Oxidic	G > MS, V; MV > V	Mixed > Shallow	NS	NS
Strontium	NS	NS	NS	NS	ACMW > YBW	NS
Nutrients						
Nitrate, as nitrogen	Mod > Mix, Pre	Oxic > Anoxic, Mixed	NS	NS	NS	NS
Radioactive constituents						
Adjusted gross-alpha particle radioactivity	NS	NS	G, MS > MV	NS	ACMW > YBW	SA > Y
Gross-beta particle radioactivity	NS	NS	G > MV	NS	ACMW > YBW	SA, C, M > Y
Inorganic constituents with SMCL or aesthetic-based benchmarks						
Chloride	NS	NS	G, MU, MV, MS > V; MV > G, MS	Mixed > Shallow	ACMW > YBW	B, SA, C > Y
Hardness, as calcium carbonate	NS	Anoxic > Oxidic	MU, MV > G, MS, V; G > V	Deep > Shallow; Mixed > Shallow, Deep	NS	NS
Manganese	NS	Anoxic, Mixed > Oxidic	MS > MU, MV	NS	NS	NS
Iron	NS	Anoxic, Mixed > Oxidic	MS > MU	NS	NS	NS

Table 12. Results of Kruskal-Wallis and posthoc Dunn rank-sum tests for differences in values of selected water quality constituents among samples classified into groups by age class, redox class, aquifer lithology class, well depth class, study area, or study unit, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.—Continued

[**Explanation:** How to read results for significant differences. “MV, MS > V” for boron means the following: The boron concentrations for sites with metavolcanic or metasedimentary lithologies are significantly greater than boron concentrations for sites with volcanic lithology. Relation of median values in sample groups tested shown for Kruskal-Wallis and posthoc Dunn tests if they 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. Test p-values were calculated using the Kruskal-Wallis test; if significant, then pairwise Dunn tests among the were used to determine which differences were significant among the different groups. **Age class:** Mod, modern; Mix, mixed (modern and pre-modern); Pre, pre-modern. **Aquifer lithology class:** G, granitic; MU, mafic-ultramafic; MV, metavolcanic; MS, metasedimentary; V, volcanic. Study unit: ACMW, American-Cosumnes-Mokelumne watersheds; YBW, Yuba-Bear watersheds. **Study area:** B, Bear; C, Cosumnes; M, Mokelumne; NA, North American; SA, South American; Y, Yuba. **Other abbreviations:** NS, not significant (statistical test indicated no significant differences among the sample groups); >, greater than; SMCL, secondary maximum contaminant level.]

Constituent	Groundwater-age class	Groundwater-redox class	Aquifer-lithology class	Well-depth class	Study unit	Study area
Inorganic constituents with SMCL or aesthetic-based benchmarks—Continued						
Specific conductance	NS	Anoxic > Oxidic	G, MU, MV > V; MU, MV > MS; MV > G	Deep, Mixed > Shallow	NS	NS
Sulfate	NS	Anoxic, Mixed > Oxidic	G, MU, MV, MS > V	Deep, Mixed > Shallow	NS	NS
Total dissolved solids (TDS)	NS	NS	G, MU, MV > MS, V	Deep, Mixed > Shallow	NS	NS
Organic constituents with health-based benchmarks						
Volatile organic compounds						
Trichloromethane (chloroform)	NS	Oxidic > Anoxic	NS	NS	NS	NS
Methyl <i>tert</i> -butyl ether (MTBE)	NS	NS	NS	NS	NS	NS
Tetrachloroethylene (PCE)	NS	NS	NS	NS	NS	NS
Toluene	NS	NS	NS	NS	NS	NS
Trichloroethylene (TCE)	NS	NS	NS	NS	NS	NS
Constituents of special interest						
Perehlorate	Mod > Pre	Oxidic > Anoxic, Mixed	NS	NS	NS	NS

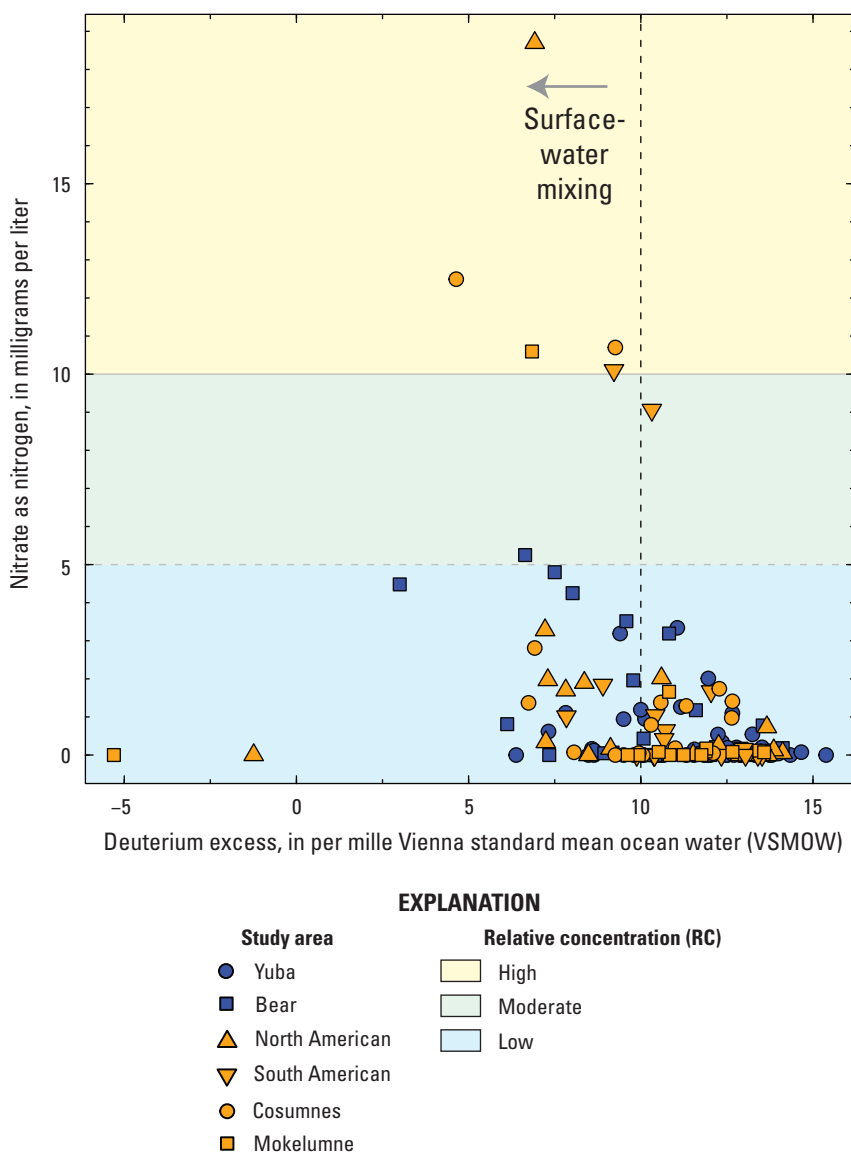


Figure 23. Relation of groundwater deuterium excess to nitrate concentration (non-detections for nitrate, that is less than 0.04 mg/L, are plotted at zero) for U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Factors Affecting Iron and Manganese

Iron and manganese are naturally present in most aquifer systems and often are found together in elevated concentrations because they are both mobilized in the subsurface under low-oxygen (reducing) conditions (Appelo and Postma, 2005). Elevated concentrations of iron and manganese in drinking water are primarily aesthetic concerns and can cause water discoloration, staining, metallic taste, and scaling in pipes (Snoeyink and Jenkins, 1980). Acute exposure to concentrated manganese can have adverse effects for human health, but this is primarily through inhalation, and the effects of relatively low levels (typically less than 1 mg/L)

normally present in drinking water are not well-known (U.S. Environmental Protection Agency, 2004). Recent studies, however, have indicated low levels of manganese in drinking water may have long-term effects on neurological development in children (Bouchard and others, 2018).

Concentrations of groundwater iron and manganese ranged from non-detection (less than respective reporting levels of 4 and 0.4 µg/L) to 4,160 and 945 µg/L in the study region, respectively. Iron was present at high RC in 11 and 13 percent of sites in the YBW and ACMW study units, respectively (table 10). Manganese was present at high RC in 19 and 27 percent of sites in the YBW and ACMW study units, respectively (table 10). Sites with moderate and high

Table 13. Results of Spearman's rho tests for correlations among selected water-quality constituents, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[p values are shown for tests in which the variables were determined to be significantly correlated on the basis of p values (not shown) being less than the critical level (α) of 0.05; NS, not significant (statistical test indicated no correlation between water-quality constituents); **blue text**, significant positive correlation; **red text**, significant negative correlation; **bold and underlined text** signifies absolute p value greater than or equal to 0.30]

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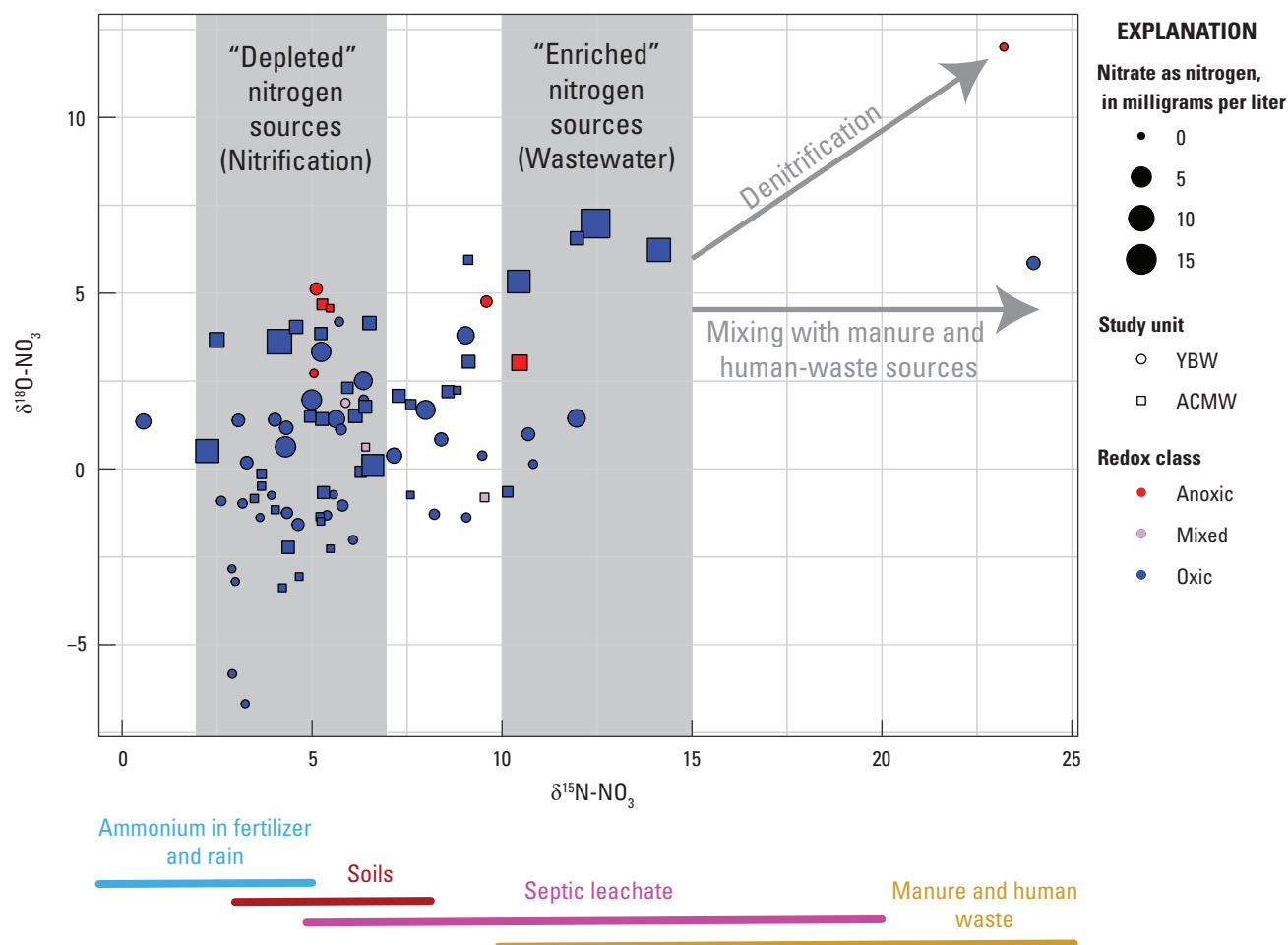


Figure 24. Relation of stable isotope of nitrogen in nitrate ($\delta^{15}\text{N-NO}_3$) to stable isotope of oxygen in nitrate ($\delta^{18}\text{O-NO}_3$) by study unit and redox classification with point radii scaled to nitrate concentration in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

RCs for iron and manganese did not appear to cluster spatially and were distributed throughout the study region (figs. 25–26). Iron and manganese concentrations were correlated with each other and inversely correlated to DO concentrations (tables 11, 13) because both species are mobilized from aquifer materials under reducing conditions. Wells with anoxic and mixed redox classifications had significantly greater iron and manganese concentrations than those with oxidic groundwater, which did not have any high-RC values for either constituent (table 12).

Aquifer lithology can be an important control for sources of dissolved iron and manganese to groundwater. Groundwater from metasedimentary aquifers had the greatest median values for iron and manganese (9.9 and 13.8 $\mu\text{g/L}$, respectively) and the least non-detections (30 and 9 percent, respectively) of the lithological groups (fig. 27). Conversely, for iron, the median concentration for every lithological group except metasedimentary was a non-detection, which means more than half of the samples in each of the four groups had iron concentrations less than the reporting level for iron (4 $\mu\text{g/L}$; fig. 27A). Although median manganese concentrations were greater than the reporting level for manganese (0.4 $\mu\text{g/L}$) for

every lithological group except mafic-ultramafic (fig. 27B), at least 40 percent of groundwater samples for each group other than metasedimentary were non-detections. Groundwater from metasedimentary aquifers had significantly higher iron concentrations than that of the mafic-ultramafic group and higher manganese concentrations than that of mafic-ultramafic or metavolcanic group (table 12).

Groundwater from wells in metasedimentary aquifers also had the highest percentage of samples with high RCs for iron and manganese; approximately one third of sample concentrations exceeded the respective SMCL-CA benchmarks of 300 and 50 $\mu\text{g/L}$ (fig. 28). The metasedimentary and metavolcanic groups had the greatest proportion of high-RC wells for iron (more than 14 percent), and the metasedimentary, granitic, and metavolcanic groups had the greatest proportion of high-RC wells for manganese (more than 20 percent; fig. 28). Overall, concentrations and aquifer-scale proportions of high-RC samples for iron and manganese tended to be greatest for wells in metasedimentary lithologies (figs. 27–28).

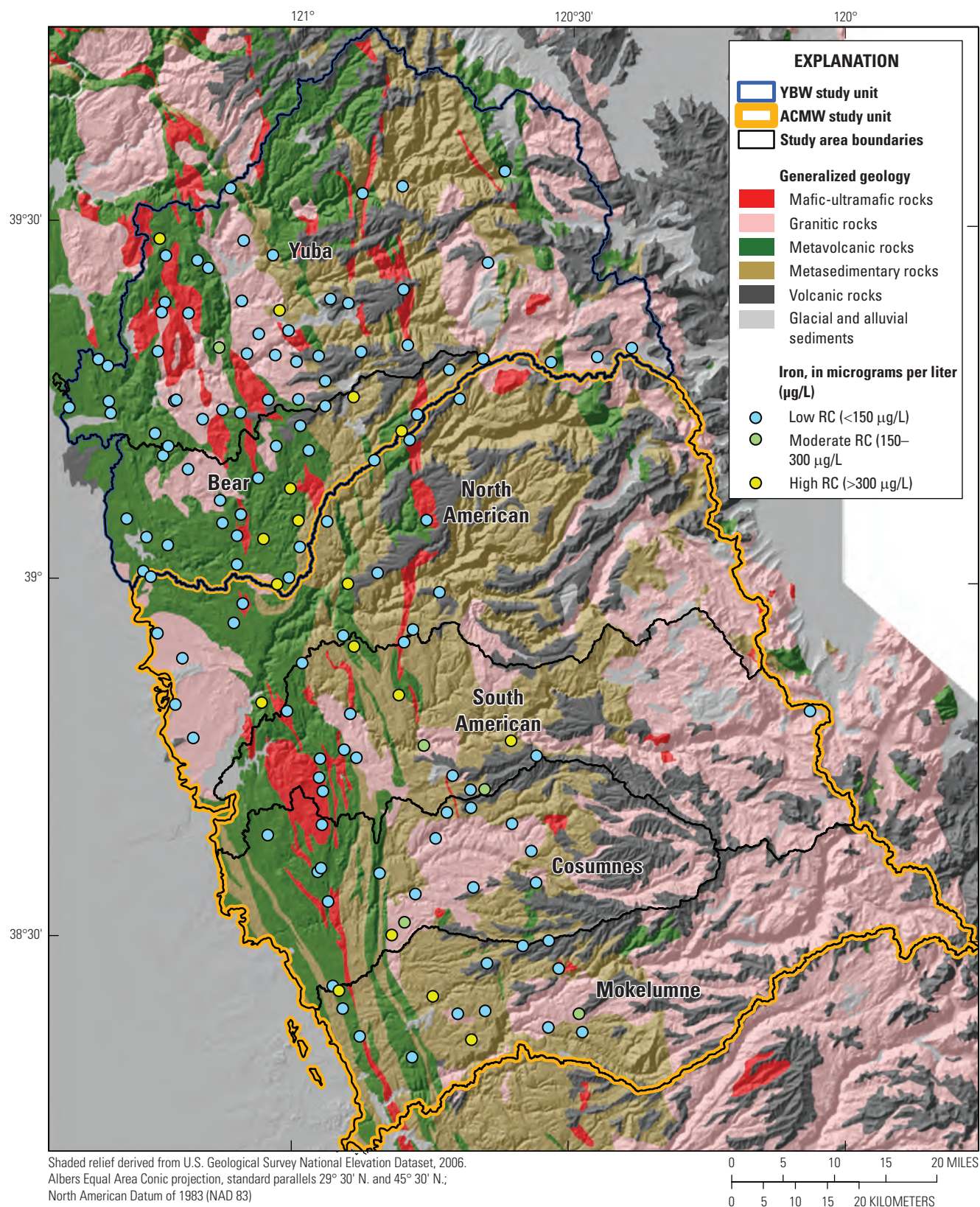


Figure 25. Relative concentrations (RC) of iron in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

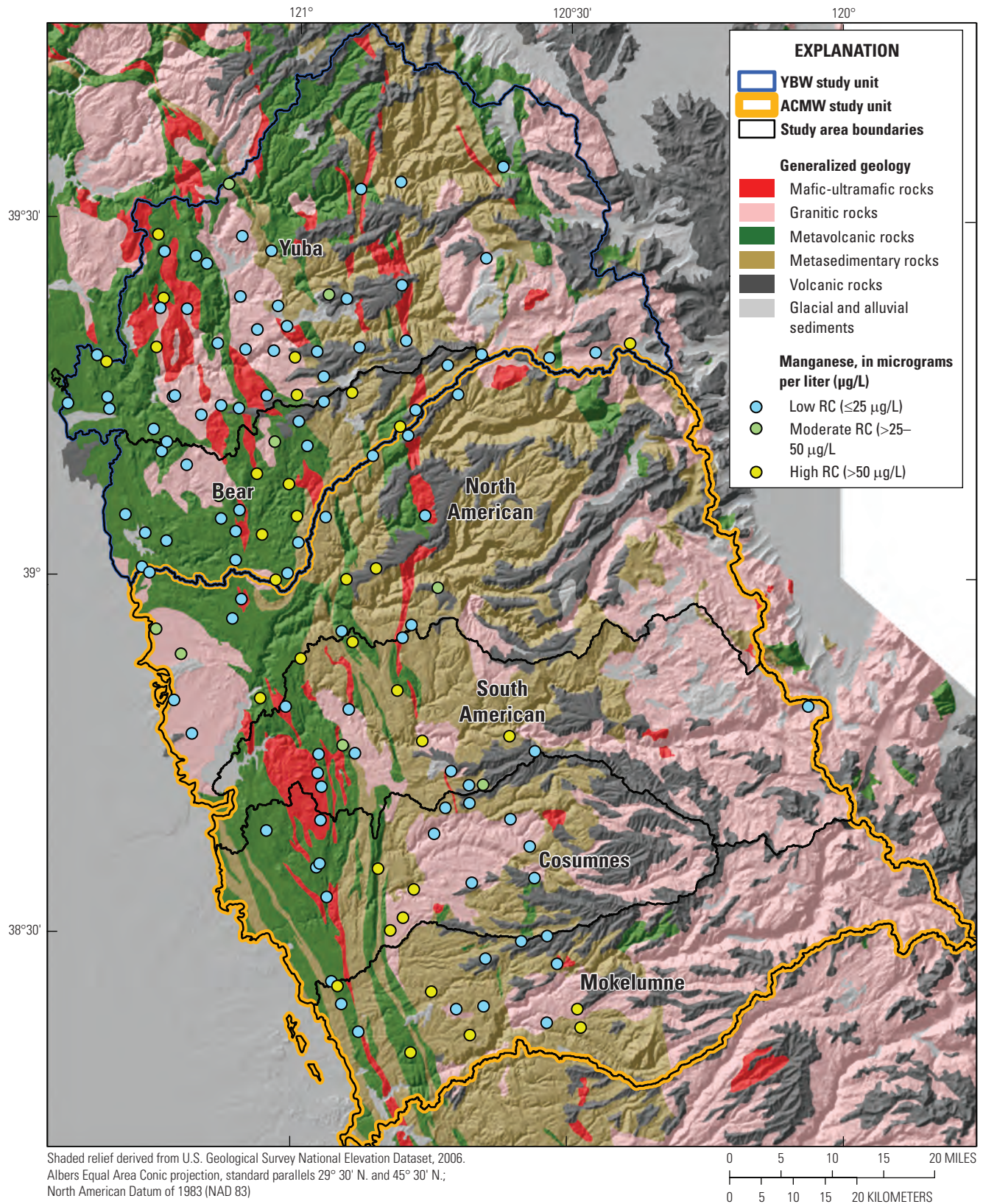


Figure 26. Relative concentrations (RC) of manganese in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

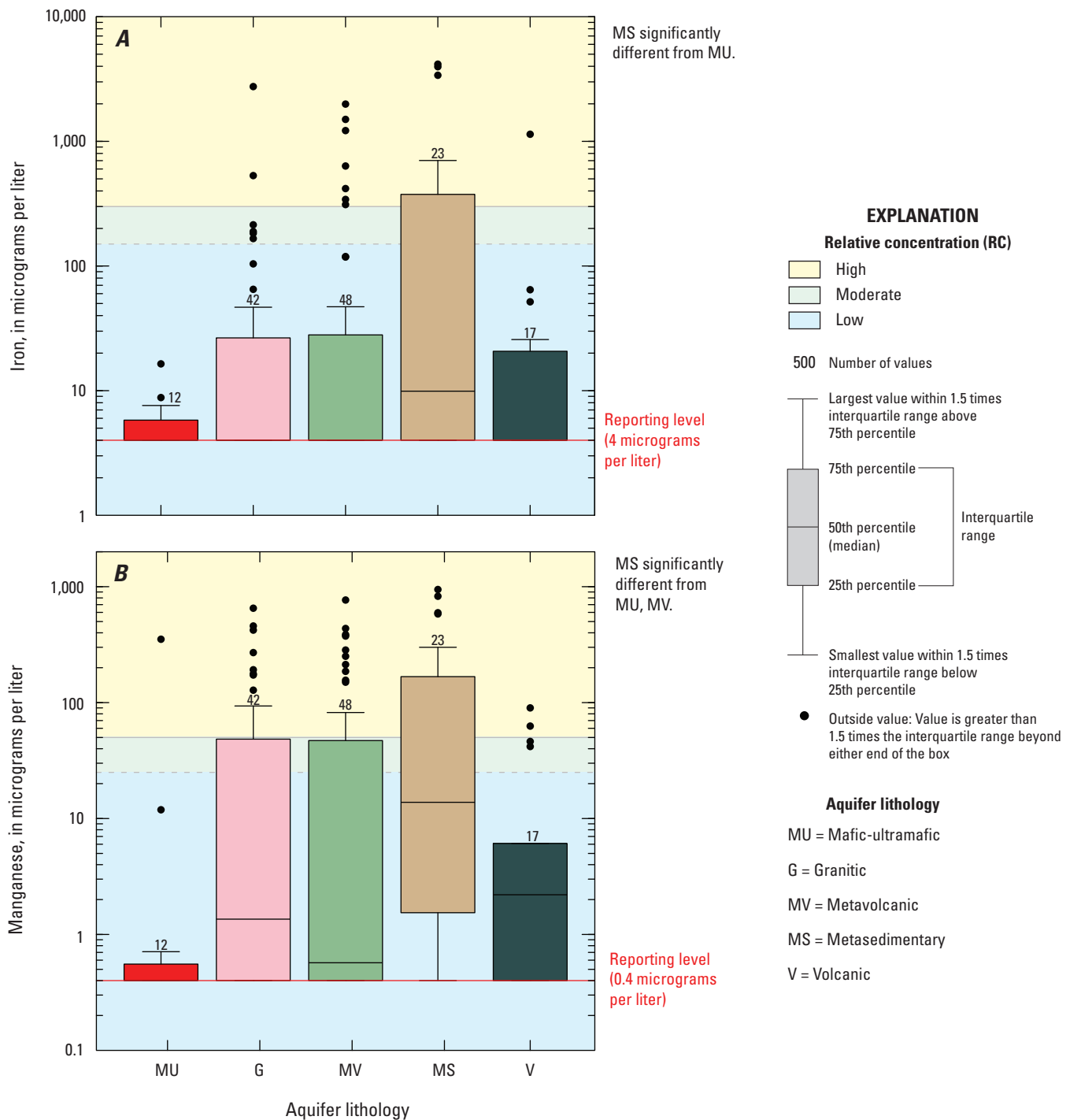


Figure 27. Results of water-quality analyses from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, for *A*, iron; and *B*, manganese concentrations by aquifer lithology (non-detections for iron and manganese are plotted at respective reporting levels of 4 and 0.4 µg/L).

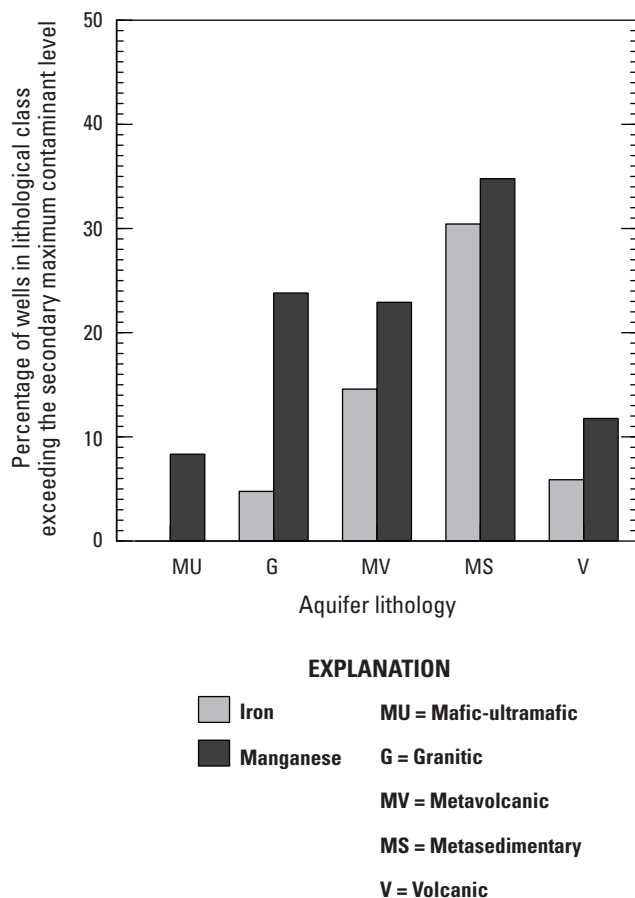


Figure 28. Percentage of groundwater wells exceeding California secondary maximum contaminant levels (SMCL-CA) for iron and manganese (300 and 50 µg/L, respectively), by aquifer lithology class from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Iron-bearing silicate, sulfide, and oxide minerals are present in a wide range of rock types, and manganese can substitute for iron in silicate minerals (Appelo and Postma, 2005). Metasedimentary rocks, such as slate and shale, are commonly composed from sediment particles with abundant iron- and manganese-oxide coatings that can dissolve in low-oxygen groundwater (Hem, 1985). Concentrated high-manganese deposits are found in ophiolites (classified as metavolcanic for the purposes of this study) associated with the Smartville complex in the northwestern part of the study region (Flohr and Huebner, 1992). Although a detailed assessment of iron- and manganese-bearing minerals within the complex geologic framework of the study region is beyond the scope of this study, these data show that high-RCs for iron and manganese are most likely present in groundwater

aquifers of metasedimentary lithology (approximately 30 percent of wells in the group) and that high RCs for manganese were also common in aquifers of metavolcanic and granitic lithologies (approximately 20 percent of samples in these groups; [fig. 28](#)).

Hardness

Water hardness is typically quantified as the sum of calcium and magnesium ions dissolved in water and is expressed as milligrams of calcium carbonate (CaCO₃) per liter. Hard water is an aesthetic concern and can decrease the efficacy of soap and household cleaners by formation of chemical complexes that decrease the ability of chelating agents in cleaning solutions to bind with organic compounds in oil, grease, and dirt (Snoeyink and Jenkins, 1980). Hard water can also cause scaling by precipitation of carbonate minerals that can clog pipes and plumbing. General guidelines for classifying water hardness are as follows: 0–60 mg/L is considered “soft,” 60–120 mg/L is “moderately hard,” 120–180 mg/L is “hard,” and greater than 180 mg/L is “very hard” (Briggs and Ficke, 1977). Although there are no established California State or Federal benchmarks for water hardness, this study uses a concentration of 180 mg/L as a purely aesthetic benchmark by which to assess water quality in the study region. Using 180 mg/L as the primary benchmark threshold for the purposes of this study results in very hard waters being classified as high RC. The low-to-moderate RC boundary was set to 120 mg/L, which results in hard water classified as moderate RC and moderately hard and soft water classified as low RC. Hardness was present at moderate and high RCs in 18 and 24 percent of the YBW study unit, respectively, and 25 and 30 percent of the ACMW study unit, respectively, ([fig. 29](#); [table 10](#)).

Factors Affecting Hardness

Water hardness ranged from 3.86 to 564 mg/L, and sites with high-RC groundwater were clustered in the western, lower elevation part of the study region ([fig. 30](#)). Hardness had a strong inverse correlation to elevation and was only present at high RCs below elevations of 1,100 m ([fig. 31A](#); [table 11](#)). Groundwater hardness was negatively correlated to DO and significantly higher for anoxic than oxic wells ([tables 11–12](#)). Groundwater hardness was significantly greater for mafic-ultramafic and metavolcanic groups than for other lithological groups and also was greater for granitic than volcanic lithologies ([fig. 32](#); [table 12](#)). Hardness was positively correlated to well depth and was greatest in wells with depths between 40 and 150 meters ([fig. 31B](#); [table 11](#)). Groundwater hardness was significantly greater for deep than shallow depth classes but was also significantly greater for wells of mixed depth than for shallow or deep depth classes ([table 12](#)).

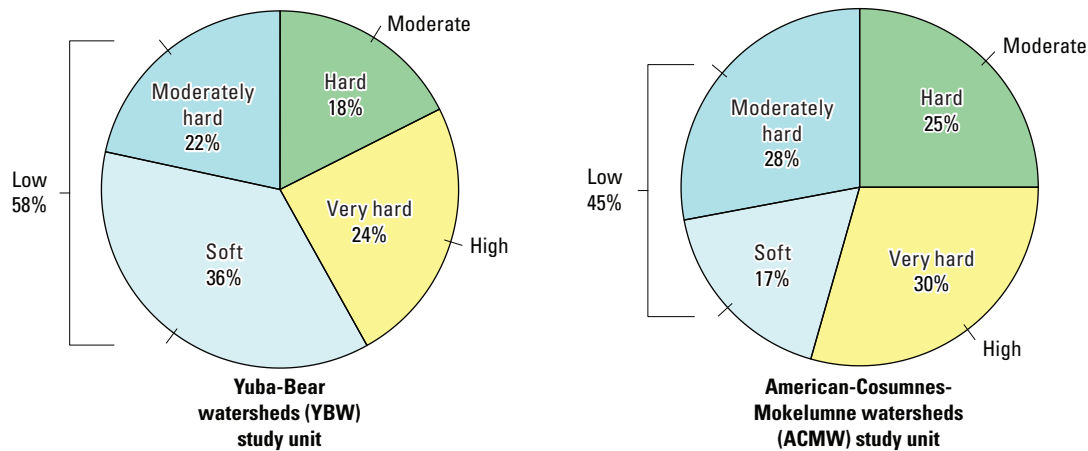


Figure 29. Hardness classifications for U.S. Geological Survey sampled grid wells in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. [%, percent]

The prevalence of hard water at lower elevations and mixed-depth zones could have to do with changes in structural geology, aquifer lithology, and well construction at lower elevations in the study region. Lower elevation sites in the study region are in the Melones fault zone (fig. 3.4). Major faults at lower elevations in the Melones fault zone could provide structural pathways for upwelling of deep groundwater with higher calcium and magnesium content than shallow groundwater (Mack and Ferrell, 1979; Mack and Schmidt, 1981). Groundwater upwelling from deep aquifers through complex fracture networks often has elevated salinity and depleted DO due to water-rock interactions with aquifer materials over long flowpaths in the subsurface (Appelo and Postma, 2005).

Aquifer lithology can also explain the prevalence of hard groundwater at lower elevations. Hardness was significantly greater in groundwater from mafic-ultramafic and metavolcanic lithologies than from other lithological groups (fig. 3.2; table 12). Wells with mafic-ultramafic and metavolcanic lithologies were more prevalent at lower elevations in the study region (figs. 7C, 8B; table 4). These lithologies consist of heterogeneous assemblages of greenstones and other serpentized mafic and ultramafic rocks, including ophiolites containing abundant peridotite (Day and others, 1985). Dissolution of magnesium-silicate minerals in serpentized mafic and ultramafic rocks can increase water hardness (Chavagnac and others, 2013; Twing and others, 2017; Giampouras and others, 2019), which was evident in groundwater samples from mafic-ultramafic group wells that had significantly higher magnesium concentrations than the other lithological groups (Dunn rank-sum test, p less than 0.001). Hardness was also positively correlated to several trace elements, specific conductance, total dissolved solids, chloride, and sulfate (table 13). Total dissolved solids, chloride, and sulfate can be increased in groundwater by weathering from rocks of marine origin, such as the metavolcanic rocks present at lower elevations in the study

region, or by upwelling along major bedrock faults and fractures (Mack and Ferrell, 1979; Mack and Schmidt, 1981; Appelo and Postma, 2005).

Wells of the mixed depth class could have greater hardness than wells in the shallow and deep classes because of differences in well location or construction. Wells of the mixed depth class sampled in this study tended to be located at lower elevations than those of the shallow depth class, which often had softer groundwater (table 4). The relation between depth class and hardness could therefore be spurious because mixed-depth wells tended to be at lower elevations where harder water is more likely because of geological factors discussed previously. Wells of the mixed-depth class also tended to have longer open intervals, however, and are more likely to intersect fracture zones transmitting deeper, upwelling groundwater with elevated hardness.

The Langelier saturation index (LSI) is defined as the difference between the pH of a water sample and the pH of the source water if it were in equilibrium with calcium carbonate, and the LSI can be used to predict whether scale is likely to form from a given source water as water travels through pipes and plumbing (Snoeyink and Jenkins, 1980). The LSI was calculated for all groundwater samples with measured values of pH, calcium, alkalinity, temperature, and total dissolved solids using methods described by Belitz and others (2016; appendix 1). Values of LSI less than -0.5 are considered to be corrosive with respect to calcium carbonate, and values greater than 0.5 are considered to have the potential to form calcium-carbonate scale (Belitz and others, 2016).

Values of LSI calculated for groundwater sampled in this study ranged from -8.4 to -1.5 ; therefore, LSI status does not indicate a risk factor for scale formation and clogging of pipes and plumbing with carbonate scale (fig. 3.3A). Although hardness was significantly correlated to pH (table 11), the pH for wells with hard water leveled off at circumneutral values (pH about 7.0; fig. 3.3B). Saturation indices (SI) for calcite, a common form of calcium carbonate, were calculated using the

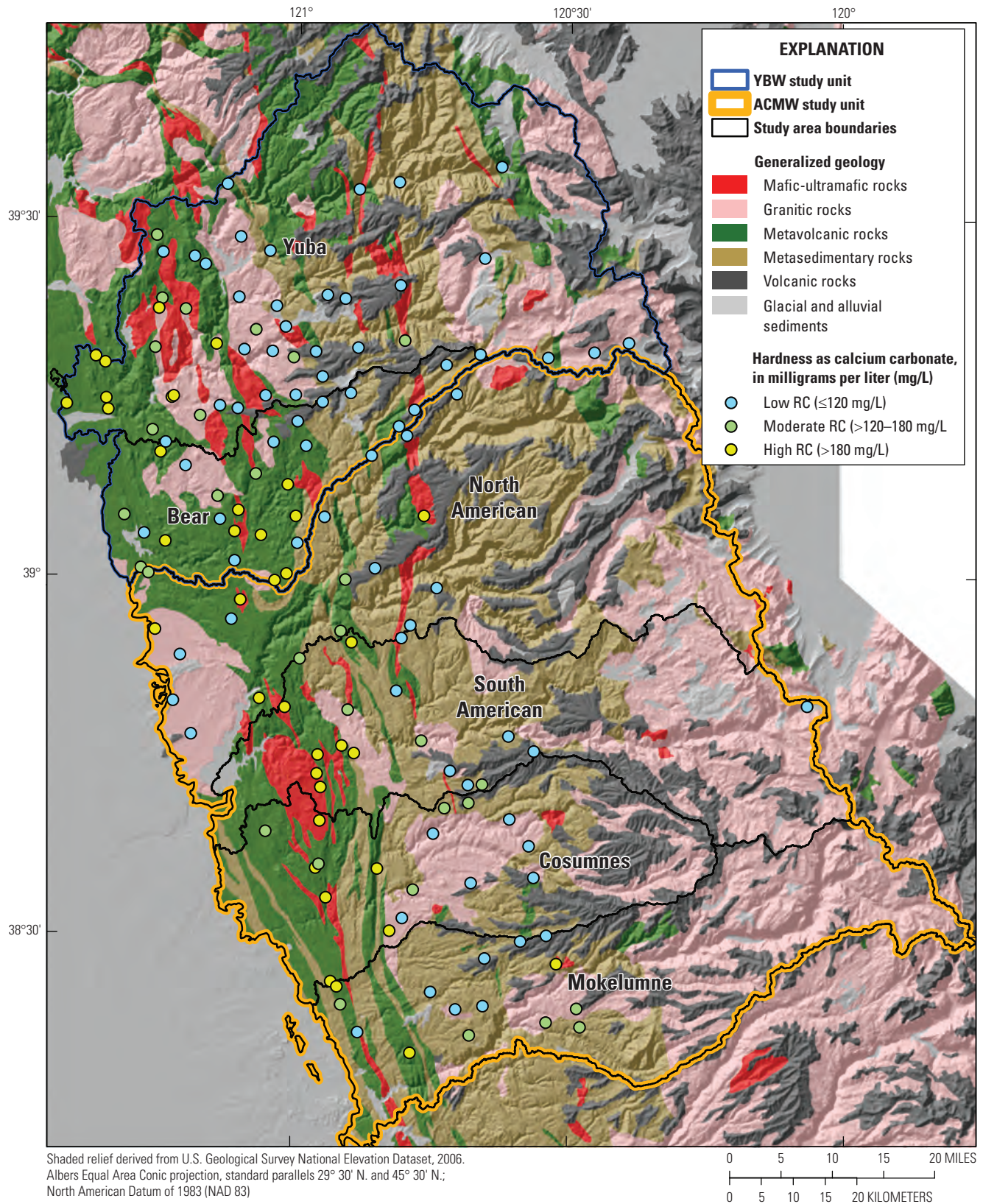


Figure 30. Relative concentrations (RC) of hardness in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

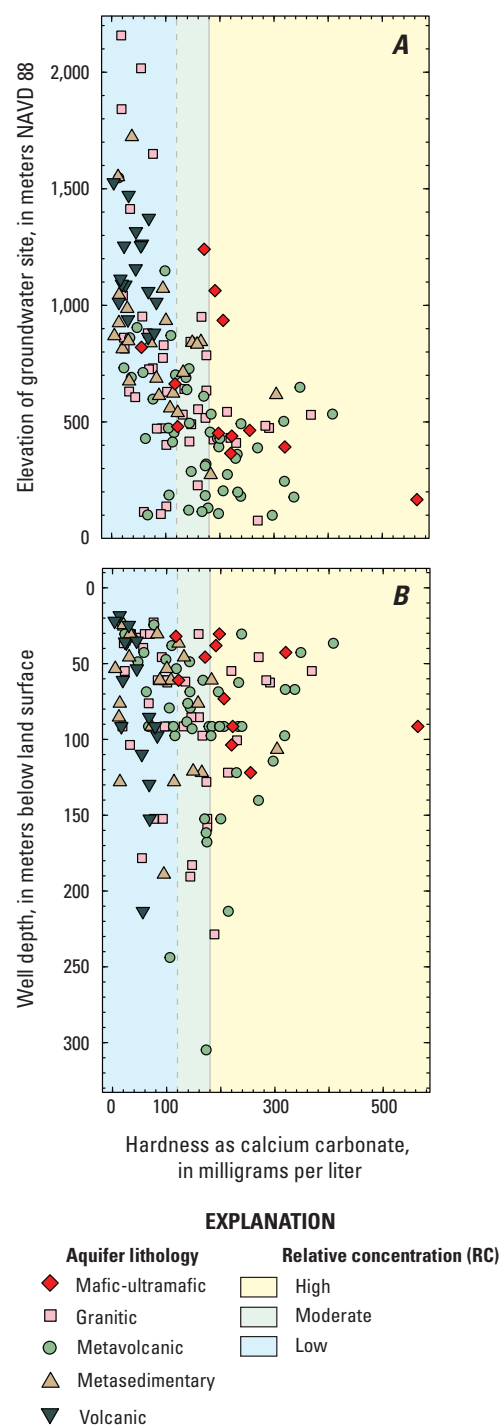


Figure 31. Hardness for samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, relative to *A*, wellhead elevation by aquifer lithology; *B*, well depth by aquifer lithology.

USGS software package PHREEQC (version 3; [appendix 1](#); Parkhurst and Appelo, 2013). Calcite SIs close to zero indicate that water is in thermodynamic equilibrium with calcite (Appelo and Postma, 2005). Groundwater samples with hard water were either slightly undersaturated or at equilibrium with calcite, confirming calcium-carbonate scale is unlikely to form from these waters and indicating that interactions with carbonate minerals are a major control on groundwater hardness and pH in the study region ([fig. 33C](#)).

Microbial Indicators

Groundwater samples were tested for presence or absence of three microbial indicators (TC, EC, and ENT). Tests for coliform bacteria (TC and EC) were made for 74 and 61 grid wells in the YBW and ACMW study units, respectively. Tests for ENT were made for 70 and 61 grid wells in the YBW and ACMW study units, respectively. At least one microbial indicator was present in 26 and 28 percent of sites in the YBW and ACMW study units, respectively ([table 14](#)). Total coliform was present in 23 and 28 percent of the YBW and ACMW study units, respectively, and *E. coli* was present in 5.4 and 9.8 percent of the YBW and ACMW study units, respectively ([table 14](#)). *E. coli* is a type of coliform bacteria, and as expected, all wells that tested positive for EC also tested positive for TC ([fig. 34](#)). *Enterococci* was present in 11 and 1.6 percent of the YBW and ACMW study units, respectively ([table 14](#)).

Bacteria classified as TC, EC, and ENT are organism assemblages that are not inherently pathogenic and are commonly used as indicators of potential microbiological contamination from human and animal waste (U.S. Environmental Protection Agency, 1986; California State Water Resources Control Board, 2016). Coliform bacteria are ubiquitous in soils and surface waters but are also present in the digestive tracts of warm-blooded animals and can indicate fecal contamination. The EC and ENT organisms are more specific to fecal-waste sources than is TC (Grisey and others, 2010).

Detections of TC and EC were distributed throughout the western, lower elevation parts of the study region, but the YBW study unit had significantly more detections of ENT than the ACMW study unit ([figs. 35–36](#); [table 14](#)). Detections of coliform bacteria (TC and EC) were significantly associated with lower elevation sites ([table 15](#)), and there were no detections at elevations above 1,000 m. Increased detections at lower elevations are most likely due to factors at lower elevations that also correlate to high-nitrate groundwater, such as irrigation of forage pasture and rural-residential land. Furthermore, *d-excess* was significantly less and nitrate significantly greater in samples that tested positive for microbial indicators ([fig. 37](#); [tables 15–16](#)). Lesser *d-excess* values and increased nitrate are indicative of irrigation recharge in the northern Sierra Nevada foothills as discussed in the “[Factors Affecting Nitrate](#)” section of this report.

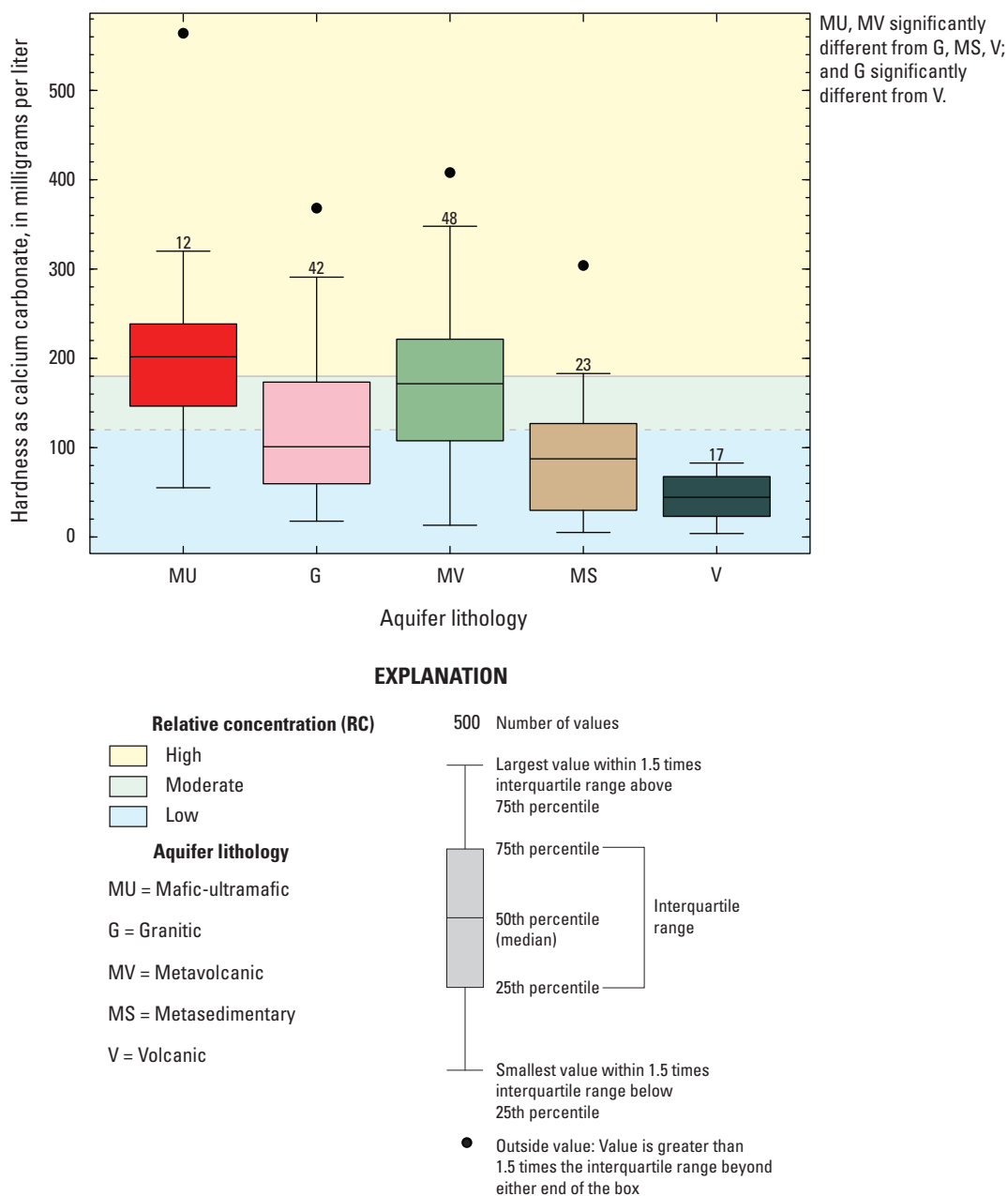


Figure 32. Groundwater hardness by aquifer lithology for U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Additionally, because TC is ubiquitous in soil and surface water, irrigation recharge could contribute to TC detections independent of any human or animal waste source.

Detection frequencies for total coliform in this study (table 14) were similar to those measured by the SWRCB for the GAMA Domestic Well Project in Yuba County (24 percent) and El Dorado County (28 percent; California State Water Resources Control Board, 2005, 2010). Wells drilled in hard-rock aquifers could be particularly susceptible to microbial contamination. In a survey of domestic wells throughout the United States, Embrey and

Runkle (2006) found higher detection frequencies for coliform bacteria in carbonate- or crystalline-rock aquifers than in those consisting of unconsolidated sediments. This is because bacteria are typically attenuated in groundwater recharge moving through porous media with characteristically longer residence times (Pandey and others, 2014). In the northern Sierra Nevada foothills, groundwater is often recharged by rapid preferential flow through bedrock fractures, which limits time and contact with aquifer materials that could attenuate microbial pathogens (Levy and others, 2020).

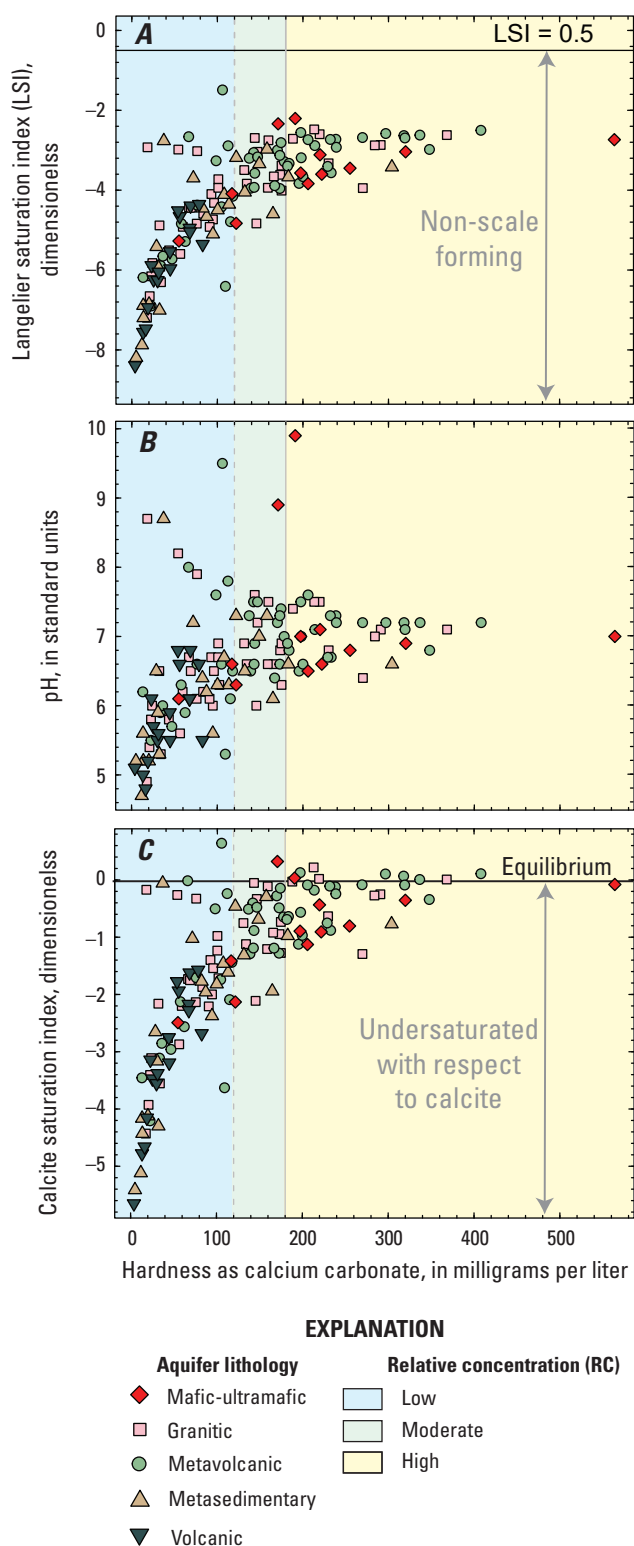


Figure 33. Hardness for samples from U.S. Geological Survey grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, relative to *A*, Langelier saturation index; *B*, pH; *C*, calcite saturation index by aquifer lithology.

Organic and Special-Interest Constituents

Many of the organic constituents evaluated as part of this study are commonly detected in groundwater affected by anthropogenic activities and are not typically measured at detectable concentrations in natural groundwater (Deeds and others, 2012; Belitz and others, 2015). At least one organic constituent was detected in 30 and 42 percent of the YBW and ACMW study units, respectively (table 9). Organic constituents were divided into two classes: volatile organic compounds (VOCs) and pesticides (including degradates). None of the organic constituents were detected at high RC in the study region. The VOCs were only detected at moderate RCs in 2.7 percent of the YBW study unit and were detected at low RC in 24 and 34 percent of the YBW and ACMW study units, respectively (table 9). Pesticides were only detected at low RCs in 5.5 and 11 percent of the YBW and ACMW study units, respectively (table 9).

The maximum RC (highest measured concentration of a water-quality constituent divided by its benchmark) was used in conjunction with the detection frequency to summarize constituents evaluated in the status assessment in both of the northern foothills study units (fig. 38A–B). Any organic or special interest constituent detected with a moderate or high maximum RC or with a detection frequency greater than 10 percent was selected for further evaluation in the status assessment. Tetrachloroethene (PCE), trichloroethene (TCE), and toluene were detected in the YBW study unit at moderate RCs and were included in the status assessment (figs. 38A, 39A). Methyl *tert*-butyl ether (MTBE) and trichloromethane (chloroform) were detected in YBW and ACMW study units at detection frequencies greater than 10 percent and are included in status and understanding assessments (figs. 38A–B, 39A). Pesticides were not included in the status assessment because none were detected at concentrations above their respective low-to-moderate RC thresholds or at detection frequencies greater than 10 percent.

Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) are so named because they have low boiling points and consequently vaporize when in contact with the atmosphere (Zogorski and others, 2006). Because groundwater below the water table is isolated from the atmosphere, VOCs tend to persist longer in aquifers than in surface-water bodies. Although VOCs can be present naturally in groundwater near hydrocarbon deposits (natural gas and oil), their presence in drinking-water aquifers outside of oil and gas fields typically indicates anthropogenic contamination (Johnson and Belitz, 2009; Deeds and others, 2012). The VOCs are present in a wide array of human-made products such as fuels, solvents, paints, refrigerants, fumigants, or disinfection byproducts (Zogorski and others, 2006).

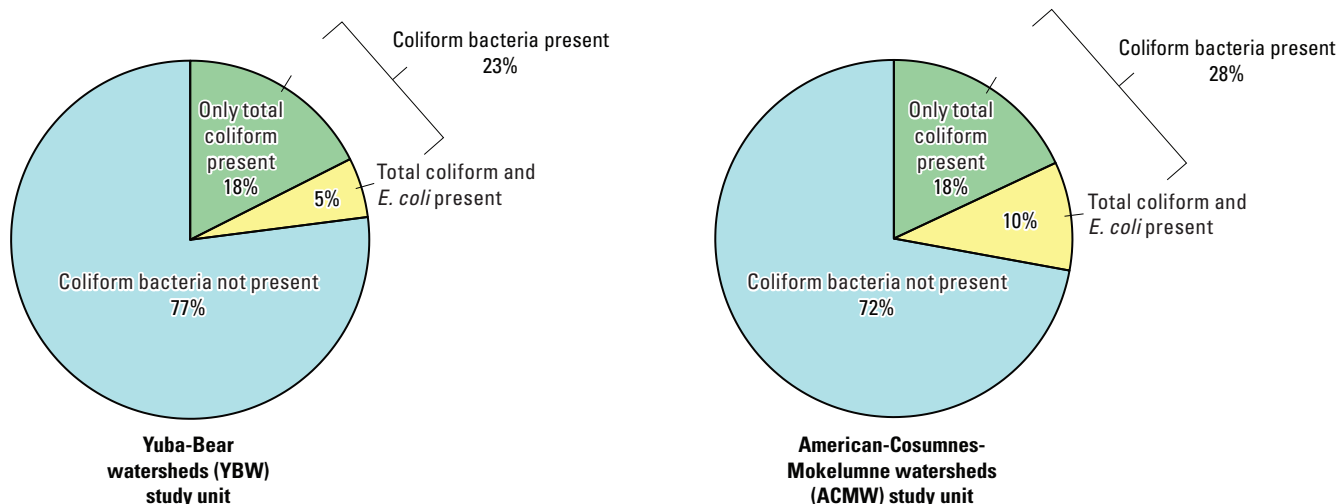


Figure 34. Detections of coliform bacteria for samples from U.S. Geological Survey sampled grid and understanding wells in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project. [%, percent]

Solvents such as PCE and TCE are commonly found at hazardous-waste sites and can persist in groundwater systems for long periods (Zogorski and others, 2006). Under anoxic conditions, TCE is a degradation byproduct of PCE through the process of reductive de-halogenation (Erbe and Siegel, 2001). In the YBW and ACMW study units, PCE had detection frequencies of 9.5 and 3.0 percent, respectively, and was detected at moderate RC in the YBW study unit (fig. 39A; table 10). In each of the two study units, TCE was only detected in one grid well, and TCE was present at moderate RC in the single well with a detection in the YBW study unit (fig. 39A; table 10). Toluene is an aromatic hydrocarbon that is commonly found in fuels and solvents and can form as a degradation byproduct of benzene under oxic conditions. Toluene can biodegrade under oxic and anoxic conditions (Lipson and Siegel, 2000). Toluene was only detected in one grid well in each of the two study units, one of which was at moderate RC in the YBW study unit (fig. 39A; table 10).

Two VOCs had study-unit detection frequencies greater than 10 percent and were therefore included in the understanding assessment. Chloroform is a disinfection byproduct and was only detected at low RCs, with detection frequencies of 14 and 15 percent in the YBW and ACMW study units, respectively (fig. 39A; table 10). MTBE is a gasoline oxygenate and was only detected at low RC with detection frequencies of 15 and 13 percent in YBW and ACMW study units, respectively (fig. 39A; table 10).

Factors Affecting Chloroform

Chloroform is a trihalomethane (THM) and is typically formed when chlorine in cleaning and disinfection products reacts with dissolved organic matter in surface and groundwater. The MCL-US for THMs as a group is 80 µg/L

and is taken as the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform (U.S. Environmental Protection Agency, 2018). Chloroform can be lethal when inhaled at high doses but is typically found dissolved in groundwater at very low concentrations (less than 70 µg/L; U.S. Environmental Protection Agency, 2000). Chloroform and other THMs can have carcinogenic effects at levels found in drinking water; however, the effects of long-term exposure to low doses of chloroform on human health are not well-known (Diana and others, 2019). Chloroform is one of the most commonly detected VOCs in groundwater throughout the United States (Zogorski and others, 2006). Chloroform can form in aquifers exposed to chlorinated drinking water, household cleaners, and disinfectants in septic leachate and other waste streams. Wells are commonly disinfected by “shock chlorination” using chlorine solutions (bleach), which can react with organic carbon in the aquifer to form chloroform (Zogorski and others, 2006). Chloroform concentrations in domestic wells may therefore be more related to well management practices by homeowners than regional-scale patterns of geology and land use.

Chloroform concentrations in the study region ranged from non-detection (less than the method detection level of 0.015 µg/L) to 4.3 µg/L, with detections mostly clustered in the three most northernmost study areas (Yuba, Bear, and North American; fig. 40). Although the correlations were not strong, chloroform was found to be positively correlated to urban land use, septic-tank density, and LUFT density (table 11), indicative of urban and rural-residential land uses in the study region. Although the respective positive and negative correlations of chloroform to DO and well depth were not strong, chloroform was only detected in wells with oxic or mixed redox water and well depths of less than 130 m (table 11; fig. 41A).

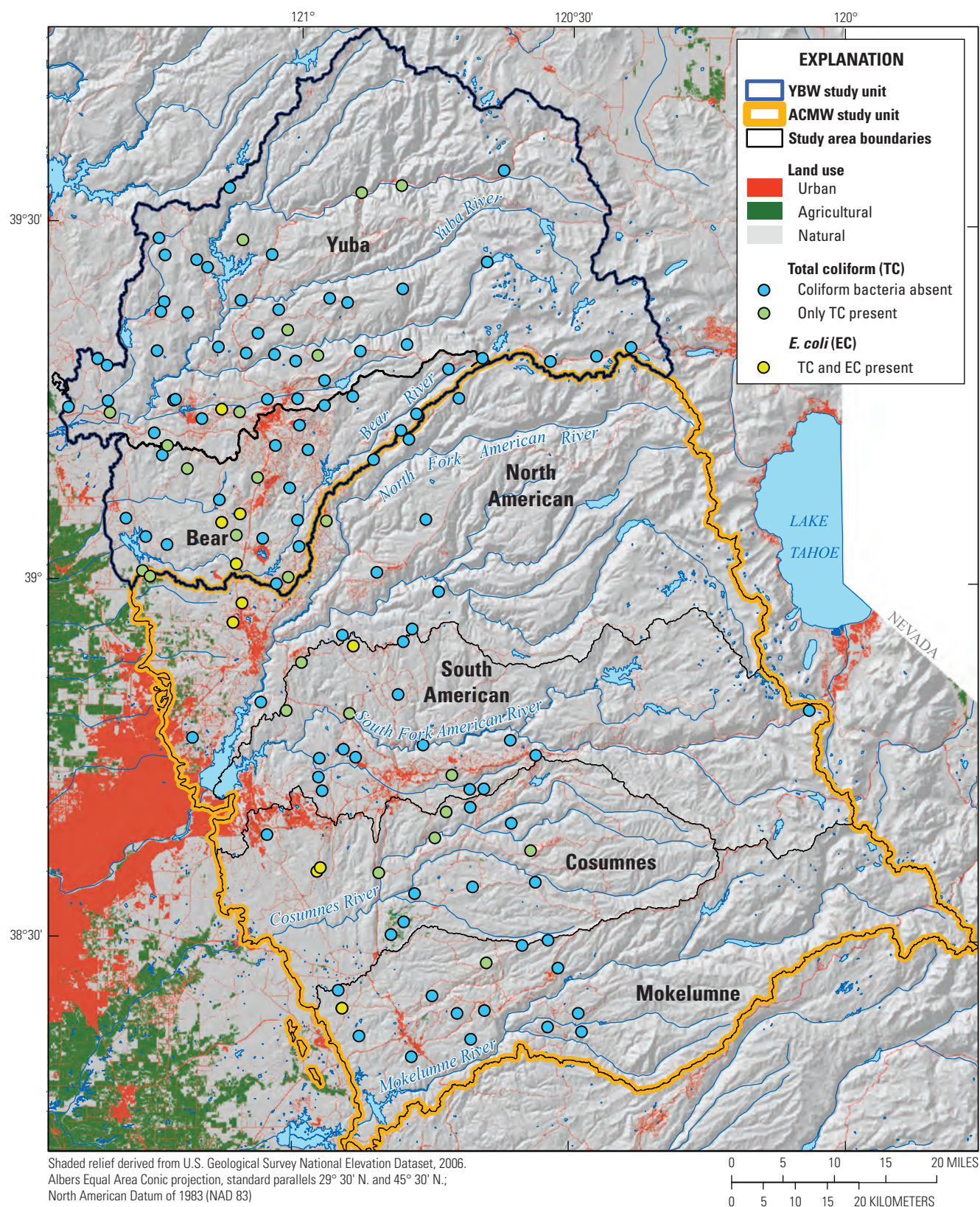


Figure 35. Detections of coliform bacteria in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

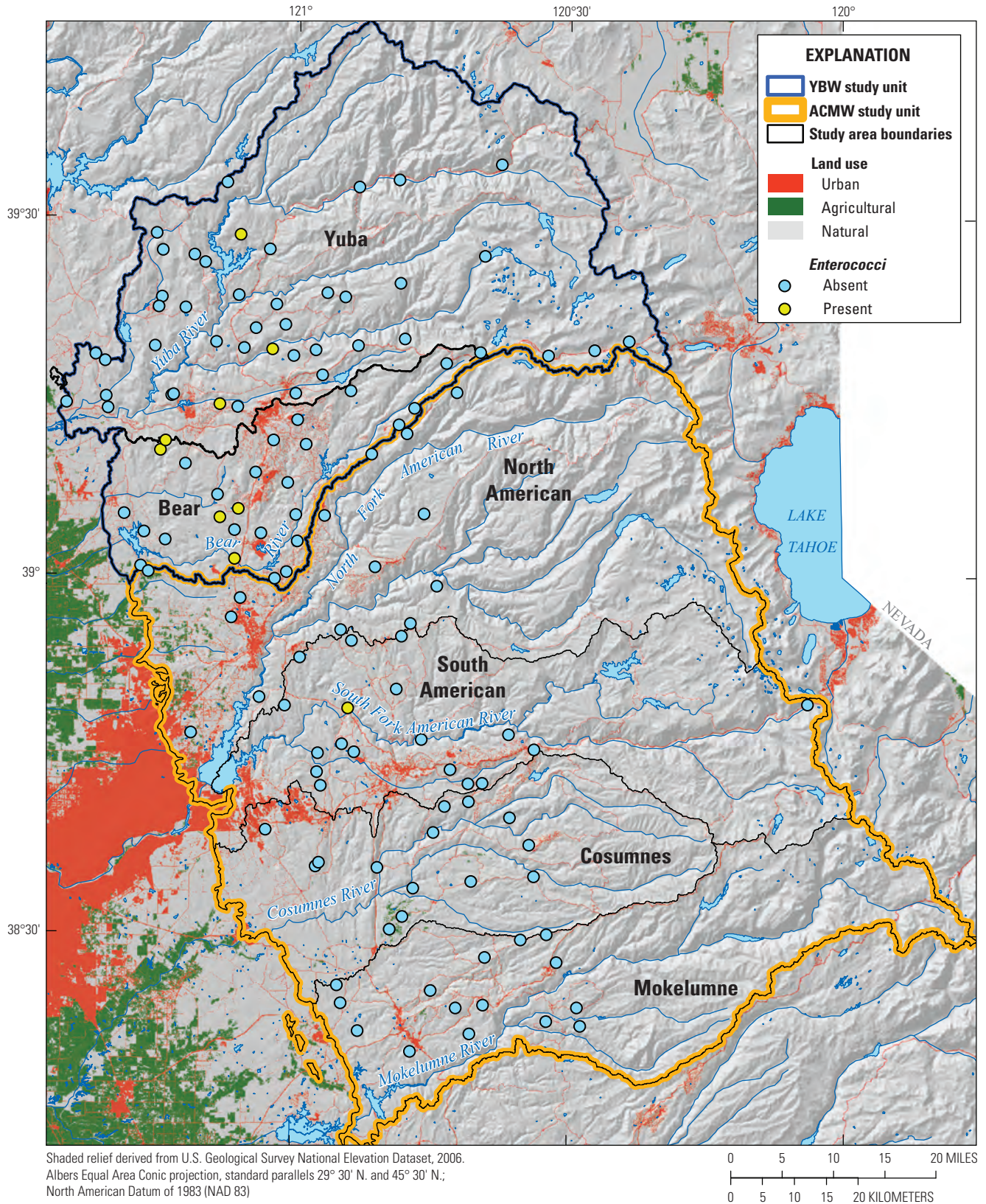


Figure 36. Detections of *Enterococci* bacteria in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

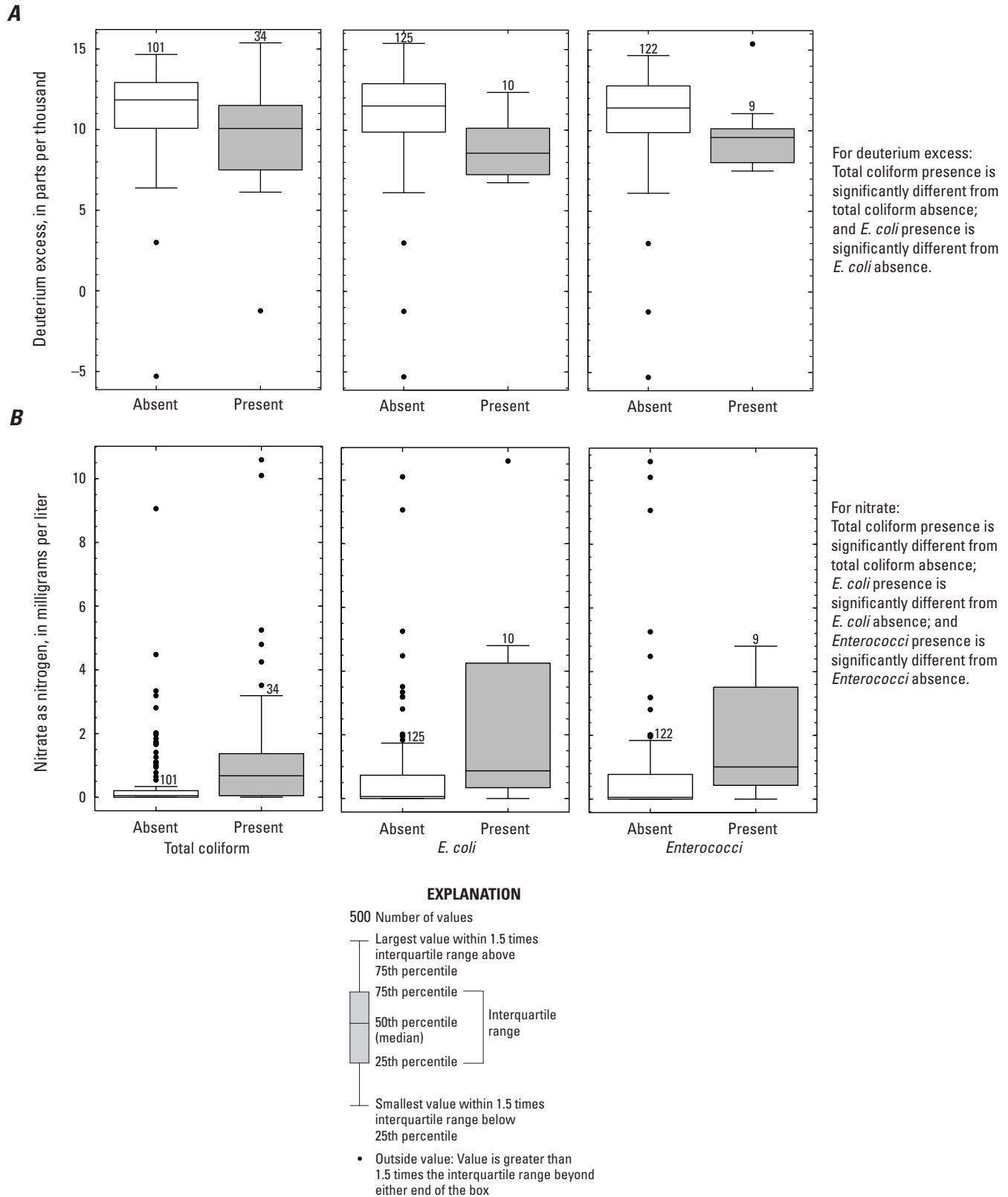


Figure 37. Distribution of groundwater variables in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, deuterium excess; *B*, nitrate concentration by presence or absence of microbial indicators.

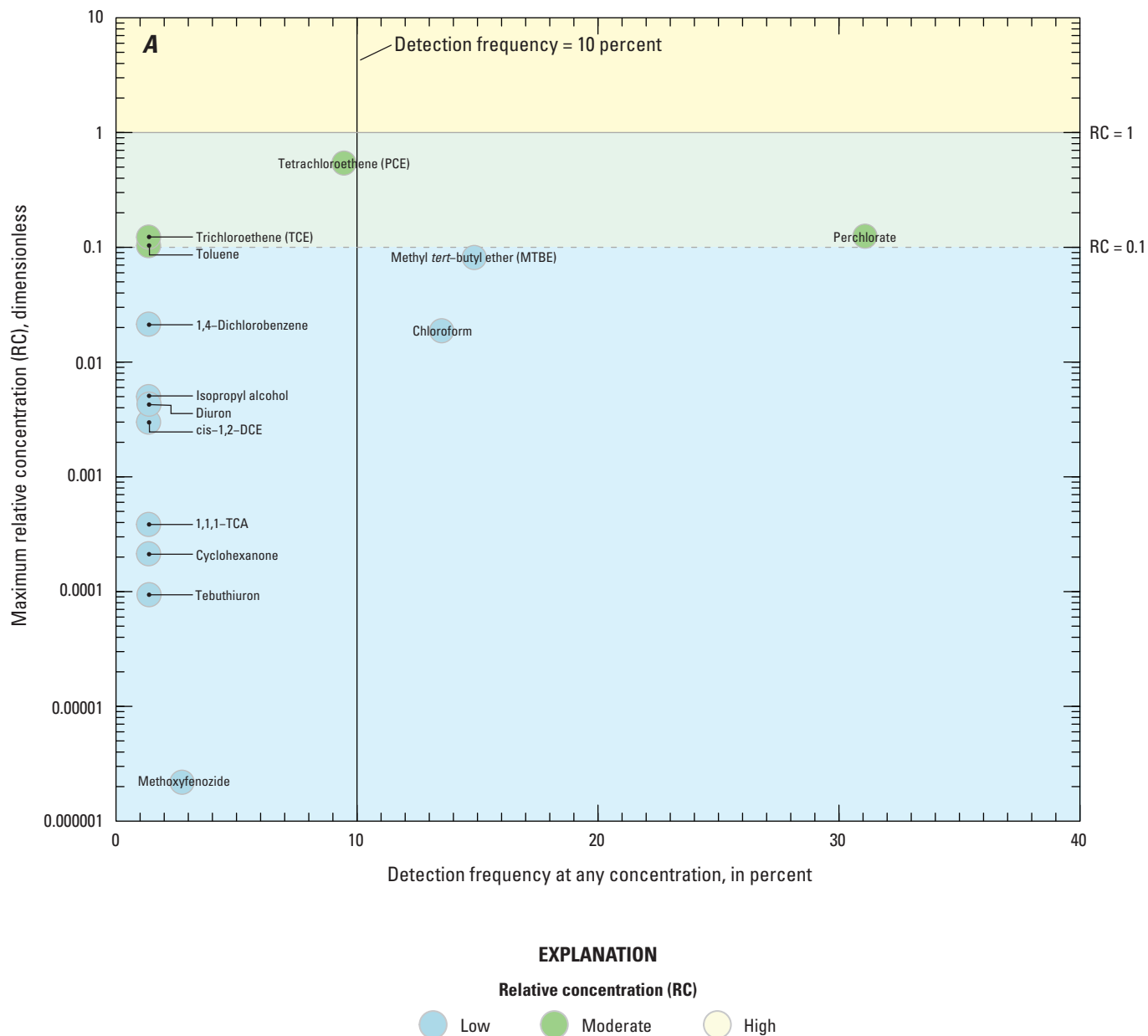


Figure 38. Detection frequency and maximum relative concentration of organic and special-interest constituents detected in samples from U.S. Geological Survey grid sites in the following study units, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project: *A*, Yuba-Bear watersheds; *B*, American-Cosumnes-Mokelumne watersheds.

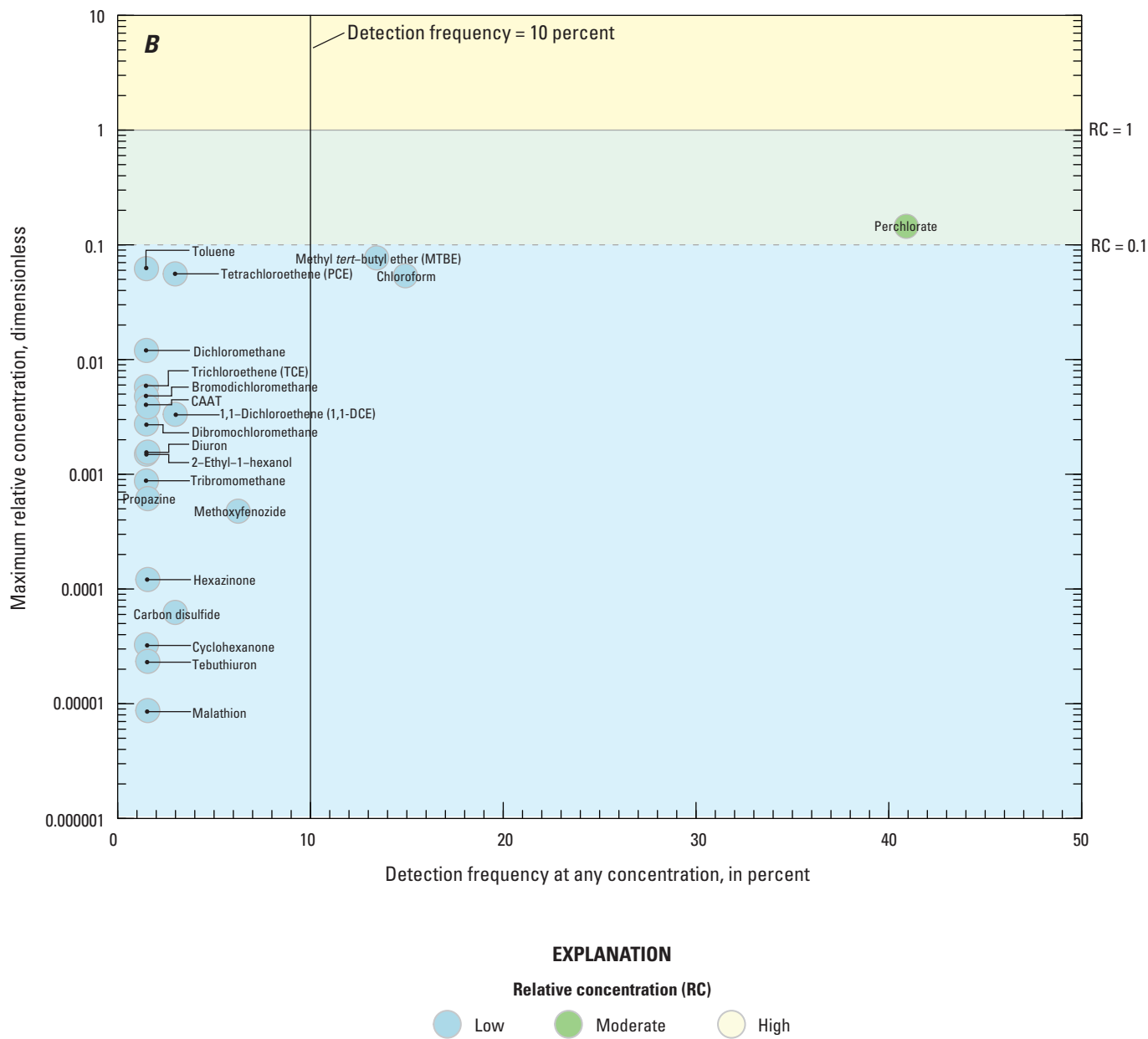


Figure 38.—Continued

Additionally, wells with oxic groundwater had significantly greater concentrations of chloroform than wells with anoxic groundwater (table 12). Chloroform does not readily degrade in oxic water but has been shown to biodegrade in anaerobic cultures seeded with bacteria derived from sewage (Bouwer and others, 1981). Consequently, oxic conditions appear to be conducive to the persistence of chloroform in shallow aquifers in the study region.

Factors Affecting Methyl *Tert*-butyl Ether

Methyl *tert*-butyl ether (MTBE) is a gasoline oxygenate that is added to gasoline to increase the efficiency of combustion. MTBE became a popular fuel additive throughout the United States to boost automotive performance in the 1970s when alkyl-lead additives were discontinued, and subsequent use of MTBE increased to improve air quality in response to the Clean Air Act Amendments of 1990 (Fiorenza and others, 2002). In California, the addition of MTBE to gasoline was phased out starting December 31, 2003, because of concerns of widespread contamination of groundwater by

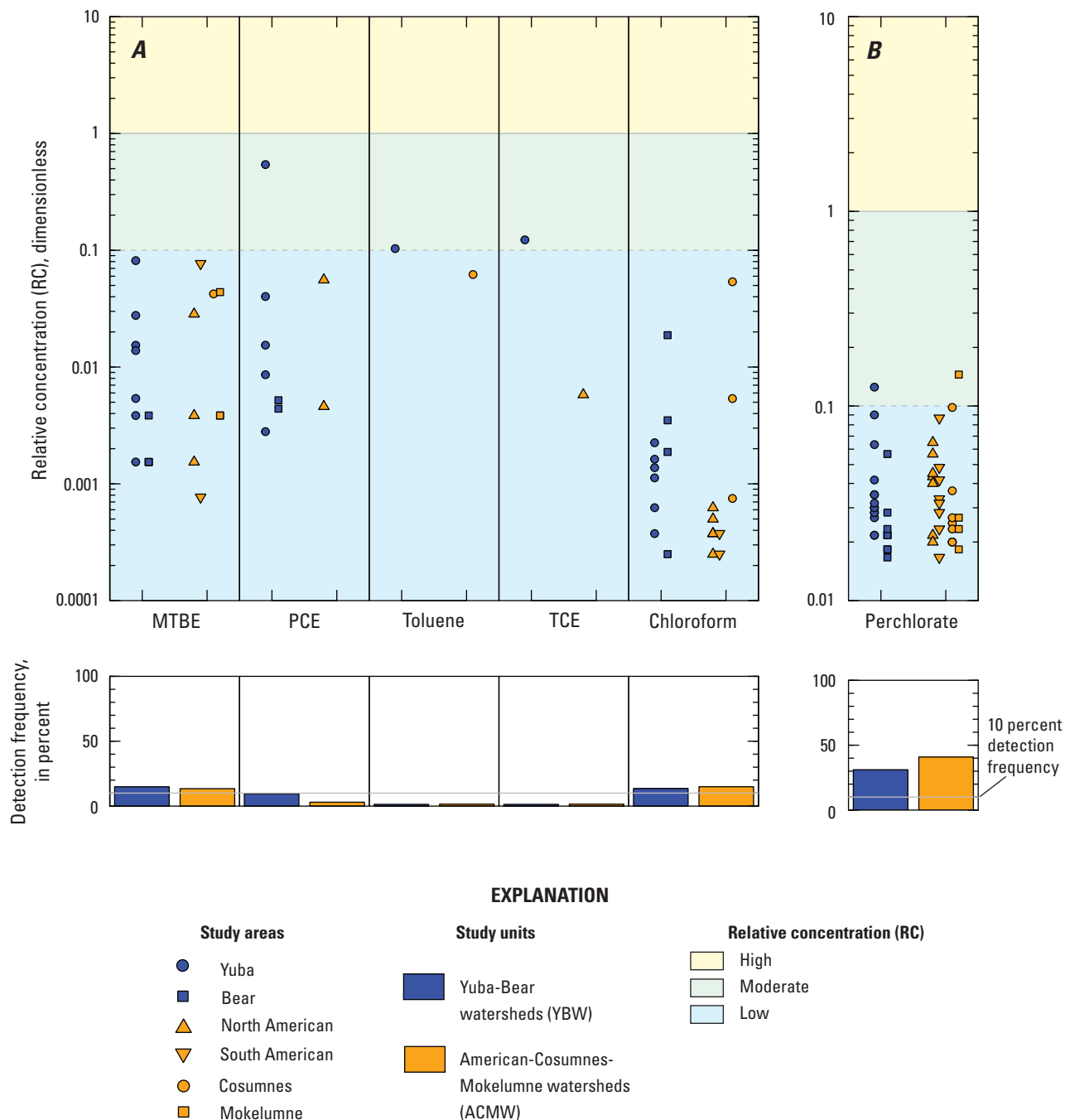


Figure 39. Relative concentrations by study area and detection frequencies by study unit for grid well detections in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project of selected A, volatile organic compounds; B, constituents of special interest (perchlorate).

LUFTs (California Air Resources Board, 2003). Happel and others (1998) estimated that groundwater at over 10,000 LUFT sites in California has been contaminated with MTBE. MTBE is more mobile and less degradable in groundwater systems than other gasoline byproducts, and MTBE plumes have been shown to be persistent and travel over kilometer-scales

in some aquifers (Kane and others, 2001; Belitz and others, 2003). Although there is no MCL-US for MTBE, carcinogenic effects have been observed in animal studies, and the State of California established an MCL-CA of 13 $\mu\text{g/L}$ in 2000 (California State Water Resources Control Board, 2017).

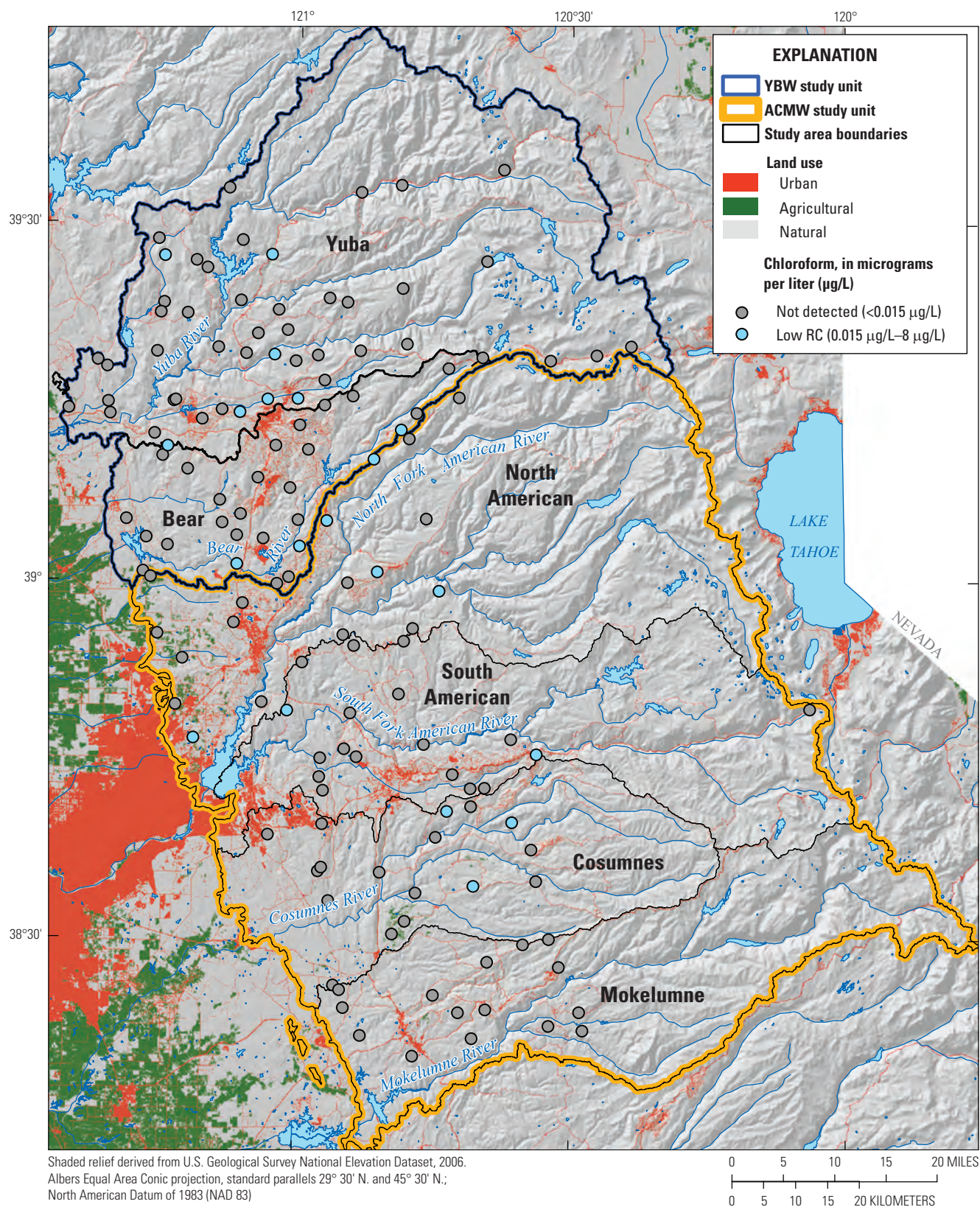


Figure 40. Relative concentrations (RC) of chloroform in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

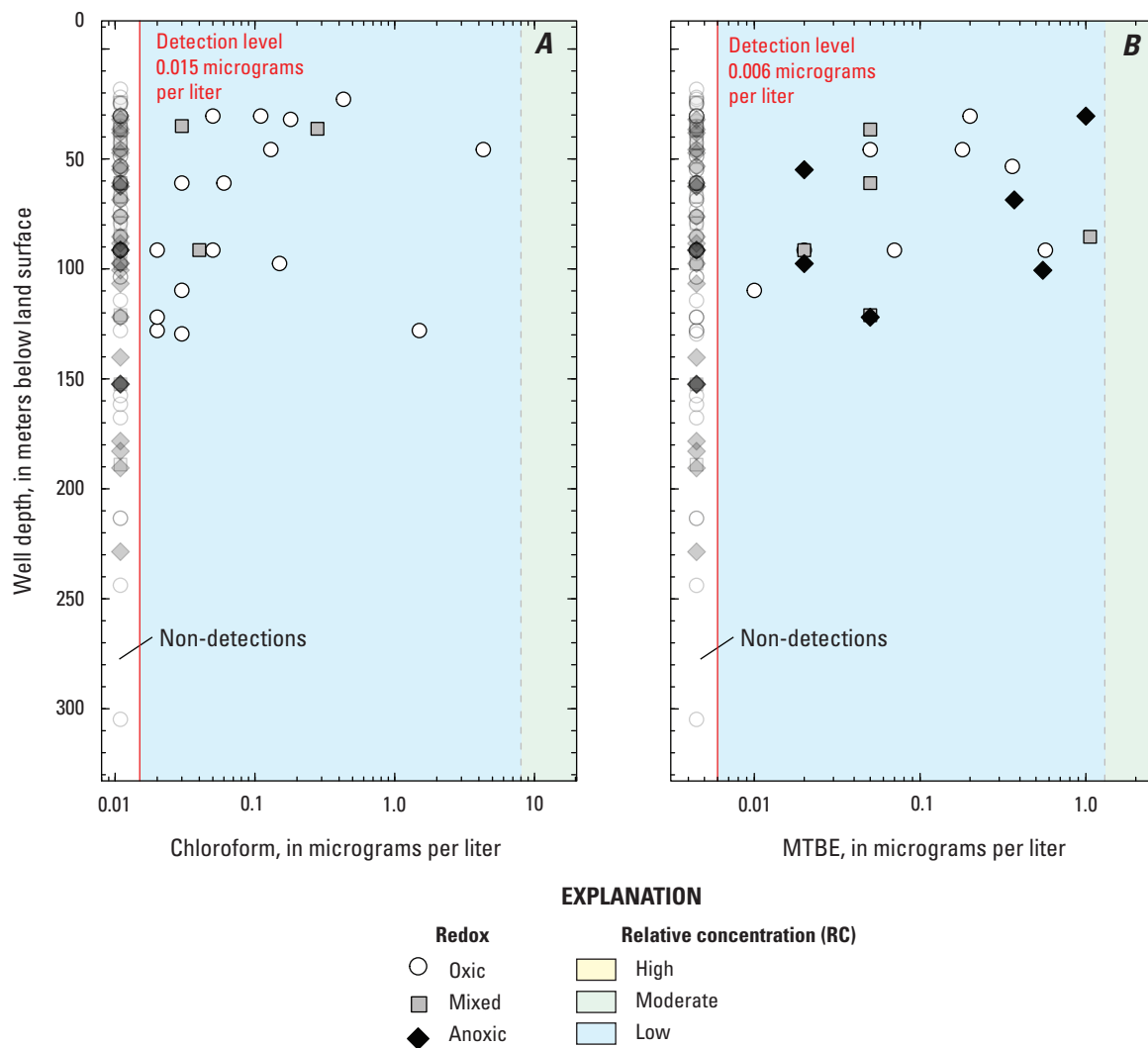


Figure 41. Relations of well depth for U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, to detections of *A*, chloroform; *B*, methyl *tert*-butyl ether (MTBE) by redox classification. Non-detections are plotted at an arbitrary value below respective method detection levels of 0.015 µg/L for chloroform and 0.006 µg/L for MTBE.

Concentrations of MTBE in the study region ranged from non-detection (less than the method detection level of 0.006 µg/L) to 1.1 µg/L, with detections distributed throughout the study region (fig. 42). Similar to chloroform, MTBE had weak positive correlations to urban land use, septic-tank density, and LUFT density (table 11). MTBE had a weak negative correlation to DO of the same magnitude as the positive correlation of chloroform to DO (table 11). MTBE was detected in wells with anoxic, mixed redox, and oxic groundwater with well depths less than 130 m—the same depth range in which chloroform was detected (figs. 41A–B). Although MTBE can be recalcitrant in both oxic and anoxic groundwater, aerobic biodegradation has been observed in laboratory microcosms by exposing anoxic aquifer

sediments to atmospheric oxygen (Kane and others, 2001). Anoxic conditions appear to be conducive to the persistence of MTBE in shallow aquifers in the study region.

Atmospheric deposition of MTBE is a potential source for groundwater that was recharged between 1994 and 2004, when MTBE was used extensively as a gasoline additive in California. Based on the equilibrium solubility of MTBE, Fram and Belitz (2014) estimated that precipitation could contain dissolved MTBE concentrations ranging from 0.6 to 7 µg/L during this period and measured concentrations of MTBE in groundwater up to 0.8 µg/L in public-supply aquifers sampled by the GAMA-PBP throughout the Sierra Nevada in 2008 at an area-weighted detection frequency of 11 percent.

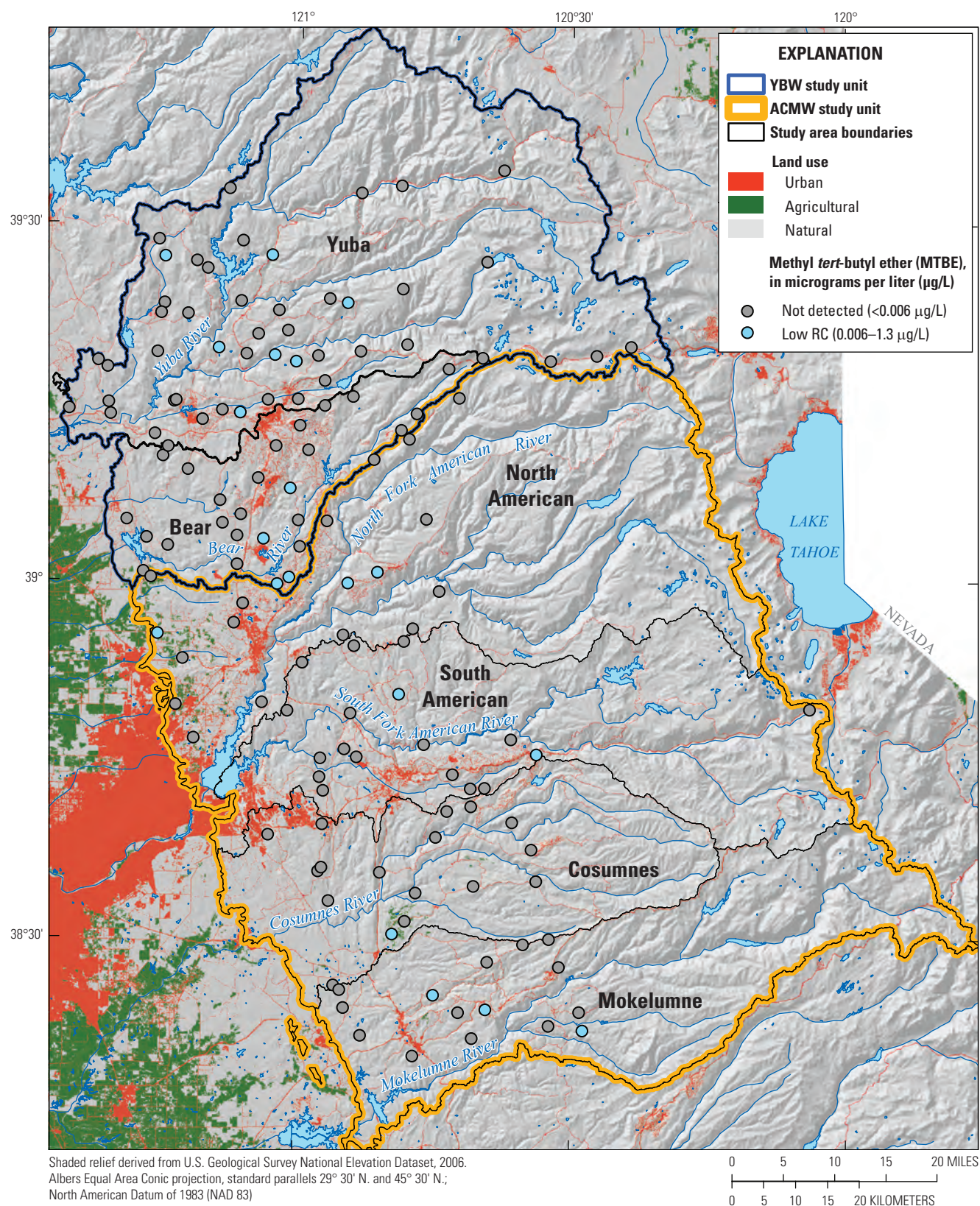


Figure 42. Relative concentrations (RC) of methyl *tert*-butyl ether (MTBE) in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

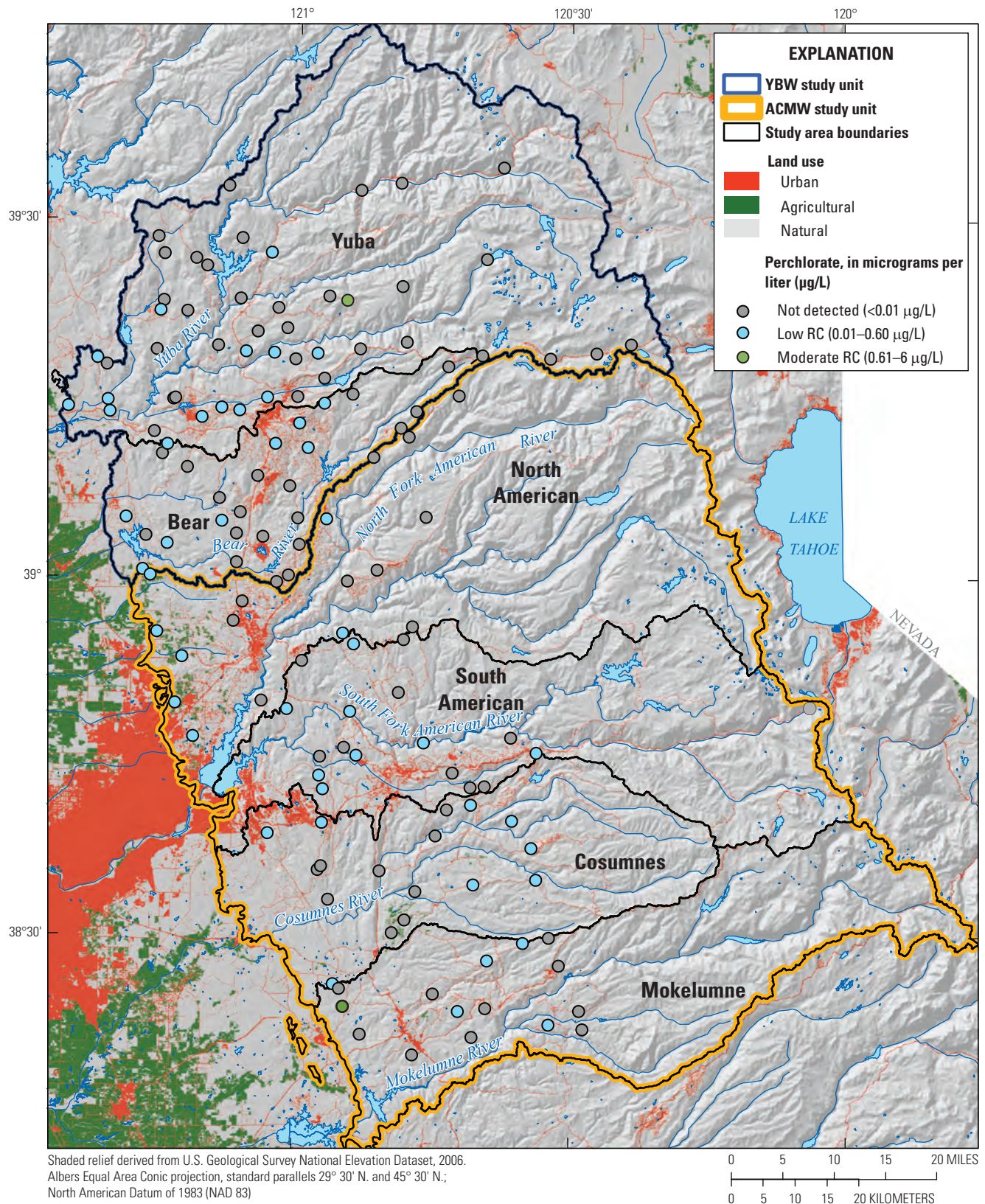


Figure 43. Relative concentrations (RC) of perchlorate in samples from U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

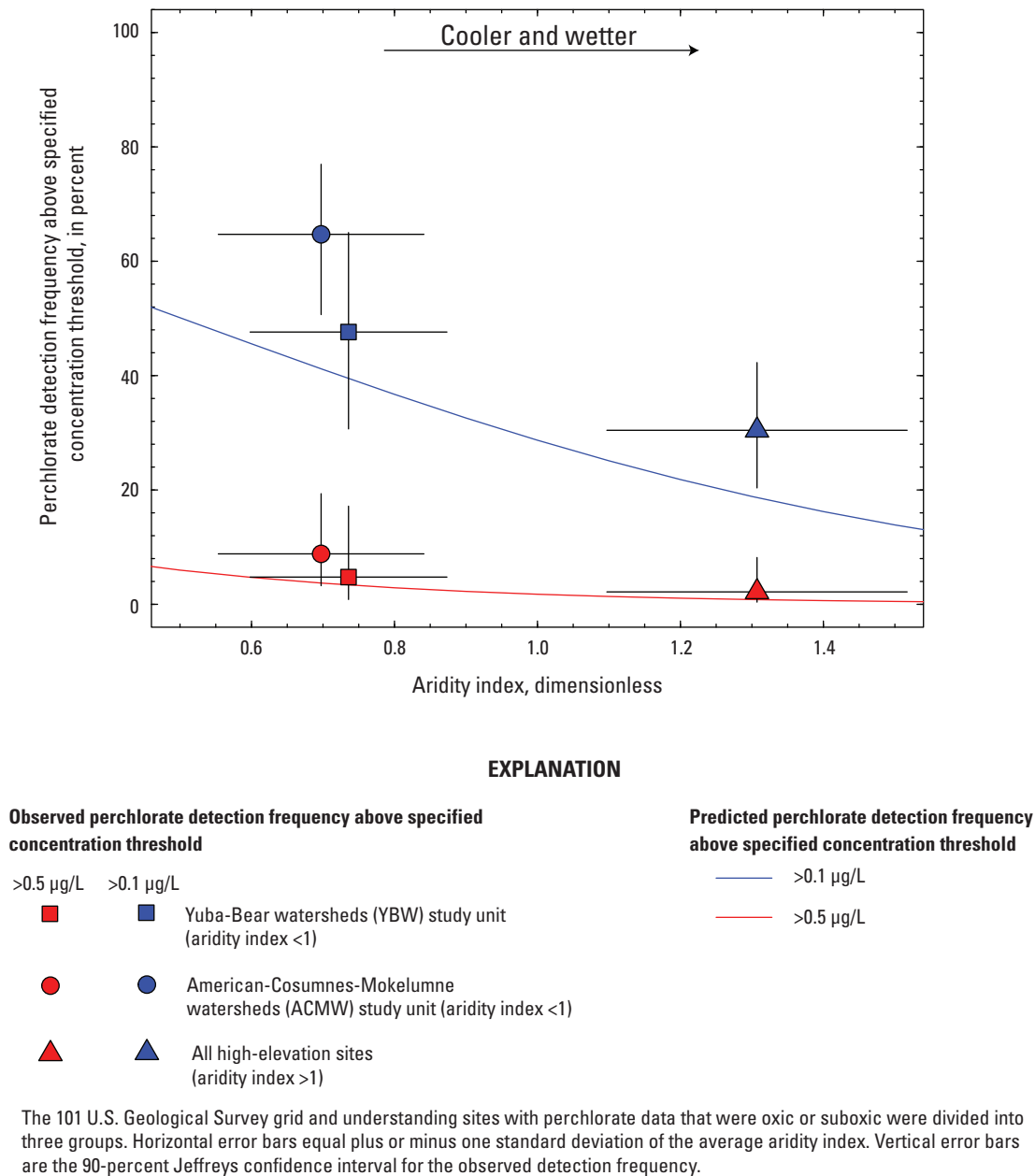
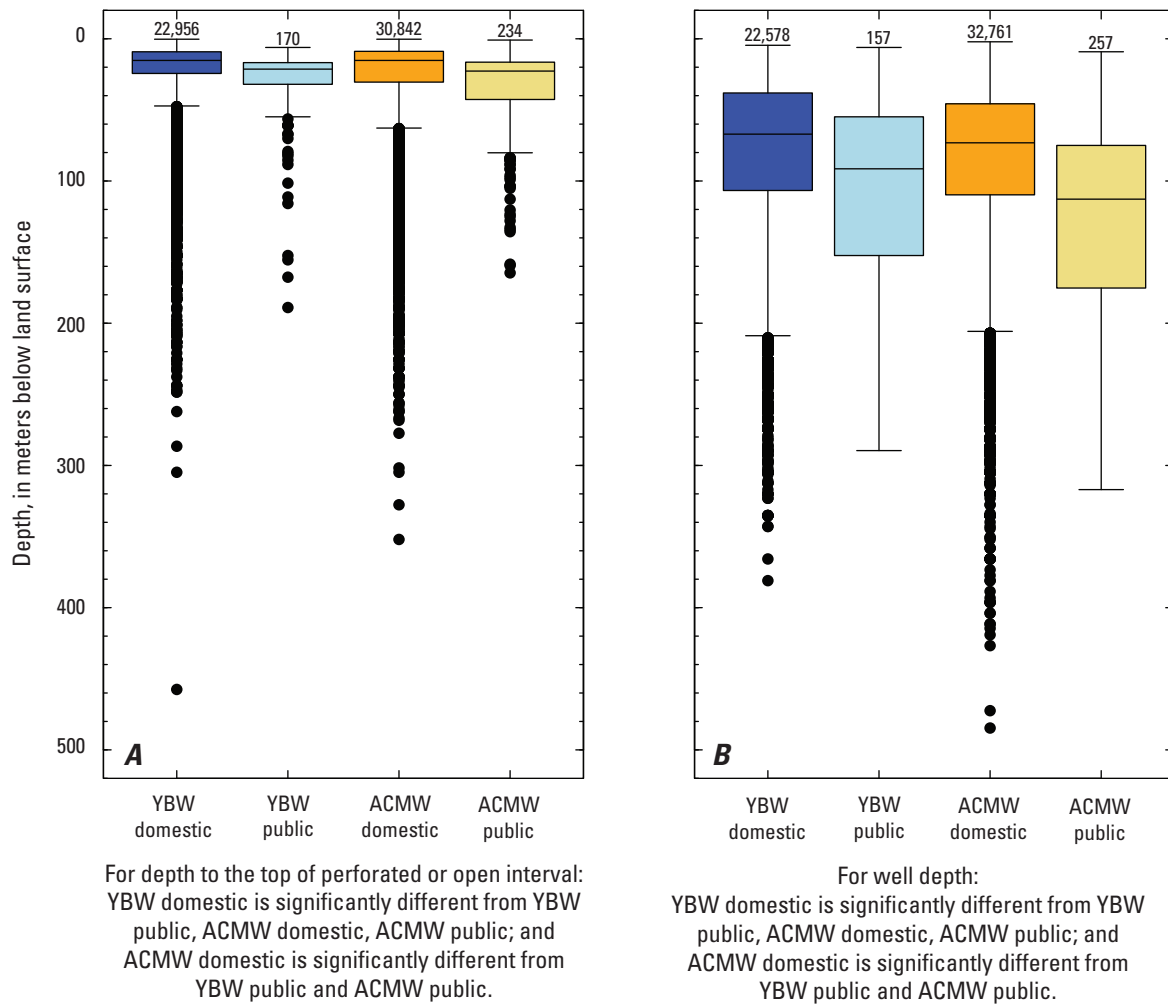


Figure 44. Predicted probability under natural conditions of detecting perchlorate in groundwater as a function of aridity index and observed detection frequency for specified concentration threshold values in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Detection frequencies and maximum concentrations measured in this study were only slightly higher than those measured in public-supply wells throughout the Sierra Nevada in the 2008 GAMA-PBP study (figs. 38A–B; table 10). Fram and Belitz (2014) suggested atmospheric deposition could be an important source of MTBE in Sierra Nevada groundwater, especially where there are no signs of anthropogenic

contamination related to land use. Of the 20 wells where MTBE was detected, however, 6 also had detections of PCE, and the correlation between these two VOCs was significant (table 13). This indicates, for at least some of the sites, anthropogenic MTBE sources related to land use and potentially LUFT-affected zones could be a more likely explanation for more than one VOC detected at the same site.



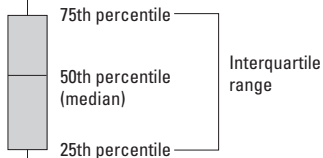
YBW = Yuba-Bear watersheds

ACMW = American-Cosumnes-Mokelumne watersheds

EXPLANATION

500 Number of values

Largest value within 1.5 times interquartile range above 75th percentile



Smallest value within 1.5 times interquartile range below 25th percentile

- Outside value: Value is greater than 1.5 times the interquartile range beyond either end of the box

Figure 45. Distribution of well-construction data from the California Department of Water Resources well-completion report database by planned use (domestic or public) and study unit (YBW, Yuba-Bear watersheds or ACMW, American-Cosumnes-Mokelumne watersheds), California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project (data from Stork and others, 2019), for *A*, depth to top of open or perforated interval; and *B*, well depth.

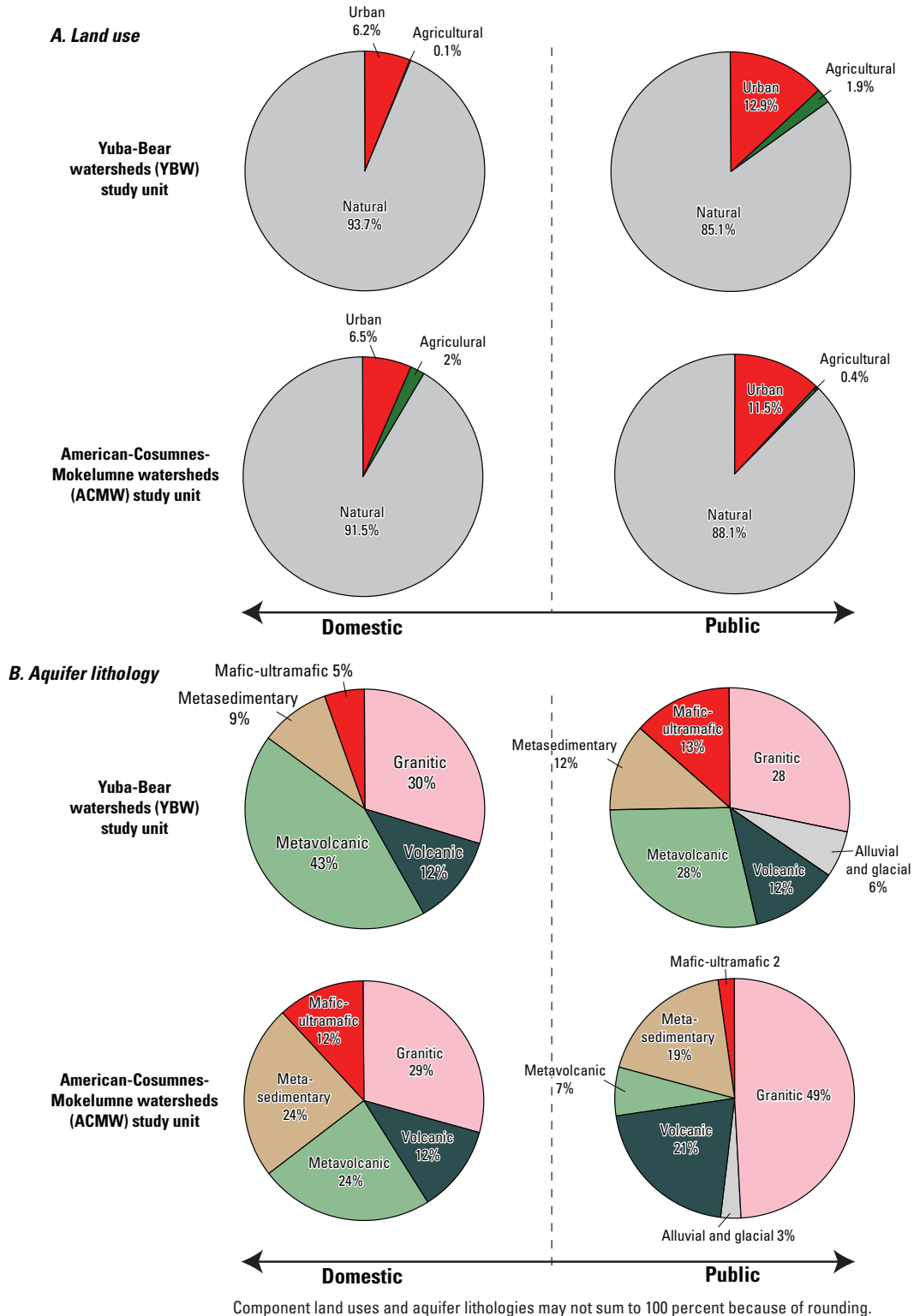


Figure 46. Percentages of land characteristics by study unit for U.S. Geological Survey sampled domestic-supply wells and public-supply wells used in the comparative assessment, northern Sierra Nevada foothills domestic-supply aquifer assessment, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, comparing *A*, average land use within a 500-meter buffer around groundwater sites; *B*, proportions of wells in various aquifer lithologies. [% , percent]

Table 14. Summary of aquifer-scale proportions for the absence or presence of microbial indicators, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[%, percent; YBW, Yuba-Bear watersheds; ACMW, American-Cosumnes-Mokelumne watersheds]

Study unit	Aquifer-scale proportions (percent)		
	Absent	Present	90% confidence interval (lower and upper limit) for aquifer-scale proportion of indicator presence, in percent ¹
Total coliform bacteria (TC)			
YBW	77	23	16–32
ACMW	72	28	19–38
<i>Escherichia coli</i> (EC)			
YBW	95	5.4	2.3–11
ACMW	90	9.8	4.9–17
<i>Enterococci</i> (ENT)			
YBW	89	11	6.3–19
ACMW	98	1.6	0.30–6.2
Any microbial indicator			
YBW	0	26	18–35
ACMW	72	28	19–38

¹Based on Jeffreys interval for the binomial distribution; for non-zero proportions, the confidence interval is calculated as a two-sided interval, and for zero, a one-sided interval is computed (Brown and others, 2001; Belitz and others, 2010).

Constituents of Special Interest

Perchlorate is a trace inorganic compound that is naturally present in groundwater but can also have anthropogenic sources (Fram and Belitz, 2011). Perchlorate is considered a constituent of special interest for the purposes of this report and was assessed using a similar framework to that of organic constituents to maintain consistency with prior GAMA-PBP assessments, which evaluated perchlorate based both on RC and on detection frequency because perchlorate is typically present at trace concentrations in groundwater. Perchlorate was not present at high RC but was present at moderate RC in 1.4 and 1.5 percent of the YBW and ACMW study units, respectively, and at low RC in 30 and 39 percent of the YBW and ACMW study units, respectively (tables 9–10; figs. 38A–B, 39B). Perchlorate was therefore included in both the status and the understanding assessments.

Factors Affecting Perchlorate

Perchlorate is a trace inorganic compound that is naturally present in precipitation and accumulates in arid-region soils (Fram and Belitz, 2011). Anthropogenic sources of perchlorate include solid rocket fuel, explosives, nitrate-based natural fertilizers, and flushing from the soil zone by irrigation recharge (Dasgupta and others, 2005). Perchlorate disrupts formation of thyroid hormones in humans by interfering with iodide uptake, and infants are particularly vulnerable to health effects (National Research Council, 2005). The State of California established an MCL-CA of 6 µg/L for perchlorate in drinking water (California State Water Resources Control Board, 2019c).

Perchlorate in grid wells ranged from non-detection (less than the reporting level of 0.1 µg/L) to 0.87 µg/L, with detections distributed throughout the study region (fig. 43). Perchlorate concentrations were greater in modern than pre-modern groundwater and greater in oxic groundwater than in groundwater having anoxic or mixed redox conditions (table 12), likely because perchlorate has anthropogenic sources and degrades under reducing conditions at about the same redox potential as nitrate (Fram and Belitz, 2011). Perchlorate concentration was positively correlated to agricultural land use, normalized NGRT, and nitrate. Perchlorate concentration was negatively correlated to *d-excess*, supporting irrigation recharge during the dry-season as a plausible transport mechanism in the study region (tables 11, 13). The strong correlation to nitrate (Spearman's rho = 0.67) could reflect that perchlorate can be present in nitrate-based fertilizers and also that groundwater nitrate frequently is higher in heavily irrigated areas where naturally present perchlorate salts can be mobilized from the unsaturated zone by recharge (Fram and Belitz, 2011). Perchlorate was also positively correlated to urban land use and density of septic tanks, indicating other potential anthropogenic sources related to urban and rural-residential land uses, such as irrigation of family orchards or gardens.

The frequency at which perchlorate is detected in groundwater under natural conditions is related to the AI because evapotranspiration of precipitation in drier areas concentrates natural atmospheric perchlorate in recharge waters (Fram and Belitz, 2011). Perchlorate was inversely correlated to AI (that is, higher concentrations were associated with drier climate conditions) in the study region (table 11), consistent with regional analyses in the southwestern United States (Fram and Belitz, 2011). Using the logistic regression approach of Fram and Belitz (2011), relations between the detection frequencies of perchlorate exceeding two concentration thresholds (0.1 and 0.5 µg/L) and AI were calculated over the range of climate conditions observed in the northern Sierra Nevada foothills region (fig. 44). Because perchlorate is degraded at around the same redox potential as nitrate, only samples that were classified as oxic or suboxic (appendix 1, table 1.1) were included in this analysis. This approach resulted in 101 samples that were subdivided into 3 groups according to climate and study unit: low-elevation

Table 15. Results of Kruskal-Wallis tests for differences in values of land-use factors, hydrologic conditions, geochemical conditions, and recharge conditions among sample groups classified by presence or absence of microbial indicators, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for significant differences. “Absent > Present” for elevation in the total coliform column means the following: The elevations of wells where total coliform was absent was significantly greater than the elevations of wells where total coliform was present. Relation of median values in sample groups tested shown for Kruskal-Wallis tests if they 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. Test p-values were calculated using the Kruskal-Wallis test; if significant, then pairwise Dunn tests among the were used to determine which differences were significant among the different groups. **Other abbreviations:** >, greater than; d-excess, deuterium excess; LUFT, leaking (or formerly leaking) underground fuel tank; MAAT, mean annual air temperature; NGRT, noble-gas recharge temperature; NS, not significant (statistical test indicated no significant differences between the sample groups).]

Explanatory factors	Total coliform bacteria (TC)	<i>Escherichia coli</i> (EC)	<i>Enterococci</i> (ENT)
Land use			
Percent agricultural land use	NS	NS	NS
Percent natural land use	NS	NS	NS
Percent urban land use	NS	NS	NS
Septic tank density	NS	NS	NS
LUFT density	NS	NS	NS
Hydrologic conditions			
Aridity index	Absent > Present	Absent > Present	NS
Elevation of land-surface datum	Absent > Present	Absent > Present	NS
Well depth	NS	NS	NS
Depth to top of screened or open interval	NS	NS	NS
Geochemical conditions			
pH	NS	NS	NS
Dissolved oxygen (DO)	NS	NS	NS
Recharge conditions			
Normalized recharge temperature (NGRT - MAAT)	NS	NS	NS
d-excess	Absent > Present	Absent > Present	NS

sites in the YBW study unit and AI less than 1 (dry sub-humid to humid climate; 21 samples), low-elevation sites in the ACMW study unit and AI less than 1 (semi-arid to humid climate; 34 samples), high-elevation sites throughout the two study units and AI greater than 1 (wet climate; 46 samples). Detection frequencies were then calculated for each of the threshold concentrations (number of detected concentrations greater than the threshold value in the climate group divided by number of analyses in the climate group).

Detections of perchlorate exceeding the 0.5 $\mu\text{g/L}$ threshold were few and could be accounted for by the modeled relation between perchlorate and AI under natural conditions (fig. 44). In contrast, low-elevation sites in the ACMW study unit and the high-elevation sites in the study region had perchlorate detection frequencies (and associated 90 percent confidence intervals based on Jeffreys interval for the binomial distribution; Brown and others, 2001; Belitz and others, 2010)

at the 0.1 $\mu\text{g/L}$ threshold that were greater than what could be explained by natural, atmospheric sources of perchlorate predicted by the logistic regression model of Fram and Belitz (2011). Increased perchlorate detection frequencies could be due to irrigation recharge because there is more agriculture in the ACMW study unit than the YBW study unit. There is little agriculture around the high-elevation sites, however, and land use is mostly natural. Homeowners can irrigate their own properties, however, leading to mobilization of perchlorate from the vadose zone. Additionally, most of the high-elevation sites were in the YBW study unit, which was sampled near the end of an extended and severe drought (Levy and others, 2020). The AI calculated using long-term climate averages, therefore, may not capture the extremely dry conditions for the 4 years preceding sampling at many of the high-elevation sites.

Table 16. Results of Kruskal-Wallis tests for differences in concentration of selected water quality constituents among sample groups classified by presence or absence of microbial indicators, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for significant differences. “Present > Absent” for nitrate in the total coliform column means the following: Nitrate concentrations for wells where total coliform was present are significantly greater than nitrate concentrations for wells where total coliform was absent. Relation of median values in sample groups tested shown for Kruskal-Wallis tests if they 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. **Other abbreviations:** NS, not significant (statistical test indicated no significant differences between the sample groups); >, greater than]

Constituent	Total coliform bacteria (TC)	<i>Escherichia coli</i> (EC)	<i>Enterococci</i> (ENT)
Inorganic constituents with health-based benchmarks			
Trace elements			
Arsenic	NS	NS	NS
Barium	NS	Absent > Present	Absent > Present
Boron	NS	NS	NS
Fluoride	NS	NS	NS
Molybdenum	NS	NS	NS
Strontium	NS	NS	NS
Nutrients			
Nitrate, as nitrogen	Present > Absent	Present > Absent	Present > Absent
Trace inorganic compounds			
Perchlorate	NS	NS	NS
Radioactive constituents			
Adjusted gross-alpha particle radioactivity	NS	NS	NS
Gross-beta particle radioactivity	NS	NS	NS
Inorganic constituents with SMCL or aesthetic-based benchmarks			
Chloride	NS	Present > Absent	NS
Hardness, as calcium carbonate	NS	NS	NS
Iron	NS	NS	NS
Manganese	Absent > Present	NS	NS
Specific conductance	NS	NS	NS
Sulfate	NS	NS	NS
Total dissolved solids (TDS)	NS	NS	NS
Organic constituents with health-based benchmarks			
Trichloromethane (chloroform)	NS	NS	NS
Methyl <i>tert</i> -butyl ether (MTBE)	NS	NS	NS
Tetrachloroethylene (PCE)	NS	NS	NS
Toluene	NS	NS	Present > Absent
Trichloroethylene (TCE)	NS	NS	NS

Comparative Assessment

The comparative assessment evaluated differences between aquifer systems used for domestic- and public-supply in the YBW and ACMW study units based on (1) well-construction characteristics and (2) water quality. Well-construction characteristics for public- and domestic-supply wells in the study region were compared using over 60,000 records of well-completion reports compiled by Stork and others (2019). Depth to the TOP, total well depth,

and generalized aquifer lithology (hard rock or alluvial) were compared by study unit (YBW and ACMW) and aquifer system (domestic and public). Next, water-quality results for constituents evaluated in the status assessments for the YBW and ACMW study units were compared with aquifer-scale proportions calculated from over 300 public-supply wells in the study region (Fram and Belitz, 2014; California State Water Resources Control Board, 2019b). Differences in land use, aquifer lithology, and landscape position ([appendix 1](#); Levy, 2020) between domestic- and public-supply wells are also discussed to further contextualize results.

Well-Construction Comparison

The vast majority of well-completion reports in the study region were for domestic-supply wells finished in hard-rock aquifers. Domestic-supply wells account for 98 percent of the regional well-completion reports, and public-supply wells make up 0.7 percent. Generalized lithologies recorded on regional well-completion reports were 91.1 percent hard rock, 2.5 percent alluvial, and 6.4 percent not reported.

Although the range of domestic-supply well depths spanned the deepest depth zones in regional aquifers, median values of depth to the TOP and well depth for public-supply wells were significantly greater than those of domestic-supply wells in both study units (Dunn rank-sum test, p less than 0.001; [fig. 45A](#)). The median depths to TOP for domestic- and public-supply wells in the YBW study unit were 15 and 21 m, respectively, and 15 and 23 m in the ACMW study unit, respectively. Although depth to TOP was greater for domestic-supply wells in the ACMW than in the YBW study units (Dunn rank-sum test, p less than 0.001; [fig. 45A](#)), there was no significant difference between depth to TOP for public-supply wells between the two study units (Dunn rank-sum test, p greater than 0.5; [fig. 45A](#)).

Median well depths for domestic- and public-supply wells were 67 and 91 m in the YBW unit, respectively, and were 73 and 112 m in the ACMW study unit, respectively. Although depths for domestic-supply wells were greater in the ACMW than in the YBW study unit (Dunn rank-sum test, p less than 0.001; [fig. 45B](#)), there was no significant difference between the study units in terms of well depths for public-supply wells (Dunn rank-sum test, $p=0.062$; [fig. 45B](#)). Overall, although public-supply wells tended to be deeper than domestic-supply wells, there was considerable overlap among the aquifer depth zones used for these two resources.

Land-Use, Aquifer-Lithology, and Landscape-Position Comparisons

Land use, aquifer lithology, and landscape position were compared for the subset of domestic- and public-supply wells used to compare water quality in the YBW and ACMW study units. Land use percentages were calculated for a 500-m buffer radius around all public-supply wells with water-quality data using the same methods as described for the domestic-supply wells ([appendix 1](#); Levy, 2020). Overall, public-supply wells had a higher percentage of urban land use than domestic-supply wells in both study units (Kruskal-Wallis rank-sum, p less than 0.001). Average urban land use percentage around public-supply wells was almost double that around domestic-supply wells in both study units ([fig. 46A](#)). Although, on average, public-supply wells had greater agricultural land use than domestic-supply wells in the YBW study unit, the difference between the two groups was not significant (Kruskal-Wallis rank-sum, p greater than 0.5). For agricultural land use in the ACMW study unit,

however, the difference between domestic- and public-supply wells was significant (Kruskal-Wallis rank-sum, $p = 0.043$), and domestic-supply wells had an average of approximately 2 percent greater agricultural land use than public-supply wells ([fig. 46A](#)).

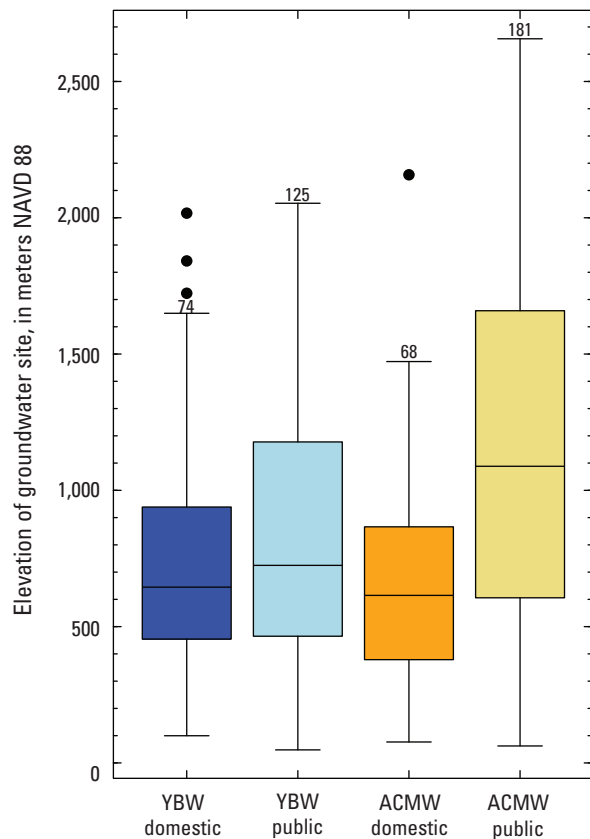
Aquifer lithologies for public-supply wells were derived in a similar manner to that of the domestic-supply wells ([appendix 1](#); Levy, 2020). Although there was no significant difference in aquifer lithology between domestic- and public-supply wells in the YBW study unit (contingency table test, $p = 0.054$; [fig. 46B](#)), the p value was extremely close to the significance level because of respectively greater and lesser proportions of mafic-ultramafic and metavolcanics lithologies for public-supply wells than for domestic-supply wells ([fig. 46B](#)). In the ACMW study unit, there was a significant difference in aquifer lithology between domestic- and public-supply wells (contingency table test, p less than 0.001; [fig. 46B](#)). This was primarily because of substantially smaller proportions of mafic-ultramafic and metavolcanic lithologies and greater proportions of granitic lithologies for public-supply wells than for domestic-supply wells ([fig. 46B](#)).

The elevations of the domestic- and public-supply wells were evaluated using land-surface elevations extracted at well point locations from the 30-m digital elevation model of California ([appendix 1](#); Levy, 2020). There was no significant difference between the elevations of domestic- and public-supply wells in the YBW study unit (Dunn rank sum test, p greater than 0.5; [fig. 47](#)); however, public-supply wells were at significantly higher elevations than domestic-supply wells in the ACMW study unit (Dunn rank sum test, p less than 0.001; [fig. 48](#)).

Water-Quality Comparison

The comparative assessment evaluated differences in aquifer-scale proportions between domestic- and public-supply aquifers for constituents that were included in the status assessment ([table 2](#)). Aquifer-scale proportions for constituent classes in the public-supply aquifer system were calculated using only the organic and inorganic constituents that had been selected for evaluation in the status assessment so that results aggregated by class could be compared for the two resources. Only data for samples of raw, untreated groundwater from public-supply wells in the SWRCB-DDW database were used for the comparison.

High-RC aquifer-scale proportions were compared for inorganic constituents, and detection frequencies were compared for organic constituents because there were no high-RC and few moderate-RC detections for organic constituents in the study region. Differences in aquifer-scale proportions were evaluated by comparing confidence intervals for aquifer-scale proportions calculated in the status assessment with those of the public-supply aquifer system using the spatially weighted method of Belitz and others (2010). If the spatially weighted estimate (public supply) fell



ACMW public is significantly different from YBW domestic, YBW public, and ACMW domestic.

EXPLANATION

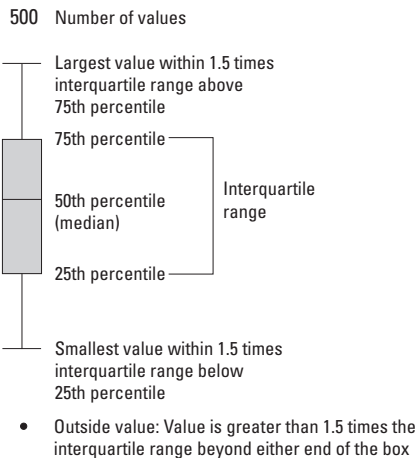


Figure 47. Distribution of groundwater-site elevation comparing U.S. Geological Survey sampled domestic wells with public wells used for water-quality comparison in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

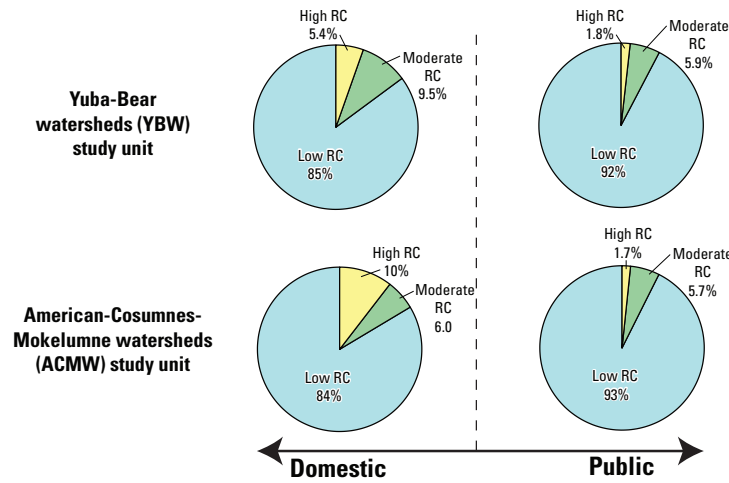
within the grid-based (domestic supply) confidence interval, aquifer-scale proportions for the two systems were considered similar. If the spatially weighted estimate was outside of the grid-based confidence interval (by at least 1 percent), the two resources were considered to be potentially different for a given constituent or constituent class and were qualitatively evaluated. Calculation of robust confidence intervals for spatially weighted estimates are required to establish statistical difference, and this level of analysis requires some knowledge of within-cell distributions of constituents, which was not well known given the limitations of the public-supply dataset (Belitz and others, 2010). Summary statistics for aquifer-scale proportions calculated for the comparative assessment for inorganic and organic constituents are presented in [tables 17–18](#).

Inorganic Constituents

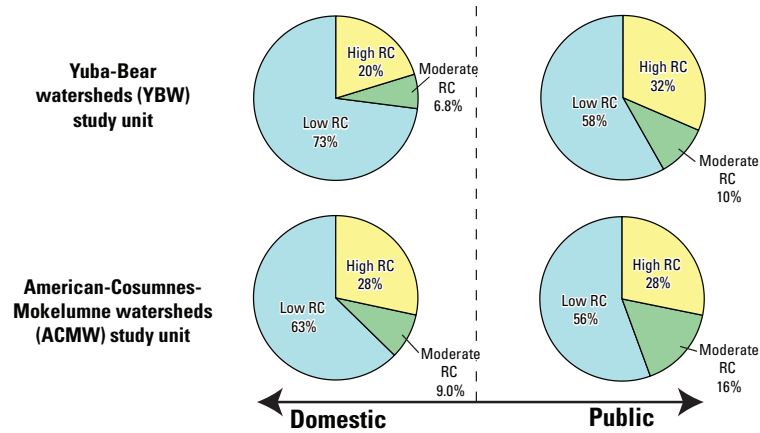
Overall, there was no significant difference for inorganic constituents with health-based benchmarks, as a class, between domestic- and public-supply aquifer systems in the YBW study unit; however, the ACMW study unit had greater high-RC aquifer proportions for domestic-supply (10 percent) than for public-supply (1.7 percent) aquifer systems, almost entirely due to nitrate ([fig. 48A](#); [table 17](#)). The YBW study unit had greater high-RC proportions for inorganic constituents with an SMCL in the public-supply (32 percent) than in domestic-supply (20 percent) aquifer systems as a result of iron and manganese; although taken separately, only iron had a significantly greater high-RC proportion in the public-supply than in domestic-supply aquifer systems ([fig. 48B](#); [table 17](#)). There was no significant difference for the SMCL constituent class in the ACMW study unit, although there were significant differences among individual constituents with SMCLs (iron and manganese; [table 17](#)).

Nitrate was the only inorganic constituent with a health-based benchmark that was significantly different between domestic and public-supply aquifer systems in the comparative assessment; however, this was only in the ACMW and not the YBW study unit ([fig. 49A](#); [table 17](#)). Nitrate was only detected at moderate RCs in domestic- and public-supply wells in the YBW study unit and public-supply wells in the ACMW study unit but was detected at high RCs in 7.5 percent of domestic-supply wells in the ACMW study unit. Differences in land use around wells could account for this result because domestic-supply wells were surrounded by a higher proportion of agricultural land use in the ACMW study unit than public-supply wells ([fig. 46A](#)). Higher nitrate groundwater in the ACMW domestic-supply aquifer was associated with higher proportions of agricultural land use in addition to irrigation return flows from forage pasture and rural-residential land uses as evidenced by isotopic and noble-gas tracers ([table 11](#); [figs. 17, 23](#)).

A. Inorganic constituents with health-based benchmarks



B. Inorganic constituents with SMCL benchmarks



C. Select volatile organic compounds (chloroform, MTBE, PCE, TCE, toluene)

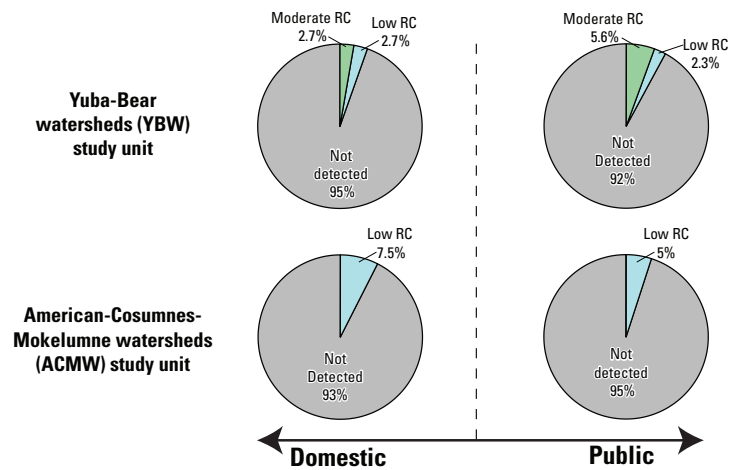


Figure 48. Percentages of aquifer-scale proportions for low, moderate, and high relative concentrations for U.S. Geological Survey sampled domestic-supply wells and public-supply wells used for water-quality comparison in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, for *A*, inorganic constituents with health-based benchmarks; *B*, inorganic constituents with secondary maximum contaminant level (SMCL) benchmarks; *C*, selected volatile organic compounds. [% , percent]

Table 17. Aquifer-scale proportions for inorganic constituents calculated using the spatially weighted method for public-supply wells compared with those calculated using the grid-based method for domestic-supply wells, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for significant differences. “Dom > Pub” for barium means the following: The domestic supply assessment has a greater high aquifer-scale proportion for barium than the public supply assessment. **Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.5 times the benchmark for inorganic constituents unless otherwise noted in table 2. Confidence intervals are given as lower and upper limits. Spatially weighted high-aquifer scale proportions for the public supply assessment are compared to 90% confidence intervals for the grid-based domestic supply assessment in order to quantify differences in the resources; if the public aquifer-scale proportion falls within the confidence interval for the domestic aquifer-scale proportion there is no significant difference between the high aquifer scale proportions of a given constituent between the two resources. Alternately, if the public aquifer-scale proportion is higher or lower than the domestic aquifer-scale proportion, there is a significant difference between the high aquifer-scale proportion for a given constituent between the two resources. **Abbreviations:** >, greater than; %, percent, NS, not significant (public- and domestic-supply high-aquifer scale proportions are not significantly different); Dom, domestic-supply assessment; Pub, public-supply assessment; SMCL, secondary maximum contaminant level, µg/L, micrograms per liter.]

Constituent	Yuba-Bear watersheds (YBW) study unit public-domestic supply comparison				American-Cosumnes-Mokelumne watersheds (ACMW) study unit public-domestic supply comparison						
	Number of grid cells covered in public well assessment (out of 75)	Spatially weighted aquifer-scale proportion for public supply assessment, in percent		90% confidence interval (with calculated value) of high-RC aquifer-scale proportion for domestic assessment, in percent ¹	High aquifer-scale proportion comparison	Number of grid cells covered in public supply assessment (out of 67)	Spatially weighted aquifer-scale proportion for public supply assessment, in percent		90% confidence interval (with calculated value) of high-RC aquifer-scale proportion for domestic assessment, in percent ¹		
		Moderate RC	High RC				Moderate RC	High RC			
All inorganic constituents with health-based benchmarks	Inorganic constituents with health-based benchmarks										
	48	5.9	1.8		2.3–11 (5.4)	NS	42	5.7	1.7	5.5–18 (10)	Dom > Pub
	43	3.7	2.7		1.4–9.2 (4.1)	NS	37	6.7	2	1.6–10 (4.5)	NS
	35	4.5	3.3		0.2–5.2 (1.4)	NS	33	3.5	3.0	0.3–5.7 (1.5)	NS
	35	0	0		0.2–5.2 (1.4)	NS	32	0	0	0–2.0 (0)	NS
Boron	26	0	0		0–1.8 (0)	NS	24	0	4.2	0.3–5.7 (1.5)	NS
Fluoride	42	0	0		0–1.8 (0)	NS	37	1.9	0	0–2.0 (0)	NS
Nutrients											
Nitrate, as nitrogen	48	2.1	0		0–1.8 (0)	NS	42	1.5	0	3.4–14 (7.5)	Dom > Pub
Radioactive constituents											
Gross-alpha particle radioactivity	36	0.9	0		0.2–5.3 (1.4) ²	NS	31	1.3	0.6	0–2.1 (0) ²	NS

Table 17. Aquifer-scale proportions for inorganic constituents calculated using the spatially weighted method for public-supply wells compared with those calculated using the grid-based method for domestic-supply wells, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project—Continued

[**Explanation:** How to read results for significant differences. “Dom > Pub” for barium means the following: The domestic supply assessment has a greater high aquifer-scale proportion for barium than the public supply assessment. **Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.5 times the benchmark for inorganic constituents unless otherwise noted in table 2. Confidence intervals are given as lower and upper limits. Spatially weighted high-aquifer scale proportions for the public supply assessment are compared to 90% confidence intervals for the grid-based domestic supply assessment in order to quantify differences in the resources; if the public aquifer-scale proportion falls within the confidence interval for the domestic aquifer-scale proportion there is no significant difference between the high aquifer scale proportions of a given constituent between the two resources. Alternately, if the public aquifer-scale proportion is higher or lower than the domestic aquifer-scale proportion, there is a significant difference between the high aquifer-scale proportion for a given constituent between the two resources. **Abbreviations:** >, greater than; %, percent, NS, not significant (public- and domestic-supply high-aquifer scale proportions are not significantly different); Dom, domestic-supply assessment; Pub, public-supply assessment; SMCL, secondary maximum contaminant level, µg/L, micrograms per liter.]

Yuba-Bear watersheds (YBW) study unit public-domestic supply comparison				American-Cosumnes-Mokelumne watersheds (ACMW) study unit public-domestic supply comparison						
Constituent	Number of grid cells covered in public well assessment (out of 75)	Spatially weighted aquifer-scale proportion for public supply assessment, in percent		90% confidence interval (with calculated value) of high-RC aquifer-scale proportion for domestic assessment, in percent ¹	High aquifer-scale proportion comparison	Number of grid cells covered in public supply assessment (out of 67)	Spatially weighted aquifer-scale proportion for public supply assessment, in percent		90% confidence interval (with calculated value) of high-RC aquifer-scale proportion for domestic assessment, in percent ¹	High aquifer-scale proportion comparison
		Moderate RC	High RC				Moderate RC	High RC		
Inorganic constituents with SMCL or aesthetic-based benchmarks										
Constituents with an SMCL ³	42	10	32	13–29 (20)	Pub > Dom	37	16	28	20–38 (28)	NS
Chloride	40	0	0	0–1.8 (0)	NS	32	0	0	0.3–5.7 (1.5)	NS
Inorganic constituents with SMCL or aesthetic-based benchmarks—Continued										
Hardness, as calcium carbonate	41	24	20	17–33 (24)	NS	34	8.9	15	21–40 (30)	Dom > Pub
Iron	39	4.3	23	6.0–18 (11)	Pub > Dom	35	12	27	7.8–21 (13)	Pub > Dom
Manganese	39	12	24	12–27 (19)	NS	35	13	17	19–36 (27)	Dom > Pub
Specific conductance	39	2.6	2.6	0–1.8 (0)	NS	35	8.8	0	0.3–5.7 (1.5)	NS
Sulfate	41	0	0	0–1.8 (0)	NS	31	0	1.1	0–2.0 (0)	NS
Total dissolved solids (TDS)	39	2.6	0	0–1.8 (0)	NS	32	6.3	1.0	0.3–5.7 (1.5)	NS

¹Based on Jeffreys interval for the binomial distribution; for non-zero proportions, the confidence interval is calculated as a two-sided interval, and for zero, a one-sided interval is computed (Brown and others, 2001; Belitz and others, 2010).

²Aquifer-scale proportions for gross alpha and adjusted gross alpha were identical for domestic grid wells in both study units.

³Hardness does not have a state or federal SMCL and is therefore not included in aquifer-scale proportion calculations for this constituent class.

Table 18. Aquifer-scale proportions for organic and special interest constituents calculated using the spatially weighted method for public-supply wells compared with those calculated using the grid-based method for domestic-supply wells, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[**Explanation:** How to read results for significant differences. “Dom > Pub” for TCE means the following: The domestic supply assessment had a higher detection frequency for TCE than the public supply assessment. **Relative-concentration (RC) 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 low-moderate concentration boundary and no constituents in group with concentration greater than benchmark; low, concentrations of all constituents in group is less than or equal to low-moderate concentration boundary. Low-moderate concentration boundary is 0.1 times the benchmark for organic constituents unless otherwise noted in [table 2](#). Confidence intervals are given as lower and upper limits. Spatially weighted detection frequencies for the public supply assessment are compared to 90% confidence intervals for the grid-based domestic supply assessment in order to quantify differences in the resources; if the public detection frequency falls within the confidence interval for the domestic detection frequency there is no significant difference between the high aquifer scale proportions of a given constituent between the two resources. Alternately, if the public detection frequency is higher or lower than the domestic detection frequency, there is a significant difference between the detection frequencies for a given constituent between the two resources. **Abbreviations:** > greater than; %, percent; NS, not significant (public- and domestic-supply high-aquifer scale proportions are not significantly different). Dom, domestic-supply assessment; Pub, public-supply assessment; SMCL, secondary maximum contaminant level.]

American-Cosumnes-Mokelumne watersheds (ACMW) study unit public-domestic supply comparison														
Yuba-Bear watersheds (YBW) study unit public-domestic supply comparison														
Constituent	Number of grid cells covered in public-supply assessment (out of 75)	Spatially weighted aquifer-scale proportion for public supply assessment, in percent			Spatially weighted detection frequency for public-supply assessment, in percent	90% confidence interval (with calculated value) of detection frequency for domestic assessment, in percent ^{1,2}	Detection frequency comparison	Number of grid cells covered in public-supply assessment (out of 67)	Spatially weighted aquifer-scale proportion for public supply assessment, in percent			Spatially weighted detection frequency for public-supply assessment, in percent	90% confidence interval (with calculated value) of detection frequency for domestic assessment, in percent ^{1,2}	Detection frequency comparison
		Low RC	Moderate RC	High RC					Low RC	Moderate RC	High RC			
Organic constituents with health-based benchmarks														
Select volatile organic compounds ³	36	2.3	5.6		7.9	2.2–11 (5.4)	NS	36	5.0	0		5.0	3.5–14 (7.5)	NS
Trichloromethane (chloroform)	35	1.0	2.9		3.8	0.2–5.2 (1.4)	NS	36	4.2	0		4.2	0.3–5.7 (1.5)	NS
Methyl <i>tert</i> -butyl ether (MTBE)	34	1.5	0		1.5	0.2–5.2 (1.4)	NS	30	0	0		0	1.6–10 (4.5)	Dom > Pub
Tetrachloroethylene (PCE)	35	0	2.9		2.9	0.2–5.2 (1.4)	NS	36	0	0		0	0–2.0 (0)	NS
Toluene	35	1.4	0		1.4	0.2–5.2 (1.4)	NS	36	0.9	0		0.9	0.3–5.7 (1.5)	NS
Trichloroethylene (TCE)	35	0	0		0	0.2–5.2 (1.4)	NS	36	0	0		0	0–2.0 (0)	NS
Constituents of special interest														
Perchlorate	35	0	0		0	0–1.8 (0) ⁴	NS	30	0	0		0	0–2.0 (0) ⁴	NS

¹Based on Jeffreys interval for the binomial distribution; for non-zero proportions, the confidence interval is calculated as a two-sided interval, and for zero, a one-sided interval is computed (Brown and others, 2001; Belitz and others, 2010).

²To facilitate comparison with public supply well data, organic constituents from the domestic assessment were re-screened to the most common detection limit for reported by public supply systems.

³Calculations for aquifer scale proportions and detection frequencies for the volatile organic compounds (VOCs) class were based on the following select VOCs: chloroform, MTBE, PCE, toluene, and TCE.

⁴To facilitate comparison with public-supply well data, the perchlorate analyses made by the GAMA-PBP for the domestic-supply assessment were reensored to the most common detection limit for reported by public-supply systems (4 µg/L). There were no detects of perchlorate above this screening level in either of the domestic-supply assessment study units.

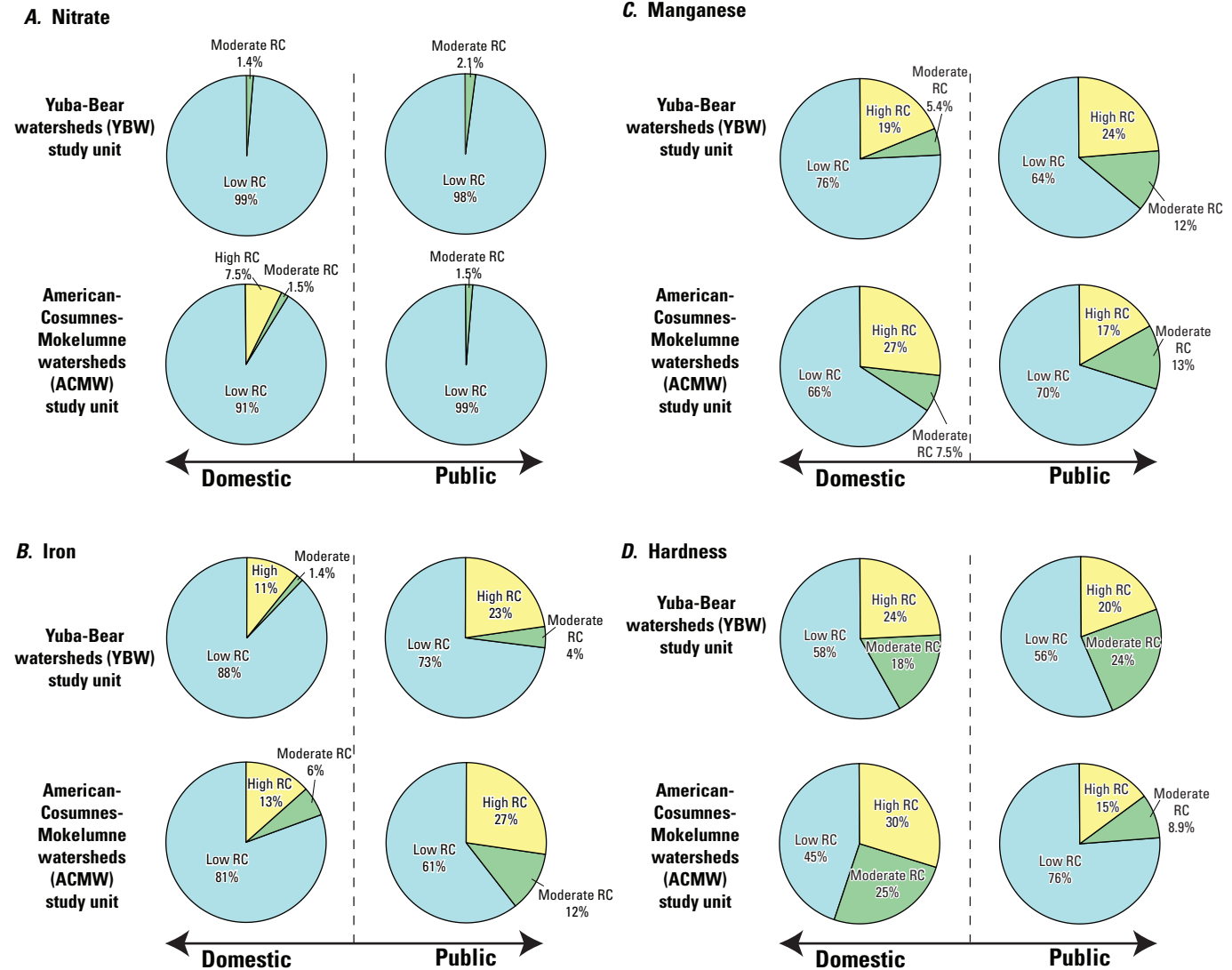


Figure 49. Percentages of aquifer-scale proportions with low, moderate, and high relative concentrations (RC) for study units and U.S. Geological Survey sampled domestic-supply wells and public-supply wells in the northern Sierra Nevada foothills domestic-supply aquifer assessment, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project, for *A*, nitrate; *B*, iron; *C*, manganese; and *D*, hardness. [% , percent]

Of the constituents with an SMCL or other aesthetic-based standard, only iron, manganese, and hardness were significantly different at high-RC aquifer proportions between domestic- and public-supply aquifer systems (table 17). Iron had greater high-RC proportions in public- than in domestic-supply aquifer systems in both the YBW study unit (public supply 23 percent, domestic supply 11 percent) and the ACMW study unit (public supply 27 percent, domestic supply 13 percent; fig. 49B; table 17). This is a potentially spurious difference, however. The GAMA-PBP filters all groundwater samples prior to analysis for dissolved metals. It is not known whether samples analyzed for iron in the SWRCB-DDW database were filtered, and often samples tested for regulatory compliance monitoring are not. Iron associated with suspended colloidal particles in

groundwater samples can greatly increase the results of iron analyses of unfiltered samples, particularly if the samples are acidified prior to analysis, which is a common protocol for preservation of samples for metals analyses. The maximum measured iron concentrations for domestic-supply wells in the YBW and ACMW study units were 4,160 and 3,970 $\mu\text{g/L}$, respectively. In contrast, maximum values for the iron data used from the SWRCB-DDW database for public-supply wells were substantially higher in the YBW and ACMW study units at 7,117 and 25,000 $\mu\text{g/L}$, respectively.

There was no significant difference in high-RC aquifer proportions for manganese in the YBW study unit between the domestic-supply (19 percent) and public-supply (24 percent) aquifer systems (fig. 49C; table 17). In the ACMW study unit, however, there were greater high-RC

proportions in the domestic-supply (27 percent) than in public-supply (17 percent) aquifer systems (fig. 49C; table 17). In the understanding assessment, it was determined that high-manganese concentrations in the study region were associated with aquifers of metasedimentary, metavolcanic, and granitic lithologies under anoxic conditions. Although public-supply wells in the ACMW study unit were open to aquifers with respectively lesser and greater proportions of metavolcanics and granitic lithologies than domestic-supply wells, the combined proportion of metasedimentary, metavolcanic, and granitic well lithologies was virtually the same (approximately 75 percent) for both resources (fig. 46B). As a result, there were no conclusive geological factors within the scope of this study that could explain the differences in high-RC proportions between the domestic- and public-supply aquifer systems in the ACMW study unit. Insufficient geochemical data were available to fully evaluate redox conditions for the public-supply wells from the SWRCB-DDW database.

There was no significant difference in high-RC aquifer proportions for hardness in the YBW study unit between the domestic-supply (24 percent) and public-supply (20 percent) aquifer systems (fig. 49D; table 17). In the ACMW study unit, however, there were greater high-RC aquifer-scale proportions in the domestic-supply (30 percent) than in public-supply (15 percent) aquifer systems (fig. 49D; table 17). In the understanding assessment, hardness was greatest in mafic-ultramafic and metavolcanic aquifers at lower elevations (figs. 30–32; table 12). Public-supply wells assessed in the ACMW study unit had significantly smaller proportions of mafic-ultramafic and metavolcanic lithologies and tended to be clustered at higher elevations in the study unit than the domestic-supply wells (figs. 46B, 47). Greater high-RC proportions for hardness in the ACMW domestic-supply than in the public-supply aquifer systems are therefore most likely related to geologic factors linked to landscape position, resulting in more of the sampled domestic wells being at lower elevations, where groundwater hardness is greater in the study region.

Organic and Special-Interest Constituents

Results for organic and special-interest constituents reported by the GAMA-PBP for the status assessment were recensored at higher reporting levels for the comparative assessment because the GAMA-PBP has much lower reporting levels for these constituents than those reported in the SWRCB-DDW database. The organic constituents evaluated in the status assessment were a select group of VOCs (chloroform, MTBE, PCE, TCE, and toluene). As a constituent class, the selected VOCs were detected in 5.4 and 7.9 percent of the domestic- and public-supply aquifer systems, respectively, in the YBW study unit with no significant difference between the two resources (fig. 48C; table 18). The selected VOCs were detected in 7.5 and 5.0 percent of the domestic- and public-supply aquifer systems, respectively,

in the ACMW study unit with no significant difference between the two resources (fig. 48C; table 18). There were no detections for perchlorate in the SWRCB-DDW public-supply dataset and no detections in the GAMA-PBP domestic-supply dataset above the recensoring threshold (4 µg/L; table 18).

In the YBW, the recensored domestic-supply data provided consistent moderate-RC detections for PCE (1.4 percent), TCE (1.4 percent), and toluene (1.4 percent). For these same three constituents, only PCE was detected at moderate RC (2.9 percent) in the public-supply aquifer system. Chloroform was found at moderate RC (2.9 percent) in the public-supply aquifer system, and although differences in detection frequency were not statistically significant, the detection frequency of chloroform was greater in the public-supply aquifer system (3.8 percent) than the domestic-supply aquifer system (1.4 percent). The detection frequency of MTBE was similar in the domestic-supply aquifer system (1.4 percent) and public-supply aquifer system (1.5 percent) in the YBW (table 18).

Of the public-supply wells in the ACMW used for the comparative assessment, TCE, PCE, and MTBE were not detected at any concentration (table 18). In the ACMW, MTBE was statistically greater in the recensored domestic-supply well data (4.5 percent) than in the public-supply well data (no detections; table 18). MTBE was associated with shallow, anoxic water in the understanding assessment (fig. 41B), and it is possible that the public-supply wells in the ACMW could draw on groundwater that is more oxidic (based on the lesser concentrations of manganese and hardness) or deeper in the aquifer system than that from domestic-supply wells (fig. 45).

Summary

Groundwater quality in the approximately 13,500 square kilometer northern Sierra Nevada foothills region of California was evaluated as part of Groundwater Ambient Monitoring and Assessment Priority Basin Project (GAMA-PBP). The region was divided into two study units: the Yuba-Bear watersheds (YBW) study unit and the American-Cosumnes-Mokelumne watersheds (ACMW) study unit. The GAMA-PBP made a spatially unbiased assessment of aquifer systems used for domestic drinking-water supply in the study region, which are predominantly composed of fractured hard-rock aquifers of heterogeneous lithologies.

This report provides a description of the regional hydrogeologic setting of the YBW and ACMW study units, a *status assessment* of water quality from domestic-supply wells for the individual study units, an *understanding assessment* evaluating natural and anthropogenic factors that could potentially affect groundwater quality in the study region, and a *comparative assessment* between groundwater resources used for domestic and public drinking-water supply in the study region. The status assessments for YBW and ACMW study units were based on water-quality data collected

from 74 and 67 individual “grid well” sites (141 total) in the two respective study units. Potential explanatory factors were compiled for groundwater sites and relations among the explanatory factors and water-quality data were evaluated using non-parametric statistical and graphical analyses. A broad comparison of well-construction data for domestic- and public-supply aquifers in the study region was accomplished by comparing over 60,000 records from the California Department of Water Resources well-completion report database. A more focused comparison of water quality between domestic- and public-supply aquifers in the study region used data from the 141 domestic-supply wells sampled by the GAMA-PBP along with water-quality data from 306 public-supply wells from prior GAMA-PBP studies and the State of California’s regulatory compliance monitoring database.

Relative concentrations (RCs; the sample concentration divided by a State or Federal water-quality benchmark) were used to contextualize and evaluate water-quality data. Aquifer-scale proportions were used as the primary metric to evaluate groundwater quality on the study-unit scale. Aquifer-scale proportion is defined as the areal percentage of the aquifer-system for a given constituent within a set range of RC thresholds. The RCs greater than 1.0 (exceeding the State or Federal water-quality benchmark) were classified as high. The RC threshold between moderate- and low-RCs was either one-half the primary benchmark for inorganic constituents, one-tenth the primary benchmark for organic and special-interest constituents, or the California State notification level (NL-CA) where applicable. Aquifer-scale proportions were calculated for low, moderate, and high RCs for individual constituents and constituent classes in addition to presence or absence of microbial indicators and detection frequencies for organic and special-interest constituents.

The quality of groundwater used for domestic drinking water in the YBW and ACMW study units was assessed using data from samples analyzed for inorganic constituents (trace elements, nutrients, radioactive constituents, and trace inorganic compounds), microbial indicators (total coliform, TC; *Escherichia coli*, EC; *Enterococci*, ENT), and organic constituents (volatile organic compounds, or VOCs, and pesticides). The status assessment characterized the quality of untreated groundwater resources in the study region for constituents measured at moderate or high RCs or organic constituents that had study-unit scale detection frequencies greater than 10 percent. The understanding assessment used statistical and graphical methods to evaluate the effects of potential explanatory factors on groundwater quality in the study region for constituents present at high RC in greater than 2 percent or organic constituents with detection frequencies greater than 10 percent on the study-unit scale. Potential explanatory factors were evaluated for land use, aquifer lithology, hydrologic conditions, well depth, groundwater age, geochemical conditions, and recharge conditions.

As a class, inorganic constituents with human-health benchmarks (trace elements, nutrients, and radioactive constituents) were present in the domestic-supply aquifer system at high RCs in 5.4 and 10 percent of the YBW and ACMW study units, respectively, and at moderate RCs in 9.5 and 6.0 percent of the YBW and ACMW study units, respectively. Inorganic constituents with health-based benchmarks evaluated in the status assessments included arsenic, barium, boron, fluoride, molybdenum, strontium, nitrate, adjusted gross-alpha particle activity, and gross-beta particle activity. Inorganic constituents having aesthetic-based benchmarks (major ions and trace elements with benchmarks, excluding hardness) as a class were present in the domestic-supply aquifer system at high RC in 20 and 28 percent of the YBW and ACMW study units, respectively, and at moderate RC in 6.8 and 9.0 percent of the YBW and ACMW study units, respectively. Inorganic constituents with aesthetic-based benchmarks or standards evaluated in the status assessment included chloride, hardness, iron, manganese, specific conductance, sulfate, and total dissolved solids. Nitrate, iron, manganese, and hardness were present at high RC in greater than 2 percent of at least one of the study units.

Groundwater samples were tested for presence or absence of three microbial indicators (TC, EC, ENT). At least one microbial indicator was present in 26 and 28 percent of domestic-supply aquifer systems in the YBW and ACMW study units, respectively. Total coliform was present in 23 and 28 percent of domestic-supply aquifer systems in the YBW and ACMW study units, respectively, and *E. coli* was present at 5.4 and 9.8 percent of the domestic-supply aquifer systems in the YBW and ACMW study units, respectively. *Enterococci* was present in 11 and 1.6 percent of domestic-supply aquifer systems in the YBW and ACMW study units, respectively. All three microbial indicators were evaluated in status and understanding assessments.

As a class, organic constituents were detected in 24 and 43 percent of domestic-supply aquifer systems in the YBW and ACMW study units, respectively, with no detections at high RCs. The organic constituents belonging to the VOC class were only detected at moderate RCs in 2.7 percent of domestic-supply aquifer systems in the YBW study unit and at low RCs in 24 and 34 percent of domestic-supply aquifer systems in the YBW and ACMW study units, respectively. Tetrachloroethene (PCE), toluene, and trichloroethene (TCE) were detected in the YBW study unit at moderate RCs. Methyl *tert*-butyl ether (MTBE) and trichloromethane (chloroform) were detected in the YBW and ACMW study units at detection frequencies greater than 10 percent. Pesticides were only detected at low RC in 2.7 and 9.1 percent of the YBW and ACMW study units, respectively. The only constituent of special interest, perchlorate, was not present at high RC, but was present at moderate RC in 1.4 and 1.5 percent of the YBW and ACMW study units, respectively, and at low RC in 30 and 39 percent of the YBW and ACMW study units, respectively.

Among the potential explanatory factors considered in the understanding assessment, elevation-dependent variables relating to climate, land use, and recharge condition were correlated to groundwater nitrate, microbial indicators, and perchlorate. These species were present at greater detection frequencies and concentrations in lower elevation, drier areas, where there is irrigation of agricultural land, forage pasture, and rural-residential lands. Isotopic and dissolved noble-gas tracers showed these water-quality constituents were linked to recharge conditions related to irrigation using diverted surface water during the dry-season at lower elevations in the study region.

Other important explanatory variables were related to aquifer lithology, geochemical condition of the groundwater, and well depth. Nitrate and perchlorate were found primarily in oxic groundwater. Iron and manganese were primarily associated with anoxic groundwater. Iron was detected at high RCs primarily in wells in metasedimentary lithologies, whereas high RCs for manganese were associated with metasedimentary, metavolcanic, and granitic lithologies. Hardness was associated with anoxic groundwater of circumneutral pH in lower elevations with aquifers of mafic-ultramafic and metavolcanics lithologies and could be influenced by upwelling of deep groundwater. In shallow groundwater wells (depths less than 130 m), chloroform and MTBE were associated with oxic and anoxic conditions, respectively.

A comparative assessment of aquifer systems used for domestic- and public-supply was based on regional well-construction and water-quality data in addition to selected explanatory factors for wells with water-quality data (aquifer lithology, land use, elevation). Domestic-supply wells accounted for 98 percent of the well-completion report records in the study region, and public-supply wells made up 0.7 percent. Median values of depth to the top of the open or perforated interval and well depth were significantly greater for public-supply than for domestic-supply wells in both study units. Public-supply wells considered in the water-quality comparison had a higher percentage of urban land use than the domestic-supply assessment wells in both study units.

Domestic-supply wells in the ACMW study unit had a greater percentage of agricultural-land use than the public-supply wells. The ACMW study unit had significantly greater proportions of public-supply wells in mafic-ultramafic and metavolcanic lithologies and smaller proportions in granitic lithologies than did domestic-supply wells.

A spatially weighted method was used to calculate aquifer-scale proportions for public-supply wells with water-quality data in the YBW and ACMW study units in order to compare to the domestic-supply assessment. High-RC aquifer-scale proportions (for inorganic constituents) and detections frequencies (for organic constituents) were generally similar for individual constituents in the domestic- and public-supply aquifer systems of both study units. In the ACMW study unit, nitrate was present at high RCs more frequently in the domestic-supply than in the public-supply aquifer system, perhaps due to greater agricultural land use around the domestic-supply wells in the ACMW study unit. Additionally, in the ACMW study unit, the domestic-supply aquifer system had greater high-RC proportions for manganese and hardness and greater detection frequencies for MTBE than the public-supply aquifer system, which could be related to differences in geochemical condition, aquifer lithology, landscape position, and well depth characterizing the two resources.

Overall, fewer samples from domestic-supply wells in the northern Sierra Nevada foothills exceeded health-based benchmarks compared to aesthetic-based benchmarks for groundwater quality. Exceedences of health-based benchmarks were primarily caused by nitrate and coliform bacteria, which were associated with recharge from diverted surface water used primarily for irrigation. Exceedences of aesthetic-based benchmarks were primarily caused by iron, manganese, and hardness, which were associated with various geologic factors. Regional irrigation practices and aquifer lithology can affect groundwater quality in fractured-rock aquifers in the northern Sierra Nevada foothills used for domestic drinking-water supply.

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Appendix 1. Attribution of Potential Explanatory Factors

Aquifer Lithology

Aquifer lithology for domestic wells was classified using California State and local geologic maps (Saucedo and Wagner, 1992; Saucedo and others, 2000) and spot checked with driller's log information from the California Department of Water Resources (DWR) well-completion report database (Stork and others, 2019; Levy, 2020). Aquifer lithologies based on California State Geologic Map descriptions were grouped into six broad categories:

- Granitic (G): Plutonic granitic rocks (Mesozoic; California State Geologic Map units grMz)
- Mafic-ultramafic (MU): Plutonic mafic and ultramafic rocks (Mesozoic; California State Geologic Map units gb and um)
- Metavolcanic (MV): Metamorphosed volcanic rocks (Paleozoic and Mesozoic; California State Geologic Map units Mzv, Pzv, m, and mv)
- Metasedimentary (MS): Metamorphosed sedimentary rocks (Paleozoic and Mesozoic; California State Geologic Map units J, Pz, and ls)
- Volcanic (V): Volcanic and volcanoclastic rocks (Cenozoic; California State Geologic Map units Tvp)
- Alluvial and glacial (A): Glacial, alluvial, fluvial, and lacustrine sediments (Cenozoic; California State Geologic Map units Ec and Qg)

Three of the domestic-supply wells used in the status and understanding assessments of the YBW and ACMW study units were initially classified as "A" (Y30, Y41, and S14) based on the California State Geologic Map. Because unconsolidated alluvial and glacial sediment layers can be shallow, however, driller's logs for these wells were spot checked, and the wells were re-classified as "G" because the wells were finished in fractured bedrock of granitic lithology. The remaining driller's logs for the domestic-supply wells were spot checked to confirm that the wells were finished in fractured bedrock. All wells were finished in bedrock except three that were classified as "V" (B25, Y29, and Y39), which were finished in unconsolidated, volcanoclastic sediments. Public-supply wells from the State Water Resources Control Board Division of Drinking Water (SWRCB-DDW) database (California State Water Resources Control Board, 2019) were broadly classified using site locations and the California State Geologic Map (Levy, 2020).

Land Use

Land use was classified using the 2011 National Land Cover Database provided by the Multi-Resolution Land Characteristics (MRLC) Consortium (Jin and others, 2013). This dataset characterizes land cover during 2011 using Landsat multispectral image data. Satellite imagery was grouped in 16 nationally consistent land-cover classes described by Homer and others (2004). For this study, these 16 classes were condensed into a three primary classes: urban, agricultural, and natural. Total land-use percentages for study units, areas, and buffer areas within a 500-m radius surrounding domestic- and public-supply wells were calculated using ArcGIS (version 9.2; Johnson and Belitz, 2009; Levy, 2020).

Underground Storage Tank and Septic Tank Densities

Leaking (or formerly leaking) underground storage-tank (LUFT) density at domestic-supply well sites was determined using a Thiessen polygon approach for spatial interpolation (Thiessen, 1911; Heywood and others, 1998; Tyler Johnson, U.S. Geological Survey, written commun., 2012). Interpolation of data from the SWRCB's GeoTracker database of environmental-cleanup sites (California State Water Resources Control Board, 2007) was made using ArcGIS software. Thiessen polygons were created by starting with a LUFT at the center and expanding the polygon edges in all directions until they extended halfway to the neighboring LUFT or reached the California State line. In most cases, there was only one LUFT in each polygon, but occasionally there were more. The total number of LUFTs per polygon were divided by the total area of the polygon, resulting in a unique LUFT density for each of the polygons. Domestic well locations were then overlaid on this map, and LUFT densities were assigned to well sites from the coincident polygon (Levy, 2020).

Septic tank density for domestic-well sites was determined from the 1990 Census of Population and Housing (U.S. Census Bureau, 1992). The mean density of septic tanks in housing census enumeration blocks was calculated from the number of Census-reported septic tanks and block areas. The density of septic tanks around domestic-well sites was then calculated as the area-weighted mean of septic-tank densities for all enumeration blocks intersecting a 500-m buffer around each site (Tyler Johnson, U.S. Geological Survey, written commun., 2013; Levy, 2020).

Hydrologic Conditions

Hydrologic conditions at groundwater sites were summarized using aridity index (AI) values and land-surface elevations. The AI is defined by the United Nations Environment Programme (1997) and the United Nations Educational, Scientific, and Cultural Organization (1979) as the ratio of average precipitation to average potential evapotranspiration. Greater values of AI correspond to cooler and wetter conditions. Values of AI less than 0.05 are considered to be hyper-arid, 0.05 to 0.20 arid, 0.20 to 0.50 semi-arid, 0.50 to 0.65 dry sub-humid, 0.65 to 1.00 humid, and greater than 1.00 wet (United Nations Educational, Scientific, and Cultural Organization, 1979; United Nations Environment Programme, 1997). Estimates of average annual precipitation were determined from raster maps of 1971–2000 normal climate used in prior GAMA-PBP assessments to maintain consistency (PRISM Climate Group, 2007). Estimates of average annual evapotranspiration at each study site were obtained from a modified dataset provided by Flint and Flint (2007). Raw evapotranspiration estimates were calibrated to California Irrigation Management Information System reference evapotranspiration values (California Irrigation Management Information System, 2005; Alan Flint, U.S. Geological Survey, oral commun., 2009; Levy, 2020).

Land-surface elevation can be used as an independent proxy for climate in the northern Sierra Nevada foothills because higher elevations have wetter and cooler climates. Land-surface elevations for domestic- and public-well study sites were obtained from the U.S. Geological Survey 30-m resolution National Elevation Dataset (U.S. Geological Survey, 2006). Elevation measurements at wellheads are reported in meters relative to the NAVD 88 datum (Levy, 2020).

Well Construction

Well-construction data were compiled from driller's logs filed in the California Department of Water Resources (DWR) well-completion report database (Stork and others, 2019). Well depths and depth to the top of the open or perforated interval were used to determine depths at which wells draw water from the surrounding aquifer. Virtually all the wells in this study were drilled into fractured rock, and boreholes were typically left open beneath the sanitary seal. Construction information is indicated as “spring” for springs because driller's log information was not available for those sites. Depths listed are in meters below the land surface. Domestic-supply well site-construction information originally compiled by Jasper and others (2017) and Shelton and others (2018) is compiled in Levy (2020). Wells were classified as “shallow,” “mixed,” or “deep” if the open intervals were respectively above, crossed over, or below a critical depth of 40 m.

Groundwater Age

Tracers of groundwater age can be used to determine the time when a parcel of water recharged to the aquifer system. Data for age-dating tracers of tritium and carbon-14 (^{14}C) were used in this report to classify groundwater in three broad age groups: pre-modern, mixed, and modern. Groundwater tritium was measured for all samples and ranged from non-detection to 3.4 tritium units (TU). The 128 samples with sufficient dissolved inorganic carbon for measurement of ^{14}C had activities ranging from 7 to 119 percent modern carbon (pmC; Levy, 2020).

Tritium is a short-lived radioactive isotope of hydrogen and has a half-life of 12.32 years (Lucas and Unterweger, 2000). Tritium is produced naturally in the atmosphere by reaction of nitrogen with cosmogenic radiation (Craig and Lal, 1961) and anthropogenically by nuclear explosions and the operation of nuclear reactors. Tritium enters the hydrologic cycle by oxidation to form tritiated water. Aboveground nuclear-bomb testing caused a large increase of tritium in precipitation starting in 1952 and peaking in 1963 when tritium activities exceeded 1,000 TU in the northern hemisphere (Michel, 1989). Background levels for tritium in precipitation at the latitude of the study region before 1952 were approximately 5–6 TU (Michel, 1989). Radioactive decay of pre-bomb-test atmospheric tritium activities to the sampling dates from 2015 to 2016 (63–64 years) would result in decay-corrected, pre-bomb tritium concentrations of less than 0.2 TU. This initial estimate of the tritium threshold for “pre-modern” (pre-1950s) groundwater was further modified by analysis of the ^{14}C data.

Dissolved inorganic carbon species (carbonic acid, bicarbonate, carbonate) are used for ^{14}C dating of groundwater. Radiogenic ^{14}C forms naturally in the atmosphere by interaction of cosmic-ray neutrons with nitrogen and, to a lesser degree, oxygen and carbon, and can also be produced anthropogenically by nuclear explosions. Radiogenic carbon becomes incorporated in atmospheric carbon dioxide, which then dissolves in precipitation and surface water exposed to the atmosphere. The ^{14}C content of inorganic carbon in groundwater therefore reflects the radioactive decay of radiogenic carbon since it was last exposed to the atmosphere. Carbon-14 has a half-life of 5,730 years and can be used to date groundwater ages from 1,000 to approximately 30,000 years before present (Clark and Fritz, 1997).

The ^{14}C data can be reported either as percent modern (pM) or percent modern carbon (pmC). The pM values reported in the data releases by Jasper and others (2017) and Shelton and others (2018) are normalized for carbon isotope fractionation based on a standard reference $\delta^{13}\text{C}$ value of –25 per mille. The non-normalized ^{14}C data reported as pmC are used in this report. Percent modern carbon refers to the percent carbon activity of the sample compared to that of the atmosphere in 1950.

Values of ^{14}C reported as pmC in excess of 100 percent are possible because nuclear bomb testing in the 1950s raised the ^{14}C activity in the atmosphere above natural background levels. Data were converted from pM to pmC using the following equation adapted from Plummer and others (2004):

$$pmC = \frac{pM \left(1 + \frac{\delta^{13}C}{1,000} \right)^2}{0.975^2} \quad (1.1)$$

where

- pmC is the measured ^{14}C value in units of percent modern carbon;
 pM is the normalized ^{14}C value in units of percent modern carbon; and
 $\delta^{13}C$ is the measured ^{13}C composition in units of per mille.

In this report, ^{14}C values in pmC were used to contextualize and group tritium concentrations in groundwater-age classes. One limitation of ^{14}C is that it can be diluted by interactions with radiocarbon “dead” carbon sources in the subsurface such as carbonate mineral dissolution and oxidation of old organic carbon, which operate to decrease the ^{14}C and thereby increase the apparent groundwater age. It was outside of the scope of this report to apply correction models to the ^{14}C data to account for these complicating factors. The $\delta^{13}C$ values for groundwater ranged from -23 to -11 per mille, indicating a wide range of inorganic carbon sources from soil respiration to carbonate dissolution, respectively. It was assumed that uncorrected ^{14}C was a “representative” indicator of groundwater age for the 55 percent of samples with radiocarbon measurements that had $\delta^{13}C$ less than -17 per mille (indicating minimal interaction with carbonate minerals) and dissolved oxygen (DO) greater than or equal to 1 mg/L (indicating minimal oxygen-depleting reactions with old, organic carbon in the subsurface; [fig. 1.1](#)).

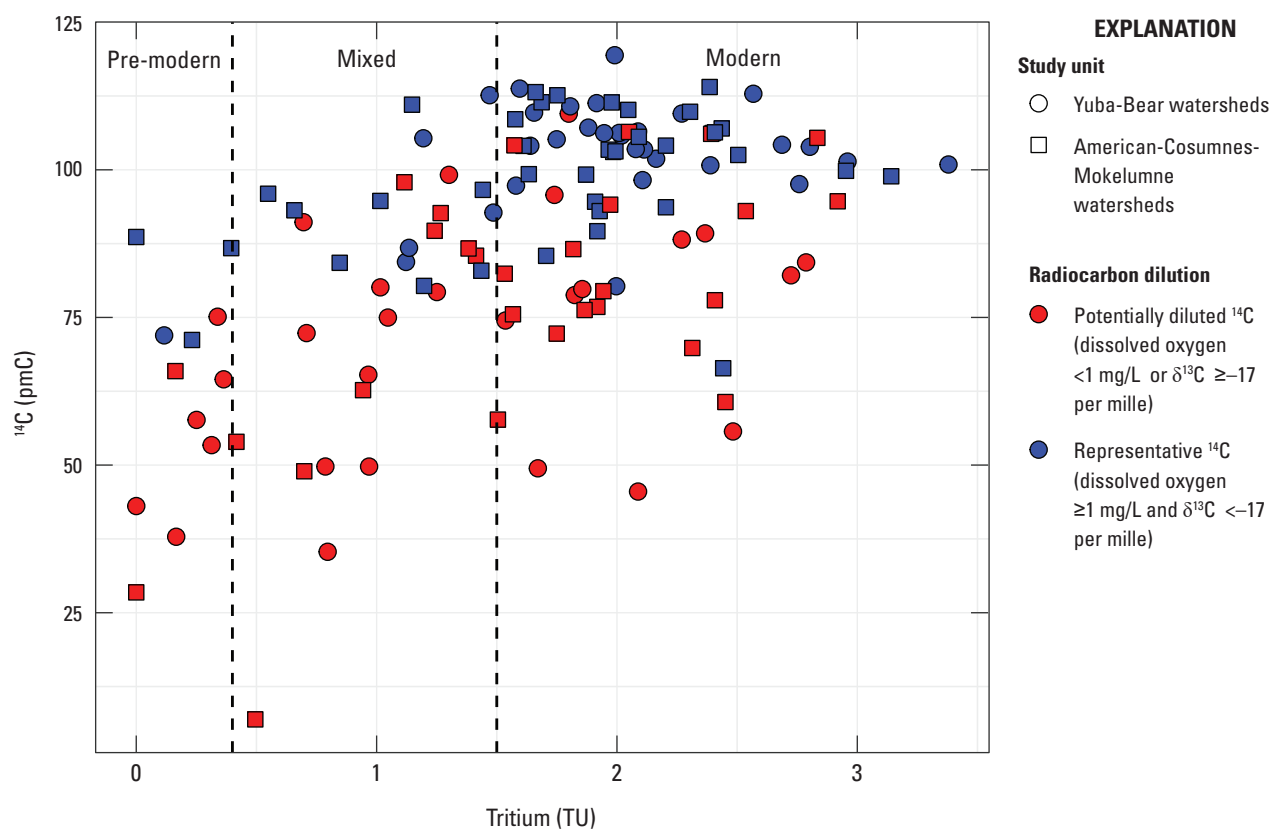


Figure 1.1. Relation of groundwater tritium activity to carbon-14 (^{14}C) activity by radiocarbon dilution classification and study unit for U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Representative ^{14}C values were used to further contextualize tritium ranges used for age classification of groundwater samples. The tritium threshold for “pre-modern” groundwater was raised from less than 0.2 TU to less than 0.4 TU, because samples with tritium less than 0.4 TU had representative ^{14}C values ranging from 71 to 89 pmC, indicative of groundwater recharged greater than 1,000 years before present. Samples with tritium activities greater than 1.5 TU were classified as “modern” because the majority (74 percent) of representative ^{14}C values for these samples were greater than 100 pmC, indicative of post-1950s recharge. Samples with tritium of or between 0.4 and 1.5 TU were defined as “mixed” and likely contain both modern and premodern groundwater with representative ^{14}C values ranging from 80 to 113 pmC (fig. 1.1).

Geochemical Condition

Geochemical conditions for groundwater samples were characterized by oxidation-reduction (redox) characteristics and pH. Redox conditions influence the speciation, mobility, and bioavailability of a wide array of dissolved constituents

in groundwater. Redox potential typically decreased along groundwater flowpaths from oxic to anoxic conditions as a predictable sequence of terminal electron acceptors are exhausted by oxidation reactions: oxygen, nitrate, manganese, iron, sulfate, and carbon dioxide (McMahon and Chapelle, 2008).

In this report, redox conditions were represented by dissolved oxygen (DO) concentrations and redox class (Levy, 2020). Groundwater DO and pH were measured in the field as reported by Jasper and others (2017) and Shelton and others (2018). Redox conditions were classified on the basis of DO, nitrate, manganese, iron, and sulfate using an adaptation of the classification system of McMahon and Chapelle (2008) by Jurgens and others (2009). Samples were classified as oxic, anoxic, or mixed (table 1.1). Samples were classified as mixed if DO concentrations were greater than or equal to 0.5 mg/L and iron and manganese were present at levels greater than their respective threshold concentrations (table 1.1). Mixed redox conditions can result when water from different parts of the aquifer mixes in the well-bore, by microbially mediated redox disequilibrium, or in the presence of redox microzones within heterogeneous aquifer materials (Lindberg and Runnells, 1984; Briggs and others, 2015).

Table 1.1. Oxidation-reduction classification system applied to groundwater samples from U.S. Geological Survey grid and understanding sites, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; n, number of samples; \geq , greater than or equal to; $<$, less than; —, criteria do not apply]

Category	Number of samples	Dissolved oxygen (mg/L)	Nitrate, as nitrogen (mg/L)	Manganese ($\mu\text{g/L}$)	Iron ($\mu\text{g/L}$)	Sulfate (mg/L)
Oxic classes (n = 93)						
Oxic classes	93	≥ 0.5	—	< 50	< 100	—
Anoxic classes (n = 33)						
Suboxic	9	< 0.5	< 0.5	< 50	< 100	—
Nitrate reducing	4	< 0.5	≥ 0.5	< 50	< 100	—
Manganese reducing	3	< 0.5	< 0.5	≥ 50	< 100	—
Iron/sulfate reducing	17	< 0.5	< 0.5	—	≥ 100	≥ 0.5
Mixed classes (n = 16)						
Oxic-manganese reducing	8	≥ 0.5	—	≥ 50	< 100	—
Oxic-iron/sulfate reducing	8	≥ 0.5	—	—	≥ 100	≥ 0.5

Recharge Condition

In this study, stable isotopes of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and dissolved noble gases (neon, argon, krypton, and xenon) were used to derive information about the source and seasonality of groundwater recharge. Stable isotopes of water were used to define the deuterium excess (*d-excess*) parameter, which can be used to identify mixing with water in which isotopic compositions have been affected by evaporation in surface water bodies (Clark and Fritz, 1997). Dissolved noble gases can be used to calculate noble-gas recharge temperatures (NGRTs), which represent the approximate temperature of recharge when it originally entered the aquifer system and became isolated from the atmosphere (Stute and Schlosser, 2000).

The stable isotopes of oxygen and hydrogen in the water molecule are expressed in delta (δ) notation, where the ratio of the more abundant to less abundant isotope in the sample (R) is related to the ratio of those isotopes in the reference Vienna standard mean ocean water (R_{VSMOW}), so that $\delta = (R/R_{\text{VSMOW}} - 1) \times 1,000$ (Clark and Fritz, 1997). Values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are expressed as the difference in delta-values from the Vienna standard mean ocean water (VSMOW) standard in parts per thousand (per mille).

Negative delta-values indicate a sample is isotopically lighter than the standard, whereas positive values indicate a sample is isotopically heavier than the standard (Clark and Fritz, 1997). The results of isotopic analyses of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for groundwater samples from the YBW and ACMW study units are included in the data releases of Jasper and others (2017) and Shelton and others (2018), respectively.

The stable isotopes of water in precipitation have a strong linear relation typically defined by a local meteoric water line (LMWL) in delta-space (cross-plots of $\delta^{18}\text{O}$ and $\delta^2\text{H}$). The LMWL in the study region has a slope of 8 and intercept of 12.6 per mille in delta-space (fig. 1.2; Levy and others, 2020). Variation of groundwater samples along this line for the study region represents the isotopic composition of precipitation recharging groundwater becoming progressively depleted (more negative delta-values) at higher elevations. This is due to the “altitude effect” on isotope fractionation of water vapor in clouds as they track from west to east over the Sierra Nevada foothills (Levy and others, 2020). At low elevations in the study area, however, the isotopic composition of groundwater samples diverges from the linear trend defined by the LMWL and falls below the average global trend for isotopes in precipitation defined by the global meteoric water line (GMWL; Craig, 1961; fig. 1.2).

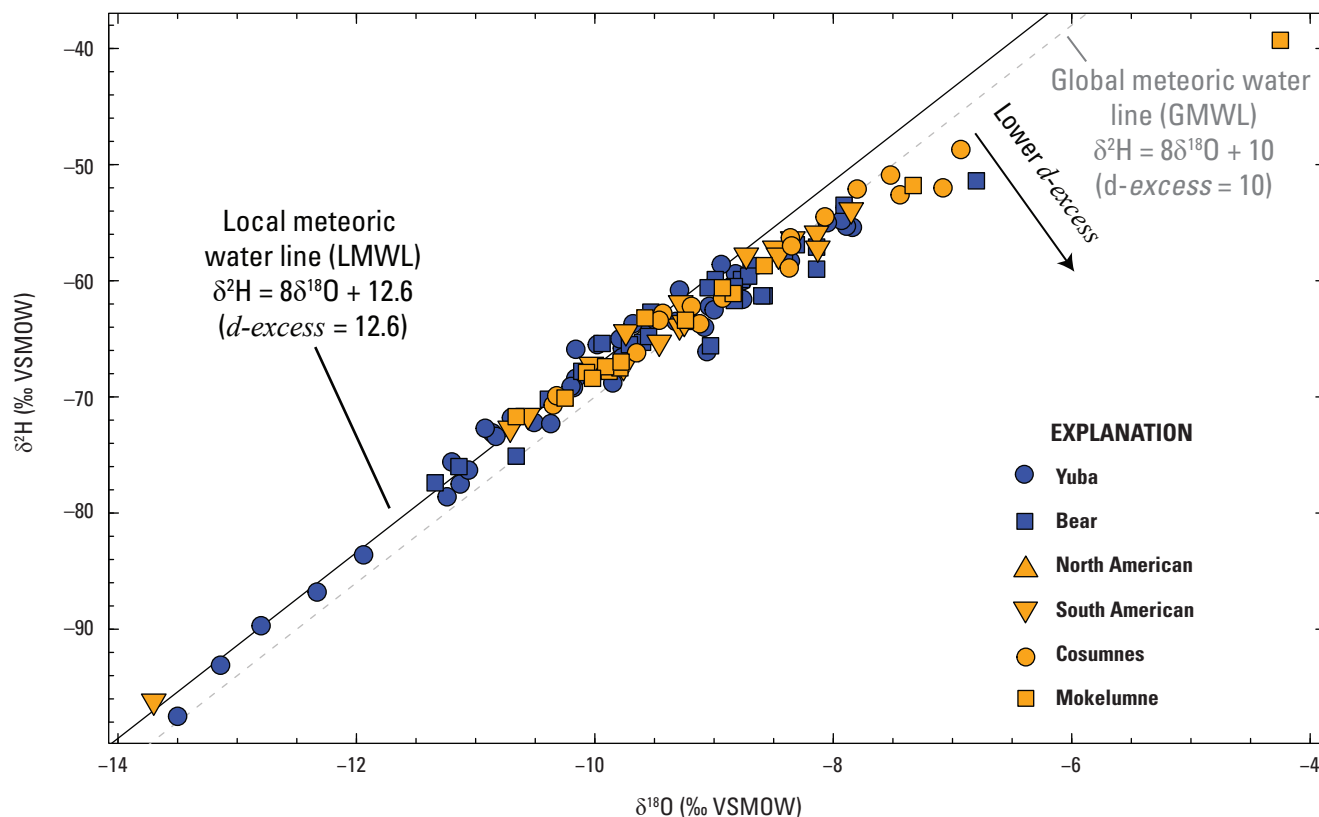


Figure 1.2. Relation of groundwater $\delta^{18}\text{O}$ to $\delta^2\text{H}$ by study area for U.S. Geological Survey sampled grid wells and understanding well in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

Variations of water isotopes from the local and global meteoric trends with slopes of approximately 8 in delta-space can be evaluated by the *d-excess* parameter (Clark and Fritz, 1997):

$$d - excess = \delta^2\text{H} - 8 \delta^{18}\text{O} \quad (1.2)$$

Values falling on the LMWL (slope = 8, intercept = 12.6 per mille) and GMWL (slope = 8, intercept = 10 per mille) have *d-excess* values of 12.6 per mille and 10 per mille, respectively, by definition (appendix fig. 1.2). Values falling below the GMWL, representing the global average trend for isotopes in precipitation, have *d-excess* values less than 10 per mille and most likely are isotopically enriched as a result of evaporation in open surface-water bodies. Surface waters throughout the study region (regional rivers, canals, and reservoirs) tend to have *d-excess* values less than 10 per mille (Levy and others, 2020). The *d-excess* values for groundwater sampled in the study region less than 10 per mille are therefore a conservative indicator of mixing with recharge from surface water. Calculated *d-excess* values for all YBW and ACMW domestic-supply well samples are presented by Levy (2020).

Because the solubility of noble gases in water is temperature dependent, NGRTs can be estimated by measuring the concentrations of dissolved noble gases in groundwater (Stute and Schlosser, 2000). Gas solubility is also dependent on pressure and salinity, which were estimated using the elevation at the wellhead and the salinity of the groundwater sample. Recharge temperatures were modeled using both an unfractionated excess air (UA) model (Heaton and Vogel, 1981), which requires estimation of an excess air parameter, and a closed-system equilibration (CE) model (Aeschbach-Hertig and others, 1999), which requires estimation of an excess air parameter and an air-water-gas fractionation parameter. The noble-gas model with the higher probability was used for each sample. Details of noble-gas models and methodologies used to derive NGRTs are included in the data release of Levy and Faulkner (2019) and further discussed in Levy and others (2020). Modeled NGRTs were

compared to mean-annual air temperature (MAAT) at each study site with noble-gas model results. The MAAT data were extracted in ArcGIS at point locations for respective study sites from a raster dataset of 1981–2010 normal MAAT for the coterminous United States (PRISM Climate Group, 2015). The NGRT and MAAT data are included in Levy (2020).

Saturation Indices

Saturation indices are used to predict if a mineral precipitate will form or dissolve in a given aqueous solution. The Langelier Saturation Index (LSI) is used to predict whether carbonate-based scale would form in pipes and plumbing systems. The LSI was calculated using methods described by Belitz and others (2016) and the measurements for pH, alkalinity (in milligrams per liter as calcium carbonate), calcium (Ca, in milligrams per liter calcium ions as calcium carbonate), total dissolved solids (TDS, in milligrams per liter), and water temperature in degrees Celsius (T) in the following equation:

$$\text{LSI} = \text{pH} - [(9.3 + A + B) - (C + D)] \quad (1.3)$$

where

$$A = [\log_{10}(\text{TDS}) - 1]/10;$$

$$B = -12.12 \times \log_{10}(T + 273) + 34.55;$$

$$C = \log_{10}(\text{Ca}) - 0.4; \text{ and}$$

$$D = \log_{10}(\text{alkalinity}).$$

The saturation index for calcite (SI calcite) is an independent metric used to predict if the mineral calcite would precipitate or dissolve in a given aqueous solution and was calculated with the geochemical speciation program PHREEQC, v. 3 (Parkhurst and Appelo, 2013). Calculated values for LSI and SI calcite are included in Levy (2020).

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Appendix 2. Public-Supply Well Data Used for Calculation of Aquifer-Scale Proportions Using the Spatially Weighted Method

Because water-quality data from public-supply wells sampled by GAMA-PBP in the study region were minimal (15 wells samples in 2008; Fram and Belitz, 2014), these data were combined with regulatory data for 306 public-supply wells in the (SWRCB-DDW) database (California State Water Resources Control Board, 2019). To calculate aquifer-scale proportions using the spatially weighted data, values from multiple wells can be used in a single grid cell, but no more than one water-quality record can be used from each well for a given water-quality constituent. Nineteen of the constituents evaluated in the status assessment had sufficient data in the SWRCB-DDW database to compare with domestic-supply aquifer results. This report used data from the entire available record of water-quality analyses for public-supply wells in the region (June 19, 1978–October 23, 2018) to maximize spatial coverage of water-quality data. For public-supply wells with multiple water-quality records for a given constituent, the record sampled closest to the temporal midpoint of the corresponding domestic-assessment sampling survey was used (October 3, 2015, for the YBW study unit and October 29, 2016, for the ACMW study unit). This prioritized use of water-quality records for public wells that were sampled as close as possible in time to the domestic-supply aquifer assessments.

For a given water-quality constituent, an average of 55 percent of records used for calculation of aquifer-scale proportions in the public-supply aquifer system were sampled within plus or minus (\pm) 3 years from the domestic-supply assessments (table 2.1, fig. 2.1). Water-quality constituents that are measured in public-supply wells on more frequent compliance-monitoring schedules had a greater proportion of measurements taken closer in time to the domestic-supply assessments. For example, 82 percent of nitrate measurements used in spatially weighted calculations were sampled within ± 3 years from the time of the domestic-supply assessments (table 2.1, fig. 2.1). Boron, however, which is monitored less frequently, only had 33 percent of measurements taken within a ± 3 -year window, so older measurements were used to increase the spatial coverage of the dataset. Concentrations of geogenic water-quality constituents are less likely to change with time than those from anthropogenic sources. Analysis of water-quality trends through time was beyond the scope of these assessments; however, and the data were used from the entire 40-year period of record in the SWRCB-DDW database to maximize spatial coverage of water-quality data used to evaluate the overall quality of groundwater used for public supply throughout the study region.

Table 2.1. Summary of water-quality data from public-supply wells used in spatially weighted calculations for aquifer-scale proportions for the public-supply aquifer assessments, northern Sierra Nevada foothills domestic-supply aquifer study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

[Temporal midpoints of the Yuba-Bear watersheds (YBW) and American-Cosumnes-Mokelumne watersheds (ACMW) domestic-supply well sampling surveys were October 3, 2015, and October 29, 2016, respectively. **Abbreviations:** ±, plus or minus]

Constituent	YBW study unit			ACMW study unit		
	Date of earliest sample used in spatially weighted calculations	Date of most recent sample used in spatially weighted calculations	Percent samples used in spatially weighted calculations collected within ±3 years of the domestic sampling midpoint date	Date of earliest sample used in spatially weighted calculations	Date of most recent sample used in spatially weighted calculations	Percent samples used in spatially weighted calculations collected within ±3 years of the domestic sampling midpoint date
Hardness	06/28/1994	09/11/2018	49	06/28/1994	09/11/2018	49
Specific conductance	06/28/1994	09/11/2018	56	06/28/1994	09/11/2018	56
Total dissolved solids	06/28/1994	09/11/2018	55	06/28/1994	09/11/2018	55
Arsenic	08/18/1997	09/11/2018	62	08/18/1997	09/11/2018	62
Barium	06/28/1994	09/11/2018	59	06/28/1994	09/11/2018	59
Iron	06/28/1994	09/11/2018	55	06/28/1994	09/11/2018	55
Manganese	06/28/1994	09/11/2018	56	06/28/1994	09/11/2018	56
Nitrate	09/08/2006	04/11/2017	82	09/08/2006	04/11/2017	82
Gross-alpha particle radioactivity	10/27/2004	09/07/2017	65	10/27/2004	09/07/2017	65
Chloride	06/28/1994	09/11/2018	55	06/28/1994	09/11/2018	55
Fluoride	06/28/1994	09/11/2018	55	06/28/1994	09/11/2018	55
Sulfate	06/28/1994	09/11/2018	56	06/28/1994	09/11/2018	56
Boron	05/02/2001	09/11/2018	33	05/02/2001	09/11/2018	33
Methyl tert-butyl ether (MTBE)	03/04/1998	09/11/2018	54	03/04/1998	09/11/2018	54
Tetrachloroethene (PCE)	04/19/1988	09/11/2018	47	04/19/1988	09/11/2018	47
Toluene	04/19/1988	09/11/2018	47	04/19/1988	09/11/2018	47
Trichloroethene (TCE)	04/19/1988	09/11/2018	47	04/19/1988	09/11/2018	47
Chloroform	04/19/1988	09/11/2018	27	04/19/1988	09/11/2018	27
Perchlorate	07/28/2003	05/21/2018	83	07/28/2003	05/21/2018	83

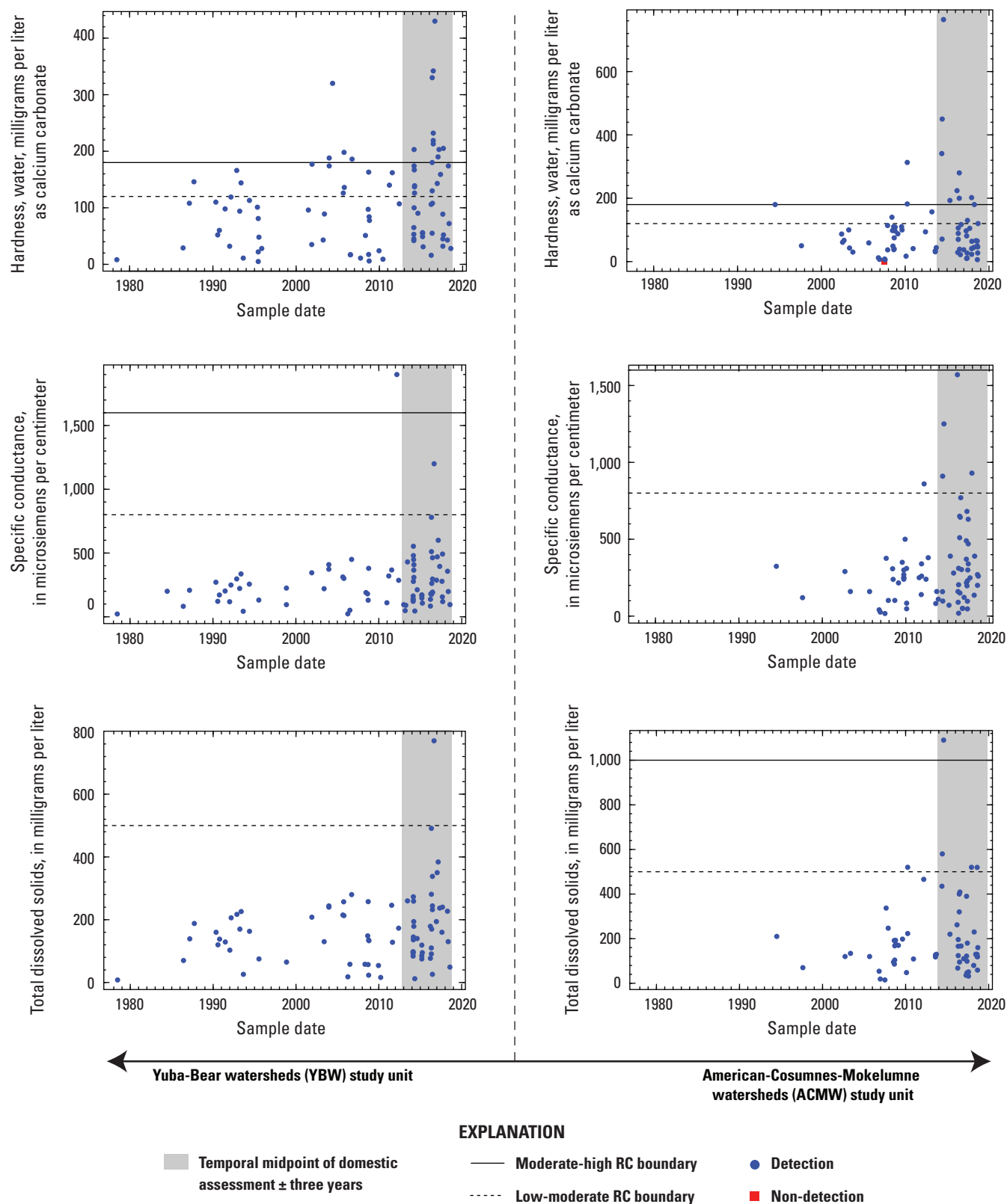


Figure 2.1. Time series of data for 19 status assessment constituents used for spatially weighted calculations of aquifer-scale proportions for public-supply wells in the domestic-public aquifer comparison in the northern Sierra Nevada foothills domestic-supply aquifer assessment study units, 2015–17, California Groundwater Ambient Monitoring and Assessment (GAMA) Program Priority Basin Project.

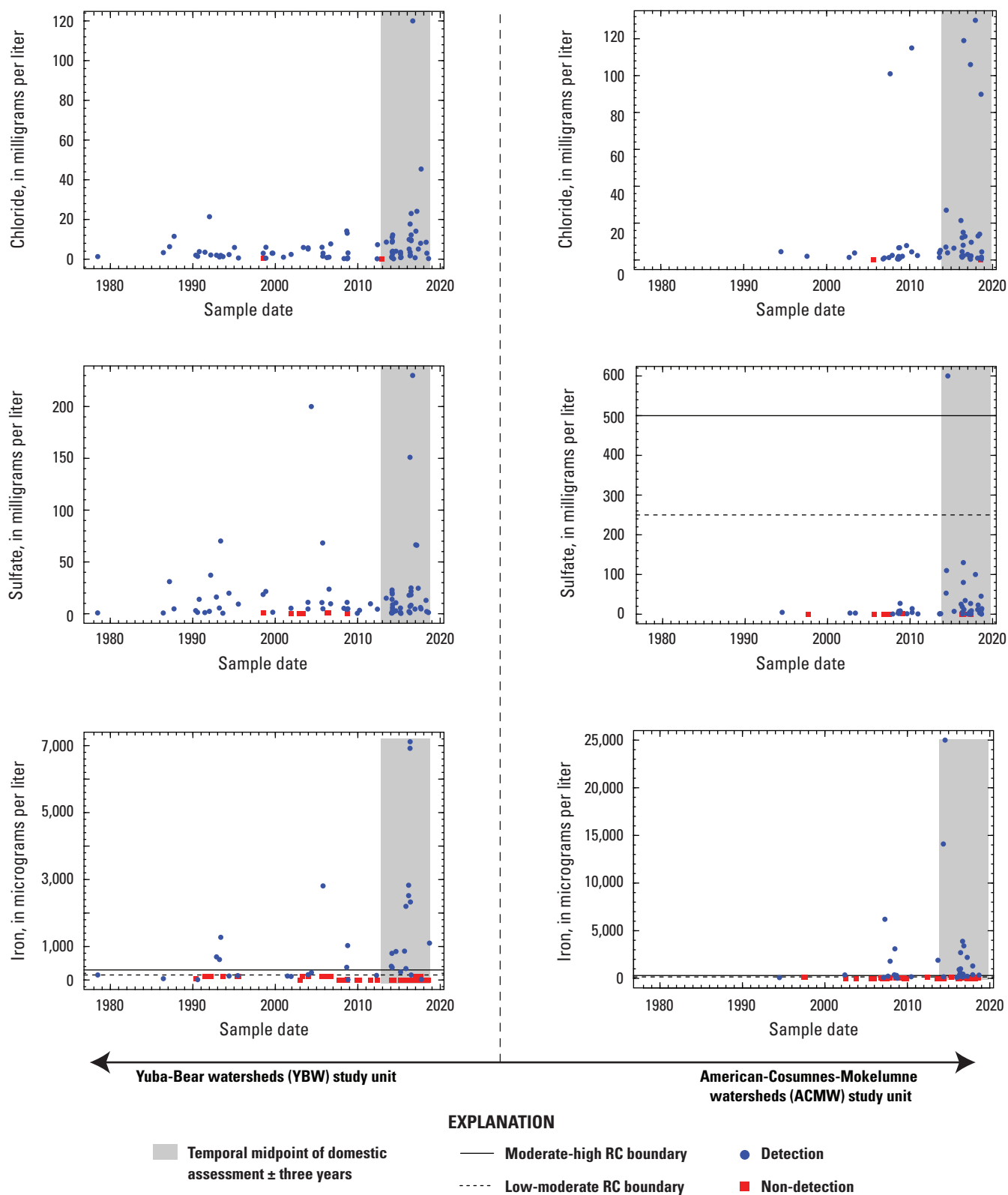
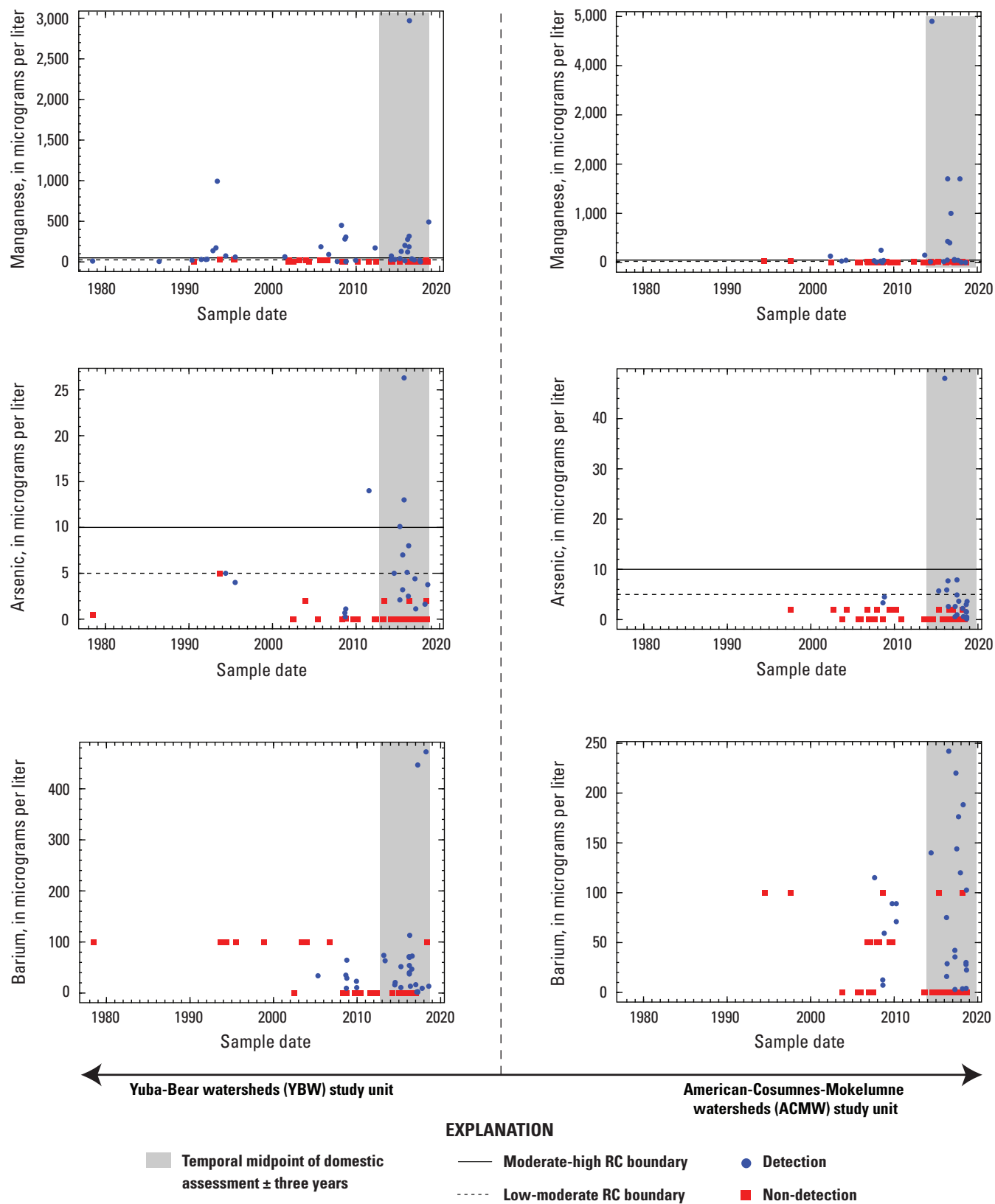


Figure 2.1.—Continued



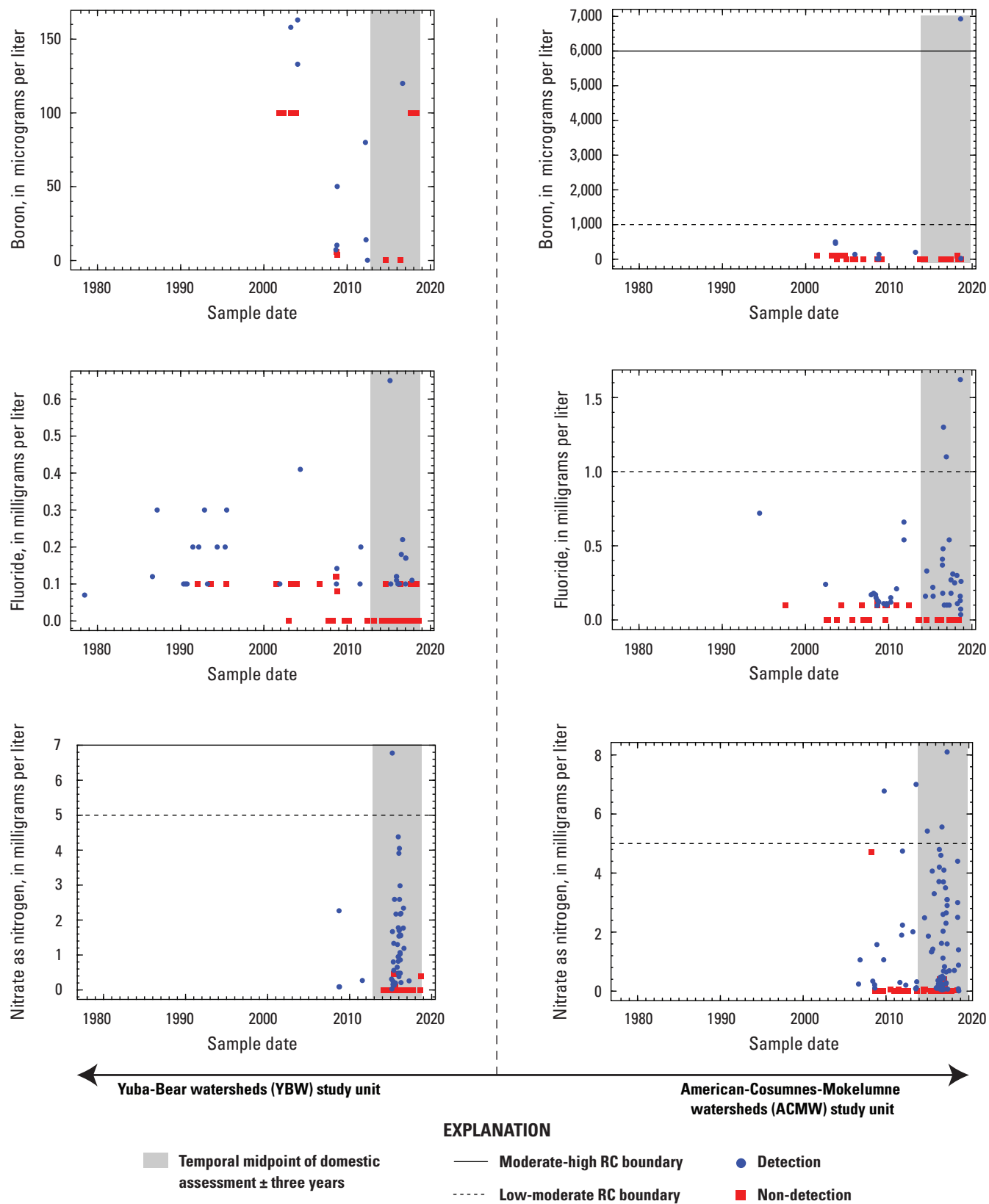


Figure 2.1.—Continued

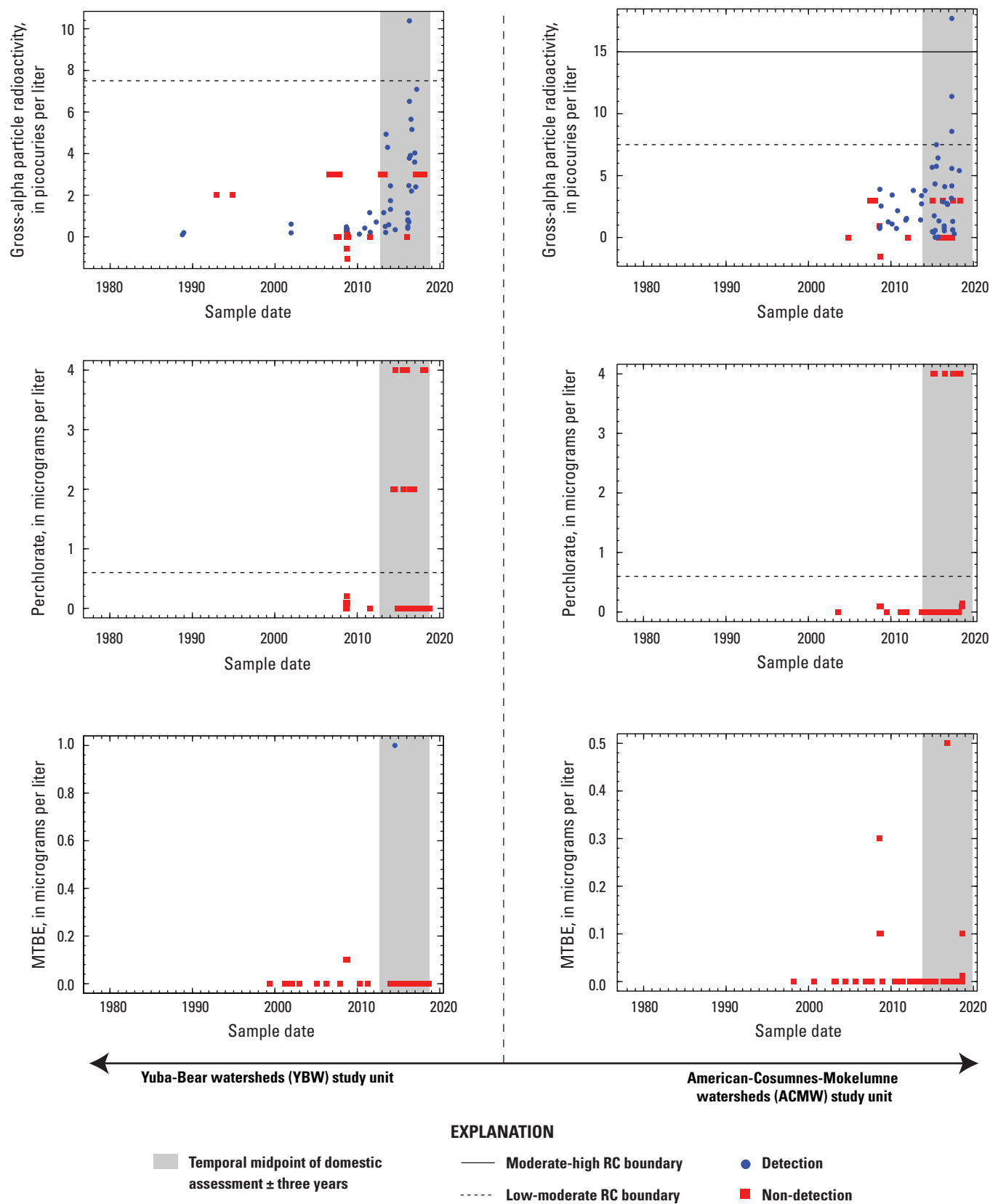


Figure 2.1.—Continued

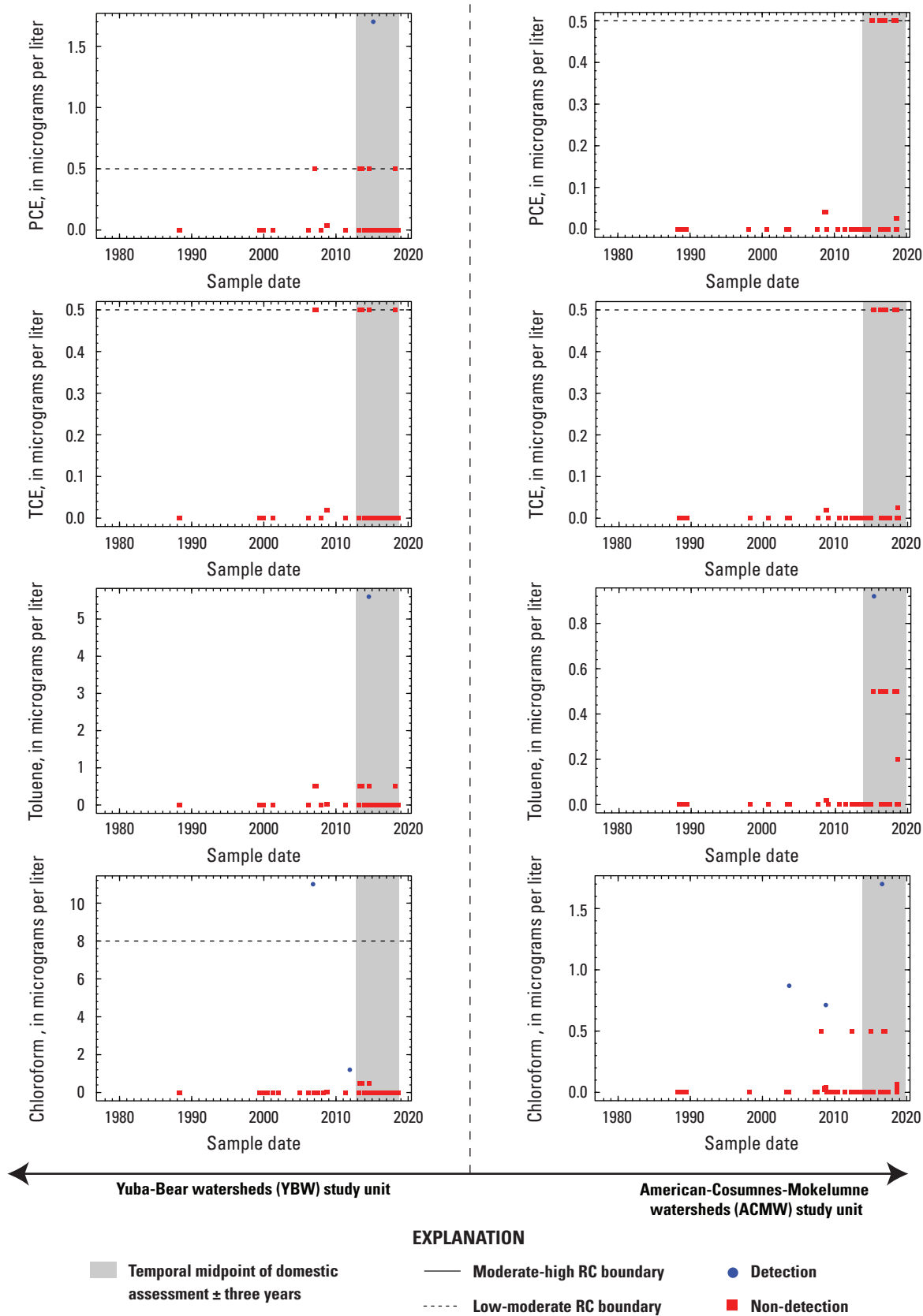


Figure 2.1.—Continued

Appendix 3. Radioactivity Indicators

The class of radioactivity indicators includes water-quality data for measurements of alpha and beta particle radioactivity, which are expressed in units of activity as opposed to concentration. Activity for these measurements is expressed as picocuries per liter. One picocurie corresponds approximately to the decay of two atoms per minute. When radioactive atoms decay, they release alpha or beta particles or gamma radiation. Gross-alpha and gross-beta particle activities are measurements of the total activity of non-volatile isotopes decaying by alpha and beta emissions, respectively (Arndt, 2010).

The MCL-US of 15 picocuries per liter (pCi/L) for gross-alpha particle activity applies to “adjusted” gross-alpha particle activity, which is equivalent to the measured gross-alpha particle activity minus the uranium activity (California State Water Resources Control Board, 2019). The gross-alpha particle activity measurements for groundwater-quality data collected in the northern Sierra Nevada foothills study units and analyzed in this report were adjusted for uranium activity and reported by Jasper and others (2017) and Shelton and others (2018). The GAMA-PBP reports data for two measurements of gross-alpha particle activity: counted 72 hours and 30 days after collection. The 30-day measurements were used in this report to maintain consistency with past studies of by GAMA-PBP in the Sierra Nevada (Fram and Belitz, 2014). Adjusted gross-alpha measurements had identical aquifer-scale proportions to unadjusted gross-alpha measurements in the domestic-supply aquifer assessments and were therefore considered suitable to compare to gross-alpha measurement data for public-supply wells in the SWRCB-DDW database, which have many more gross-alpha measurements than adjusted gross-alpha measurements.

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