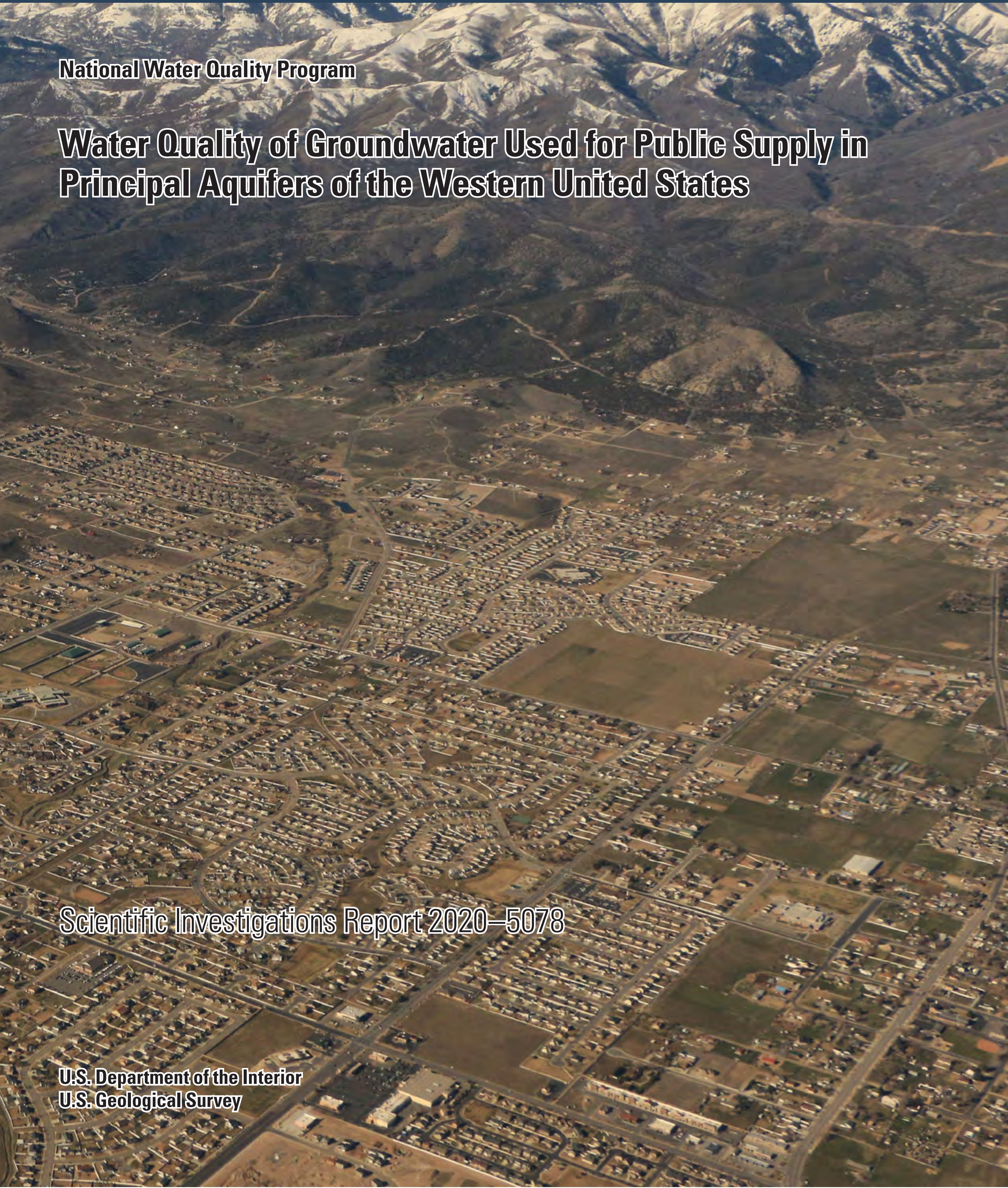

National Water Quality Program

Water Quality of Groundwater Used for Public Supply in Principal Aquifers of the Western United States

Scientific Investigations Report 2020–5078

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

Cover: High-density housing and Oquirrh Mountains, Riverton, Utah, March 16, 2014. Photograph taken by Alan Cressler, U.S. Geological Survey.

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By Celia Z. Rosecrans and MaryLynn Musgrove

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DAVID BERNHARDT, Secretary

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

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

$$°C = (°F - 32) / 1.8.$$

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, 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 (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L).

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 a measurement standard.

Abbreviations

°F	degrees Fahrenheit
AMCL	alternative maximum contaminant level
EPA	U.S. Environmental Protection Agency
GAMA	Groundwater Ambient Monitoring and Assessment
HB	health-based
HBSL	health-based screening level
HCO_3	bicarbonate
MCL	maximum contaminant level
MDL	method detection limit
NAWQA	National Water Quality Assessment
PA	principal aquifer
PSWs	public supply wells
QC	quality control
RL	reporting limit
RSD	relative standard deviation
SD	standard deviation
SMCL	secondary-maximum contaminant level
TDS	total dissolved solids
THMs	trihalomethanes
USGS	U.S. Geological Survey
VOCs	volatile organic compounds

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By Celia Z. Rosecrans and MaryLynn Musgrove

Abstract

Groundwater provides nearly half of the Nation's drinking water. As the Nation's population grows, the importance of (and need for) high-quality drinking-water supplies increases. As part of a national-scale effort to assess groundwater quality in principal aquifers (PAs) that supply most of the groundwater used for public supply, the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Project staff sampled six principal aquifers in the western United States between 2013 and 2017: (1) the Basin and Range carbonate-rock aquifers, (2) Basin and Range basin-fill aquifers, (3) Rio Grande aquifer system, (4) High Plains aquifer, (5) Colorado Plateaus aquifers, and (6) Columbia Plateau basaltic-rock aquifers. These six PAs supply a large part of the Nation's drinking water and cover a large geographic extent of the western conterminous United States. Groundwater samples were analyzed for a large suite of water-quality constituents including major ions, nutrients, trace elements, volatile organic compounds (VOCs), pesticide compounds, radioactive constituents, age tracers, and, in selected PAs, perchlorate. Two types of assessments were made: (1) a *status assessment* that describes the quality of the groundwater resource at time of collection and (2) an *understanding assessment* that evaluates relations between groundwater quality and potential explanatory factors that represent characteristics of the aquifer system. The assessments characterize untreated groundwater quality, which might be different than the quality of drinking water delivered to consumers. The assessments are based on water-quality data collected from 352 wells and 6 springs using an equal-area grid sampling design. This sampling approach allows for the estimation of the proportion of high, moderate, or low concentrations relative to federal water-quality benchmarks of selected constituents in the area of each PA. Results were compared to established benchmarks for drinking-water quality to provide context for evaluating the quality of untreated groundwater: Federal regulatory benchmarks for protecting human health, non-regulatory human-health benchmarks, and non-regulatory benchmarks for nuisance chemicals. Not all constituents that were analyzed have benchmarks and thus were not considered for assessments. Concentrations are characterized as high if they are greater than their benchmark. Concentrations are considered moderate if they are greater than one-half their benchmark (for inorganic constituents), or greater than one-tenth their benchmark (for organic constituents). Concentrations are considered low if they are less than moderate or the constituent was not detected.

Status assessment results indicated that inorganic constituents more commonly occurred at high and moderate concentrations in the six PAs than organic constituents, and organic constituents predominately occurred at low concentrations. Inorganic constituents that exceeded health-based benchmarks (high concentrations) were present in all six PAs; aquifer-scale proportion were 30 percent in the Rio Grande aquifer system, 22 percent in the Basin and Range basin-fill aquifers, 20 percent in the Basin and Range carbonate-rock aquifers, 19 percent in the High Plains aquifer, 16 percent in the Colorado Plateaus aquifers, and 8 percent in the Columbia Plateau basaltic-rock aquifers. Arsenic, fluoride, manganese, and total dissolved solids were the constituents most commonly present at high concentrations. Organic constituents with human-health benchmarks (pesticide compounds and VOCs) did not occur at high concentrations and moderate concentrations were infrequent; aquifer-scale proportions ranged from 0 to 5 percent. Detections of organic compounds at low concentrations, however, occurred in all six PAs, with detection frequencies ranging from 10 to 26 percent for pesticide compounds and from 10 to 46 percent for VOCs. Specific organic constituents with detection frequencies greater than 10 percent were four herbicides (atrazine, didealkylatrazine, bromoform, and propazine), one insecticide (propoxur), and two VOCs (the trihalomethanes chloroform and bromodichloromethane). Where collected—in the Rio Grande aquifer system and High Plains aquifer—perchlorate did not occur at high concentrations; moderate aquifer-scale proportions were 3 and 11 percent, respectively.

The *understanding assessment* included statistical tests to evaluate relations between constituent concentrations and potential explanatory factors to identify natural and human factors that affect groundwater quality. Potential explanatory factors included depth to bottom of well perforation, groundwater age category, land use, aquifer lithology, hydrologic conditions, and geochemical conditions. Higher concentrations of trace elements, radioactive constituents, and constituents with non-health-based benchmarks generally were associated with unconsolidated sand and gravel aquifer lithologies, premodern groundwater age, greater aridity, and more alkaline pH. Organic constituents with detection frequencies greater than 10 percent generally were associated with urban land use, shallower well depths, and higher total dissolved solids concentrations. The results for the six western PAs provide important insights into the quality of groundwater that is used for drinking water in the western United States, as well as natural and human factors that affect groundwater quality in this region.

Introduction

Groundwater provides nearly half of the Nation's drinking water. The increasing population places a demand on the Nation's water resources, and specifically on groundwater as a source for high-quality public water supplies. An estimated 76,500 million gallons per day (Mgal/day) of fresh groundwater was withdrawn from 66 principal aquifers (PAs) in the United States (U.S.) in 2000 (Maupin and Barber, 2005). This total includes groundwater withdrawals used for irrigation, public supply, and self-supplied industry. Groundwater withdrawals used for irrigation account for the largest proportion (74 percent), whereas withdrawals used for public and self-supplied industry account for the remaining proportion (26 percent). The U.S. Geological Survey (USGS) has mapped 62 of the uppermost PAs of the United States (U.S. Geological Survey, 2003) and identified 20 PAs that supply approximately 75 percent of the groundwater used for public supply and 85 percent of the groundwater used for domestic supply (Arnold and others, 2016). Public-supply wells provide water to public water systems serving at least 15 service connections (or serving an average of at least 25 people for at least 60 days per year) and are subject to federal regulatory and non-regulatory water-quality benchmarks (after treatment and before distribution), whereas private wells (considered domestic in this work) are not regulated by federal regulatory and non-regulatory water-quality benchmarks; private well owners are responsible for the quality of their water (U.S. Environmental Protection Agency, 2017, 2019a). From 2012 to 2021, the USGS National Water-Quality Assessment (NAWQA) Project is evaluating the water quality of source water (that is, untreated water) from public-supply wells (PSWs) in 20 PAs that are important sources of drinking water. The NAWQA Project objectives are to describe water-quality conditions of the Nation's water resources, assess how water quality is changing with time, and improve understanding of the natural and human factors that affect water quality. The water-quality evaluations of PAs are referred to as principal aquifer studies and focus on public-supply wells, which often access deeper groundwater resources than shallower domestic-supply wells. Each principal aquifer study evaluates water quality by sampling spatially distributed PSWs or springs using an equal-area grid sampling approach (Belitz and others, 2010).

This report assesses the quality of groundwater used for public supply in six western U.S. PAs (fig. 1):

- the Basin and Range carbonate-rock aquifers
- the Basin and Range basin-fill aquifers
- the Rio Grande aquifer system
- the High Plains aquifer
- the Colorado Plateaus aquifers
- the Columbia Plateau basaltic-rock aquifers

The assessments consider the physical setting and the susceptibility and vulnerability to contamination for each PA. Two types of assessments were made for each PA: (1) *status:* an assessment that describes the quality of the groundwater resource at time of collection and (2) *understanding:* an evaluation of the natural and human factors affecting the quality of groundwater, including an explanation of statistically significant associations between water quality and selected explanatory factors. These assessments characterize untreated groundwater quality, which might be different than the quality of drinking water delivered to consumers. The purpose of the USGS -principal aquifer studies is to evaluate the quality and availability of drinking water in the Nation's aquifers, and to improve our understanding of where and why water quality is degraded and how it might respond to changes in climate and land use (Burow and Belitz, 2014). The *understanding assessment* objective is to improve understanding about why specific constituents are present in the groundwater at moderate to high concentrations or are frequently detected. The *understanding assessment* does not, however, identify sources of constituents to individual wells or springs.

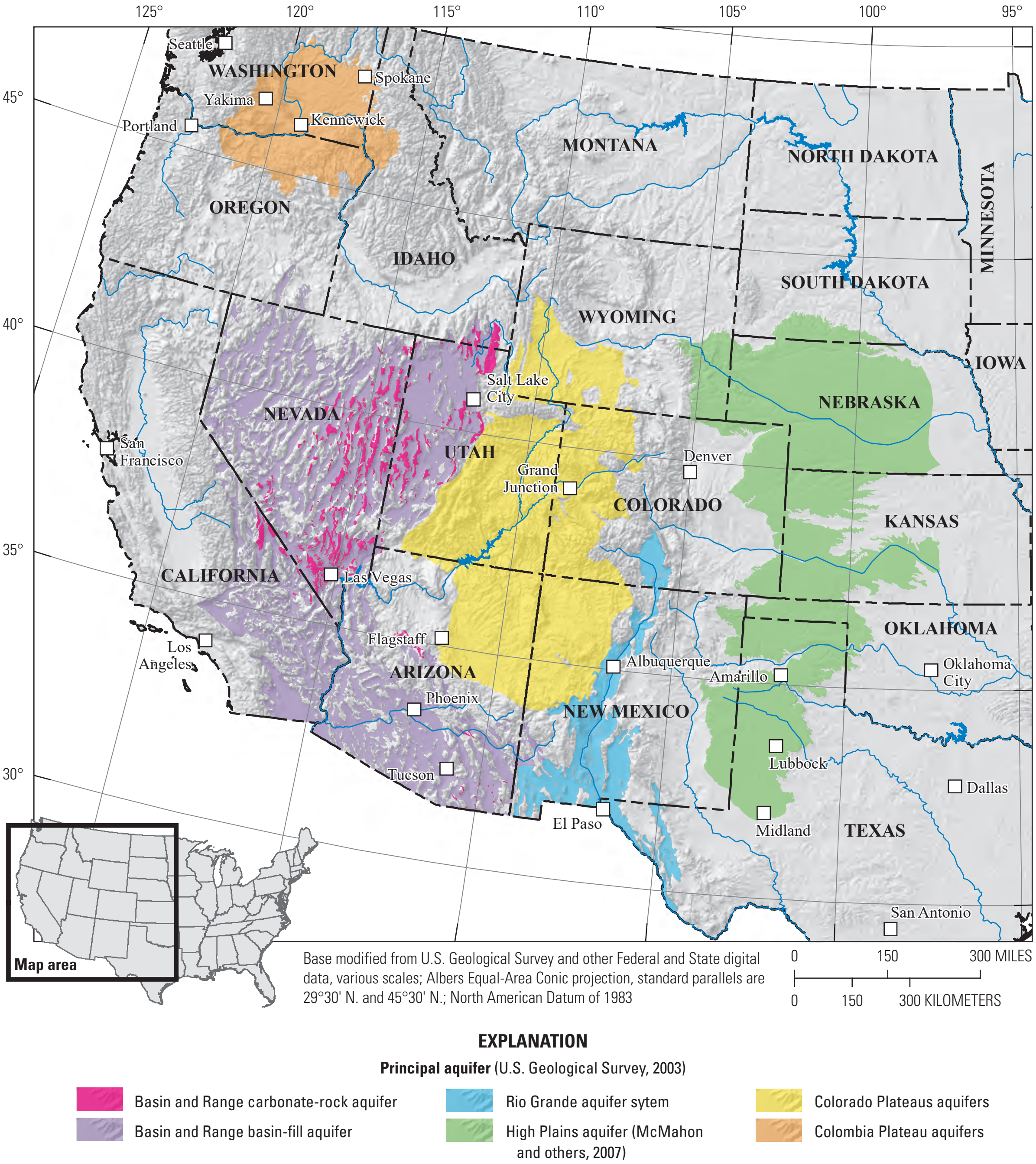


Figure 1. Six western U.S. principal aquifers selected for assessment of the quality of groundwater used for public supply, sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Western U.S. aquifers were selected for sampling and assessment based on their national ranking as a source of groundwater used for public supply and other characteristics (table 1). Four of the six western PAs rank in the top 20 aquifer systems providing public supply. Additionally, the Colorado Plateaus aquifers are included because of their large geographic extent in the conterminous western United States, and the Basin and Range carbonate-rock aquifers are included because of their hydraulic connection to portions of the Basin and Range basin-fill aquifers, which collectively constitute a significant regional groundwater resource (Harrill and Prudic, 1998). The California Coastal Basin aquifers and Central Valley aquifer system, which rank in the top 20 of aquifer systems providing public supply, have been extensively studied by the California Groundwater Ambient Monitoring and Assessment (GAMA) Program (https://www.waterboards.ca.gov/gama) and are not considered herein. The California GAMA Priority Basin Project design provides statistically robust assessments of untreated groundwater quality in the primary aquifer systems used for drinking water in California (Fram and Belitz, 2012). The assessment methods and results presented herein are comparable to those of the GAMA Priority Basin Project.

Purpose and Scope

The purpose of this report is to provide:

- A description of the hydrogeologic setting of the six PAs in the western United States recently sampled by the NAWQA Project
- A *status assessment* summarizing the quality of groundwater used for drinking water at public-supply depths
- An *understanding assessment* identifying natural and human factors affecting groundwater quality and relations between water quality and selected potential explanatory factors

Untreated groundwater samples in the six PAs were collected from a total of 352 PSWs and 6 springs used for public supply between March 2013 and December 2017. Samples were analyzed for numerous water-quality constituents including major ions, trace elements, nutrients, radioactive constituents, volatile organic compounds (VOCs), pesticide compounds (which include pesticide degradants), selected isotopes and age tracers, and perchlorate (in selected PAs). To provide context for water-quality data, constituent concentrations of untreated groundwater were compared to available water-quality benchmarks. The quality of water received by consumers can be different because after withdrawal, groundwater might be treated before delivery. Federal regulatory benchmarks for protecting human health (maximum contaminant levels [MCLs]; U.S. Environmental Protection Agency [EPA] primary drinking water regulations; U.S. Environmental Protection Agency, 2018a) were used for this evaluation. Additionally, non-regulatory human-health benchmarks (health-based screening levels [HBSLs]; Norman and others, 2018; U.S. Geological Survey, 2018a); and federal non-regulatory benchmarks for nuisance chemicals (EPA secondary maximum contaminant levels [SMCLs]; U.S. Environmental Protection Agency, 2018b) were used. This report was written to consider benchmarks in the context of health-based (MCLs and HBSLs) and non-health-based (SMCLs) benchmarks.

Table 1. Summary of aquifer characteristics, descriptive information, and groundwater use for six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project 2013–2017.

[mi², square miles; <, less than; —, not applicable; Mgal/day, million gallons per day]

Principal aquifer name	Aquifer characteristics and descriptive information								
		Aquifer sampling			Land use[2]				
	Lithology[1]	Number of cells in network	Sample collection (fiscal year)	Buffered cell size[3] (mi^2)	Total aquifer area[4] (mi^2)	Natural (percent)	Urban (percent)	Agriculture (percent)	Irrigated agriculture (percent)
Basin and range carbonate-rock aquifers	Carbonate rock	[5]20	2013 and 2015	3.6	16,000	99	<1	<1	<1
Basin and range basin-fill aquifers	Unconsolidated to semiconsolidated sand and gravel	78	2013	7.2	148,000	92	4	4	3
Rio Grande aquifer system	Unconsolidated to semiconsolidated sand and gravel	60	2014	1.8	29,000	91	4	5	8
High Plains aquifer	Unconsolidated to semiconsolidated sand and gravel	80	2015 and 2016	—	170,000	58	1	41	12
Colorado Plateaus aquifers	Sandstone	60	2017	7.2	140,000	97	1.0	2	1
Columbia Plateau basaltic-rock aquifers	Igneous and metamorphic rock	60	2016	—	42,000	76	1	23	7

Principal aquifer name	Groundwater use[6]					
	Public supply		Irrigation		Total of public supply, irrigation, and self-supplied industrial	
	Withdrawal (Mgal/day)	Rank	Withdrawal (Mgal/day)	Rank	Withdrawal (Mgal/day)	Rank
Basin and range carbonate-rock aquifers	71.2	35	0.5	62	73.6	47
Basin and range basin-fill aquifers	1,010	4	4,550	4	5,620	4
Rio Grande aquifer system	240	18	867	11	1,120	11
High Plains aquifer	389	13	17,000	1	17,500	1
Colorado Plateaus aquifers	102	28	81.9	34	198	36
Columbia Plateau basaltic-rock aquifers	223	19	674	13	933	15

[1] As defined by the U.S. Geological Survey Principal Aquifers Map (U.S. Geological Survey, 2003).

[2] Natural, urban, agricultural, and mixed land use totals are for 2012 from Falcone (2015); 2012 Irrigated land use from U.S. Geological Survey (2014). Differences in agricultural land use and irrigated land use might result from different sources used to quantify land-use types.

[3] For sparsely populated regions, where wells are not evenly distributed the study area was delineated by placing a buffer around existing wells; an equal-area grid was then defined within the buffered area.

[4] Source of aquifer areas: Basin and Range carbonate-rock aquifers and Rio Grande aquifer system (Arnold and others, 2018); Basin and Range basin-fill aquifers (Arnold and others, 2016); High Plains aquifer and Colorado Platueau and Columbia Plateau (Arnold and others, 2020).

[5] Includes both public-supply wells and springs used for public supply.

[6] Groundwater use withdrawals for public supply, irrigation, and self-supplied industrial for year 2000 are from Maupin and Barber (2005), adjusted for stream-valley from Sargent and others (2008). National rankings for public supply and total public supply, irrigation, and self-supplied industrial are from Arnold and others (2016).

Principal Aquifer Descriptions and Settings

The geographic setting, aquifer characteristics, and hydrogeology for each of the six PAs included in this study are presented later in the report, and background information that can be useful for understanding water-quality results is provided. Aquifer characteristics, descriptive information, and groundwater use are summarized in table 1. The PAs lie within (or nearly coincident with) physiographic provinces (fig. 2*A*) and have lithology classes defined in the USGS PA map (U.S. Geological Survey, 2003) as either carbonate rock; unconsolidated to semiconsolidated sand and gravel (hereinafter referred to as unconsolidated sand and gravel); sandstone; or igneous and metamorphic rock (fig. 2*B*). Except for the High Plains PA, aquifer extents are defined by the USGS PA map (U.S. Geological Survey, 2003). In this work, the High Plains PA extent used is that defined by McMahon and others (2007), which does not include glacial unconsolidated sediments—an area of overlap with the Glacial principal aquifer study in northeastern Nebraska (fig. 2*B*). The water quality of the Glacial principal aquifer study, which includes this northeastern part of the High Plains, is reported in Stackelberg (2017).

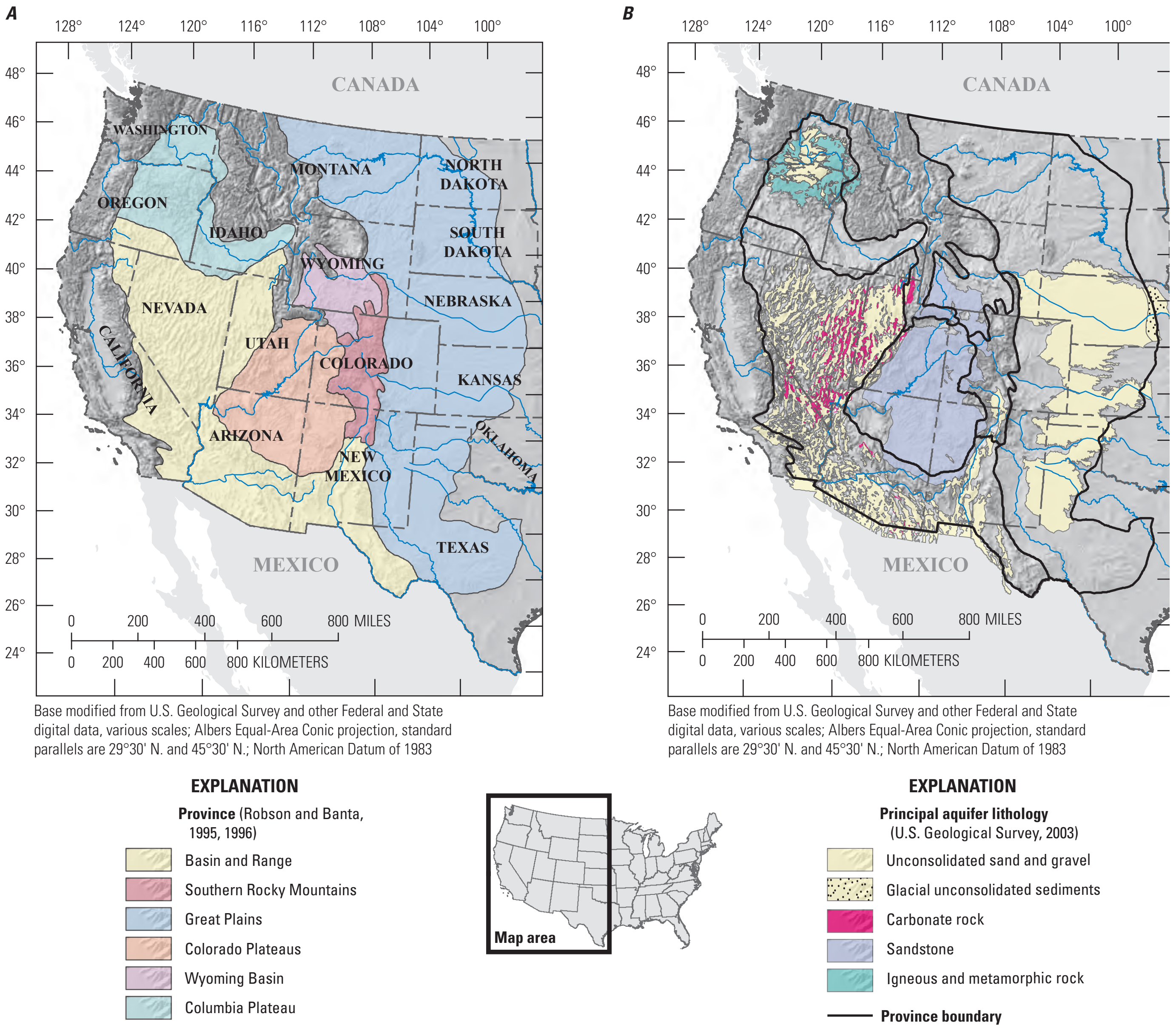
Basin and Range Carbonate-Rock Aquifers

The Basin and Range carbonate-rock aquifers underlie an area of about 16,000 square miles (mi^2; Arnold and others, 2018) in parts of Utah, Nevada, Idaho, California, and Arizona (fig. 3). The aquifers rank 35th in the Nation as a source of groundwater for public supply (Arnold and others, 2016; table 1). The approximate land use overlying the Basin and Range carbonate-rock aquifers in 2012 was nearly 99-percent natural with less than 1 percent categorized as urban and agricultural land use, respectively (Falcone, 2015). Although the dominant land use overlying the aquifer is largely undeveloped, the cities of Las Vegas, Nevada, and Salt Lake City, Utah, are located in the area of the carbonate-rock aquifers and have estimated populations of 2.1 million and 1.2 million, respectively (U.S. Census Bureau, 2018). The carbonate-rock aquifer system is a potential source of water for these cities and anticipated population growth will likely increase demand on groundwater resources.

The carbonate-rock aquifers are within the Basin and Range Province (fig. 2*A*; Dettinger and others, 1995; Harrill and Prudic, 1998; Anning and Konieczki, 2005). The Basin and Range Province has a characteristic topographic pattern of elongated mountain ranges alternating with long expanses of flat, dry basins that resulted from a dynamic fault system. The Province includes the Basin and Range carbonate-rock aquifers and the Basin and Range basin-fill aquifers (described later). Only small parts of the Basin and Range carbonate-rock aquifers are mapped at the surface because they are commonly overlain by basin-fill sediments (fig. 3). The lateral extent of the carbonate-rock aquifers is approximated in some areas, and the stratigraphic thickness varies owing to thrusting and structural compression and extension (Harrill and Prudic, 1998; Schaefer and others, 2005). The carbonate-rock aquifers generally are considered to be stratigraphically below the basin-fill aquifers; however, during parts of the Paleozoic and Mesozoic Eras, tectonic compression of the Great Basin resulted in thrusted sequences of carbonate and clastic rocks (Planert and Williams, 1995). The thickness of these sequences ranges from about 0 to 30,000 feet (ft) in eastern Nevada and western Utah (Schaefer and others, 2005).

The carbonate-rock aquifers are composed of thick sequences of Paleozoic and Mesozoic limestone and dolomite with lesser amounts of shale, sandstone, and quartzite that underlie several topographic basins (Planert and Williams, 1995). In general, the overall thickness of the carbonate rocks is greater than the clastic rocks (Harrill and Prudic, 1998), with estimates of carbonate rock thickness up to 25,000 ft in parts of southern Nevada (Dettinger and others, 1995). The carbonate-rock units can extend across topographic basins and mountain blocks, forming multi-basin groundwater flow systems (Eakin, 1966) that result in extensive aquifers that can store and transmit large quantities of water along faults and fractures. Dettinger and others (1995) estimated the volume of water stored in the carbonate-rock aquifer of southern Nevada to be approximately 800 million acre-feet (acre-ft). Discharge from these aquifers can be in the form of large springs, extensive wetlands, and evapotranspiration (Schaefer and others, 2005). Evapotranspiration is the largest source of groundwater discharge in the Great Basin (Harrill and Prudic, 1998). Prudic and others (1995) simulated discharge by evapotranspiration in the carbonate-rock aquifers of the Great Basin as part of the USGS Great Basin Regional Aquifer-System Analysis (RASA) study. Simulated discharge from this work estimated evapotranspiration at 1,213,000 acre-feet per year (acre-ft/yr) with an additional 211,000 acre-ft/yr estimated to discharge from regional springs, much of which was lost to evapotranspiration.

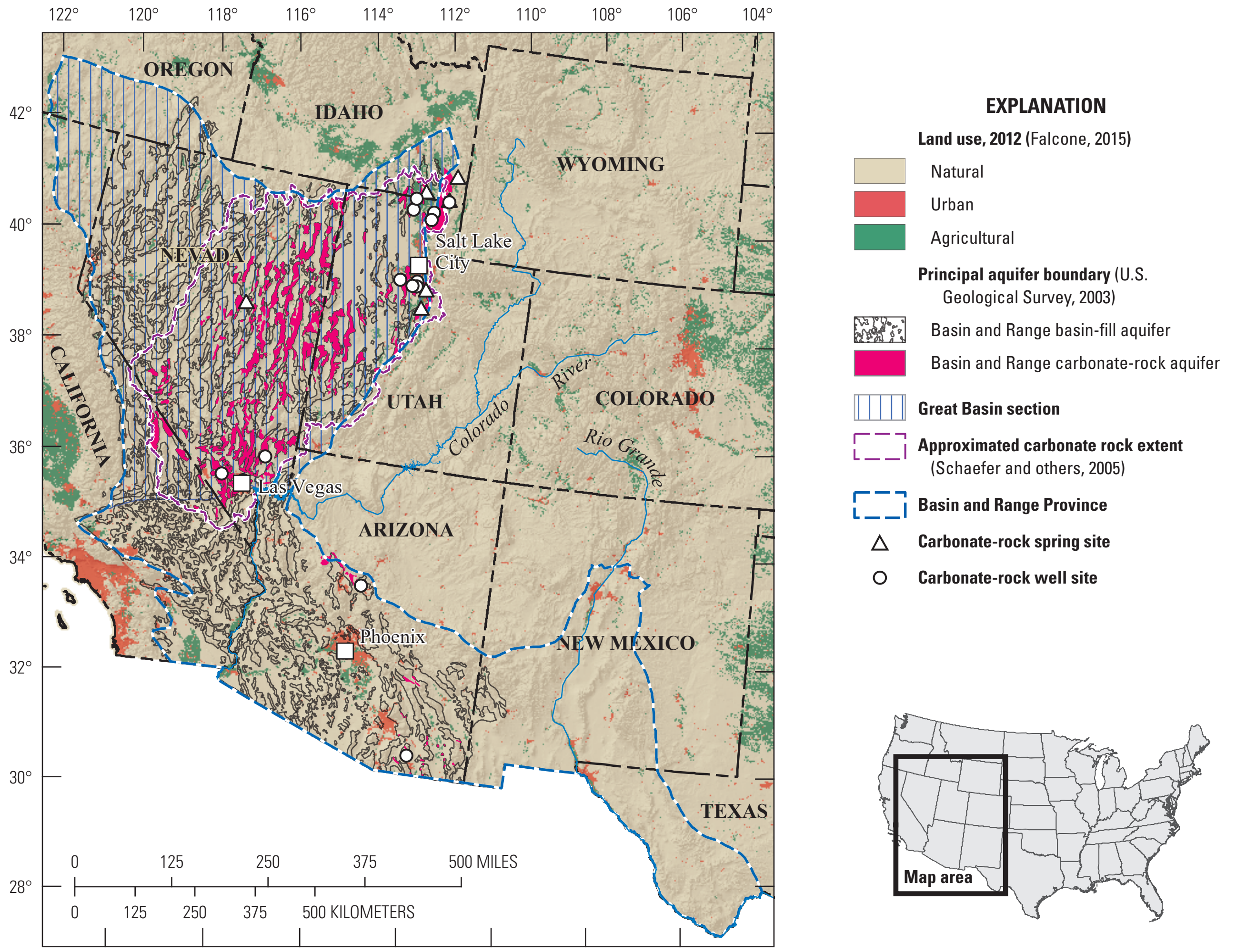
The climate generally is arid to semiarid; however, the differences of altitude from the many mountain ranges cause climatic variations. Mean annual precipitation ranges from less than 5 inches (in.) in the valleys to more than 60 in. in mountain regions (Prudic and others, 1995). Most of the precipitation falls during the winter months as snow in the mountains. The snowpack melts during the spring and summer, which provides essential groundwater recharge to the carbonate-rock aquifers (Schaefer and others, 2005). Water that recharges the carbonate-rock aquifers in the mountains can travel through or beneath several basins and ranges before reaching a discharge area (Schaefer and others, 2005). Mean annual temperatures range from 30 degrees Fahrenheit (°F) in some northern valleys to about 77 °F in the extreme southern valleys (Prudic and others, 1995; U.S. Climate Data, 2020). The low humidity and fairly constant light to moderate winds cause high rates of evapotranspiration (Robson and Banta, 1995; Schaefer and others, 2005).



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

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

Figure 2. *A,* Western U.S. physiographic provinces coincident with *B,* selected western principal aquifer boundaries by lithology.

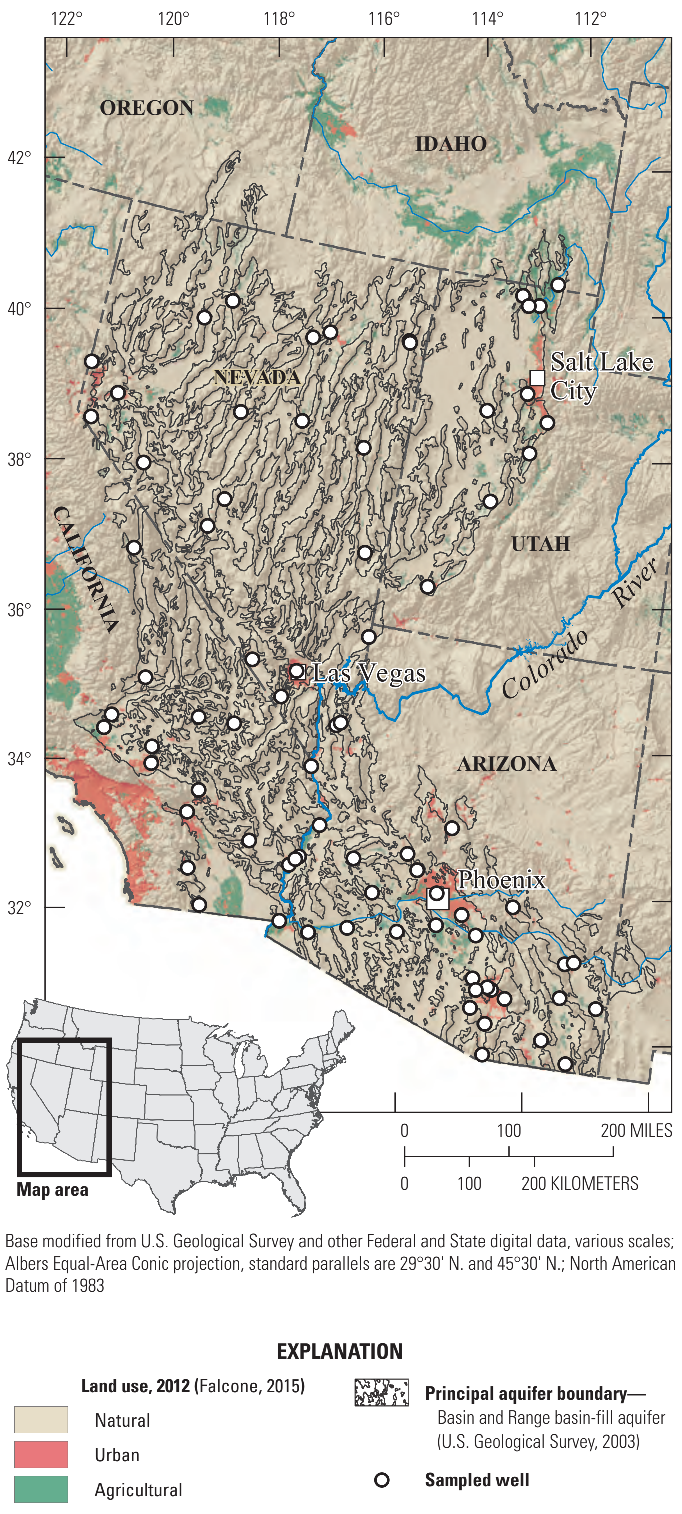


Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Figure 3. Basin and Range carbonate-rock aquifers, land use, and groundwater wells and springs sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Basin and Range Basin-Fill Aquifers

The Basin and Range basin-fill aquifers underlie an area of about 148,000 mi^2 (Arnold and others, 2016) and consist of approximately 330 sediment-filled basins separated by mountain ranges in Nevada, California, Arizona, Utah, and adjacent states (fig. 4; Anning and Konieczki, 2005; Thiros and others, 2014). Land use overlying the Basin and Range basin-fill aquifers in 2012 was approximately 92-percent natural, 4-percent agricultural, and 4-percent urban (Falcone, 2015). The basin-fill aquifers rank fourth in the Nation as a source of groundwater for public supply and rank fourth in the Nation as a source for irrigation (Arnold and others, 2016; table 1). Groundwater development for public supply is expected to increase for some of the most populous cities in the Basin and Range Province—Phoenix, Arizona (4.1 million); Las Vegas, Nevada (2.2 million); and Salt Lake City, Utah (1.2 million; U.S. Census Bureau, 2018). In some basins, groundwater withdrawals for public supply and irrigation is the primary component of discharge and have altered directions of groundwater flow (Thiros and others, 2014). In 2012, approximately 3 percent of the land cover overlying the Basin and Range basin-fill aquifers was mapped as irrigated lands (U.S. Geological Survey, 2014). Additionally, groundwater withdrawals from deep wells typically used for public supply have enhanced the movement of groundwater from shallower to deeper parts of the basin-fill aquifers. The development of water from the deeper parts of the aquifer might result in susceptibility of water-quality degradation by human activities at the land surface and increased vulnerability to contaminants where sources are present (Bexfield and others, 2011). Further, increased groundwater withdrawals have led to overdraft of aquifers resulting in land subsidence in many areas of the arid southwestern United States (Arizona Department of Water Resources, 2013, 2014, 2017, 2019; Leake, 2016).



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

Figure 4. Basin and Range basin-fill aquifers, land use, and groundwater wells sampled by the U.S. Geological National Water-Quality Assessment Project, 2013–2017.

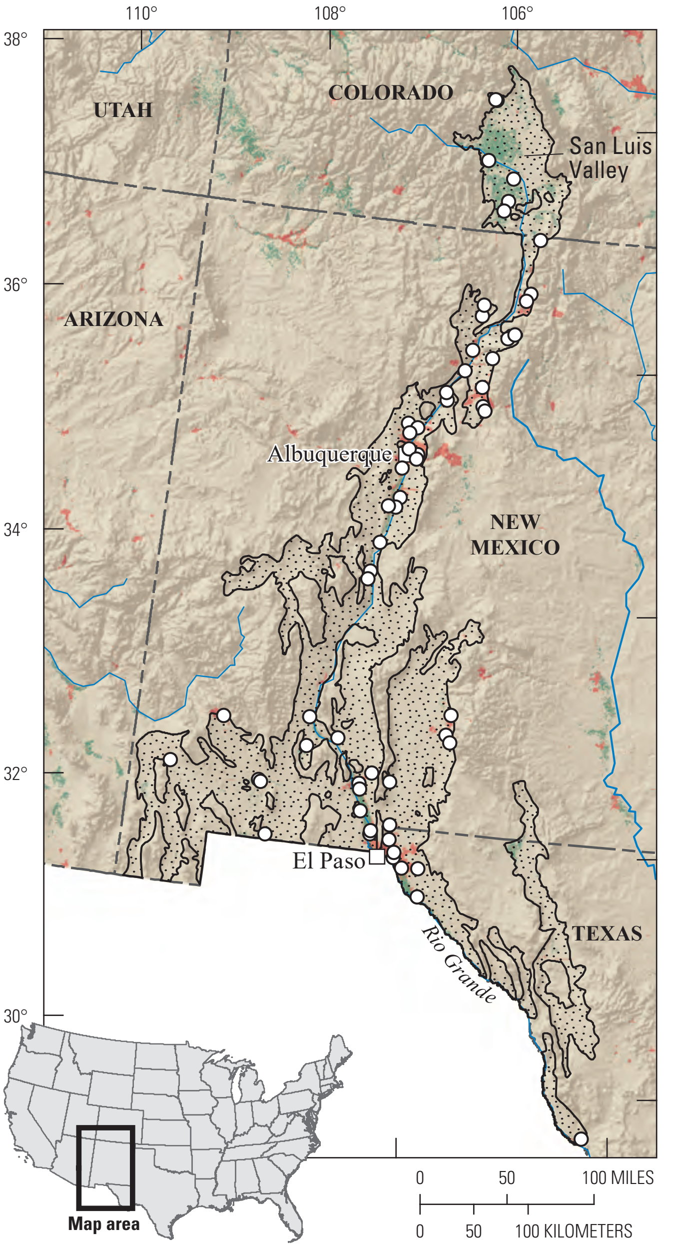
The basin-fill aquifers are within the Basin and Range Province–a structural province characterized by numerous north-south trending mountain ranges separated by intervening basins (Dettinger and others, 1995). The topographic basins generally overlie the Basin and Range carbonate-rock aquifers in the Great Basin area (fig. 3) of the Basin and Range Province and, in some places, could be hydraulically connected to the adjacent and underlying carbonates (Schaefer and others, 2005). The basins were created in response to an east-northeast to west-southwest regional extension field that resulted in a network of north to northwest-trending horst and grabens bound by high-angle normal faults (Harrill and Prudic, 1998). The subsidence of these grabens and subsequent erosion resulted in late Cenozoic basin-fill deposits (Harrill and Prudic, 1998). Basin-fill materials vary from unconsolidated to well-consolidated deposits of cobble, gravel, silt, and clay and can contain evaporite deposits or Quaternary basalt flows (Anning and Konieczki, 2005). The thickness of many of the alluvial basins is unknown, but many basin fills range in thickness from 1,000 to 5,000 feet and can be more than 10,000 feet in the middle of some basins in Utah and Arizona (Robson and Banta, 1995). The basin-fill aquifers are unconfined in most areas, but can be confined locally (Anning and Konieczki, 2005).

The climate of the Basin and Range Province generally is arid to semiarid. Average annual precipitation ranges from less than 4 inches in southwestern Arizona to about 16 inches in Utah (Robson and Banta, 1995). Most recharge to the basin-fill aquifers typically occurs along mountain fronts through infiltration of mountain stream runoff and inflow from fractured rock (Robson and Banta, 1995). In some basins, irrigation is a major source of recharge and also some rivers regionally, such as the Colorado River in California (Planert and Williams, 1995; Thiros and others, 2014). Although natural discharge of some basin-fill aquifers occurs through streams and springs, the largest component of discharge is evapotranspiration, and most spring discharge is consumed by evapotranspiration (Robson and Banta, 1995; Harrill and Prudic, 1998).

Rio Grande Aquifer System

The Rio Grande aquifer system underlies an area of about 29,000 mi^2 in parts of Colorado, New Mexico, and Texas (fig. 5; Arnold and others, 2017). Approximate land use overlying the Rio Grande aquifer system primarily is natural land cover (91 percent) with relatively small areas of agriculture (5 percent) and urban (4 percent) land use (Falcone, 2015). The two largest cities are Albuquerque, New Mexico (population of about 890,000), and El Paso, Texas (population of about 800,000; U.S. Census Bureau, 2018). The Rio Grande aquifer system ranks 18th in the Nation for groundwater withdrawals used for public supply and ranks 11th for withdrawals used for irrigation in 2000 (Arnold and others, 2016; table 1). In some basins, groundwater withdrawals for irrigation and public supply have become a substantial discharge component altering groundwater flow directions (Robson and Banta, 1995; Bexfield and others, 2011; Thiros and others, 2014). In 2012, mapped irrigated land cover accounted for approximately 5,320 mi^2 (8 percent) of the area overlying the Rio Grande aquifer system (U.S. Geological Survey, 2014), whereas agricultural land accounted for 5 percent (Falcone, 2015); differences likely resulted from different sources and methods used to quantify land-use types.

The Rio Grande aquifer system is within the Basin and Range Physiographic Province and the southern part of the Southern Rocky Mountains Province (fig. 2*A*). The aquifer system is characterized by alluvial fans near the base of mountains that slope toward the relatively flat basin floor (Robson and Banta, 1995) and consists of a network of hydraulically interconnected basin-fill aquifers in about 20 alluvial basins extending along the Rio Grande Valley and nearby valleys (Robson and Banta, 1995; Wilkins, 1998). The basin-fill alluvial aquifers of the Rio Grande generally are unconfined and water loss to evapotranspiration is an important factor affecting groundwater quality in areas of irrigated agriculture or areas of shallow depth to water (Bexfield and others, 2011; DeSimone and others, 2015). Evapotranspiration (evaporation of water from soil and transpiration of water from plants) leaves solutes behind, resulting in an increase to the dissolved-solids concentration in the remaining groundwater through time.



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

EXPLANATION

Land use, 2012 (Falcone, 2015)

🟨 Natural

🟥 Urban

🟩 Agricultural

▨ **Principal aquifer boundary**—Rio Grande aquifer system (U.S. Geological Survey, 2003)

○ **Sampled well**

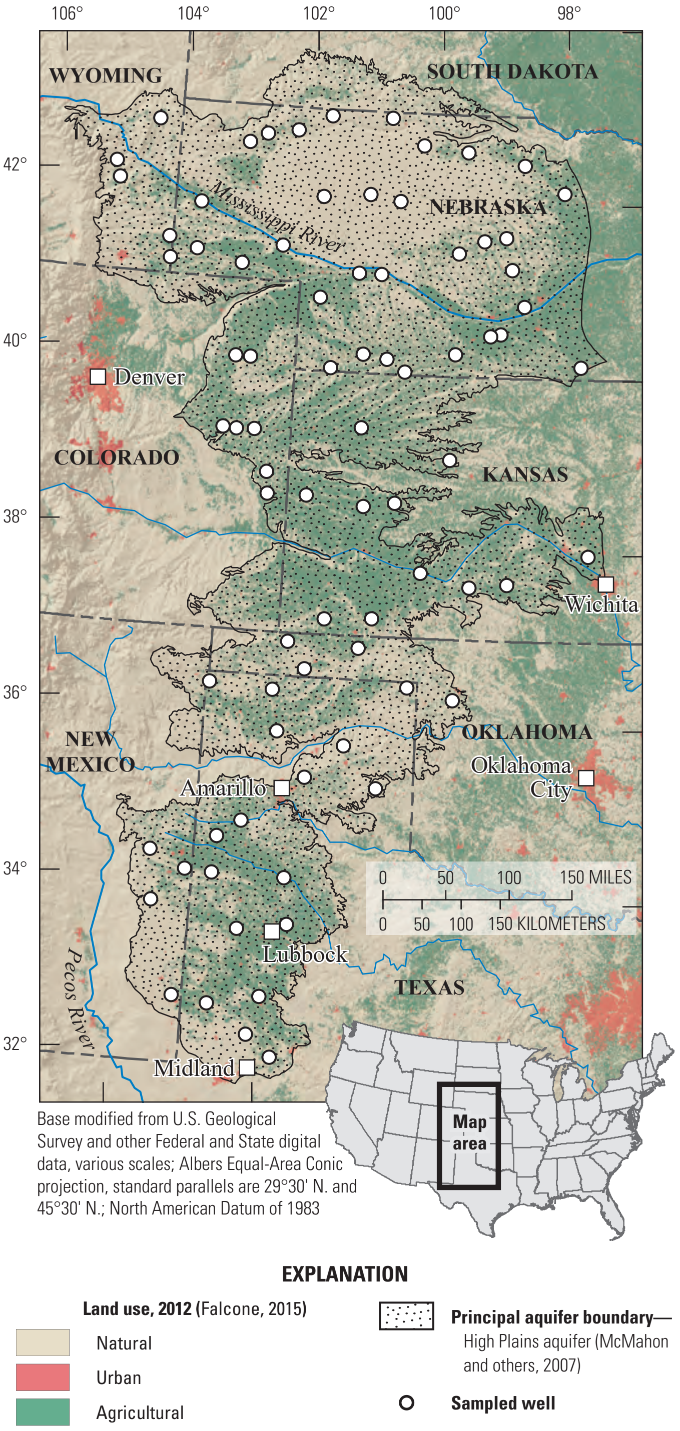
Figure 5. Rio Grande aquifer system, land use, and groundwater wells sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

The principal water-yielding units are the Tertiary and Quaternary Santa Fe Group and younger unconsolidated deposits of sand, silt, and clay interbedded with Quaternary gravel (Robson and Banta, 1995; Wilkins, 1998). The Santa Fe Group primarily is unconsolidated to moderately consolidated deposits of gravel, sand, and clay interbedded with volcanic-flows and tuff in some areas (Wilkins, 1998). The thickness of the basin fill varies greatly, with estimates as much as 30,000 ft in the San Luis Valley, 20,000 ft near Albuquerque, New Mexico, and approximately 2,000 ft near El Paso, Texas (Robson and Banta, 1995). The basins are bounded by Precambrian-, Mesozoic- and Cenozoic-age sedimentary, igneous, and metamorphic bedrock formations (Wilkins, 1998). The Rio Grande Rift, a northward-trending fault-bounded structural rift zone, is the principal geologic feature in the area (Robson and Banta, 1995). The rift consists of uplifted blocks on the east and west and down-dropped, alluvial-filled grabens in the middle (Wilkins, 1998). The configuration of the rift in the bounding highlands affects precipitation, runoff, groundwater recharge, source material of the basin fill, aquifer characteristics, and water quality (Robson and Banta, 1995).

Recharge to the Rio Grande aquifer system primarily originates as precipitation in the mountainous areas that surround the basins (Wilkins, 1998). Runoff from snowmelt or rainfall enters the basins by two pathways: (1) flow across alluvial fans and subsequent percolation downward through streambeds or (2) mountain-front recharge in which fractures or permeable layers in bedrock aquifers discharge directly to basin-fill aquifers in the subsurface at the mountain front or discharge to mountain streams as baseflow near the mountain front (Robson and Banta, 1995). The movement of water from recharge to discharge areas can take thousands of years because of the distance traveled and the aquifer characteristics (Anderholm and others, 1995). The flood plain of the Rio Grande River is a major point of discharge for deeper regional and shallower local flow systems. Regional groundwater flow is from the basin margins toward the Rio Grande River and southward from basin to basin. Groundwater discharge mostly occurs near the center of the basins or in the subsurface to the adjacent downstream alluvial basin and primarily occurs through evapotranspiration and groundwater pumping (Bexfield and Anderholm, 1997). Discharge of groundwater through evapotranspiration in the flood plain of the Rio Grande is substantial because of shallow depths to groundwater, which results in salts concentrated at and near the land surface and in shallow groundwater (Bexfield and Anderholm, 1997; Thiros and others, 2014). Local recharge and discharge flow systems have developed in the flood plain due to irrigation practices in which surface water is diverted from the Rio Grande River and delivered to fields through unlined canals and laterals (Bexfield and Anderholm, 1997). Irrigated fields, canals, and laterals provide local recharge of surface water to the aquifer, whereas localized discharge occurs through irrigation wells, evapotranspiration from fields, and constructed groundwater-tiles that are intended to keep the water table below a certain level (Bexfield and Anderholm, 1997). The climate of the region (south-central Colorado, central New Mexico, and west Texas) is arid to semiarid and is characterized by warm average daily temperatures, low relative humidity, and a high rate of evaporation that substantially exceeds mean annual precipitation (Thiros and others, 2014). Pan evaporation rates in New Mexico range from near 56 inches in the north-central mountains to more than 110 inches in southeastern valleys (Western Regional Climate Center, 2018). Most precipitation in the alluvial basins falls between July and October. Mean annual precipitation ranges from less than 10 inches over much of the Rio Grande Valley to more than 20 inches at higher elevations in New Mexico (Western Regional Climate Center, 2018).

High Plains Aquifer

The High Plains aquifer underlies an area of about 170,000 mi^2 in parts of eight western States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 6; Arnold and others, 2018). The High Plains aquifer is the principal source of water in one of the major agricultural areas of the United States and ranks first in the Nation for groundwater withdrawals used for irrigation and total withdrawals (Arnold and others, 2016; table 1). In 2000, withdrawals from the High Plains aquifer accounted for 21.2 percent of groundwater withdrawn in the United States (Hutson and others, 2004), making it the most intensively used PA in the Nation. Population estimates for the three largest cities in the High Plains aquifer boundary are for Lubbock, Texas (about 317,000), Amarillo, Texas (about 265,000), and Midland, Texas (about 171,000; U.S. Census Bureau, 2018). In 2012, land use overlying the High Plains aquifer was approximately 58-percent natural, 41-percent agricultural, and 1-percent urban (Falcone, 2015). The agricultural land use was dominated by crop production (39 percent), followed by pasture/hay (1 percent), and grazing potential (1 percent). Crops grown in the High Plains are a substantial percentage of total crop production for the United States (U.S. Department of Agriculture, 2014). Historically, the primary crop was wheat, followed by corn, sorghum, hay/alfalfa, cotton, soybeans, and peanuts (McMahon and others, 2007). In 2012, approximately 12 percent of the land cover overlying the High Plains aquifer was mapped as irrigated lands (U.S. Geological Survey, 2014). The differences in the percentage of agricultural land use and the percentage of irrigated land use reflected dryland farming (table 1). Dryland farming is a type of farming practiced in arid and semiarid regions in which drought resistant crops are grown without the use of irrigation (Peterson, 2005; Stewart, 2016).



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

Figure 6. High Plains aquifer, land use, and groundwater wells sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

The aquifer occupies the higher elevations of the Great Plains Province (fig. 2*A*), an area known as the High Plains. The Great Plains Province, which extends from the Canadian border south into Texas, contains most of the High Plains aquifer (fig. 2*B*). The topography of the High Plains aquifer is characterized by flat to gently rolling terrain, a remnant of the vast plain formed by sediments that were deposited by ancestral streams flowing eastward from the Rocky Mountains (Weeks and others, 1988). The High Plains aquifer consists of near-surface sedimentary deposits of Tertiary and Quaternary age that form six hydraulically connected hydrogeologic units of the regionally unconfined aquifer (Gutentag and others, 1984; Dennehy and others, 2002; McMahon and others, 2007). Of these six hydrogeologic units, the Ogallala Formation has the largest areal extent of the geologic units (134,000 mi^2; Luckey and others, 1986) and composes a large part of the High Plains aquifer where saturated (McMahon and others, 2007). Water in the underlying bedrock can contain large concentrations of dissolved solids that could affect the quality of water in the High Plains aquifer (McMahon and others, 2007). The average saturated thickness across the aquifer is about 200 ft and is greatest in central Nebraska where it ranges between 600 and 1,000 ft (McMahon and others, 2007). Regional groundwater flow generally is west to east; however, variability exists near high-capacity pumping wells and major rivers that locally affect hydraulic gradients and regional groundwater flow (McMahon and others, 2007). Recharge to the High Plains aquifer occurs by infiltration of irrigation water, areally diffuse infiltration from precipitation, focused infiltration of storm- and irrigation-runoff, and upward movement of water from underlying aquifers (McMahon, 2001). Discharge occurs primarily by irrigation wells, discharge to streams and underlying aquifers, groundwater flow across the eastern boundary of the aquifer, and evapotranspiration (Luckey and others, 1986).

Because of the large areal extent of the High Plains aquifer, the climate is diverse; mean annual temperature increases from north to south, ranging from 39 °F in the north to 64 °F in the south, and mean annual precipitation increases from west to east, from about 12 to 33 inches (McMahon and others, 2007). Most of the High Plains has a middle-latitude, dry continental climate with abundant sunshine, moderate precipitation, frequent winds, low humidity and high rates of evaporation (Weeks and others, 1988). Evaporation rates are among the highest in the United States because of high summer air temperatures and persistent winds, which leaves little available precipitation to recharge the aquifer (Gutentag and others, 1984; Weeks and others, 1988). Evaporation rates range from 60 inches in the north to 109 inches in the south (Gutentag and others, 1984). Elevations range from about 1,000 ft along the eastern boundary to about 8,000 ft along the northwestern boundary (McMahon and others, 2007).

Colorado Plateaus Aquifers

The Colorado Plateaus aquifers cover an area of about 140,0000 mi^2 in southwestern Wyoming, southeastern Utah, western Colorado, northwestern New Mexico, and northeastern Arizona (fig. 7). Land use overlying the Colorado Plateaus aquifers is approximately 97-percent natural, 2-percent agricultural, and 1-percent urban (Falcone, 2015). The Colorado Plateaus aquifers rank 28th in the Nation for groundwater withdrawals used for public supply (Arnold and others, 2016; table 1). In 2012, 1 percent of the land cover overlying the Colorado Plateaus aquifers was mapped as irrigated agriculture (U.S. Geological Survey, 2014). The two largest cities in the PA boundary are Grand Junction, Colorado (population of about 152,000), and Flagstaff, Arizona (population of about 141,000; U.S. Census Bureau, 2018).

The Colorado Plateaus aquifers are nearly coincident with the extent of the Colorado Plateau Province, except that they include the Wyoming Basin Province and the western margins of the Southern Rocky Mountains Province (fig. 2*A*). The Colorado Plateaus Province is characterized by vast regions of plateaus, mesas, and deep canyons. The Colorado Plateaus aquifers generally are composed of permeable, moderate to well-consolidated sedimentary rocks that vary greatly in thickness, lithology, and hydraulic characteristics (Robson and Banta, 1995, 1996). The Colorado Plateaus aquifers are a complex sequence of water-yielding layers resulting from structural deformation and erosion since deposition of the aquifer sediments (Robson and Banta, 1995). For example, in uplifted areas, younger rocks have eroded away, resulting in aquifer units present only in older rocks that underlie more extensive units in the Colorado Plateaus Province, whereas younger aquifer units are present only in the Wyoming Basin Province (fig. 2*A*).

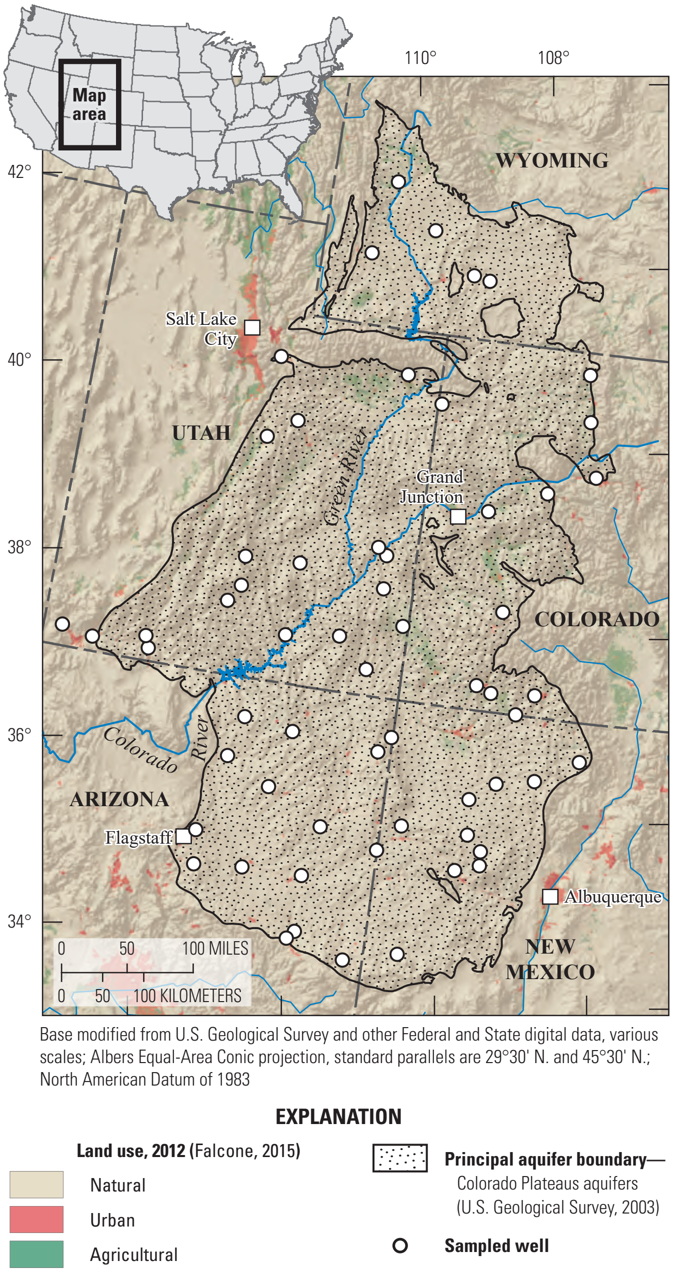


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Figure 7. Colorado Plateaus aquifers, land use, and groundwater wells sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Groundwater recharge to the Colorado Plateaus aquifers generally occurs in areas of higher altitude that receive more precipitation than the lower elevation basins. Recharge also occurs along basin margins. Groundwater flow generally is toward the center of structural basins that consist of broad basins and uplifts but is complex where aquifers have been intensely folded and faulted (Robson and Banta, 1995, 1996). Groundwater discharges from the aquifers directly to streams, springs, and seeps, or indirectly by transpiration from vegetation growing along stream valleys and evaporation from shallow groundwater by upward movement through confining layers into overlying aquifers, or by withdrawal from wells (Robson and Banta, 1995). The climate of the Colorado Plateaus Province, the southwest part of the Wyoming Province and the western margins of the Southern Rocky Mountains Province, is arid to semiarid; annual precipitation (1900–2000) in the Colorado Plateaus Province (fig. 2*A*) has ranged from 5.4 to 26.3 inches per year (in/yr), with a median of 11.8 in/yr (Hereford and others, 2002). Most precipitation falls in winter and spring with brief and intense summer thunderstorms that produce 20–40 percent of annual precipitation (Robson and Banta, 1995).

Columbia Plateau Basaltic-Rock Aquifers

The Columbia Plateau Province, in the northwest corner of the western United States (fig. 2*A*) is characterized by extensive basalt formations and is overlain by unconsolidated to semiconsolidated sedimentary deposits. The Province contains the Columbia Plateau regional aquifer system (fig. 8*A*), which is composed of the Columbia Plateau basaltic-rock aquifers overlain by the Columbia Plateau basin-fill aquifers (Kahle and others, 2009; fig. 2*B*). The Columbia Plateau basaltic-rock aquifers rank 19th in the Nation as a source of groundwater used for public supply (Arnold and others, 2020; table 1). The basin-fill aquifers rank 67th for public supply and were not sampled for this study. The Columbia Plateau basaltic-rock aquifers cover an area of approximately 42,000 mi^2 and extend across small portions of northwestern Idaho, northeastern Oregon, and a large part of southeastern Washington (Arnold and others, 2020).

The natural land cover of the Columbia Plateau regional aquifer system largely determines corresponding land use. Except for the forested mountains in the highlands and barren rock at mid-elevation, the regional aquifer system is predominately shrub and grasslands in which dryland agricultural includes winter and spring lentils and wheat (Kahle and others, 2011). In 2012, land use overlying the regional aquifer system was approximately 76-percent natural, 23-percent agricultural, and 1-percent urban (Falcone, 2015). In 2012, about 7 percent of the land use was irrigated agriculture (U.S. Geological Survey, 2014) which predominantly occurred overlying the basin-fill aquifers (fig. 8*B*). Irrigated crops include the Nation's largest production of apples and hops, as well as potatoes, onions, mint, and increasingly, wine grapes (Kahle and others, 2011). Population estimates for the three largest cities in the regional aquifer system boundary are Spokane, Washington (about 564,000), tri-cities area, Washington (about 290,000), and Yakima, Washington (about 250,000; U.S. Census Bureau, 2018).

The Columbia Plateau basaltic-rock aquifers lie in a structural and topographic basin, the Columbia Plateau, which is a wide basalt plateau bounded on the west by the Cascade Range, on the east by the Rocky Mountains, and on the north by the Okanogan Highlands (Kahle and others, 2011). The Plateau consists of a series of basalt flows, the Columbia River Basalt Group (CRBG), which were extruded during the Miocene era between 17 million and 6 million years ago (Whiteman and others, 1994). More than 300 flow events have been identified, with thicknesses from 10 ft to more than 300 ft (Tolan and others, 1989; Drost and others, 1990). Reidel and others (2002) reported total thickness of the CRBG to be greater than 14,000 ft near Pasco, Washington. The Columbia Plateau regional aquifer system is divided into four informal physiographic sub-provinces that represent structural regions—the Yakima Fold Belt, Blue Mountains, Palouse Slope, and the Clearwater Embayment (Reidel and others, 2002; fig. 8*B*). Variations in stratigraphy, depositional environment, and post-depositional folding and faulting result in unique groundwater characteristics and important flow barriers associated with each of these structural regions. Miocene- to Holocene-aged sedimentary deposits overlie large areas of the Columbia Plateau and range in thickness from 0 to 1,300 ft, with a median thickness of 47 ft (Kahle and others, 2009). These deposits comprise the Columbia Plateau basin-fill aquifers, which are unconsolidated to semiconsolidated sediments and minor basalt and andesite (Drost and others, 1990; Vaccaro, 1999; Kahle and others, 2009; fig. 8).

Regional groundwater flow is from areas of high altitude to surface drainage features in the lowlands—principally the Columbia River and its tributaries. Groundwater discharge is to surficial features such as rivers, lakes, waterways, and to subsurface features such as drains and wells. Groundwater flows laterally and vertically in the basaltic-rock aquifers. Lateral movement generally is confined to basalt-interflow areas, defined as the brecciated areas of basalt flow tops and bottoms that commonly have open and highly connected pore structures (Whiteman and others, 1994). Basalt-interflow zones are separated by low hydraulic conductivity flow interiors in which most of the fractures are cooling joints that are mostly orientated vertically (Burns and others, 2011), thereby enabling a mostly vertical movement of groundwater.

Much of the Columbia Plateau region is semiarid. Elevation in the central part of the Plateau ranges from 350 to 2,000 ft with precipitation ranging from 7 to 15 in/year (Kahle and others, 2011). The surrounding forested mountains have elevations ranging from 2,000 to 3,500 ft, where annual precipitation can exceed 45 inches (Kahle and others, 2011). Mean monthly temperatures in the low-lying areas range from 37 to 86 °F, and from 27 to 54 °F in the higher mountainous areas (Vaccaro, 1999).

Methods

This section describes sample collection and quality-assurance methods. Quality-assurance results are detailed in appendix 1. This section also describes methods used in the *status* and *understanding* assessments. The *status assessment* methods include descriptions of water-quality benchmarks used for evaluating groundwater quality, the criteria for selecting constituents for further evaluation, and methods used to calculate aquifer-scale proportions for selected constituents. The *understanding assessment* methods include a description of the treatment of concentrations below method detection limits (MDL) and the statistical methods used to identify significant correlations between potential explanatory factors and selected water-quality constituents.

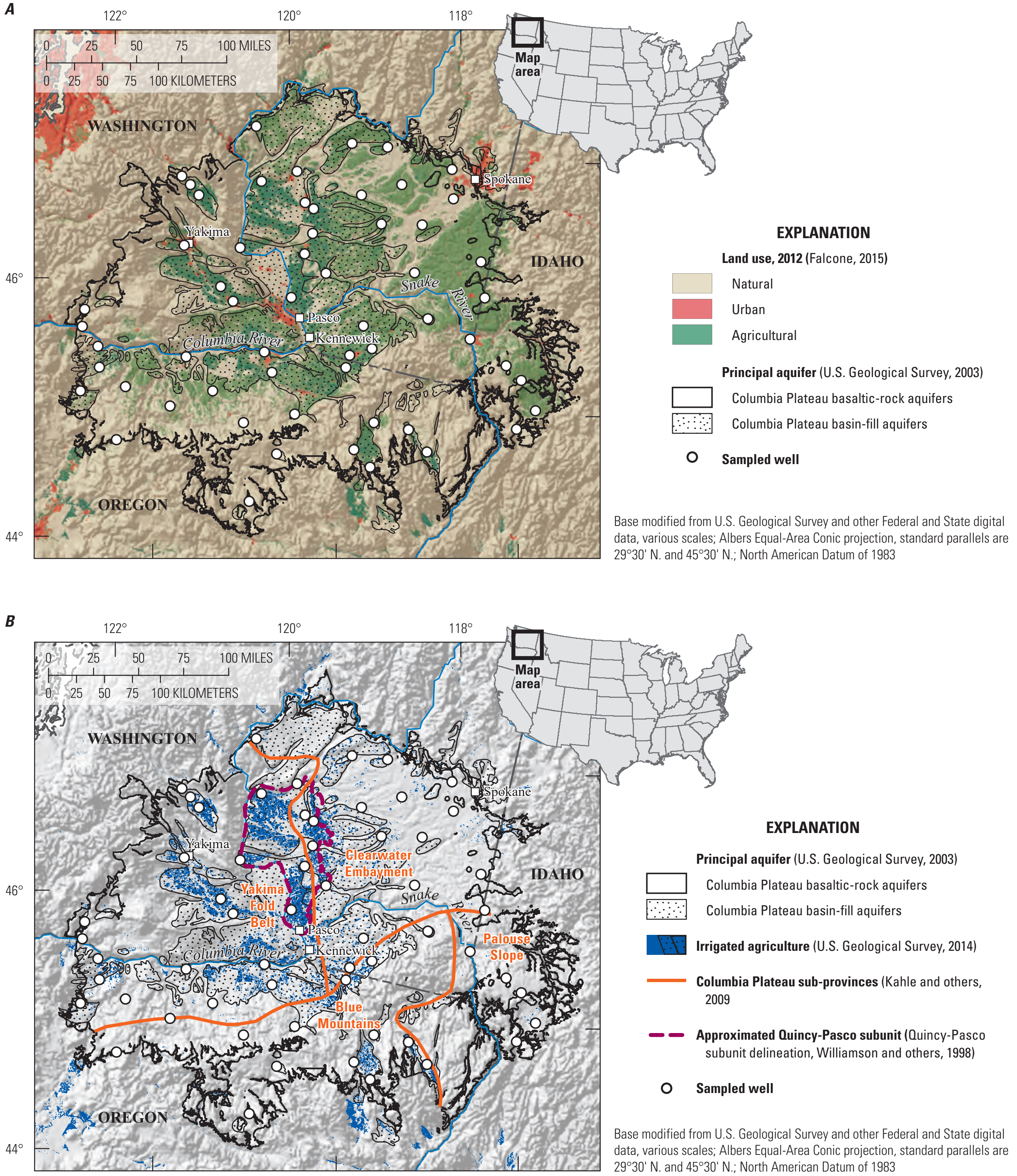

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Figure 8. *A,* Columbia Plateau basaltic-rock aquifers, land use, and groundwater wells sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017; and *B,* sub-provinces of the Columbia Plateaus regional aquifer system.

Sample Collection and Analysis

The NAWQA Project has developed rigorous protocols to ensure that the data collected are of known and high quality. Water-quality samples are collected by using established USGS protocols and procedures to obtain a representative sample and to avoid contamination (Koterba and others, 1995). The network of principal aquifer studies consists of PSWs with some springs in the Basin and Range carbonate-rock aquifers that yield water from the part of the aquifers used for public drinking-water supply (Burow and Belitz, 2014). Hereafter, the discussion of principal aquifer study networks described as PSWs also includes these public-supply spring samples. Each PA was divided into equal-area grid cells (fig. 9); a method that allows for evaluation of a constituent concentration at a regional scale (Belitz and others, 2010) and is described in more detail in the "*Status Assessment*" section. One well per grid cell was randomly selected for sampling from a population of existing PSWs (Burow and Belitz, 2014). For some PAs, parts of the region are sparsely populated, and PSWs are not equally distributed (specifically the Basin and Range basin-fill aquifers, Basin and Range carbonate-rock aquifers, Rio Grande aquifer system, and Colorado Plateaus aquifers). In these PAs, the study area was delineated by placing buffers around the existing PSWs and an equal area grid was then defined within the buffered area. Buffer sizes varied and ranged from 3.1 miles (mi; 5 kilometers[km]) for the Rio Grande aquifer system, to 12.4 mi (20 km; fig. 9). Sample sites in the Basin and Range carbonate-rock aquifers included a mix of PSWs (total number, n; n=14) and springs (n=6) because springs are commonly used for public supply in this PA (table 1). Sample sites for the Colorado Plateaus PA included two PSWs located outside the extent of the buffered area, but within the PA boundary, based on availability of the PSWs for sampling (fig. 7).

Water-quality samples were analyzed for most constituents at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. Analytes included major and minor ions, nutrients and dissolved organic carbon, pesticide compounds, VOCs, radionuclides, selected isotopes and age tracers, and perchlorate (in selected PAs). Not all measured constituents are described in this report. Constituents discussed in this report that were measured at other laboratories are radionuclides, tritium (^3H), and perchlorate. Radionuclides were analyzed by Test America in Richland, Washington, for samples collected from the Basin and Range basin-fill aquifers, Basin and Range carbonate-rock aquifers, and Rio Grande aquifer system. Radionuclide samples from the High Plains aquifer, the Colorado Plateaus aquifers, and the Columbia Plateau basaltic-rock aquifers were analyzed by ALS Environmental in Fort Collins, Colorado. Perchlorate samples were analyzed by Weck Laboratories, Inc., in Industry, California. Tritium samples were analyzed at the USGS Tritium Laboratory in Menlo Park, California, or at the University of Miami Tritium Laboratory in Miami, Florida. The detection level was 0.1 tritium units (TU) or better at both labs (Thatcher and others, 1977).

Data Reporting and Quality-Assurance and Quality-Control Methods

Groundwater-quality data and quality-assurance and quality-control (QA-QC) results for data collected by the NAWQA Project during each year are published in USGS Data Series reports. Analytical results for the western PAs are publicly available as follows:

- Basin and Range basin-fill aquifers, Arnold and others (2016)
- Rio Grande aquifer system, Arnold and others (2017)
- Basin and Range carbonate-rock aquifers and the High Plains aquifer (excluding samples collected in Texas), Arnold and others (2018)
- High Plains aquifer (samples collected in Texas) and the Columbia Plateau basaltic rock aquifers, Arnold and others (2020)
- Colorado Plateaus aquifers, as a USGS data release (Rosecrans, 2020).

The quality of environmental samples was determined by the analysis of blank, replicate, and spike samples collected in each PA. The quality-assurance plan for the NAWQA Project groundwater samples was derived from previous NAWQA studies (Koterba and others, 1995) and the USGS National Field Manual (U.S. Geological Survey, variously dated). Blanks are collected to determine if water samples might become contaminated during sample collection, field processing transport, or laboratory analysis (Mueller and others, 2015). Sequential replicate samples were collected to assess the precision of the water-quality data and to evaluate whether the differences between concentrations in samples were from differences in groundwater quality or from variability resulting from the collection, processing, and laboratory analysis of the samples. Spike samples are used to indicate the accuracy of reported results. Spike samples are prepared by adding a known concentration of target analyte to a known volume of water collected from groundwater and indicate effects of matrix interference and sample handling on recovery of the analyte. Quality-assurance and quality-control results for all western principal aquifer study samples except for the Colorado Plateaus aquifers, are detailed in Arnold and others (2016, 2017, 2018, and 2020). Quality-assurance and quality-control results for the Colorado Plateaus aquifers are detailed in appendix 1.

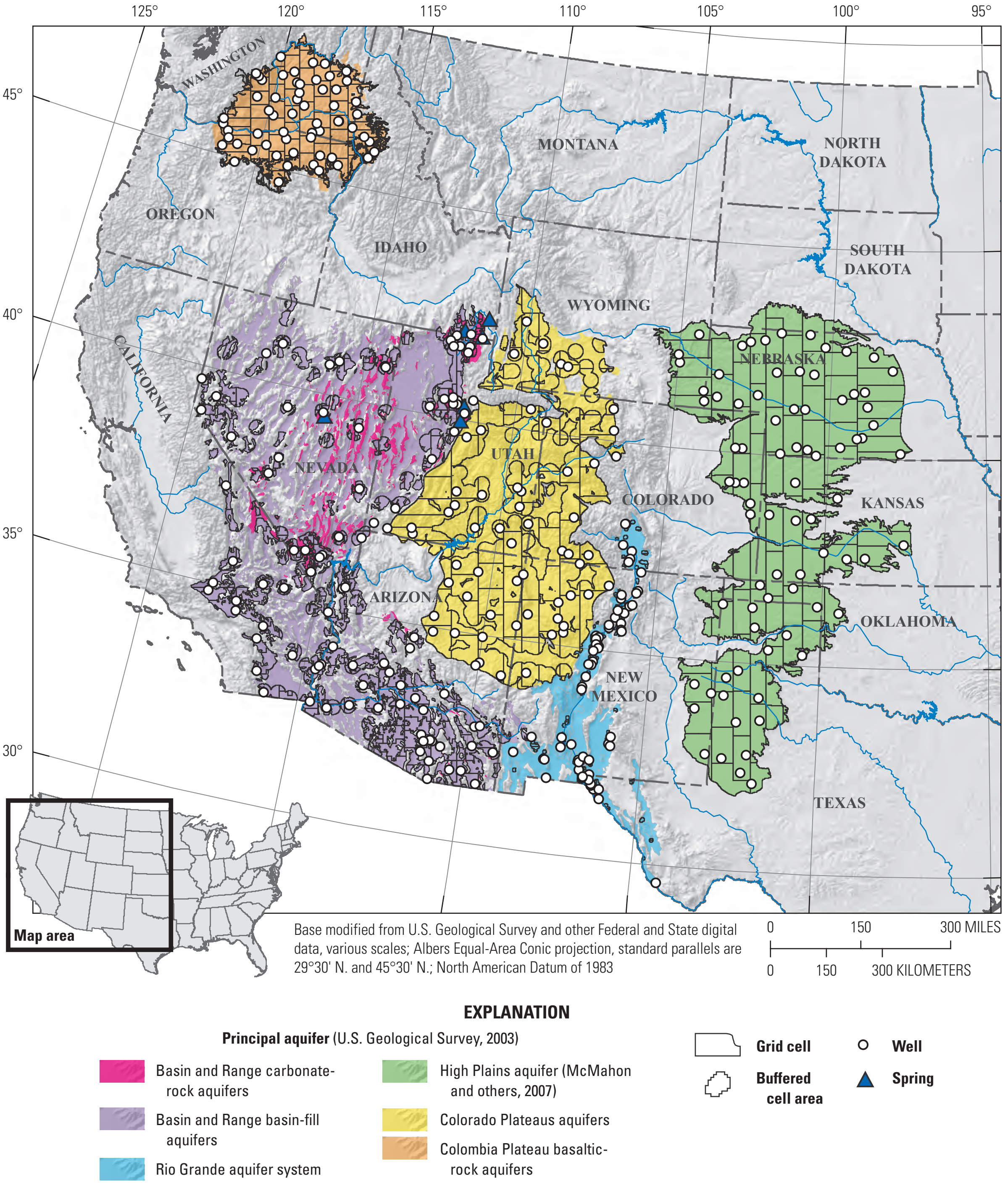

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Figure 9. Equal-area grid and sampled groundwater wells and springs for six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Status Assessment

The *status assessment* quantifies groundwater quality at the aquifer scale relative to drinking water benchmarks. This section describes the methods used to (1) describe groundwater quality using established drinking-water standards, (2) select constituents for further evaluation by the *understanding assessment*, and (3) calculate aquifer-scale proportions.

Benchmarks for Evaluating Groundwater Quality and Relative Concentrations

To provide context for evaluating the quality of untreated groundwater at the depth zone used for public supply, groundwater samples are compared to established drinking-water standards (health-based and non-health-based). The quality of water received by the consumer can be different than untreated groundwater because after withdrawal, groundwater might be treated before delivery. The concentrations of constituents in groundwater samples collected in the NAWQA principal aquifer studies are compared to three water-quality benchmarks: (1) regulatory EPA MCLs (U.S. Environmental Protection Agency, 2018a); (2) non-regulatory EPA and non-regulatory USGS HBSLs (Norman and others, 2018; U.S. Geological Survey, 2018a); and (3) non-regulatory EPA SMCLs (U.S. Environmental Protection Agency, 2018b). Maximum contaminent levels are enforceable standards that represent the maximum level of a contaminant allowed in drinking water used for public supply and are established to protect the consumer against drinking-water contaminants that have potential human-health effects. Health-based screening levels are non-enforceable water-quality benchmarks used to evaluate water-quality data in a human-health context (Norman and others, 2018). Health-based screening levels were developed by the USGS and EPA using EPA methodologies for establishing drinking water standards and the most recent EPA peer-reviewed, publicly available human-health toxicology information (Norman and others, 2018). Health-based screening levels can be used to prioritize contaminants of concern that could warrant further monitoring and provide an early indication of contaminant concentrations of potential human-health concern in water resources (Toccalino, 2007). Of the more than 50 inorganic constituents evaluated for water quality, 28 had human-health benchmarks, and out of the more than 300 organic constituents evaluated for water quality, 170 had human-health benchmarks. Secondary maximum contaminant levels are non-enforceable guidelines that assist public water systems in managing their drinking water for aesthetic effects (such as taste, odor, or color), technical effects (such as corrosivity, scaling, and sedimentation), and cosmetic effects (such as tooth or skin discoloration).

Groundwater quality was defined in terms of relative concentration (RC), which relates measured concentrations in groundwater samples to water-quality benchmarks:

$$RelativeConcentration = \frac{sampleconcentration}{benchmarkconcentration} \qquad (1)$$

Relative concentrations were classified as high, moderate, or low based on the following criteria:

Category	Relative concentration for inorganic constituents	Relative concentration for organic constituents and perchlorate
High	>1	>1
Moderate	>0.5 and ≤1	>0.1 and ≤1
Low	≤0.5	≤0.1

Organic constituents and perchlorate have a lower threshold because they generally are less prevalent and have smaller concentrations relative to benchmarks than inorganic constituents (Toccalino and others, 2004). Concentrations are considered low if they are less than moderate or the constituent was not detected. Several inorganic constituents have MCL and SMCL benchmarks. For example, fluoride has a health-based MCL benchmark of 4 micrograms per liter (µg/L) and a SMCL of 2 µg/L; therefore, where applicable, inorganic results can be discussed for both health-based and non-health-based benchmarks. Relative concentrations are discussed throughout this report as high, moderate, or low concentrations.

Selection of Constituents for the *Understanding Assessment*

Almost 400 inorganic and organic constituents were analyzed for samples from the six western PAs assessed in this report. Only a subset, however, are considered herein for additional evaluation by application of an *understanding assessment*; the selection criteria were different for inorganic and organic constituents. For inorganic constituents, only those detected at high or moderate concentrations were selected. For organic constituents, the selection criteria included constituents with detection frequencies greater than or equal to 10 percent. Samples for the special interest constituent, perchlorate, were collected in only two PAs—the High Plains aquifer and the Rio Grande aquifer system—for which the same selection criteria were applied as for organic constituents. The selection criteria for an application of an *understanding assessment* identified 21 inorganic constituents, 7 organic constituents, and perchlorate (table 2). An additional 28 inorganic and 118 organic constituents were measured at detectable concentrations but were not selected for further evaluation. Inorganic constituents that were not selected include those that do not have benchmarks or that were only detected at low concentrations, whereas organic constituents not selected include those with detection frequencies less than 10 percent or those that do not have benchmarks (table 3). Most of the organic constituents detected and listed in table 3 were single occurrence detections at low concentrations.

Aquifer-Scale Proportions

The principal aquifer studies included the full extent of the PAs described in the “Principal Aquifer Description and Settings” section and used an equal-area grid sampling approach (Belitz and others, 2010). The one-well-per-cell sampling design provides a spatially unbiased estimate of the aquifer-scale proportion that is equal to the observed detection frequency of a concentration above a given threshold or benchmark (Belitz and others, 2010). Thus, aquifer-scale proportions allow for estimating the percentage of a PA with low, moderate, or high concentrations for selected constituents or constituent groups. A constituent could be considered more important or notable not because it has a higher median concentration or higher concentration but because its concentration is high in a larger part of the aquifer (Belitz and others, 2010).

Understanding Assessment

The *understanding assessment* identifies natural and human factors affecting groundwater quality and evaluates statistically significant correlations—among potential explanatory factors and between potential explanatory factors and water quality—to provide physical and chemical context for groundwater quality. Potential explanatory factors considered in this report include depth to bottom of well perforation, groundwater age category, land use, aquifer lithology, hydrologic conditions, and geochemical conditions. Potential explanatory factors are described in more detail in subsequent sections.

Assessment Levels

A common data “assessment level” was assigned for all data for statistical analysis. Water-quality results from the PAs had numerous concentrations reported as below the MDL with a ‘<’ remark code (that is, a nondetection). Additionally, some constituents are reported as estimated and assigned a remark code of ‘E’. A value coded with ‘E’ typically is less than the MDL and refers to values that were quantified detections, but the concentration has more uncertainty because it approaches the lower analytical capability of the instrumentation. The ‘E’ coded values reported above the MDL for a given constituent were considered at their estimated value and ranked for nonparametric statistical tests accordingly; ‘E’ coded values reported at less than the MDL were considered as nondetections. If multiple MDLs were reported for individual constituents with ‘E’ coded values, only ‘E’ coded values above the highest reported MDL were considered at their estimated value and were ranked accordingly. Except for pesticide compounds, the assessment level applied to statistical analysis using ranks (nonparametric statistics) accounted for nondetections by setting the concentration below the lowest MDL before ranking. The assessment level applied for pesticide compounds was slightly different and based on a method used in other national assessments of pesticides (Gilliom and others, 2006). When ranking pesticides for a statistical test, all pesticide nondetections were assigned a rank below the lowest reported ‘E’ value, and results with ‘E’ values and quantified detections were assigned ranks on the basis of their reported value.

Table 2. Benchmark type and value for constituents selected for additional evaluation in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[Inorganic constituents selected for understanding assessment included those with maximum concentrations greater than 0.5 times a benchmark concentration. Organic constituents selected if frequency of detection, at any concentration, was greater than or equal to 10 percent. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, EPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HHBP-NC, EPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, EPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; mg/L, milligram per liter; pCi/L picocurie per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for additional evaluation in understanding assessment; D-eval, detected and selected for additional evaluation in understanding assessment —, not detected; na, not analyzed for in respective principal aquifer]

		Benchmarks			Principal aquifer					
Constituent	Typical use or source	Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Inorganic constituents with health-based benchmarks										
Trace elements										
Antimony	Naturally occuring	MCL	6	µg/L	D-eval	D	D	D	D	D
Arsenic	Naturally occuring	MCL	10	µg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval
Cobalt	Naturally occuring	HBSL-NC	2	µg/L	D	D-eval	D	D-eval	D-eval	D-eval
Fluoride	Naturally occuring	MCL	4	mg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval
Iron	Naturally occuring	HBSL-NC	4,000	µg/L	D	D	D	D-eval	D-eval	D
Manganese	Naturally occuring	HBSL-NC	300	µg/L	D	D-eval	D-eval	D-eval	D-eval	D-eval
Molybdenum	Naturally occuring	HBSL-NC	30	µg/L	D	D-eval	D-eval	D-eval	D	D-eval
Selenium	Naturally occuring	MCL	50	µg/L	D	D-eval	D	D-eval	D	D
Strontium	Naturally occuring	HBSL-NC	4,000	µg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D
Thallium	Naturally occuring	MCL	2	µg/L	D-eval	D	D	D	D	D
Uranium	Naturally occuring	MCL	30	µg/L	D	D-eval	D-eval	D-eval	D-eval	D-eval
Nutrients										
Nitrate, as nitrogen	Natural, fertilizer, sewage	MCL	10	mg/L	D	D-eval	D	D-eval	D	D-eval
Radionuclides										
Gross alpha-particle activity	Naturally occuring	MCL	15	pCi/L	D	D-eval	D-eval	D-eval	D-eval	D-eval
Radium-226 and radium-228 (combined)	Naturally occuring	MCL	5	pCi/L	D-eval	D	D-eval	D	D-eval	D
Radon-222	Naturally occuring	MCL-proposed	4,000	pCi/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval

Table 2. Benchmark type and value for constituents selected for additional evaluation in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Inorganic constituents selected for understanding assessment included those with maximum concentrations greater than 0.5 times a benchmark concentration. Organic constituents selected if frequency of detection, at any concentration, was greater than or equal to 10 percent. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, EPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HHBP-NC, EPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, EPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; mg/L, milligram per liter; pCi/L picocurie per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for additional evaluation in understanding assessment; D-eval, detected and selected for additional evaluation in understanding assessment —, not detected; na, not analyzed for in respective principal aquifer]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Inorganic constituents with secondary maximum constaminant level benchmarks										
Chloride	Naturally occuring and anthropogenic	SMCL	250	µg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D
Fluoride	Naturally occuring and anthropogenic	SMCL	2	mg/L	D	D-eval	D-eval	D-eval	D-eval	D-eval
Iron	Naturally occuring and anthropogenic	SMCL	300	µg/L	D	D-eval	D-eval	D-eval	D-eval	D-eval
Manganese	Naturally occuring and anthropogenic	SMCL	50	µg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval
Sulfate	Naturally occuring and anthropogenic	SMCL	250	mg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval
Total dissolved solids (TDS)	Naturally occuring and anthropogenic	SMCL	500	mg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval
Organic and special-interest constituents with health-based benchmarks										
Pesticides										
Atrazine	Herbicide	MCL	3,000	ng/L	—	D	—	D-eval	—	D-eval
Bromacil	Herbicide	HBSL-NC	100,000	ng/L	—	D	D	D-eval	—	D
Didealkylatrazine	Herbicide degradate	HHBP-NC	12,000	ng/L	D	D	—	D-eval	D	—
Propazine	Herbicide	HBSL-NC	40,000	ng/L	—	D	—	D-eval	—	D
Propoxur	Insecticide	HBSL-NC	2,000	ng/L	—	D	—	D	D	D-eval
Volatile organic compounds										
Chloroform	Disinfection by-product	MCL[1]	80	µg/L	D-eval	D-eval	D-eval	D-eval	D-eval	D-eval
Bromodichloromethane	Disinfection by-product	MCL[1]	80	µg/L	D-eval	D	D	D-eval	D	D
Constituents of special interest										
Perchlorate	Natural, fertilizer, rocket fuel	HBSL-NC	15	µg/L	na	na	D-eval	D-eval	na	na

[1] EPA MCL for trihalomethanes is the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform.

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Inorganic constituents with benchmarks										
Aluminum	Naturally occurring	SMCL	200	µg/L	D	D	D	D	D	D
Aluminum	Naturally occurring	HBSL-NC	6,000	µg/L	D	D	D	D	D	D
Barium	Naturally occurring	MCL	2,000	µg/L	D	D	D	D	D	D
Beryllium	Naturally occurring	MCL	4	µg/L	D	D	D	D	D	D
Boron	Naturally occurring	HBSL-NC	6,000	µg/L	D	D	D	D	D	D
Cadmium	Naturally occurring	MCL	5	µg/L	D	D	D	D	D	D
Chromium	Naturally occurring	MCL	100	µg/L	D	D	D	D	D	D
Copper	Naturally occurring	MCL	1,300	µg/L	D	D	D	D	D	D
Gross beta-particle activity	Naturally occurring	MCL	50	pCi/L	D	D	D	D	D	D
Lead	Naturally occurring	MCL	15	µg/L	D	D	D	D	D	D
Nickel	Naturally occurring	HBSL-NC	100	µg/L	D	D	D	D	D	D
Nitrite, as nitrogen	Natural, fertilizer, sewage	MCL	1	mg/L	D	D	D	D	D	D
Silver	Naturally occurring	HBSL-NC	100	µg/L	D	D	D	—	D	—
Zinc	Naturally occurring	HBSL-NC	2,000	µg/L	D	D	D	D	D	D
Inorganic constituents with no benchmarks										
Ammonia, as nitrogen	Natural, fertilizer, sewage	None	None	mg/L	D	D	D	D	D	D
Bicarbonate	Naturally occurring	None	None	mg/L	D	D	D	D	D	D

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Bromide	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Calcium	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Carbonate	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Cobalt	Naturally occurring	None	None	µg/L	D	D	D	D	D	D
Dissolved organic carbon	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Lithium	Naturally occurring	None	None	µg/L	D	D	D	D	D	D
Magnesium	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Nitrogen, total	Natural, fertilizer, sewage	None	None	mg/L	D	D	D	D	D	D
Orthophosphate	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Potassium	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Silica	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Sodium	Naturally occurring	None	None	mg/L	D	D	D	D	D	D
Vanadium	Naturally occurring	None	None	µg/L	D	D	D	D	D	D
Organic constituents with benchmarks										
Bromodichloromethane (THM)	Disinfection by-product	MCL	80	µg/L	—	D	D	—	D	D
Bromoform (THM)	Disinfection by-product	MCL	80	µg/L	—	D	D	D	D	D
Dibromochloromethane (THM)	Disinfection by-product	MCL	80	µg/L	—	D	D	D	D	D
1,2-Dichloropropane (1,2-DCP)	Fumigant	MCL	5	µg/L	—	D	—	D	D	D
1,4-Dichlorobenzene	Fumigant	MCL	75	µg/L	—	D	—	—	D	D

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Bromomethane	Fumigant	HHBP-NC	140	µg/L	—	—	—	—	D	—
Metalaxyl	Fungicide	HHBP-NC	474,000	ng/L	—	D	—	—	—	—
Propiconazole	Fungicide	HHBP-NC	600,000	ng/L	—	D	—	—	—	—
1H-1,2,4-Triazole	Fungicide degradate	HHBP-NC	30,000	ng/L	—	—	—	D	—	—
Carbendazim	Fungicide degradate	HHBP-C	160,000	ng/L	—	—	—	—	D	—
2,4-Dichlorophenoxyacetic acid (2,4-D)	Herbicide	MCL	70,000	ng/L	—	D	—	—	D	—
Acetochlor	Herbicide	HHBP-NC	100,000	ng/L	—	—	D	—	—	—
Asulam	Herbicide	HHBP-NC	230,000	ng/L	—	—	—	D	—	—
Atrazine	Herbicide	MCL	3,000	ng/L	—	D	—	—	D	—
Bentazon	Herbicide	HBSL-NC	1,000,000	ng/L	—	—	—	—	—	D
Bromacil	Herbicide	HBSL-NC	100,000	ng/L	—	D	D	—	—	D
Chlorsulfuron	Herbicide	HHBP-NC	300,000	ng/L	—	—	—	—	—	D
Dimethenamid	Herbicide	HHBP-NC	300,000	ng/L	—	—	—	D	—	—
Diuron	Herbicide	HBSL-C	20,000	ng/L	—	D	—	D	D	D
Fluometuron	Herbicide	HBSL-C	40,000	ng/L	—	D	—	—	D	—
Hexazinone	Herbicide	HBSL-NC	300,000	ng/L	—	D	—	D	—	D
Imazaquin	Herbicide	HHBP-NC	1,600,000	ng/L	—	D	—	—	—	—
Imazethapyr	Herbicide	HHBP-NC	16,000,000	ng/L	—	D	—	—	—	—
Linuron	Herbicide	HHBP-NC	49,000	ng/L	—	D	—	—	—	—
Metolachlor	Herbicide	HBSL-NC	600,000	ng/L	—	D	—	D	—	—

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Nicosulfuron	Herbicide	HHBP-NC	8,000,000	ng/L	—	D	—	—	—	—
Norflurazon	Herbicide	HHBP-NC	96,000	ng/L	—	D	—	D	—	D
Pendimethalin	Herbicide	HHBP-NC	2,000,000	ng/L	—	—	—	D	—	—
Prometon	Herbicide	HBSL-NC	300,000	ng/L	—	D	D	D	—	—
Propazine	Herbicide	HBSL-NC	40,000	ng/L	—	D	—	—	—	D
Simazine	Herbicide	MCL	4,000	ng/L	—	D	D	D	—	D
Sulfentrazone	Herbicide	HHBP-NC	900,000	ng/L	—	—	—	—	—	D
Sulfometuron-methyl	Herbicide	HHBP-NC	1,760,000	ng/L	—	—	—	—	—	D
Sulfosulfuron	Herbicide	HHBP-NC	1,500,000	ng/L	—	D	—	—	—	—
Tebuthiuron	Herbicide	HBSL-NC	900,000	ng/L	—	—	—	D	D	D
Terbuthylazine	Herbicide	HBSL-NC	2,000	ng/L	—	D	—	—	—	—
Triclopyr	Herbicide	HHBP-NC	300,000	ng/L	—	—	—	—	D	—
2-Hydroxyatrazine (OIET)	Herbicide degradate	HHBP-NC	60,000	ng/L	—	—	—	D	—	D
Didealkylatrazine (CAAT)	Herbicide degradate	HHBP-NC	12,000	ng/L	D	D	—	—	D	—
Bifenthrin	Insecticide	HHBP-NC	70,000	ng/L	—	D	—	—	—	—
Carbaryl	Insecticide	HBSL-C	4,000,000	ng/L	D	—	—	—	—	—
Diflubenzuron	Insecticide	HHBP-NC	100,000	ng/L	—	D	—	—	—	—
Methoxyfenozide	Insecticide	HHBP-NC	600,000	ng/L	—	—	—	—	—	D
Pyridaben	Insecticide	HHBP-NC	30,000	ng/L	—	—	D	—	—	—

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

		Benchmarks			Principal aquifer					
Constituent	**Typical use or source**	**Type**	**Value**	**Units**	**Basin and Range carbonate-rock aquifers**	**Basin and Range basin-fill aquifers**	**Rio Grande aquifer system**	**High Plains aquifer**	**Colorado Plateaus aquifers**	**Columbia Plateau basaltic-rock aquifers**
Tebufenozide	Insecticide	HHBP-NC	120,000	ng/L	—	—	—	D	—	—
Desulfinylfipronil	Insecticide degradate	HBSL-NC	1,000	ng/L	—	—	D	—	—	—
Piperonyl butoxide	Pesticide synergist	HHBP-NC	992,000	ng/L	—	—	—	—	—	—
1,1,1-Trichloroethane (TCA)	Solvent	MCL	200	µg/L	—	—	D	—	D	—
1,1,2-Trichloroethane	Solvent	MCL	5	µg/L	—	—	—	—	D	—
1,2,4-Trichlorobenzene	Solvent	MCL	70	µg/L	—	—	—	—	D	—
1,2-Dichlorobenzene	Solvent	MCL	600	µg/L	—	D	—	D	D	—
1,2-Dichloroethane	Solvent	MCL	5	µg/L	—	—	—	—	D	—
1,1-Dichloroethane	Solvent	HBSL-NC	1,000	µg/L	—	D	—	—	D	—
1,4-Dioxane	Solvent	HBSL-C	30	µg/L	—	D	—	—	—	—
Carbon tetrachloride (tetrachloromethane)	Solvent	MCL	5	µg/L	—	—	—	D	D	D
Chlorobenzene	Solvent	MCL	100	µg/L	—	D	—	—	D	—
cis-1,2-Dichloroethylene	Solvent	MCL	70	µg/L	—	D	—	D	—	—
Dichloromethane (methylene chloride)	Solvent	MCL	5	µg/L	—	D	—	D	D	—
Tetrachloroethylene (PCE)	Solvent	MCL	5	µg/L	—	D	D	D	D	D
trans-1,2-Dichloroethylene	Solvent	MCL	100	µg/L	—	—	—	—	D	—
Trichloroethylene (TCE)	Solvent	MCL	5	µg/L	—	D	D	D	D	D
Isopropyl alcohol	Solvent	HBSL-NC	10,000	µg/L	—	D	D	D	D	D
1,1-Dichloroethylene	Solvent, organic synthesis	MCL	7	µg/L	—	—	—	D	D	—
Cyclohexanone	Solvent, organic synthesis	HBSL-NC	30,000	µg/L	—	—	—	D	D	—
Carbon disulfide	Natural, organic synthesis	HBSL-NC	600	µg/L	—	D	D	D	D	D

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Bromochloromethane	Organic synthesis, fire retardant	HBSL-NC	60	µg/L	—	—	—	—	D	—
1,2,3-Trichloropropane (1,2,3-TCP)	Organic synthesis, former fumigant	HBSL-NC	30	µg/L	—	D	—	—	—	D
1,2,4-Trimethylbenzene	Gasoline hydrocarbon	HBSL-NC	60	µg/L	—	D	D	D	—	D
Benzene	Gasoline hydrocarbon	MCL	5	µg/L	—	D	—	—	D	—
Ethylbenzene	Gasoline hydrocarbon	MCL	700	µg/L	—	—	—	D	—	—
m- and p-Xylene	Gasoline hydrocarbon	MCL	10,000	µg/L	—	—	—	D	—	—
o-Xylene	Gasoline hydrocarbon	MCL	10,000	µg/L	—	—	—	—	D	—
Toluene	Gasoline hydrocarbon	MCL	1,000	µg/L	—	D	—	D	D	D
Organic constituents with no benchmarks										
N-(3,4-Dichlorophenyl)-N’-methylurea (DCPMU)	Herbicide degradate	None	None	ng/L	—	D	—	D	D	—
4-Hydroxychlorothalonil	Fungicide degradate	None	None	ng/L	—	—	—	D	—	D
2-Isopropyl-6-methyl-4-pyrimidinol	Insecticide degradate	None	None	ng/L	—	D	—	D	D	—
Acetochlor oxanilic acid	Herbicide degradate	None	None	ng/L	—	—	—	D	—	—
Alachlor oxanilic acid	Herbicide degradate	None	None	ng/L	—	—	—	—	—	D
Deisopropylatrazine (CEAT)	Herbicide degradate	None	None	ng/L	—	D	D	D	—	—
Deethylatrazine (CIAT)	Herbicide degradate	None	None	ng/L	—	D	D	D	—	D
Dechlorometolachlor	Herbicide degradate	None	None	ng/L	—	—	—	D	—	—
Demethyl hexazinone B	Herbicide degradate	None	None	ng/L	—	D	—	D	—	—

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Demethyl norflurazon	Herbicide degradate	None	None	ng/L	—	—	—	—	—	D
Desamino metribuzin	Herbicide degradate	None	None	ng/L	—	—	—	—	—	D
Desamino-diketo metribuzin	Herbicide degradate	None	None	ng/L	—	—	—	—	—	D
Desulfinylfipronil amide	Insecticide degradate	None	None	ng/L	—	—	D	—	—	—
Didemethyl hexazinone F	Herbicide degradate	None	None	ng/L	—	—	D	—	—	—
Diketonitrile-isoxaflutole	Herbicide degradate	None	None	ng/L	—	—	D	—	—	—
Dimethenamid sulfonic acid	Herbicide degradate	None	None	ng/L	—	—	—	D	—	—
Dimethenamid sulfinylacetic acid	Herbicide degradate	None	None	ng/L	—	D	D	—	—	—
Disulfoton sulfone	Insecticide degradate	None	None	ng/L	—	D	—	—	—	—
Demethyl fluometuron (DMFM)	Herbicide degradate	None	None	ng/L	—	D	—	D	—	—
Fenamiphos sulfone	Insecticide degradate	None	None	ng/L	—	—	—	—	D	—
Fipronil amide	Insecticide degradate	None	None	ng/L	—	—	—	D	—	—
2-(1-Hydroxyethyl)-6-methylaniline	Herbicide degradate	None	None	ng/L	—	D	—	—	—	—
Hydroxyacetochlor	Herbicide degradate	None	None	ng/L	—	—	—	D	—	—
Hydroxyalachlor	Herbicide degradate	None	None	ng/L	—	—	—	D	—	—
Hydroxy monodemethyl fluometuron	Herbicide degradate	None	None	ng/L	—	—	D	—	—	—
Hydroxymetolachlor	Herbicide degradate	None	None	ng/L	—	D	—	D	—	—
Metolachlor oxanilic acid	Herbicide degradate	None	None	ng/L	—	—	—	D	—	—

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Metolachlor sulfonic acid	Herbicide degradate	None	None	ng/L	—	—	D	D	D	D
Deethylhydroxyatrazine (OIAT)	Herbicide degradate	None	None	ng/L	—	D	—	D	—	D
Tebuthiuron Transformation Product 109	Herbicide degradate	None	None	ng/L	—	—	D	—	—	—
Alachlor sulfonic acid	Herbicide degradate	None	None	ng/L	—	—	—	D	—	D
Chloromethane (Methylchloride)	Solvent, organic synthesis	None	None	µg/L	—	—	—	—	D	—
Chlorodifluoromethane (HCFC-22)	Refrigerant and propellant	None	None	µg/L	—	D	—	D	—	D
Acetonitrile	Solvent, organic synthesis	None	None	µg/L	—	D	—	—	D	—
tert-Butyl alcohol (TBA)	Gasoline oxygenate and degradate	None	None	µg/L	—	D	D	D	D	—
n-Pentanal	Flavoring agent	None	None	µg/L	—	—	—	—	D	—
Chloropicrin	Fumigant	None	None	µg/L	—	—	—	D	—	—
Methyl *tert*-butyl ether (MTBE)	Gasoline oxygenate and degradate	None	None	µg/L	—	D	—	D	D	D
1,1-Dichloro-2-propanone	Disinfection by-product	None	None	µg/L	—	—	—	—	D	—
Butane	Fuel, refrigerant and propellant	None	None	µg/L	—	D	—	—	D	—
Dimethoxymethane	Solvent, organic synthesis	None	None	µg/L	—	D	—	D	—	—

Table 3. Constituents detected in samples but not selected for the *status assessment* in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.—Continued

[Detected constituents were not selected for understanding assessment if they had no benchmarks, or for inorganic constituents if the maximum concentration measured was less than 0.5 times benchmark concentration, or for organic constituent if the detection frequecy at any concentration was less than 10 percent and (or) maximum concentration measured was less than 0.1 times benchmark concentration. **Benchmark type**: *Regulatory, health-based benchmark*: MCL, USEPA maximum contaminant level; *Non-regulatory health-based benchmarks*: HBSL-NC, USGS noncancer health-based screening level; HBSL-C, USGS cancer health-based screeing level, HHBP-NC, USEPA Chronic noncancer human health benchmarks for pesticides; *Non-regulatory, aesthetic-based benchmarks*: SMCL, USEPA secondary maximum contaminant level. **Benchmark units**: µg/L, microgram per liter; pCi/L picocurie per liter; mg/L, milligram per liter; ng/L, nanograms per liter. **Abbreviations**: D, detected but not selected for understanding assessment; —, not detected]

Constituent	Typical use or source	Benchmarks			Principal aquifer					
		Type	Value	Units	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Hexane	Solvent	None	None	µg/L	—	—	—	—	D	—
n-Pentane	Blowing agent, solvent	None	None	µg/L	—	D	—	D	D	D
1-Chloro-1,1-difluoroethane	Refrigerant and propellant	None	None	µg/L	—	—	—	—	D	—

Statistical Tests of Correlation

Because water-quality data generally are not normally distributed (Helsel and Hirsch, 2002), nonparametric statistical methods were used to identify significant correlations. For all results discussed in this report, the significance level (p) was compared to an alpha (α) value of 0.05 to determine if a relation was statistically significant (p<α); p values below 0.05 are considered significant and only those correlations are reported herein. Explanatory factors considered included categorical (for example, groundwater age category) and discrete variables (for example, depth to bottom of well perforation, pH, aridity index). In this report, we define discrete variables from the perspective of sample collection, that is, the value used for the statistical test sample was collected at a discrete time (or depth) rather than the statistical perspective that defines these types of measurements as continuous for the respective statistical testing methods applied. The two nonparametric statistical tests used for the categorical and discrete samples were:

- Spearman's rho, which was used to evaluate correlations between discrete variables. The rank-order coefficient, ρ (rho), was reported if correlations were statistically significant.
- The Kruskal-Wallace test and the Wilcoxon rank-sum test were used to detect differences among groups of data. The Wilcoxon-rank sum is equivalent to the Kruskal-Wallace when there are only two groups of data. The null hypothesis for both tests is that the median values of the continuous variables grouped by the categorical variables are not different from one another. If a Kruskal-Wallace test indicated statistical significance among groups, the nonparametric Tukey's test was used to determine the ordering of groups. Consistent with the nonparametric approach, the Tukey's test was performed based on ranks; results are based on the group means of ranks.

Potential Explanatory Factors

Potential explanatory factors (depth to bottom of well perforation, groundwater age category, land use, aquifer lithology, hydrologic conditions, and geochemical conditions) assigned to wells or springs in each of the six PAs are described in this section. Significant correlations among these explanatory factors that might affect relations with water-quality constituents also are described. As noted in the previous section, potential explanatory factors are either categorical (groundwater age category) or discrete, where a value is assigned for each groundwater sample or sample site (depth to bottom of well perforation, land use, hydrologic conditions, and geochemical conditions). Aquifer lithology, although a categorical variable, is assumed to be consistent for all sites in a PA.

Depth to Bottom of Well Perforation

Available construction information for sampled wells generally included depth to bottom of well perforation (that is, well screen opening). For instances where the depth to bottom of well perforation was not available, well depth was substituted. Median well-bottom perforation depths for the six PAs ranged from 248 feet below land surface (ft bls) for the High Plains aquifer to 595 ft bls for the Rio Grande aquifer system (fig. 10). Well-bottom perforation depths for the High Plains aquifer were notably shallower than the other PAs and primarily reflected the depth of the Ogallala Formation, a near-surface geologic unit that composes a large part of the High Plains aquifer. Median well-bottom perforation depths also are relatively deep (more than 500 ft bls in the Basin and Range carbonate-rock aquifers, Basin and Range basin-fill aquifers, and Colorado Plateaus aquifers).

Groundwater Age Category

Groundwater age refers to the residence time of groundwater in an aquifer, measured as the time elapsed since the water was in contact with the atmosphere and recharged the aquifer. Groundwater samples were classified as *modern*, *premodern*, or *mixed* based on measured ^{3}H concentrations (Lyndsey and others, 2019). Atmospheric concentrations of ^{3}H increased sharply above natural background levels from above-ground nuclear weapon testing in the middle part of the 20th century. Groundwater age categories were based on curves of ^{3}H in local precipitation (Michel and others, 2018) for samples predominantly recharged after 1953 (*modern*), prior to 1953 (*premodern*), or a mixture of modern and premodern groundwater (*mixed*). Available groundwater age categories for the six western PAs are detailed in table 4 and figure 11 (relative to available depth to bottom of well perforation).

Deeper wells in the western PAs generally are associated with older, premodern groundwater (fig. 11). The Basin and Range basin-fill aquifers, Rio Grande aquifer system, and Colorado Plateaus aquifers had the largest proportions (greater than 50 percent) of wells classified as premodern (table 4). Groundwater wells classified as mixed were highest in the Columbia Plateau basaltic-rock aquifers (50 percent) and the High Plains aquifer (39 percent). Groundwater wells classified as modern were associated with the shallowest depths to bottom of well perforation for all PAs (and included all spring samples from the Basin and Range carbonate-rock aquifers). Although springs sampled in the Basin and Range carbonate-rock aquifers have an assigned depth of zero for the bottom of well perforation (fig. 3), this might not adequately reflect complexities of the carbonate rocks where water is transmitted along faults and fractures.

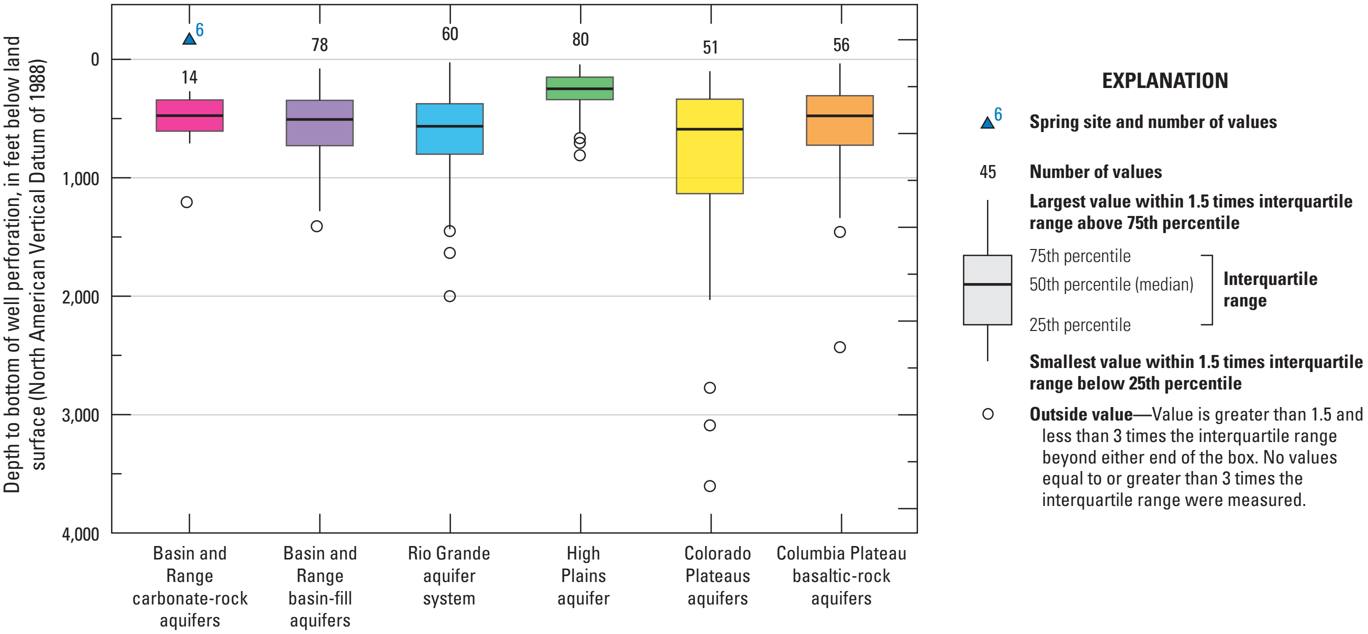


Figure 10. Depth to bottom of well perforation by principal aquifer in wells sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Table 4. Groundwater age category by principal aquifer in wells and springs sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Principal aquifer	Number of sample sites in network[1]	Number of samples with age category[1]	Groundwater age category					
			Number			Percent		
			Modern	Mixed	Premodern	Modern	Mixed	Premodern
Basin and Range carbonate-rock aquifers	20	19	9	3	7	47	16	37
Basin and Range basin-fill aquifers	78	77	16	21	40	21	27	52
Rio Grande aquifer system	60	60	13	8	39	22	13	65
High Plains aquifer	80	80	21	31	28	26	39	35
Colorado Plateaus aquifers	60	58	16	11	31	28	19	53
Columbia Plateau basaltic-rock aquifers	60	60	8	30	22	13	50	37

[1] Differences between number of samples in network and those with an age category assigned reflect samples for which tritium was not sampled for or analyzed.

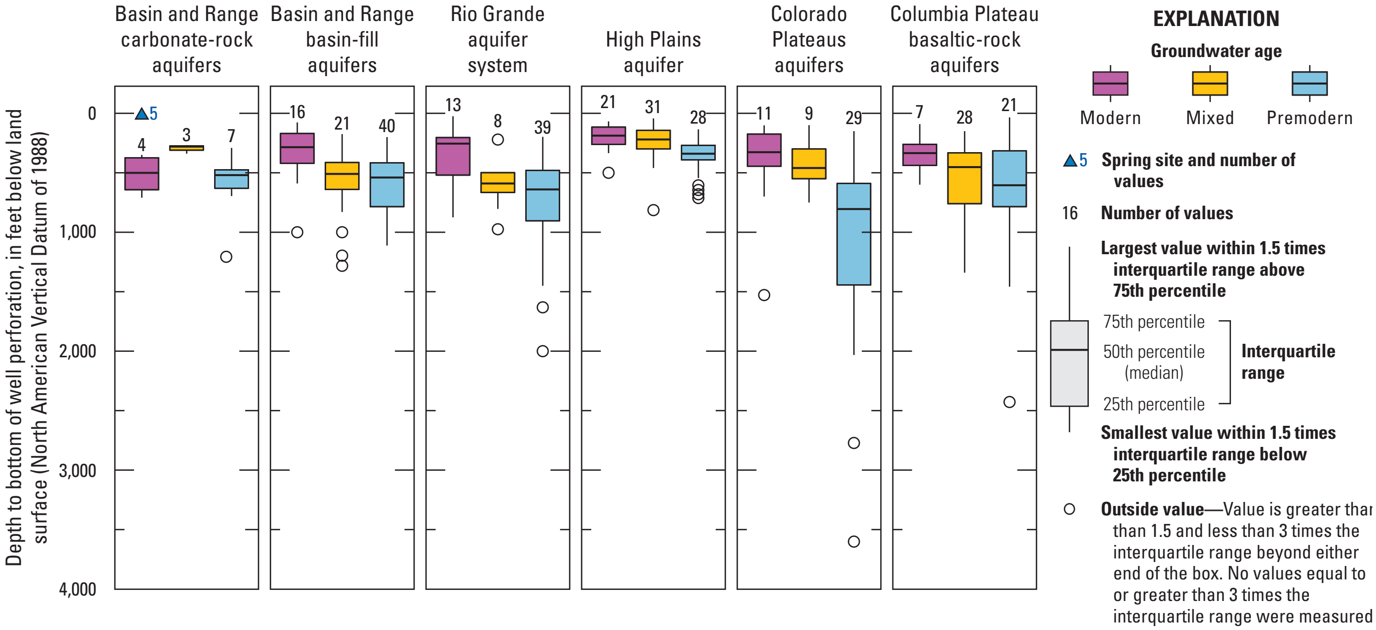


Figure 11. Depth to bottom of well perforation by available groundwater age category for six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Land Use

Land use was quantified as the percentage of three land covers—natural, urban, and agricultural—calculated for areas (1) within a radius of 500 m (500-m buffer) around each sample site for each PA (fig. 12*A*) and (2) within the extent of each PA boundary (fig. 12*B*). Land-use values are based on the conterminous U.S. wall-to-wall anthropogenic land-use trends (NWALT), 1974–2012 (Falcone, 2015) and might differ slightly from other PA summaries (for example, Arnold and others, 2016, 2017, 2018, 2020). NWALT classifications were grouped into natural (water, low use, very low use, and natural resource-production classes that included mining/extraction and timber and forest activities), urban (developed and semi-developed), and agricultural (production of crops, pasture/hay, and grazing potential) categories. The fourth land-use category, mixed, was assigned to sites where there was not a dominant category (that is, land-use percentages within the 500-m buffer were less than 50 percent for each of the natural, urban, or agricultural categories).

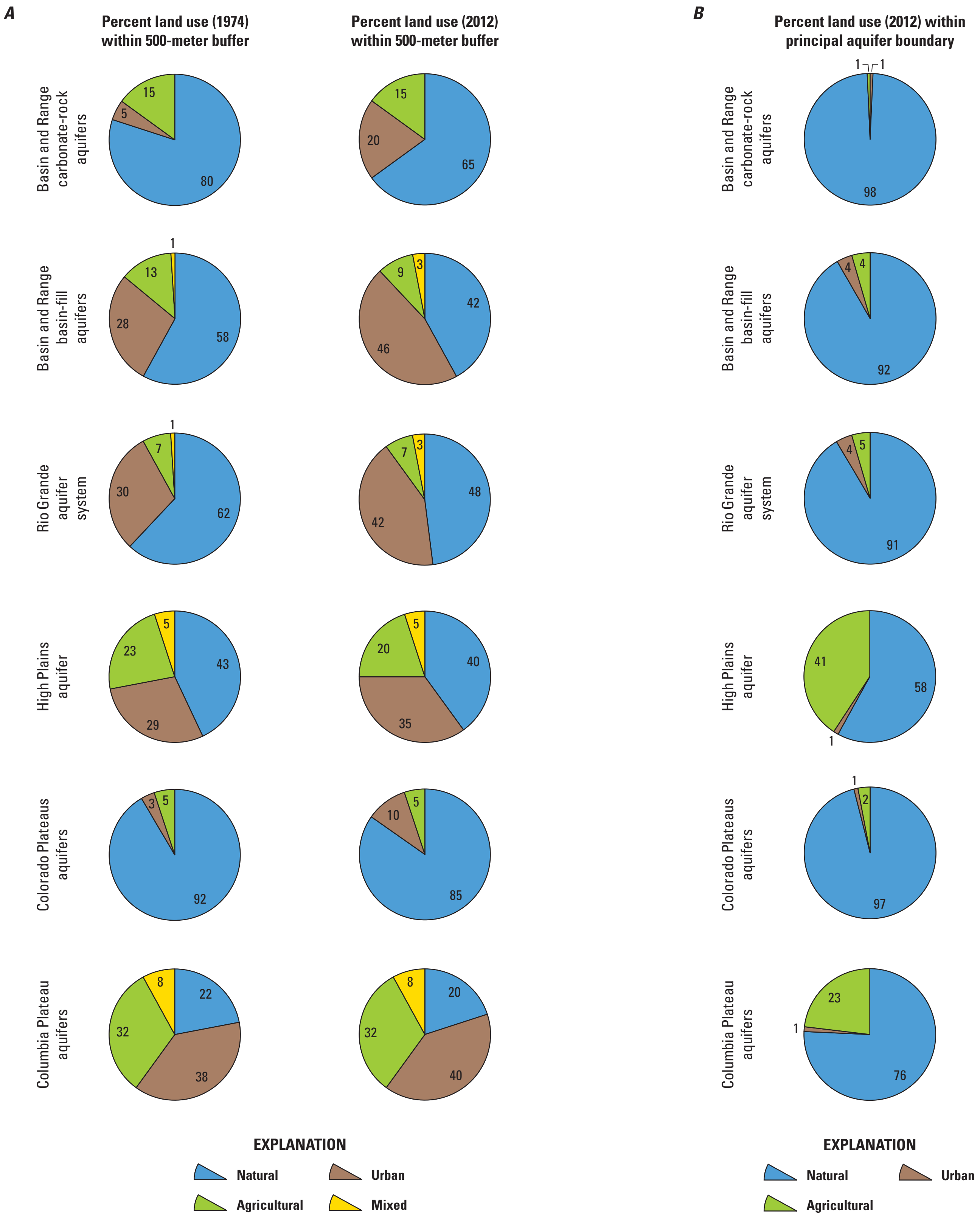


Figure 12. *A,* Comparison of the 1974 percentage of land use to the 2012 percentage of land use calculated within the 500-m buffer around sampled wells and springs; and *B*, the 2012 percentage of land use calculated within the principal aquifer boundary of six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017. Note that the boundary for the Columbia Plateau aquifer system includes the area of the Columbia Plateau basaltic-rock aquifers and the Columbia Plateau basin-fill aquifers.

Available land-use data from 1974 and 2012 indicated that some land-use changes occurred during this period (fig. 12), with an overall decrease in natural land use accompanied by an increase in urban land use. Decreases in natural land use within the 500-m buffer ranged from 16 percent in the Basin and Range basin-fill aquifers to 2 percent in the Columbia Plateau basaltic-rock aquifers. Corresponding increases in urban land use ranged from 18 percent in the Basin and Range basin-fill aquifer to 2 percent in the Columbia Plateau basaltic-rock aquifers. Agricultural land use within the 500-m buffer during the about 40-year period remained unchanged in most PAs, with less than a 5 percent decrease in two PAs, the Basin and Range basin-fill aquifers and the High Plains aquifer.

There are notable differences between the 2012 land use within the 500-m buffer zone (fig. 12*A*) and the overall land use for each PA (fig. 12*B*). Urban land use was consistently higher for the 500-m buffer zone estimation, which likely reflects the spatial distribution of PSWs in populated areas, resulting in a bias toward urban land use. Urban land use for each PA overall generally was low, with the highest value (4 percent) occurring in the Basin and Range basin-fill aquifers and the Rio Grande aquifer system. Agricultural land use was highest for the High Plains aquifer (41 percent) and Columbia Plateau basaltic-rock aquifers (23 percent) and was 4 percent or less in the other PAs. For the understanding assessment, only land use within the 500-m buffer zone was considered as a potential explanatory factor.

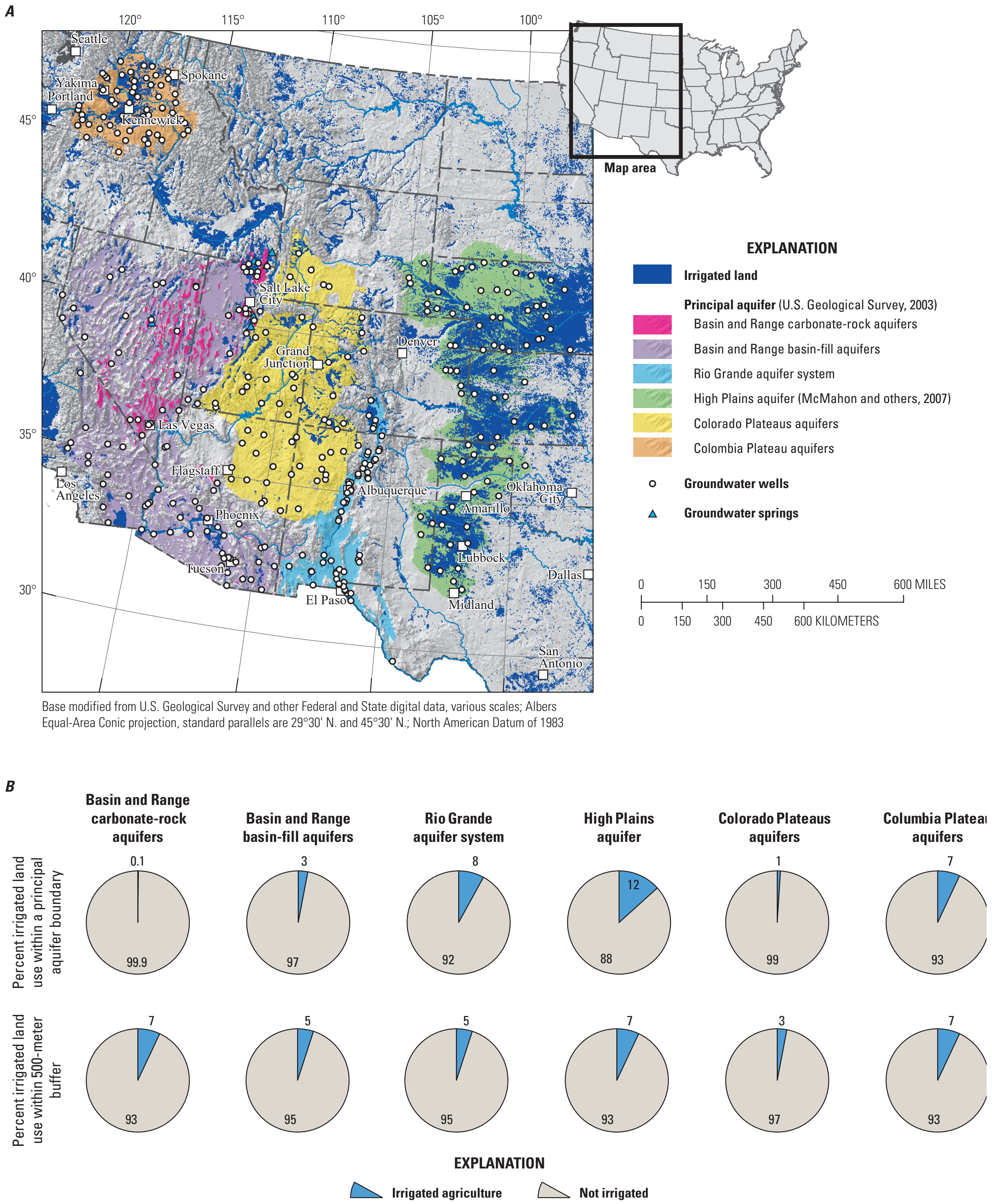
Irrigated land use, associated with irrigated agriculture, also was considered as a potential explanatory factor. The Moderate Resolution Imaging Spectrodiometer (MODIS) Irrigated Agriculture Dataset for the United States (MIrAD-US; U.S. Geological Survey, 2014) was used to quantify the percentage of irrigated land for (1) individual 500-m well buffer zones and (2) the extent of each PA (fig. 13*A*). Differences in the proportion of irrigated land use between the 500-m buffer zone and the overall land use for each PA likely reflect the bias of PSWs generally being in populated (that is, urban land-use) areas (fig. 13*B*). For example, the High Plains aquifer had the largest percentage of irrigated land use by PA (12 percent), whereas the estimate for the 500-m buffer zone was only 7 percent. For the understanding assessment, only irrigated land use for the 500-m well buffer zone was considered as a potential explanatory factor.

Aquifer Lithology

The six western PAs are composed of four defined lithology classes (U.S. Geological Survey, 2003): carbonate rock, unconsolidated to semiconsolidated sand and gravel, sandstone, and igneous and metamorphic rock (table 1; fig. 2*B*). Groundwater samples were dominantly collected from unconsolidated sand and gravel (61 percent), with less from sandstone (17 percent), igneous and metamorphic rocks (16 percent), and carbonate rocks (6 percent, including the six spring samples).

Hydrologic Conditions

Hydrologic conditions were represented by two potential explanatory factors: the land-surface elevation of each sample site and a calculated aridity index (fig. 14*A*). Land-surface elevation (elevation) is considered a proxy for the relative hydrologic position within a PA flow system, with higher elevation generally associated with distal boundaries of a flow system. The aridity index is calculated by dividing average annual evapotranspiration by average annual precipitation; values were extracted for each sample site from the Consortium for Spatial Information Global Aridity Index dataset (Trabucco and Zomer, 2019). The aridity index is considered an indicator of climate and was grouped into climate classes (arid, semiarid, dry subhumid, and humid, fig. 14*B*) using the generalized classification scheme for global-aridity values (United Nations Environment Programme, 1997). Differences in the climate classifications can be attributed to well elevation, variations in north-to-south trending regional evapotranspiration rates, and west-to-east trending precipitation rates. For example, samples from the Columbia Plateau basaltic-rock aquifers followed a general trend of increasing aridity index (from arid to humid) with increasing elevation, except for two wells. These two wells are along the westernmost edge of the PA and coincide with the western slopes of the Pacific Northwest Cascade Range; this area likely receives relatively high precipitation compared to the central and eastern parts of the PA. Sample sites for the three PAs in the Basin and Range Province (fig. 2*A*)—the Basin and Range carbonate-rock and basin-fill aquifers and the Rio Grande aquifer system—are semiarid to arid with aridity generally increasing from the northeast to southwest (fig. 14*B*). In the High Plains aquifer, aridity generally decreases from west to east, from semiarid to dry subhumid, consistent with a west to east increase in mean annual precipitation from about 12 to 33 inches (McMahon and others, 2007). The climate of the High Plains aquifer is unique among the studied PAs in that it does not follow the generalized association of higher precipitation occurring at higher land-surface elevation or latitude. Elevation across the High Plains aquifer generally decreases from west to east from about 8,000 ft at the northwest boundary to about 1,000 ft at the eastern boundary (McMahon and others, 2007); this elevation gradient results in the highest amounts of precipitation falling on the lower elevations of the PA. The climate of the Colorado Plateaus aquifers generally is arid to semiarid, with dry subhumid conditions on the eastern and western boundaries (fig. 14*B*).



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

Figure 13. *A,* Irrigated land use for six western U.S. principal aquifers; and *B,* comparison of the 2012 percentage of irrigated land use calculated within the 500-m buffer around sampled wells and springs and within the principal aquifer boundary.

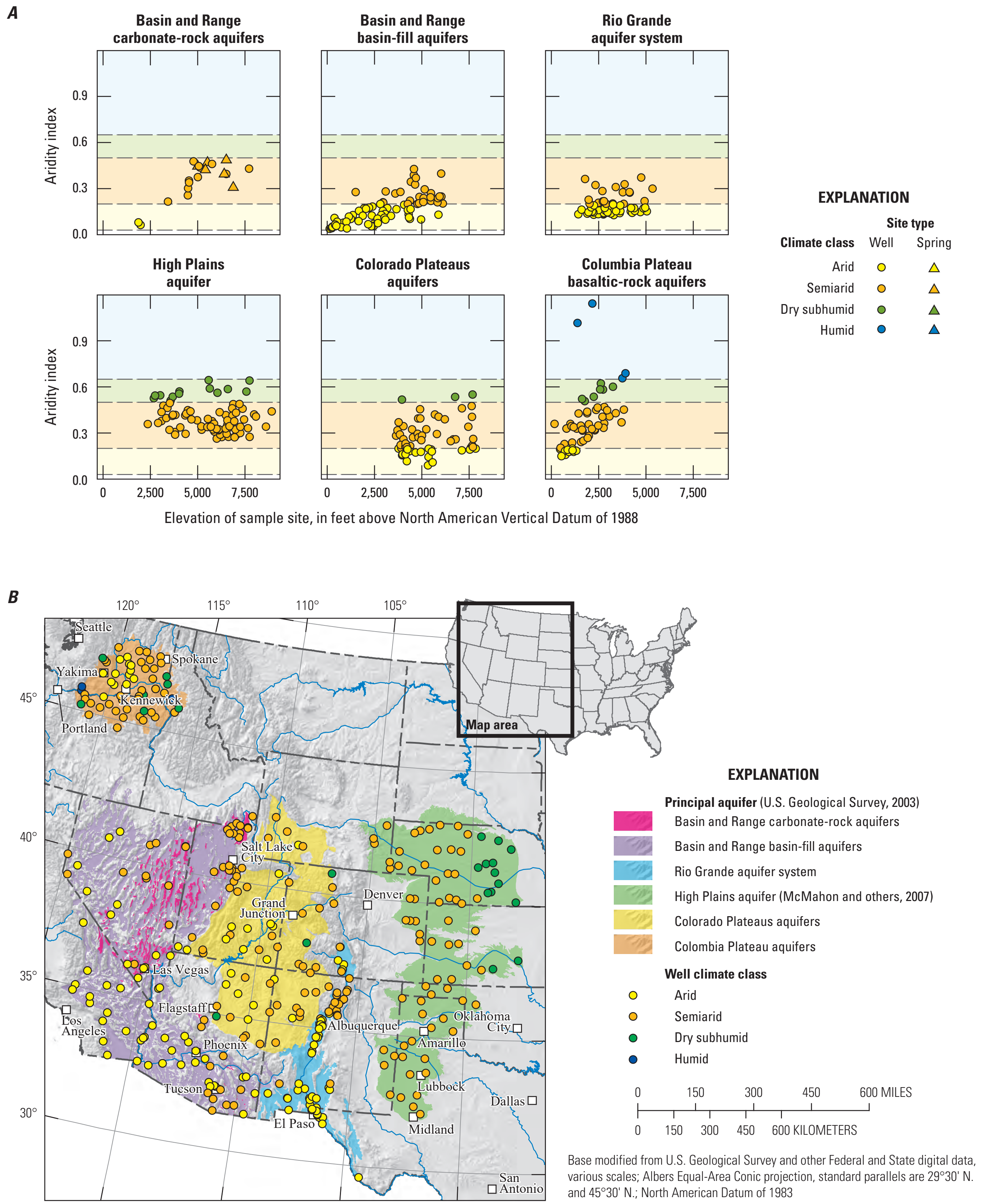


Figure 14. *A,* Relations between elevation and aridity index at well and spring sites; and *B,* regional climate class values mapped for six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Geochemical Conditions

Geochemical conditions in groundwater result from a broad combination of influences: flow through an aquifer and reaction with surrounding minerals, soil, and bedrock; groundwater age, land use, aquifer lithology, and hydrologic conditions. Geochemical conditions can strongly affect the mobility and occurrence of many constituents, including those with human-health benchmarks. Knowledge of geochemical conditions in an aquifer can provide insight into concentrations of constituents. Several expressions of geochemical conditions were considered as potential explanatory factors: oxidation-reduction (redox), pH, bicarbonate (HCO_3) concentration, and total dissolved solids (TDS) concentration.

Groundwater redox and pH are often primary controls on contaminant fate in an aquifer, affecting the degree of natural attenuation through chemical transformation or sorption (Appelo and Postma, 1999; McMahon and Chapelle, 2008; McMahon and others, 2009). Redox conditions were assessed based on the concentration of dissolved oxygen: A concentration greater than or equal to 0.5 milligrams per liter (mg/L) was considered oxic and a concentration less than 0.5 mg/L was considered anoxic. Oxic groundwater conditions were prevalent across all PAs (81 percent of samples), regardless of well depth (fig. 15*A*). Groundwater pH is affected by the rates and types of rock weathering processes, which can vary across aquifer lithologies (DeSimone and others, 2015). Values of pH ranged from 6.2 to 9.8 (fig. 15*B*). The Colorado Plateaus aquifers had the largest range of pH values (6.2–9.8), whereas the Basin and Range carbonate-rock aquifers had the smallest range (6.7–7.6). Some samples in most of the PAs had relatively high pH values (greater than 8.5), excluding the Basin and Range carbonate-rock aquifers. The narrow range in the Basin and Range carbonate-rock aquifers likely reflects the carbonate-rock lithology, which buffers pH, resulting in near-neutral conditions. Relatively low pH values (less than 6.5) were measured in only two PAs, the Basin and Range basin-fill aquifers and the Colorado Plateaus aquifers. Values of pH have a recommended (SMCL) range of 6.5 to 8.5 (U.S Environmental Protection Agency, 2018b).

Alkalinity is a measure of the capacity of water to neutralize acid. In most groundwater, alkalinity is dominantly produced by concentrations of carbon dioxide species, carbonate (CO_3) and HCO_3 and is specifically dominated by HCO_3 at the measured pH range in western PAs (Hem, 1985). Bicarbonate concentration, as a measure of alkalinity, is considered herein as a potential explanatory factor. There is no benchmark for alkalinity or HCO_3 (table 3). Bicarbonate concentrations for the six western PAs are considered relative to calcium concentrations and pH and categorized by groundwater age (fig. 16). Variations in groundwater alkalinity and HCO_3 are often related to weathering reactions and changes in pH. Groundwater in carbonate-rock lithologies and unconsolidated aquifers with carbonate sediments typically have near-neutral pH or alkaline conditions (pH greater than 7) because of the buffering capacity of carbonate minerals (DeSimone and others, 2015). The weathering of silicate minerals, a major component in source rock of the unconsolidated sand and gravel aquifers in western U.S., also consumes acidity, but silicate weathering occurs much slower than carbonate dissolution (DeSimone and others, 2015); as a result, groundwater in unconsolidated sand and gravel or volcanic-rock lithologies in the western United States with long residence times (that is, a premodern age category) tends to be alkaline.

Total dissolved solids, which is a measure of groundwater salinity, also was considered as a potential explanatory factor because of (1) its prevalence at elevated concentrations in the PAs of the arid west (Dennehy and others, 2007; Thiros and others, 2010; Bexfield and others, 2011; DeSimone and others, 2015) and (2) numerous mechanisms that can result in elevated TDS concentrations in groundwater. All groundwater naturally contains dissolved constituents resulting from the weathering and dissolution of minerals in rocks and sediments. Concentrations of TDS can be high because of natural factors or because of human activities. Natural sources of elevated TDS include mineral dissolution and evaporative concentration in shallow groundwater, or alternatively can result from prolonged water-rock interaction in old groundwater. Human activities, such as applications to the land surface of road salt, fertilizers, or other chemicals in urban and agricultural areas can result in elevated TDS concentrations (Hem, 1985). Human alteration of groundwater flow systems and irrigation water are two factors that contribute to elevated TDS concentrations (Anning and others, 2007; Bexfield and others, 2011; DeSimone and others, 2015). Irrigation water in arid climates has the potential to evaporate, thereby increasing salinity; dissolved salts in irrigation water are left behind when water evaporates or is taken up by plants, and percolation of excess irrigation water to the water tables carries these salts to groundwater (DeSimone and others, 2015). Correlation between TDS and other potential explanatory factors can provide insight into factors contributing to relative high TDS at the PA scale.

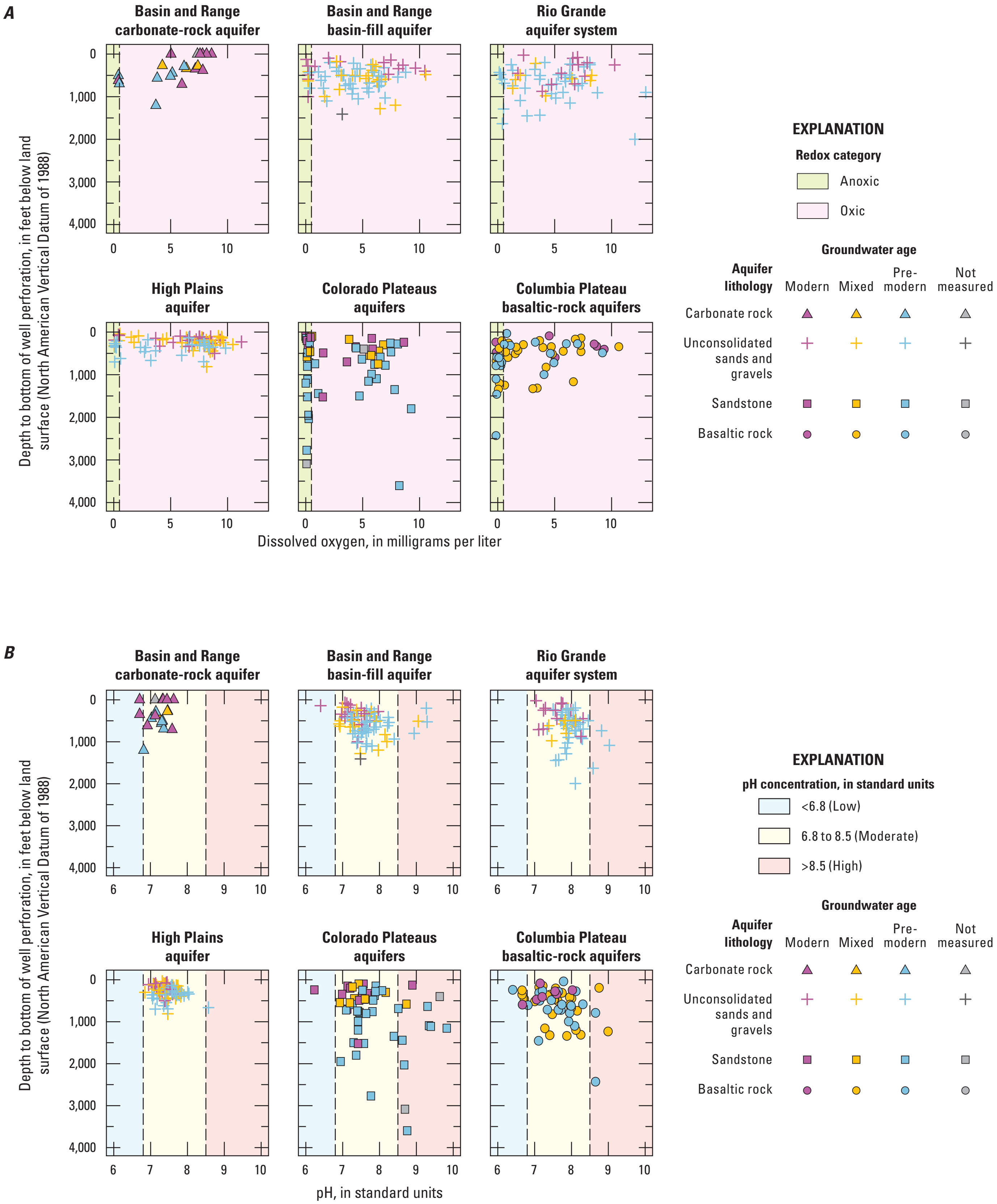


Figure 15. Relations for six western U.S. principal aquifers of *A,* dissolved oxygen concentration with depth to bottom of well perforation and aquifer lithology; and *B,* pH values with depth to bottom of well perforation and aquifer lithology sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

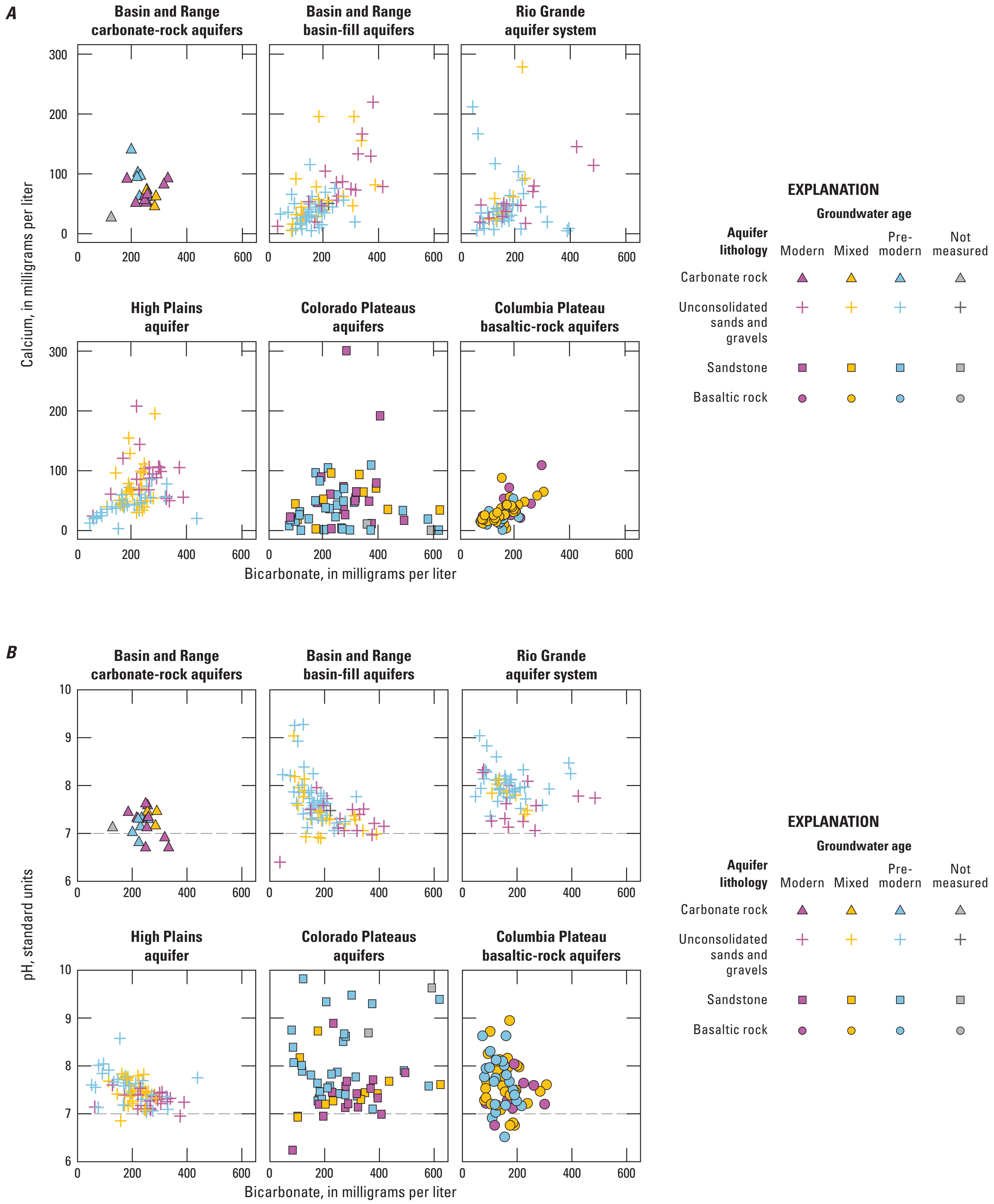


Figure 16. Relations for six western U.S. principal aquifers of bicarbonate concentration with *A,* calcium concentration, aquifer lithology and groundwater age category; and *B,* pH, aquifer lithology, and groundwater age category in springs and wells sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

The SMCL for TDS is 500 mg/L (U.S Environmental Protection Agency, 2018b). Concentrations above 1,500 to 2,600 mg/L can be problematic for irrigation of crops with low median salt tolerance (Ayers and Westcott, 1994; Maas and Grattan, 1999; Grieve and others, 2012). High TDS (exceeding the SMCL) results were relatively common in western PAs, with most exceedances being in PAs with unconsolidated sand and gravel or sandstone lithologies (figs. 2*B*, 17). High aquifer-scale proportions occurred in about a third of samples from the Basin and Range basin-fill aquifers (32 percent), the Rio Grande aquifer system (35 percent), and the Colorado Plateaus aquifers (37 percent); about a quarter of samples from the High Plains aquifer (26 percent) and the Basin and Range carbonate-rock quarter (25 percent) also had high aquifer-scale proporitons (tables 9*A*–*E*). Concentrations of TDS above the 500 mg/L SMCL benchmark were generally observed at shallower depths (that is, depth to bottom of well perforation) in the Basin and Range basin-fill, Rio Grande, and High Plains aquifers (fig. 17).

Correlation Between Potential Explanatory Factors

The interpretation of explanatory factors and their correlation with water-quality constituents might be affected by correlation between potential explanatory factors. Correlations between potential explanatory factors and groundwater age category are presented for each PA in table 5. Correlations between other potential explanatory factors for each of the six PAs are presented in tables 6*A*–*F*, respectively. Aquifer lithology, which is defined for each PA rather than each sample (table 1; fig. 2*B*), is not included in this comparison of potential explanatory factors. Relations between aquifer lithology and other potential explanatory factors are briefly discussed here where applicable and detailed subsequently when evaluating individual constituents or constituent groups.

There were numerous differences among groundwater age categories with potential explanatory factors (table 5). In some PAs, these differences were systematic with significant differences among the three groundwater age categories. For example, in the High Plains aquifer, all three age-category groups were significantly different with respect to depth to the bottom of well perforation and the median values for depth to bottom of well perforation increased from modern, to mixed, to premodern. This relation is consistent with the general observation that groundwater age (as measured by the groundwater age categories modern, mixed and premodern) tended to increase with increasing depth to bottom of well perforation (fig. 11). In other PAs, differences between groundwater age and explanatory factors were causative. Premodern groundwater age generally was associated with higher pH values (table 5) and might reflect the weathering of silicate minerals over long groundwater residence times in several PAs (the Basin and Range basin-fill aquifers, Rio Grande aquifer system, High Plains aquifer, and the Colorado Plateaus aquifers), for example. Differences of TDS with groundwater age also can be explained by causative associations. Higher TDS concentrations were associated with modern groundwater in the High Plains aquifer and the Columbia Plateau basaltic-rock aquifers system (table 5); this relation might reflect irrigated land use and the large amounts of agriculture associated with these PAs, where agricultural land use and irrigated land use were both relatively high (table 1). Relatively high TDS values were associated with premodern groundwater in the Basin and Range carbonate-rock aquifers (table 5; fig. 17), perhaps reflecting longer residence time allowing for dissolution of carbonate minerals.

Non-causative differences between groundwater age and percent land use occurred in the Basin and Range basin-fill aquifers and the Rio Grande aquifer system (table 5). For example, in the Basin and Range basin-fill aquifers, correlations of percent agricultural land use with modern groundwater might result from modern recharge occurring at shallower depths and subsequent movement into deeper parts of the aquifer used for water supply. Recharge in the basin-fill aquifers generally occurs along mountain fronts through infiltration of mountain stream runoff and inflow from fractured rock (Robson and Banta, 1995), and groundwater withdrawals from deep wells in the basin-fill aquifers have enhanced the movement of groundwater from shallower to deeper parts of the aquifers (Bexfield and others, 2011). Additionally, in the Rio Grande aquifer system, urban land use is correlated with premodern groundwater age (table 5) and depth to bottom of well perforation (table 6*C*); PSWs commonly located in urban areas access deeper and older groundwater.

Significant correlations between hydrologic conditions and geochemical conditions varied across the PAs and generally are attributed to causative associations (tables 6*A*–*F*). For example, relations between agricultural land use and irrigated land use in the High Plains aquifer are positive; the corresponding relations between natural land use and agricultural and irrigated land are negative (table 6*D*). The aridity index and sample site elevation were positively correlated in all the PAs except for the High Plains aquifer (tables 6*A*–*F*). The aridity index typically increases with elevation and latitude because of increasing precipitation; however, in the High Plains aquifer (table 6*D*), a negative correlation reflects the west to east decrease in elevation and increase in precipitation for the High Plains Province (McMahon and others, 2007). Positive correlations between dissolved oxygen, well elevation, and the aridity index in the Basin and Range basin-fill aquifers (table 6*B*) likely reflect recent recharge near the proximal boundary of basins where redox reactions have not consumed dissolved oxygen.

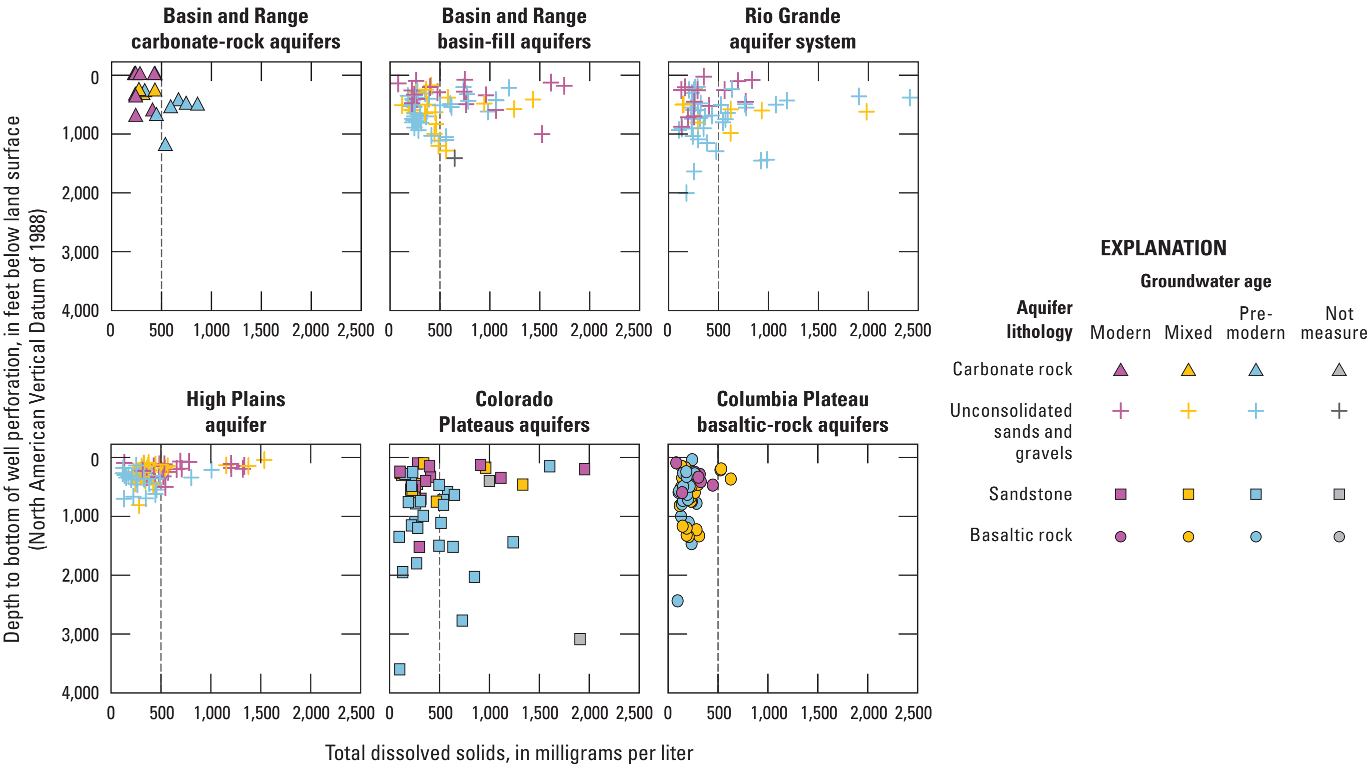


Figure 17. Relations for six western U.S. principal aquifers of total dissolved solids with depth to bottom of well perforation, aquifer lithology, and groundwater age category in springs and wells sampled with the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Causative relations also likely account for inverse correlations between pH and the aridity index in PAs with unconsolidated sand and gravel aquifers (tables 6*B*–*D*) or sandstone lithologies (table 6*E*). Recent recharge to groundwater in more arid areas (with a higher aridity index) generally has lower pH values resulting from low pH of rainfall controlled by equilibrium between atmospheric carbon dioxide and carbonic acid, as well as limited time for hydrolysis reactions to occur with silicate minerals in the aquifer lithology. A similar explanation might account for inverse correlations between TDS and the aridity index and well elevation observed in PAs with unconsolidated sand and gravel (tables 6*B*–*D*) or igneous and metamorphic-rock lithologies (table 6*F*). Groundwater recharge from rainfall at relatively high elevations and high aridity index values likely is dilute with limited weathering and dissolution reactions having occurred, resulting in lower TDS concentrations. Many other complex patterns of correlation between aquifer lithology, land use, hydrologic conditions, or geochemical conditions are evident in correlations between potential explanatory factors (tables 6*A*–*F*). Selected examples are discussed in subsequent sections that address individual constituents or constituent groups.

Relations between potential explanatory factors also could be related to specific groundwater processes. Oxic groundwater conditions were prevalent in all PAs (fig. 15*A*). Dissolved oxygen concentrations generally decreased with well depth, except for the Basin and Range carbonate-rock aquifers, Rio Grande aquifer system, and Columbia Plateau basaltic-rock aquifers as demonstrated by inverse correlation with depth to bottom of well perforation (tables 6*A, C, F*). Redox reactions likely consume dissolved oxygen along flow paths associated with deeper and older groundwater. Differences among groundwater age categories generally were not significant for dissolved oxygen, except in the Basin and Range carbonate-rock aquifers (table 5; fig. 15*A*).

Table 5. Results of Kruskal-Wallis and Wilcoxon rank-sum test by principal aquifer for differences in values of selected potential explanatory factors among groundwater age categories in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[Only significant differences between groundwater age categories and the discrete potential explanatory factors are reported ($p<0.05$). Median values for potential explanatory factors are in parenthesis for a given groundwater age category. Statistical tests of significance for given land use type were done on percent of a given land use type within the 500-meter buffer of a sampled well. **Abbreviations**: ns, no significance; >, greater than; ft, feet; mg/L, milligrams per liter]

Potential explanatory factor	Principal aquifer					
	Basin and Range carbonate-rock aquifers	Basin and Range basin-fill aquifers	Rio Grande aquifer system	High Plains aquifer	Colorado Plateaus aquifers	Columbia Plateau basaltic-rock aquifers
Depth to bottom of well perforation	ns	Premodern (540 ft) > Modern (285 ft); Mixed (510 ft) > Modern (285 ft)	Premodern (640 ft) > Modern (255 ft)	Premodern (340 ft) > Modern (188 ft); Premodern (340 ft) > Mixed (220 ft)	Premodern (805 ft) > Modern (327 ft); Premodern (805 ft) > Mixed (460 ft)	ns
Percent natural land use	Modern (100 percent) > Mixed (2 percent); Premodern (57 percent) > Mixed (2 percent)	ns	ns	ns	Premodern (99 percent) > Mixed (80 percent)	ns
Percent urban land use	ns	ns	Premodern (48 percent) > Modern (9 percent)	Modern (62 percent) > Mixed (3 percent)	ns	ns
Percent agricultural land use	ns	Modern (8.5 percent) > Premodern (0 percent)	ns	ns	ns	ns
Percent irrigated land use	ns	ns	ns	ns	ns	ns
Aridity index	Modern (0.34) > Premodern (0.30)	ns	Modern (0.22) > Premodern (0.16)	ns	Modern (0.34) > Premodern (0.22)	Premodern (0.35) > Modern (0.18)
Land surface elevation of well	Modern (5,760 ft) > Premodern (4,493 ft); Modern (5,760 ft) > Mixed (4,545 ft)	ns	Modern (6,525 ft) > Premodern (4,826 ft)	ns	Modern (6,860 ft) > Mixed (5,881 ft)	Mixed (1,828 ft) > Modern (895 ft); Premodern (1,980 ft) > Modern (895 ft)
Dissolved oxygen	Modern (7.6 mg/L) > Premodern (3.8 mg/L)	ns	ns	ns	ns	ns
pH	ns	Premodern (7.6) > Modern (7.3); Premodern (7.6) > Mixed (7.3)	Premodern (8.0) > Modern (7.6)	Premodern (7.6) > Modern (7.3); Mixed (7.4) > Modern (7.3)	Premodern (7.8) > Modern (7.4)	ns
Bicarbonate (HCO_3)	ns	Modern (263 mg/L) > Premodern (154 mg/L); Modern (263 mg/L) > Mixed (176 mg/L)	ns	Modern (266 mg/L) > Premodern (182 mg/L); Modern (266 mg/L) > Mixed (201 mg/L)	ns	ns
Total dissolved solids (TDS)	Premodern (573 mg/L) > Modern (219 mg/L); Premodern (573 mg/L) > Mixed (293 mg/L)	ns	ns	Modern (533 mg/L) > Premodern (270 mg/L); Modern (533 mg/L) > Mixed (341 mg/L)	ns	Modern (328 mg/L) > Premodern (192 mg/L)

Table 6*A*. Spearman's rho (ρ) correlation results between potential explanatory factors in the Basin and Range carbonate-rock aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[rho (ρ), Spearman’s correlation statistic; ρ values are shown for tests in which the variables were determined to be significantly correlated (p-values less than 0.05). **Abbreviation**: ns, no significance between factors]

rho (ρ)	Depth to bottom of well perforation	Percent natural land use	Percent urban land use	Percent agricultural land use	Percent irrigated land use	Aridity index	Elevation of well	Dissolved oxygen	pH	Bicarbonate (HCO_3)	Total dissolved solids (TDS)
Depth to bottom of well perforation		ns	ns	ns	ns	ns	ns	–0.71	ns	ns	0.50
Percent natural land use			–0.77	–0.58	ns	ns	ns	ns	ns	ns	ns
Percent urban land use				ns	ns	ns	ns	ns	ns	ns	ns
Percent agricultural land use					ns	ns	ns	ns	ns	ns	ns
Percent irrigated land use[1]						ns	ns	ns	ns	ns	ns
Aridity index							0.61	ns	ns	ns	ns
Elevation of well								ns	ns	ns	–0.57
Dissolved oxygen									ns	ns	–0.66
pH										ns	ns
Bicarbonate (HCO_3)											ns
Total dissolved solids (TDS)											

[1] Based on values for irrigated land use within the 500-meter well buffer zone of each sampled well.

Table 6*B*. Spearman's rho (ρ) correlation results between potential explanatory factors in the Basin and Range basin-fill aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[rho (ρ), Spearman’s correlation statistic; ρ values are shown for tests in which the variables were determined to be significantly correlated (p-values less than 0.05). **Abbreviation**: ns, no significance between factors]

rho (ρ)	Depth to bottom of well perforation	Percent natural land use	Percent urban land use	Percent agricultural land use	Percent irrigated land use	Aridity index	Elevation of well	Dissolved oxygen	pH	Bicarbonate (HCO_3)	Total dissolved solids (TDS)
Depth to bottom of well perforation		ns	0.25	ns	ns	ns	ns	ns	0.26	ns	ns
Percent natural land use			0.88	ns	ns	ns	0.36	ns	0.28	ns	ns
Percent urban land use				–0.31	–0.23	ns	–0.36	ns	ns	ns	ns
Percent agricultural land use					0.66	ns	ns	ns	ns	0.35	0.27
Percent irrigated land use[1]						ns	ns	–0.30	ns	0.37	ns
Aridity index							0.74	0.55	–0.30	ns	–0.44
Elevation of well								0.51	ns	ns	–0.46
Dissolved oxygen									ns	ns	–0.31
pH										–0.60	ns
Bicarbonate (HCO_3)											0.33
Total dissolved solids (TDS)											

[1] Based on values for irrigated land use within the 500-meter well buffer zone of each sampled well.

Table 6*C*. Spearman's rho (ρ) correlation results between potential explanatory factors in the Rio Grande aquifer system sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[rho (ρ), Spearman’s correlation statistic; ρ values are shown for tests in which the variables were determined to be significantly correlated (p-values less than 0.05). **Abbreviation**: ns, no significance between factors]

rho (ρ)	Depth to bottom of well perforation	Percent natural land use	Percent urban land use	Percent agricultural land use	Percent irrigated land use	Aridity index	Elevation of well	Dissolved oxygen	pH	Bicarbonate (HCO_3)	Total dissolved solids (TDS)
Depth to bottom of well perforation		–0.27	0.28	ns	ns	ns	ns	–0.27	ns	–0.26	ns
Percent natural land use			–0.89	ns	0.26	0.30	ns	ns	ns	0.26	ns
Percent urban land use				ns	ns	ns	ns	ns	ns	ns	ns
Percent agricultural land use					0.66	ns	ns	ns	ns	0.25	ns
Percent irrigated land use[1]						ns	0.31	ns	–0.44	ns	–0.31
Aridity index							0.87	0.38	–0.26	ns	–0.49
Elevation of well								0.26	ns	ns	–0.65
Dissolved oxygen									–0.27	ns	ns
pH										–0.44	ns
Bicarbonate (HCO_3)											0.40
Total dissolved solids (TDS)											

[1] Based on values for irrigated land use within the 500-meter well buffer zone of each sampled well.

Table 6*D*. Spearman's rho (ρ) correlation results between potential explanatory factors in the High Plains aquifer sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[rho (ρ), Spearman’s correlation statistic; ρ values are shown for tests in which the variables were determined to be significantly correlated (p-values less than 0.05). **Abbreviation**: ns, no significance between factors]

rho (ρ)	Depth to bottom of well perforation	Percent natural land use	Percent urban land use	Percent agricultural land use	Percent irrigated land use	Aridity index	Elevation of well	Dissolved oxygen	pH	Bicarbonate (HCO_3)	Total dissolved solids (TDS)
Depth to bottom of well perforation		ns	ns	ns	ns	ns	ns	ns	0.24	ns	–0.36
Percent natural land use			–0.61	–0.32	–0.28	ns	ns	ns	ns	ns	–0.25
Percent urban land use				–0.43	ns	ns	ns	ns	ns	ns	ns
Percent agricultural land use					0.57	ns	ns	ns	ns	ns	ns
Percent irrigated land use[1]						0.22	ns	ns	ns	ns	ns
Aridity index							–0.74	–0.31	–0.23	–0.27	–0.40
Elevation of well								0.32	0.40	ns	ns
Dissolved oxygen									0.38	ns	ns
pH										–0.46	0.69
Bicarbonate (HCO_3)											ns
Total dissolved solids (TDS)											

[1] Based on values for irrigated land use within the 500-meter well buffer zone of each sampled well.

Table 6*E*. Spearman's rho (ρ) correlation results between potential explanatory factors in the Colorado Plateaus aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[rho (ρ), Spearman's correlation statistic; ρ values are shown for tests in which the variables were determined to be significantly correlated (p-values less than 0.05). **Abbreviation**: ns, no significance between factors]

rho (ρ)	Depth to bottom of well perforation	Percent natural land use	Percent urban land use	Percent agricultural land use	Percent irrigated land use	Aridity index	Elevation of well	Dissolved oxygen	pH	Bicarbonate (HCO_3)	Total dissolved solids (TDS)
Depth to bottom of well perforation		0.31	–0.38	ns	ns	ns	ns	ns	ns	ns	ns
Percent natural land use			–0.76	–0.54	–0.35	ns	ns	ns	ns	ns	ns
Percent urban land use				ns	ns	ns	ns	ns	ns	ns	ns
Percent agricultural land use					0.54	ns	ns	ns	ns	ns	ns
Percent irrigated land use[1]						ns	ns	ns	ns	ns	ns
Aridity index							0.71	ns	–0.35	ns	ns
Elevation of well								ns	ns	ns	ns
Dissolved oxygen									ns	–0.47	–0.47
pH										ns	ns
Bicarbonate (HCO_3)											0.73
Total dissolved solids (TDS)											

[1] Based on values for irrigated land use within the 500-meter well buffer zone of each sampled well.

Table 6*F*. Spearman's rho (ρ) correlation results between potential explanatory factors in the Columbia Plateau basaltic-rock aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[rho (ρ), Spearman's correlation statistic; ρ values are shown for tests in which the variables were determined to be significantly correlated (p-values less than 0.05). **Abbreviation**: ns, no significance between factors]

rho (ρ)	Depth to bottom of well perforation	Percent natural land use	Percent urban land use	Percent agricultural land use	Percent irrigated land use	Aridity index	Elevation of well	Dissolved oxygen	pH	Bicarbonate (HCO_3)	Total dissolved solids (TDS)
Depth to bottom of well perforation		ns	0.32	ns	ns	ns	ns	–0.41	0.30	ns	ns
Percent natural land use			–0.57	ns	ns	ns	ns	ns	ns	ns	ns
Percent urban land use				–0.52	ns	–0.27	–0.34	ns	0.30	ns	ns
Percent agricultural land use					0.37	ns	ns	ns	ns	0.37	ns
Percent irrigated land use[1]						ns	ns	0.29	–0.27	ns	ns
Aridity index							0.69	ns	ns	ns	–0.37
Elevation of well								ns	ns	ns	–0.30
Dissolved oxygen									–0.42	ns	ns
pH										ns	ns
Bicarbonate (HCO_3)											0.80
Total dissolved solids (TDS)											

[1] Based on values for irrigated land use within the 500-meter well buffer zone of each sampled well.

Status and Understanding Assessments of Water Quality

As described in the "Methods" section, the *status assessment* quantifies groundwater quality at the aquifer scale relative to drinking-water benchmarks (table 2) and it includes a summary of detection frequencies, aquifer-scale proportions, and graphical representations of the concentrations of selected constituents that met the criteria for further evaluation. The *understanding assessment* identifies natural and human factors affecting groundwater quality and evaluates statistically significant correlations among potential explanatory factors and between potential explanatory factors and water quality to provide physical and chemical context for groundwater quality. The *understanding assessment* objective is to improve understanding about why specific constituents are present in the groundwater at moderate to high concentrations or are frequently detected. The *understanding assessment* does not, however, identify sources of constituents to individual wells or springs. The *understanding assessment* includes discussion of the relations between potential explanatory factors and selected constituents for each principal aquifer study and is presented after the *status assessment* for individual constituents or groups of constituents. Relatively weak correlations (Spearman's rho values less than 0.3) generally are not discussed because the goal is to focus the discussion on stronger correlations that are more likely to represent controlling factors for constituents detected at moderate and high concentrations. Relatively weak correlations also could represent an artifact of other potential factors that were not considered.

Inorganic Constituents

Most inorganic constituents in groundwater are present naturally because groundwater reacts with minerals in rocks, soils, and sediment. Inorganic constituents in groundwater also could be altered by human activities such as irrigation and groundwater pumping, or by natural factors such as geochemical conditions. Inorganic constituents are described later in the report by four groups—trace elements, radionuclides, salinity indicators, and nutrients. Of the almost 50 inorganic constituents analyzed, 28 had regulatory or non-regulatory health-based benchmarks and 7 had non-regulatory aesthetic benchmarks. Of the 35 inorganic constituents with benchmarks, 18 were selected for additional evaluation (table 2) because they were detected at moderate or high concentrations in at least one PA (fig. 18); remaining constituents either had no benchmarks, no detections, or were detected only at low concentrations (table 3).

Aquifer scale proportions of high, moderate, and low relative concentrations for inorganic benchmarks, such as health-based (HB) and non-health-based benchmarks (SMCL), are summarized in pie charts for each PA (fig. 19). The proportion of each aquifer's area that had high concentrations for inorganic constituents with HB benchmarks ranged from 8 percent in the Columbia Plateau basaltic-rock aquifers to 30 percent in the Rio Grande aquifer system (fig. 19*A*). Trace elements with HB benchmarks accounted for the largest proportion of high concentrations across all PAs (table 7). The proportion of high concentrations for inorganic constituents with SMCL benchmarks ranged from 20 percent in the Columbia Plateau basaltic-rock aquifers to 48 percent in the Colorado Plateaus aquifers (fig. 19*B*). Salinity indicators accounted for the largest proportion of high concentrations of constituents with SMCL benchmarks across all PAs except for the Columbia Plateau basaltic-rock aquifers (table 8). The constituent pH has an SMCL range defined by two benchmarks—less than 6.5 or greater than 8.5; aquifer-scale proportions were calculated as the percentage less than or greater than, respectively. Values of pH less than the lower SMCL benchmark occurred in 2 percent or less of the Basin and Range basin-fill the and Colorado Plateaus PAs. Exceedances of pH values above the upper pH SMCL benchmark occurred in all of the PAs except for the Basin and Range carbonate-rock aquifers and ranged from 1 to 22 percent in the PAs (table 8). Aquifer-scale proportions of inorganic constituents with HB benchmarks (table 7) and SMCL benchmarks (table 8) selected for further evaluation are summarized for each PA and discussed for each constituent group later in the report.

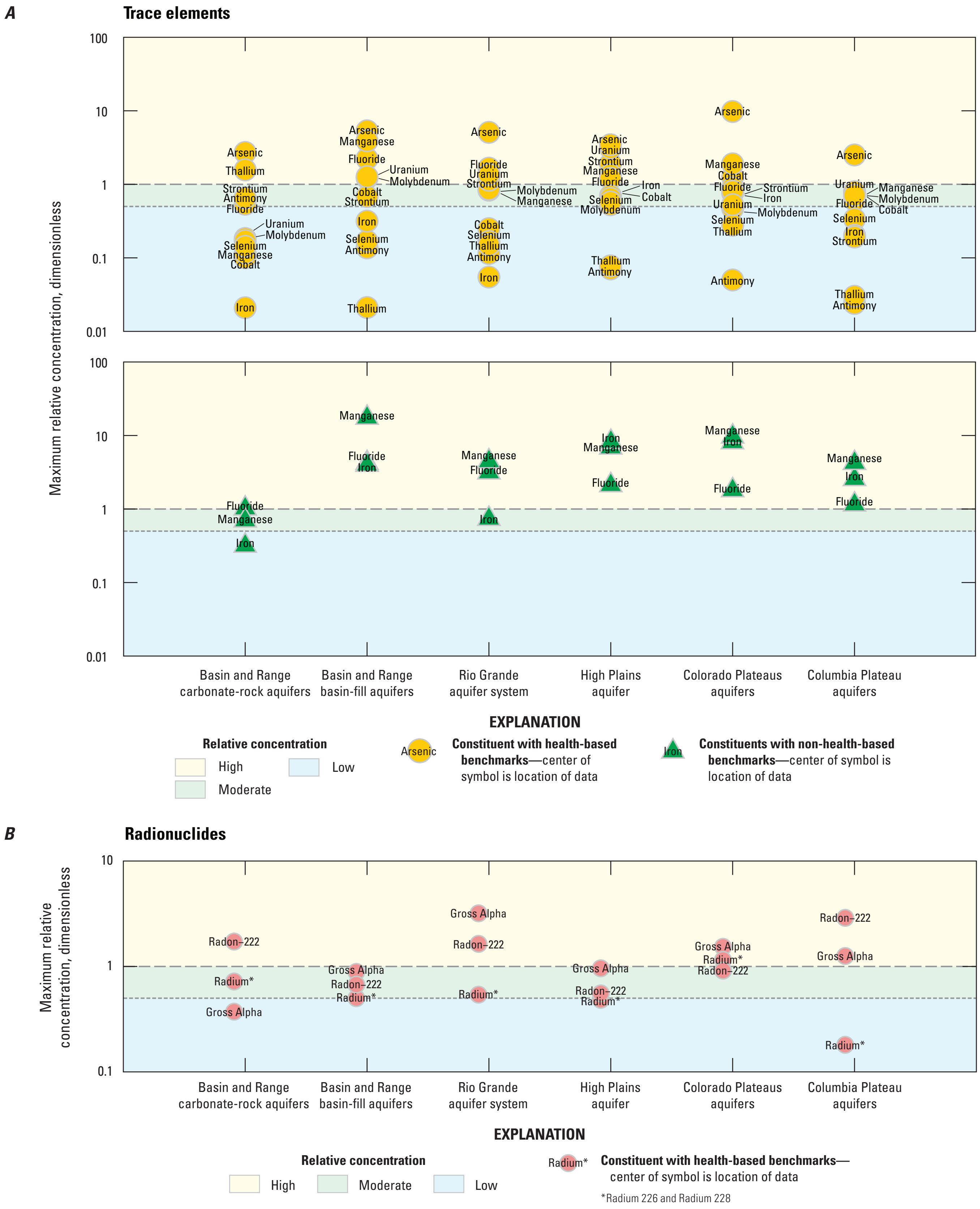


Figure 18. Maximum relative concentrations of constituents with health-based benchmarks and considered in the *Understanding assessment* for *A,* trace elements; *B,* radionuclides; *C,* salinity indicators; and *D,* nutrients in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

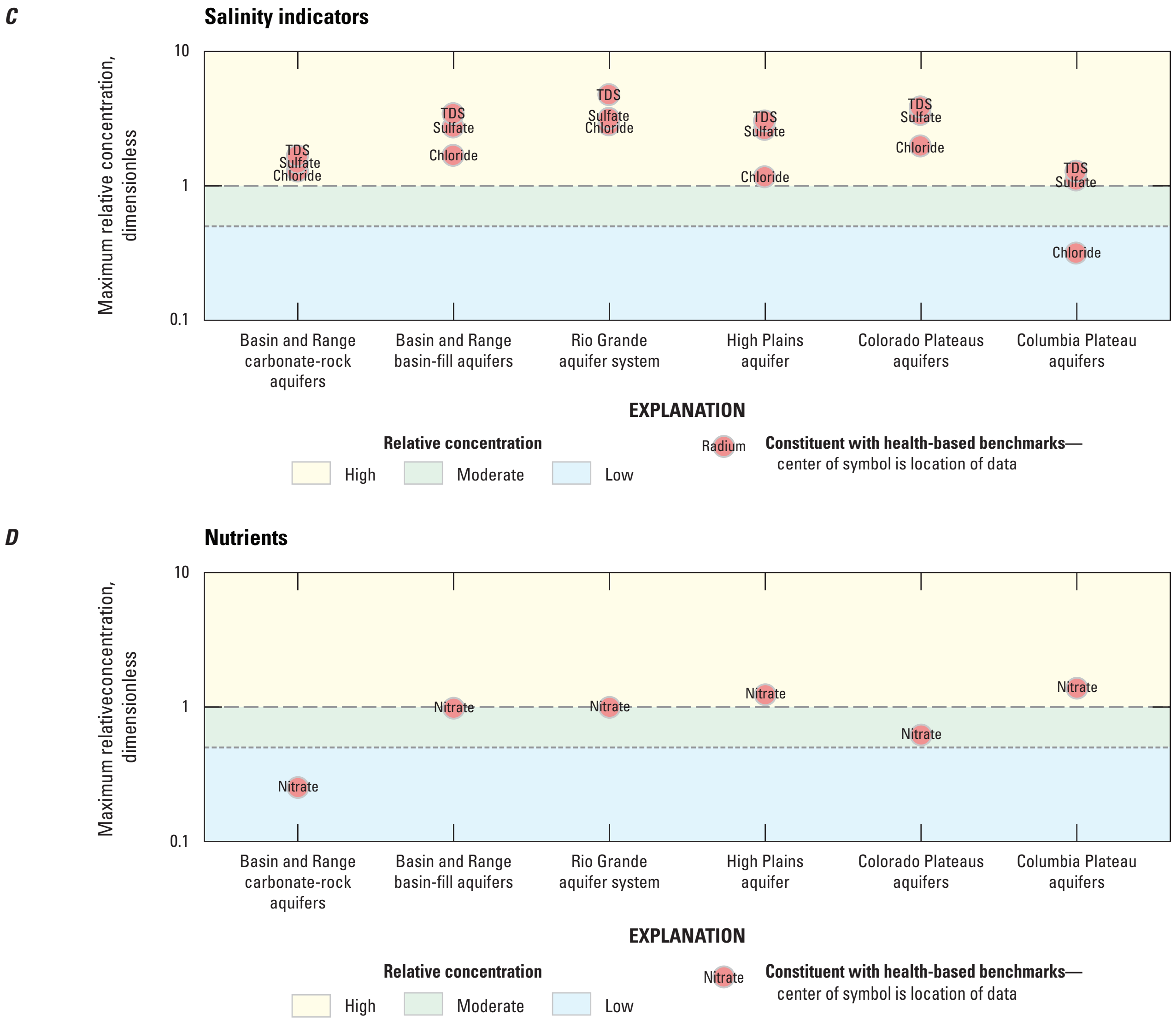


Figure 18. —Continued

Trace Elements

The trace element group includes metallic and non-metallic constituents that are typically present in groundwater at concentrations less than 1 mg/L (Hem, 1985). Concentrations of trace elements in groundwater often reflect their presence and abundance in aquifer materials and are mobilized primarily by rock weathering, geochemical conditions, the presence and abundance of complexing ions and organic matter, or attenuated by processes such as adsorption (Hem, 1985; Salbu and Steinnes, 1994). Human activities, such as mining, agricultural land use, and waste disposal, also can affect concentrations of trace elements in groundwater (Ayotte and others, 2011). Eleven trace elements were selected for evaluation by the *status assessment*—antimony, arsenic, cobalt, fluoride, manganese, iron, molybdenum, strontium, selenium, thallium, and uranium—because they were detected at moderate or high concentrations in at least one PA (fig. 20). Manganese, iron, and fluoride were evaluated for HB and SMCL benchmarks. The trace element constituent group had the highest proportions of moderate and high concentrations among inorganic groups (table 7). Concentrations of trace elements tended to be higher in unconsolidated sand and gravel aquifers (tables 1, 7). The proportion of each aquifer having at least one trace element with a high concentration ranged from 5 percent (Columbia Plateau basaltic-rock aquifers) to 27 percent (Rio Grande aquifer system), and the proportion of each aquifer having at least one trace element with a moderate concentration ranged from 7 percent (Columbia Plateau basaltic-rock aquifers) to 50 percent (High Plains aquifer, table 7). High concentrations of trace elements relative to SMCL benchmarks ranged from 10 percent (Basin and Range carbonate-rock aquifers) to 26 percent (High Plains aquifers), and moderate concentrations ranged from 5 percent (Basin and Range carbonate-rock aquifers) to 16 percent (High Plains aquifer and Columbia Plateau basaltic-rock aquifers, table 8).

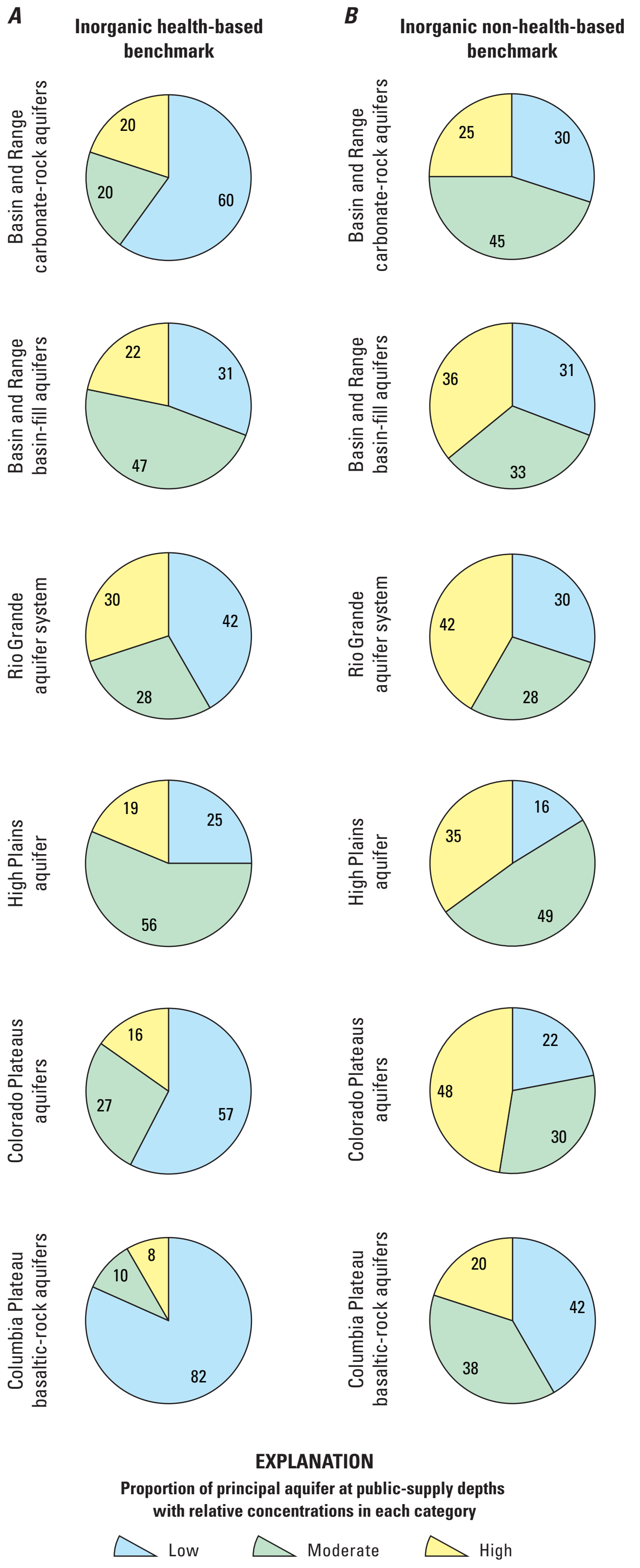


Figure 19. Aquifer scale proportions for inorganic constituents with *A,* health-based (HB); and *B,* non-health-based (SMCL) benchmarks in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Table 7. Summary of aquifer scale proportions (low, moderate, or high concentrations) for inorganic constituent groups with health-based benchmarks in six western U.S. principal aquifers sampled in springs and wells by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Concentration categories**: high, concentration of at least one constituent greater than water-quality benchmark; moderate, concentration of at least one constituent greater than 0.5 of benchmark but less than benchmark; low, concentration of all constituents less than or equal to 0.5 of benchmark]

Principal aquifer	Number of samples	Aquifer scale proportion (percent)		
		Low	Moderate	High
Nutrients with health-based benchmarks				
Basin and Range carbonate-rock aquifers	20	100	0	0
Basin and Range basin-fill aquifers	78	91	9	0
Rio Grande aquifer system	60	98	0	2
High Plains aquifer	80	86	11	3
Colorado Plateaus aquifers	60	98	2	0
Columbia Plateau basaltic-rock aquifers	60	91	7	2
Trace elements with health-based benchmarks				
Basin and Range carbonate-rock aquifers	20	65	20	15
Basin and Range basin-fill aquifers	78	40	38	22
Rio Grande aquifer system	60	48	25	27
High Plains aquifer	80	34	50	16
Colorado Plateaus aquifers	60	65	22	13
Columbia Plateau basaltic-rock aquifers	60	88	7	5
Radioactive constituents with health-based benchmarks				
Basin and Range carbonate-rock aquifers	20	90	5	5
Basin and Range basin-fill aquifers	78	85	15	0
Rio Grande aquifer system	60	85	10	5
High Plains aquifer	80	84	15	[1]1
Colorado Plateaus aquifers	60	82	13	5
Columbia Plateau basaltic-rock aquifers	60	95	2	3
All inorganic constituents with health-based benchmarks				
Basin and Range carbonate-rock aquifers	20	60	20	20
Basin and Range basin-fill aquifers	78	47	31	22
Rio Grande aquifer system	60	42	28	30
High Plains aquifer	80	25	56	19
Colorado Plateaus aquifers	60	57	27	16
Columbia Plateau basaltic-rock aquifers	60	82	10	8

[1] Represents high concentration of 72-hour gross alpha activity detected in one well; however only 30-day gross alpha activities were evaluated and discussed in the report.

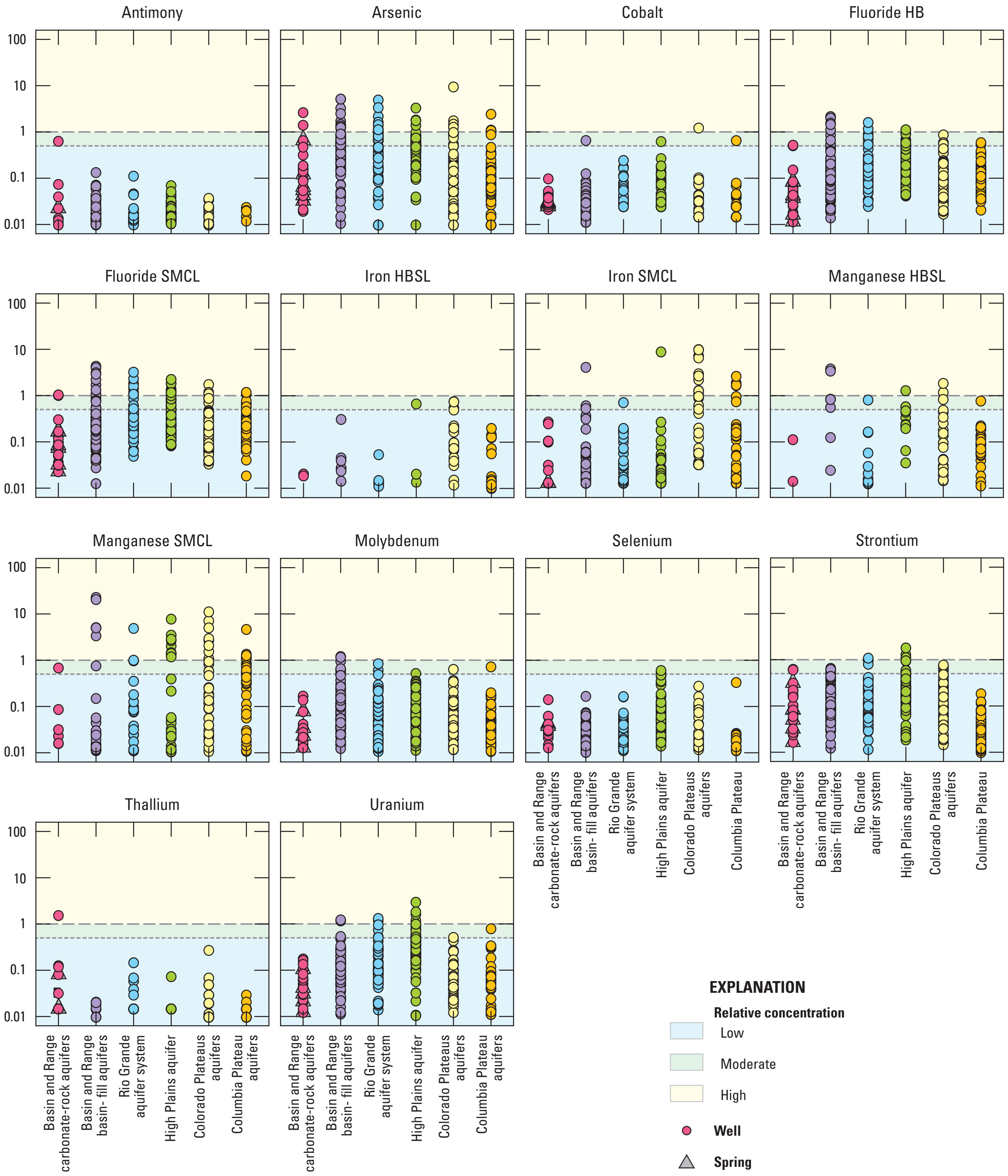


Figure 20. Concentrations of trace elements relative to health-based (HB) and non-health-based benchmarks (SMCL) measured in six principal aquifers of the western U.S. sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Table 8. Summary of aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituent groups with non-health-based benchmarks in six western U.S. principal aquifers sampled in springs and wells by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Concentration categories**: high, concentration of at least one constituent greater than water-quality benchmark; moderate, concentration of at least one constituent greater than 0.5 of benchmark but less than benchmark; low, concentration of all constituents less than or equal to 0.5 of benchmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Principal aquifer	Number of samples	Aquifer scale proportion (percent)		
		Low	Moderate	High
Trace elements with SMCL benchmarks				
Basin and Range carbonate-rock aquifers	20	85	5	10
Basin and Range basin-fill aquifers	78	72	9	19
Rio Grande aquifer system	60	75	10	15
High Plains aquifer	80	58	16	26
Colorado Plateaus aquifers	60	67	8	25
Columbia Plateau basaltic-rock aquifers	60	67	16	17
Salinity indicators with SMCL				
Basin and Range carbonate-rock aquifers	20	30	45	25
Basin and Range basin-fill aquifers	78	32	36	32
Rio Grande aquifer system	60	33	32	35
High Plains aquifer	80	20	54	26
Colorado Plateaus aquifers	60	28	35	37
Columbia Plateau basaltic-rock aquifers	60	56	37	7
All constituents with SMCL benchmarks				
Basin and Range carbonate-rock aquifers	20	30	45	25
Basin and Range basin-fill aquifers	78	31	33	36
Rio Grande aquifer system	60	30	28	42
High Plains aquifer	80	16	49	35
Colorado Plateaus aquifers	59	22	30	48
Columbia Plateau basaltic-rock aquifers	60	42	38	20
		<6.5	**>8.5**	**sum**[1]
pH				
Basin and Range carbonate-rock aquifers	20	0	0	0
Basin and Range basin-fill aquifers	78	1	5	5
Rio Grande aquifer system	60	0	7	4
High Plains aquifer	80	0	1	1
Colorado Plateaus aquifers	60	2	22	14
Columbia Plateau basaltic-rock aquifers	60	0	7	4

[1] Sum of pH exceedances less than 6.5 and (or) greater than 8.5 standard pH units.

Factors Affecting Antimony

Antimony (Sb) is a rare heavy metal that occurs at about 0.2 part per million (ppm) in the Earth's crust (Butterman and Carlin, 2004; Seal and others, 2017). It is an important mineral commodity that is used worldwide to produce alloys in industrialized societies (Miller, 1973; Butterman and Carlin, 2004; U.S. Geological Survey, 2016). Stibnite (Sb_2S_3) is the most common antimony ore mineral (and over 100 minerals also contain antimony; Miller, 1973; Butterman and Carlin, 2004; Seal and others, 2017). In the U.S., the leading use for antimony (as antimony trioxide) is as a fire retardant in adhesives, paints, papers, plastics, and sealants; secondary uses are in alloys for batteries and solders (Seal and others, 2017). Natural sources of antimony in soil and water originate from mineral weathering; anthropogenic sources include mining, industrial processes, and pesticide application of some metal-containing pesticides (Arai, 2010).

The EPA MCL benchmark for antimony in drinking water is 6 µg/L (U.S. Environmental Protection Agency, 2018a). Antimony was detected at moderate concentrations in only one well (5 percent) of the Basin and Range carbonate-rock PA (table 9*A*). Antimony had significant negative correlations with dissolved oxygen (Spearman's rho= –0.66) and no other explanatory factors. The geochemistry of antimony has similar traits to arsenic and often coexists with arsenic in the natural environment (Arai, 2010; Wilson and others, 2010). Both trace elements most commonly occur in relativity oxic environments as antimonates and arsenates or in anoxic environments as antimonites and arsenites (Wilson and others, 2010). Of the 14 wells and 6 springs sampled in the Basin and Range carbonate-rock aquifers, only 2 wells had anoxic groundwater conditions, one of which had a moderate antimony concentration. A low concentration of arsenic co-occurred in this same well indicating the anoxic geochemical conditions favored the release of antimony and arsenic from the surrounding aquifer material.

Factors Affecting Arsenic

Arsenic (As), which is toxic to humans in small amounts, occurs in many minerals, such as metal arsenides and sulfides (Hem, 1985). Moderate and high concentrations of arsenic occurred in all six PAs and accounted for the highest trace-element group detection frequencies in most of the PAs (fig. 21*A*; tables 9*A*–*F*). Natural sources of arsenic in groundwater include the dissolution of arsenic-bearing minerals, desorption of arsenic from mineral surfaces, and mixing with hydrothermal fluids (Welch and others, 2000; Smedley and Kinniburgh, 2002; Barringer and Reilly, 2013). Potential anthropogenic sources include copper ore smelting, coal combustion, arsenical pesticides, arsenical veterinary pharmaceuticals, and wood preservatives (Fram and Belitz, 2012). Natural sources of arsenic in drinking water adversely affect large human populations across broad regional areas (Welch and others, 2000; Smedley and Kinniburgh, 2002).

Table 9*A*. Detection frequency and aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituents that met criteria for additional evaluation by the *status assessment* for the Basin and Range carbonate-rock aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.5 of water quality benchmark but less than benchmark; low, concentrations less than 0.5 of bechmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency		Raw detection frequency (percent)		Aquifer-scale proportion (percent)			
	Number of wells with analysis	Detection frequency (percent)	Number of springs with analysis	Detection frequency (percent)	Number of samples	Low	Moderate	High
Nutrients								
Nitrate, as nitrogen	14	100	6	100	20	100	0	0
Trace elements								
Antimony	14	79	6	50	20	95	5	0
Arsenic	14	100	6	100	20	85	5	10
Cobalt	14	86	6	50	20	100	0	0
Fluoride	14	100	6	100	20	90	10	0
Iron	14	57	6	0	20	100	0	0
Manganese	14	36	6	0	20	100	0	0
Molybdenum	14	100	6	100	20	100	0	0
Selenium	14	100	6	100	20	100	0	0
Strontium	14	100	6	100	20	90	10	0
Thallium	14	36	6	17	20	95	0	5
Uranium	14	100	6	100	20	100	0	0
Inorganic constituents with SMCL								
Chloride	14	100	6	100	20	85	10	5
Fluoride	14	100	6	100	20	90	0	10
Iron	14	57	6	0	20	100	0	0
Manganese	14	36	6	0	20	95	5	0
Sulfate	14	100	6	100	20	80	15	5
Total dissolved solids (TDS)	14	100	6	100	20	30	45	25
Radioactive constituents								
Gross alpha activity (30-day)	14	100	6	100	20	100	0	0
Radium-226 and radium-228 (combined)	14	100	6	100	20	94	6	0
Radon activity[1]	14	100	5	100	19	95	0	5

[1] Radon-222 was evaluated at the proposed maximum contaminant level of 4,000 picocuries per liter.

Table 9*B*. Detection frequency and aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituents that met criteria for additional evaluation by the *status assessment* for the Basin and Range basin-fill aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.5 of water quality benchmark but less than benchmark; low, concentrations less than 0.5 of bechmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency		Aquifer-scale proportion (percent)		
	Number of samples	Detection frequency (percent)	Low	Moderate	High
Nutrients					
Nitrate, as nitrogen	78	91	82	9	0
Trace elements					
Antimony	78	77	77	0	0
Arsenic	78	100	52	35	13
Cobalt	78	80	99	1	0
Fluoride	78	100	89	5	6
Iron	78	51	100	0	0
Manganese	78	72	92	5	3
Molybdenum	78	100	87	9	4
Selenium	78	99	100	0	0
Strontium	78	100	95	5	0
Thallium	78	9	100	0	0
Uranium	78	100	96	1	3
Inorganic constituents with SMCL					
Chloride	78	100	78	10	12
Fluoride	78	100	81	8	11
Iron	78	51	96	3	1
Manganese	78	72	91	1	8
Sulfate	78	100	73	14	13
Total dissolved solids (TDS)	78	100	32	36	32
Radioactive constituents					
Gross alpha activity (30-day)	78	100	99	1	0
Radium-226 and radium-228 (combined)	67	100	100	0	0
Radon activity[1]	76	100	95	5	0

[1] Radon-222 was evaluated at the proposed maximum contaminant level of 4,000 picocuries per liter.

Table 9*C*. Detection frequency and aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituents that met criteria for additional evaluation by the *status assessment* for the Rio Grande aquifer system sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.5 of water quality benchmark but less than benchmark; low, concentrations less than 0.5 of bechmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency		Aquifer-scale proportion (percent)		
	Number of samples	Detection frequency (percent)	Low	Moderate	High
Nutrients					
Nitrate, as nitrogen	60	85	98	0	2
Trace elements					
Antimony	60	72	100	0	0
Arsenic	60	93	60	22	18
Cobalt	60	63	100	0	0
Fluoride	60	100	88	8	4
Iron	60	48	100	0	0
Manganese	60	28	98	2	0
Molybdenum	60	100	95	3	2
Selenium	60	88	100	0	0
Strontium	60	100	95	2	3
Thallium	60	3	100	0	0
Uranium	60	100	90	7	3
Inorganic constituents with SMCL					
Chloride	60	100	82	8	10
Fluoride	60	100	78	10	12
Iron	60	48	47	2	0
Manganese	60	28	23	2	3
Sulfate	60	100	70	23	7
Total dissolved solids (TDS)	60	100	33	32	35
Radioactive constituents					
Gross alpha activity (30-day)	60	100	98	2	0
Radium-226 and radium-228 (combined)	60	100	98	2	0
Radon activity[1]	60	100	92	5	3

[1] Radon-222 was evaluated at the proposed maximum contaminant level of 4,000 picocuries per liter.

Table 9*D*. Detection frequency and aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituents that met criteria for additional evaluation by the *status assessment* for the High Plains aquifer sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.5 of water quality benchmark but less than benchmark; low, concentrations less than 0.5 of bechmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency		Aquifer-scale proportion (percent)		
	Number of samples	Detection frequency (percent)	Low	Moderate	High
Nutrients					
Nitrate, as nitrogen	80	95	86	11	3
Trace elements					
Antimony	80	92	100	0	0
Arsenic	80	99	49	44	6
Cobalt	80	49	99	1	0
Fluoride	80	100	85	12	3
Iron	80	38	99	1	0
Manganese	80	32	98	1	1
Molybdenum	80	99	99	1	0
Selenium	80	96	97	3	0
Strontium	80	99	89	7	4
Thallium	80	0	100	0	0
Uranium	80	98	77	15	8
Inorganic constituents with SMCL					
Chloride	80	100	94	2	4
Fluoride	80	100	67	18	15
Iron	80	38	99	0	1
Manganese	80	33	89	0	11
Sulfate	80	100	79	11	10
Total dissolved solids (TDS)	80	100	20	54	26
Radioactive constituents					
Gross alpha activity (30-day)	80	100	96	4	0
Radium-226 and radium-228 (combined)	80	100	100	0	0
Radon activity[1]	79	100	99	1	0

[1] Radon-222 was evaluated at the proposed maximum contaminant level of 4,000 picocuries per liter.

Table 9*E*. Detection frequency and aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituents that met criteria for additional evaluation by the *status assessment* for the Colorado Plateaus aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.5 of water quality benchmark but less than benchmark; low, concentrations less than 0.5 of bechmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency		Aquifer-scale proportion (percent)		
	Number of samples	Detection frequency (percent)	Low	Moderate	High
Nutrients					
Nitrate, as nitrogen	60	62	98	2	0
Trace elements					
Antimony	59	29	100	0	0
Arsenic	59	83	78	14	8
Cobalt	59	25	100	0	2
Fluoride	60	100	95	5	0
Manganese	60	58	93	4	3
Iron	60	43	93	7	0
Molybdenum	60	97	98	2	0
Selenium	59	59	100	0	0
Strontium	59	100	93	7	0
Thallium	59	5	100	0	0
Uranium	59	93	98	2	0
Inorganic constituents with SMCL					
Chloride	60	100	91	7	2
Fluoride	60	100	88	7	5
Iron	60	43	77	7	16
Manganese	60	58	80	7	13
Sulfate	60	100	72	12	16
Total dissolved solids (TDS)	60	100	28	35	37
Radioactive constituents					
Gross alpha activity (30-day)	60	17	98	2	0
Radium-226 and radium-228 (combined)	45	44	94	2	4
Radon activity[1]	60	100	95	5	0

[1] Radon-222 was evaluated at the proposed maximum contaminant level of 4,000 picocuries per liter.

Table 9*F*. Detection frequency and aquifer-scale proportions (low, moderate, or high concentrations) for inorganic constituents that met criteria for additional evaluation by the *status assessment* for the Columbia Plateau basaltic-rock aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.5 of water quality benchmark but less than benchmark; low, concentrations less than 0.5 of bechmark. **Abbreviation**: SMCL, secondary maximum contaminant level]

Constituent	Raw detection frequency		Aquifer-scale proportion (percent)		
	Number of samples	Detection Frequency (percent)	Low	Moderate	High
Nutrients					
Nitrate, as nitrogen	60	67	91	7	2
Trace elements					
Antimony	60	37	100	0	0
Arsenic	60	77	93	2	5
Cobalt	60	18	98	2	0
Fluoride	60	100	97	3	0
Iron	60	60	100	0	0
Manganese	60	43	98	2	0
Molybdenum	60	100	98	2	0
Selenium	60	63	100	0	0
Strontium	60	100	100	0	0
Thallium	60	2	100	0	0
Uranium	60	77	98	2	0
Inorganic constituents with SMCL					
Chloride	59	100	100	0	0
Fluoride	59	100	88	9	3
Iron	59	42	90	3	7
Manganese	59	61	76	14	10
Sulfate	59	100	95	3	2
Total dissolved solids (TDS)	59	100	56	37	7
Radioactive constituents					
Gross alpha activity (30-day)	60	100	97	0	2
Radium-226 and radium-228 (combined)	60	100	100	0	0
Radon activity[1]	60	100	97	0	3

[1] Radon-222 was evaluated at the proposed maximum contaminant level of 4,000 picocuries per liter.

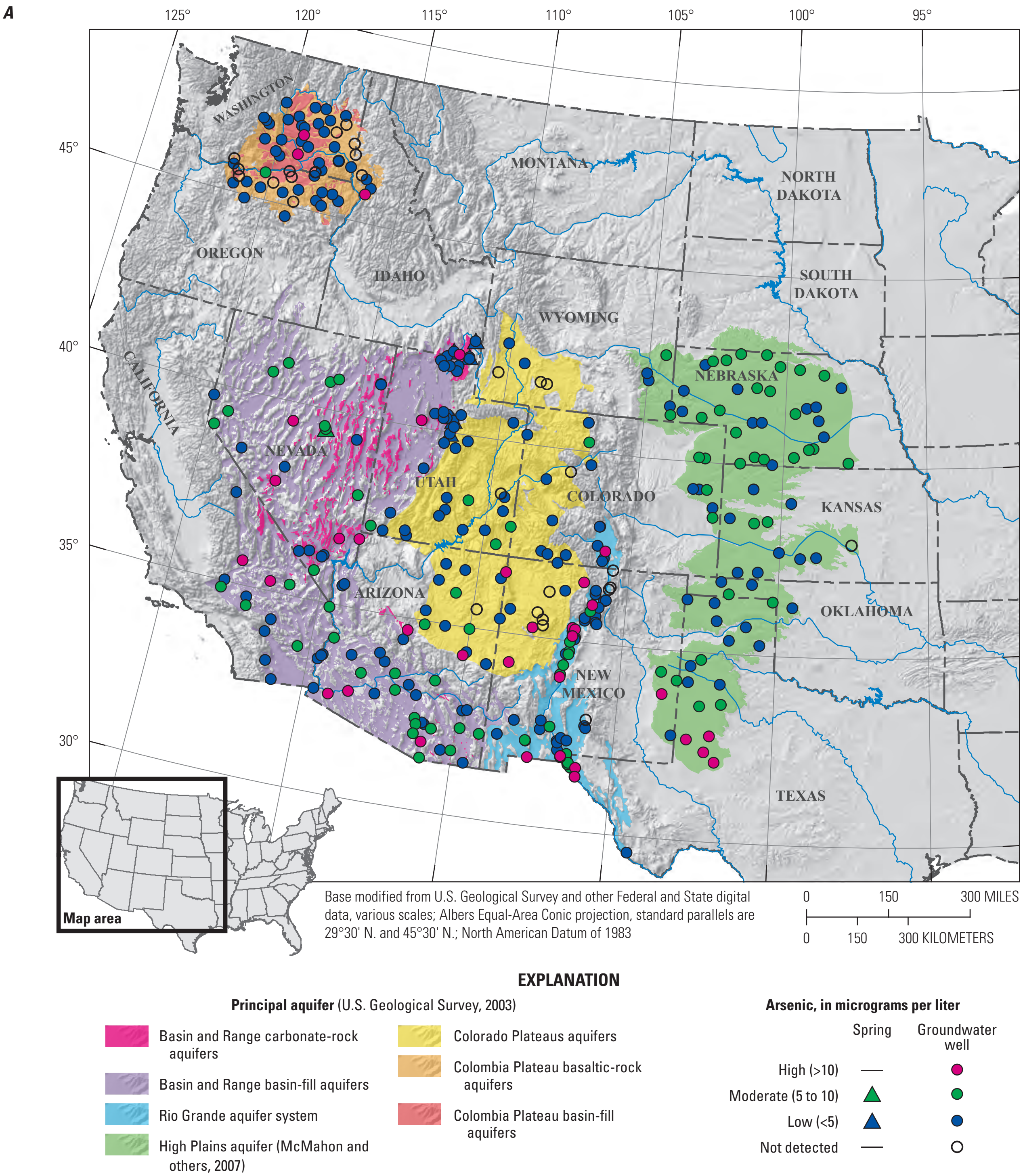
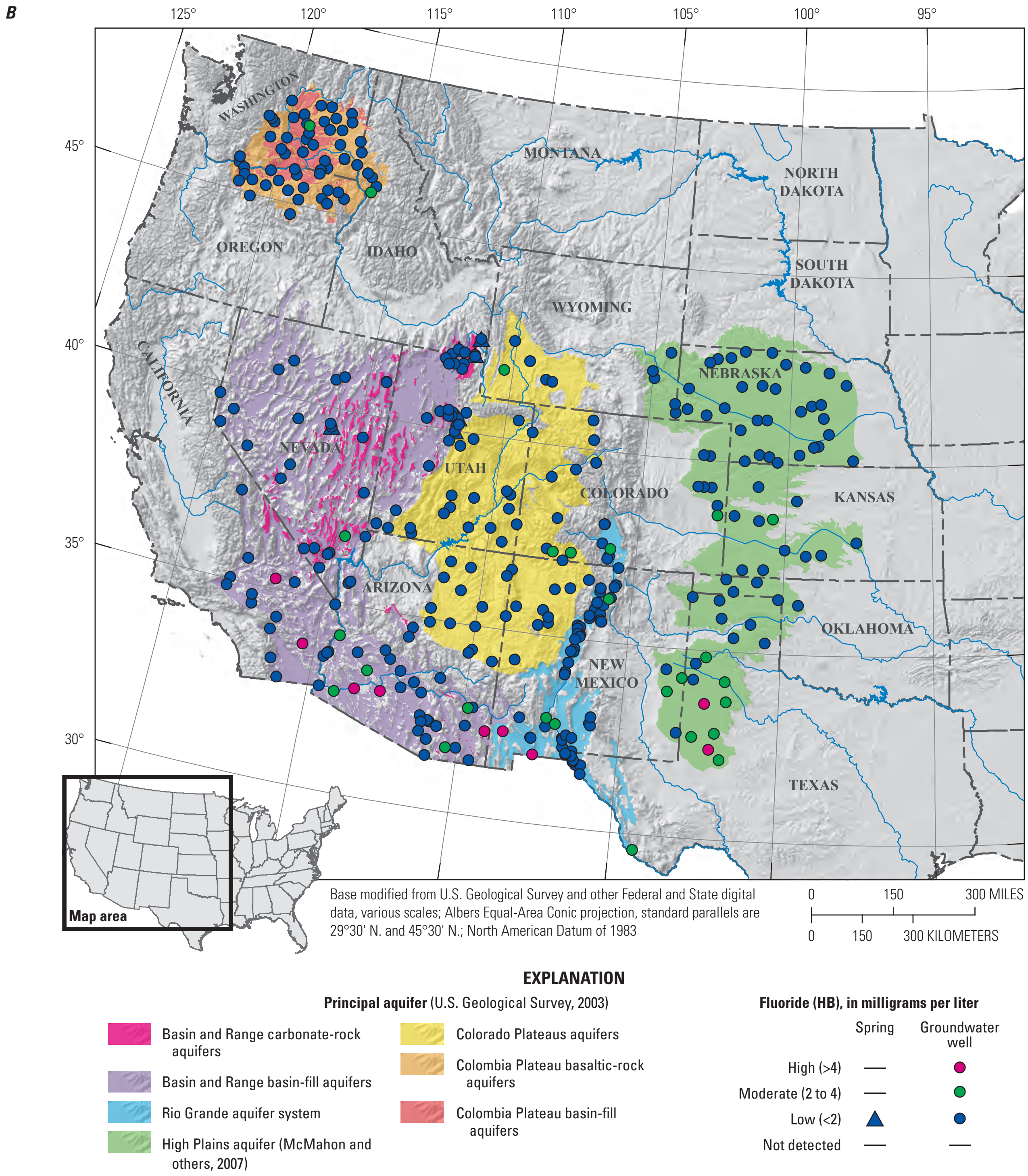


Figure 21. Concentrations of *A,* arsenic; *B,* fluoride health-based (HB) benchmark; *C,* fluoride non-health-based (SMCL) benchmark; *D,* cobalt; *E,* manganese HB benchmark; *F,* manganese SMCL benchmark; *G,* iron HB benchmark; *H,* iron SMCL benchmark; *I,* molybdenum; *J,* selenium; *K,* strontium and *L,* uranium in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.



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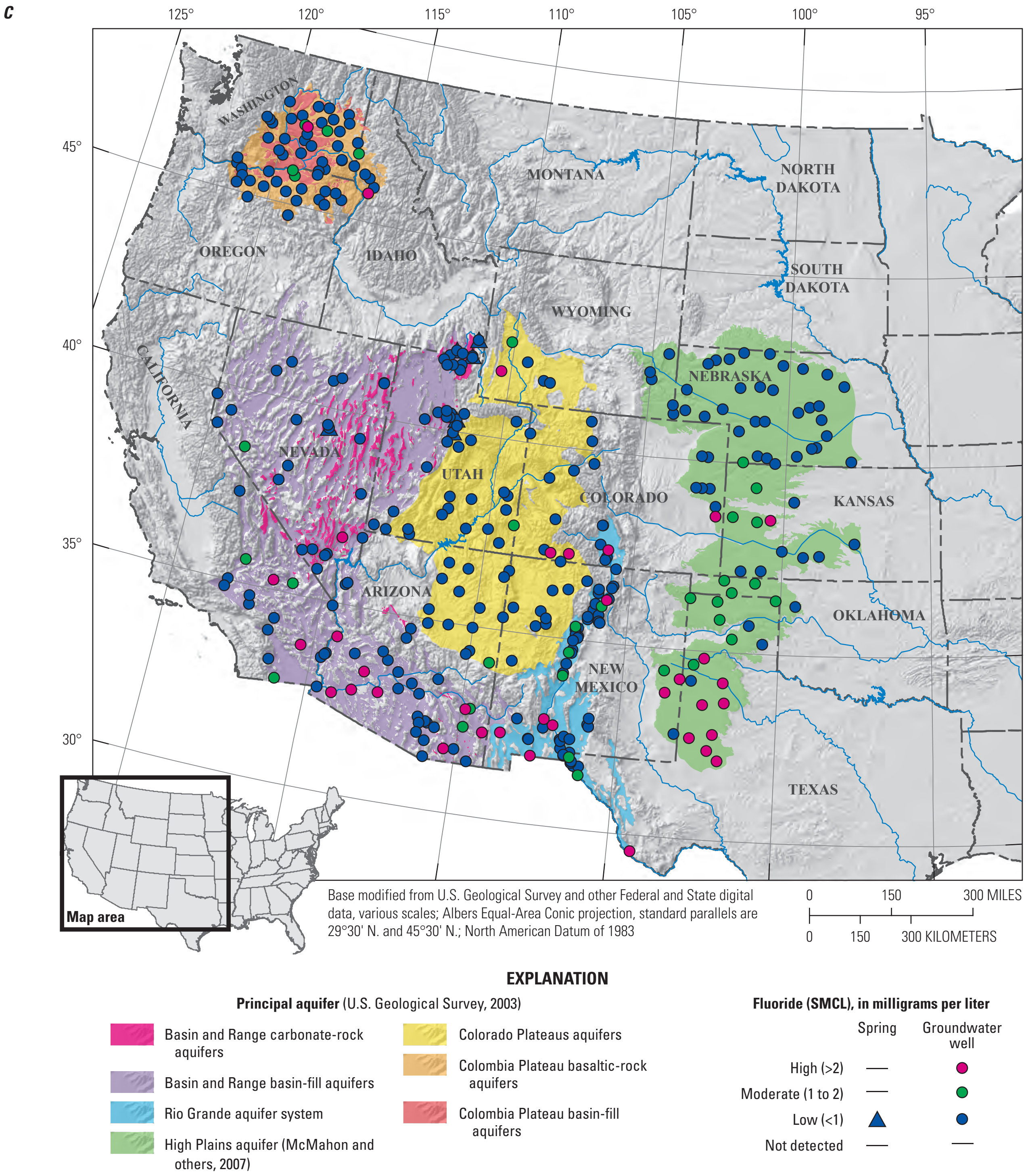

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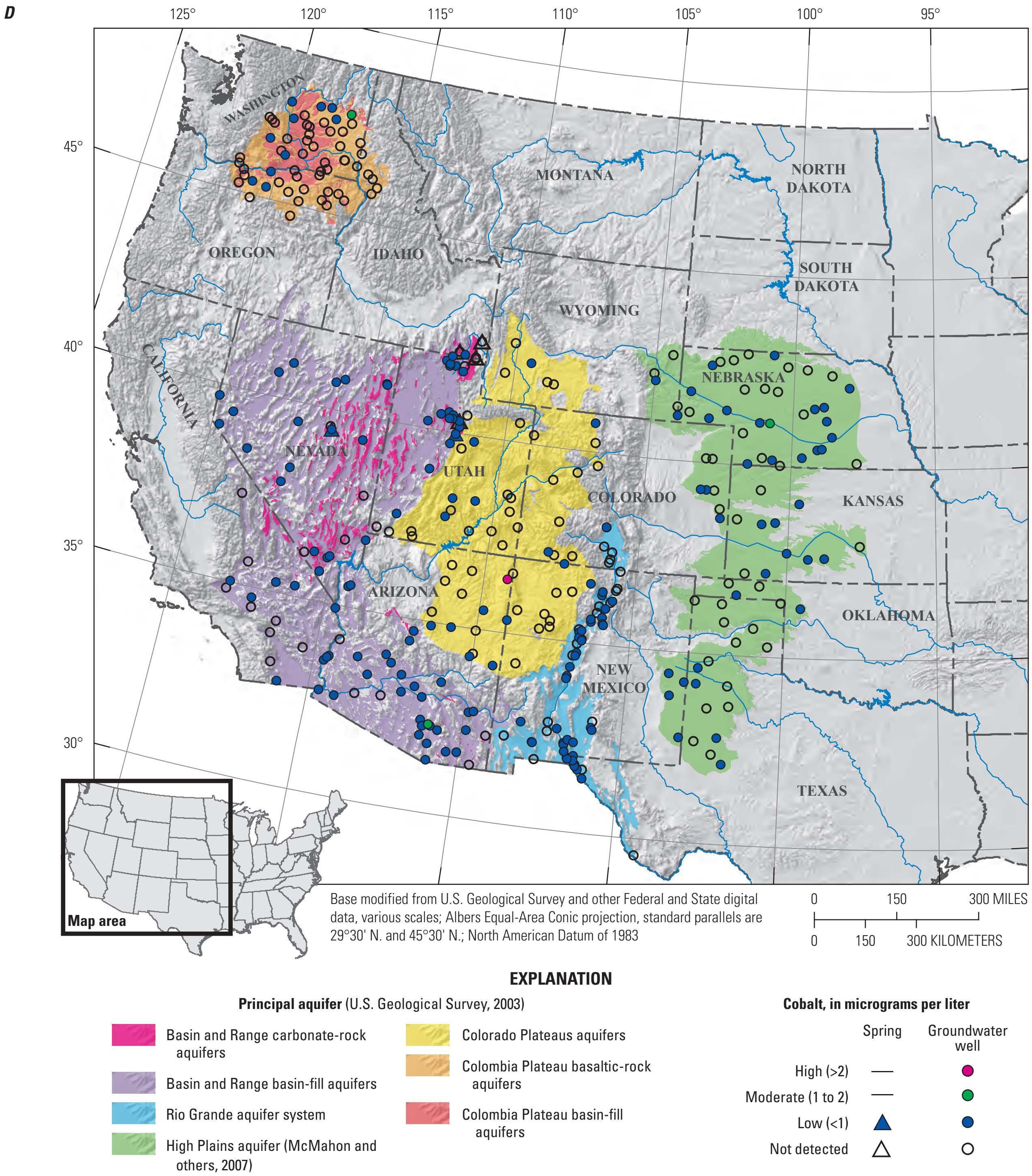
Figure 21. —Continued



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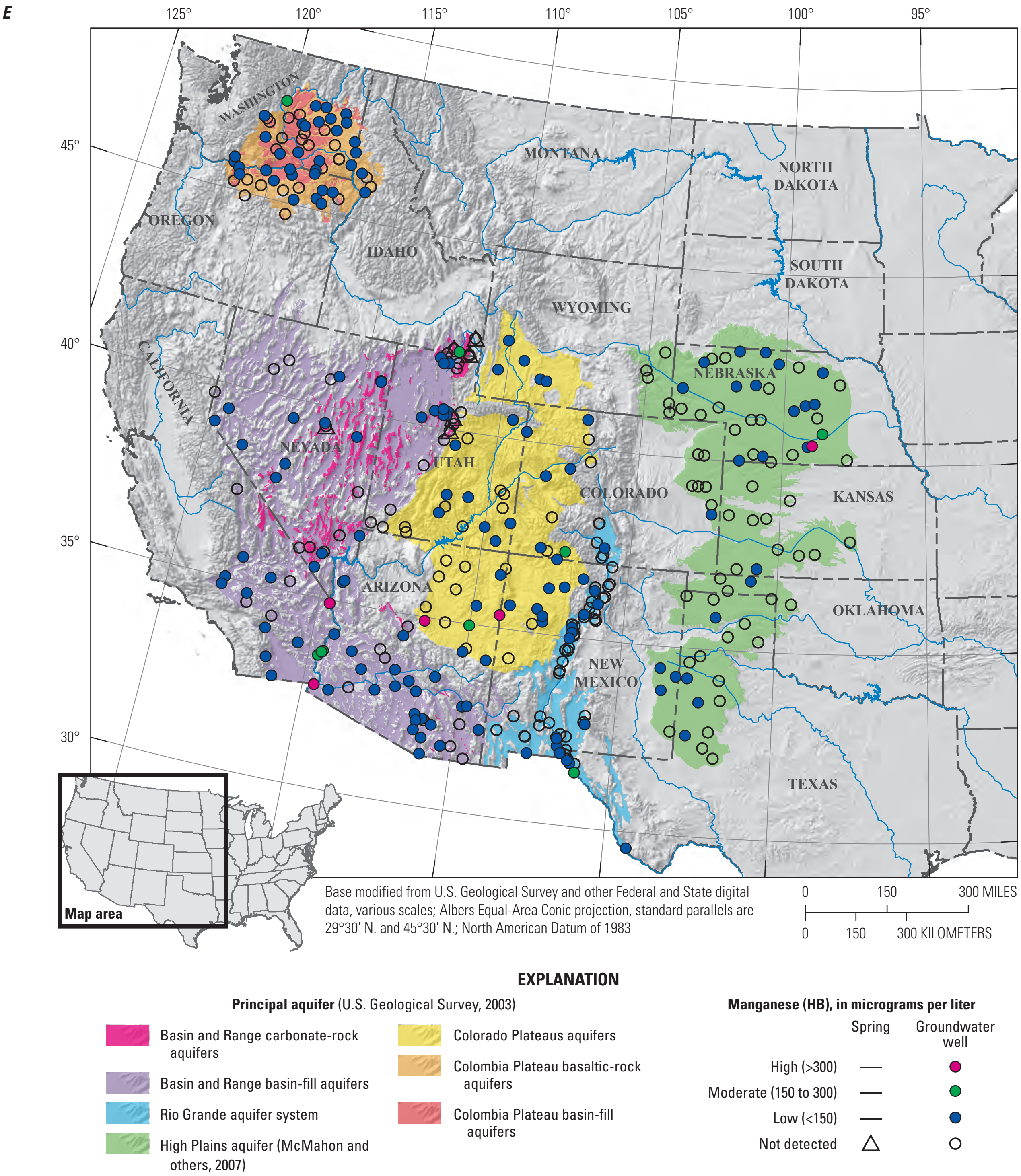

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EXPLANATION

Principal aquifer (U.S. Geological Survey, 2003)

- Basin and Range carbonate-rock aquifers
- Basin and Range basin-fill aquifers
- Rio Grande aquifer system
- High Plains aquifer (McMahon and others, 2007)
- Colorado Plateaus aquifers
- Colombia Plateau basaltic-rock aquifers
- Colombia Plateau basin-fill aquifers

Manganese (HB), in micrograms per liter

	Spring	Groundwater well
High (>300)	—	●
Moderate (150 to 300)	—	●
Low (<150)	—	●
Not detected	△	○

Figure 21. —Continued

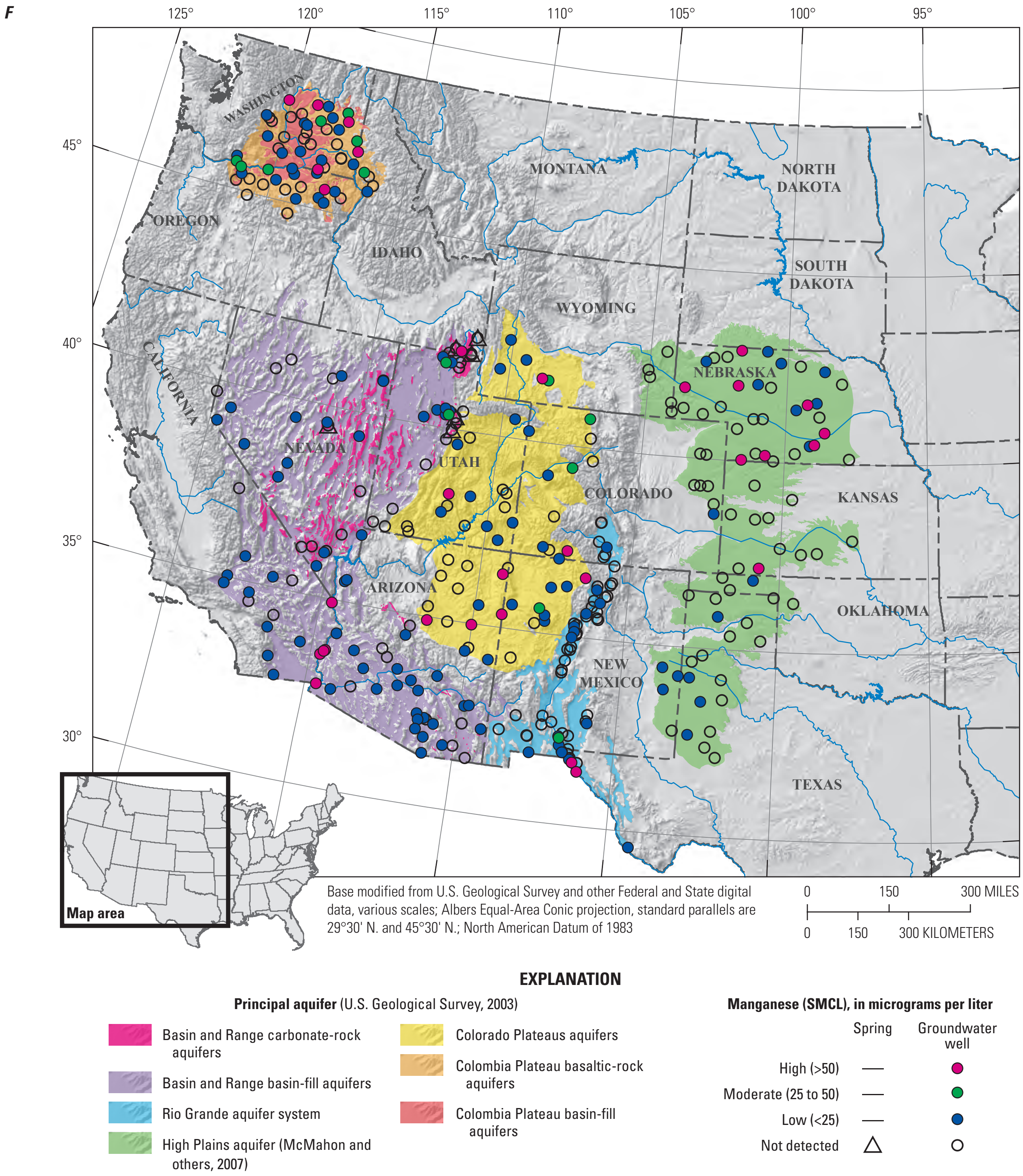

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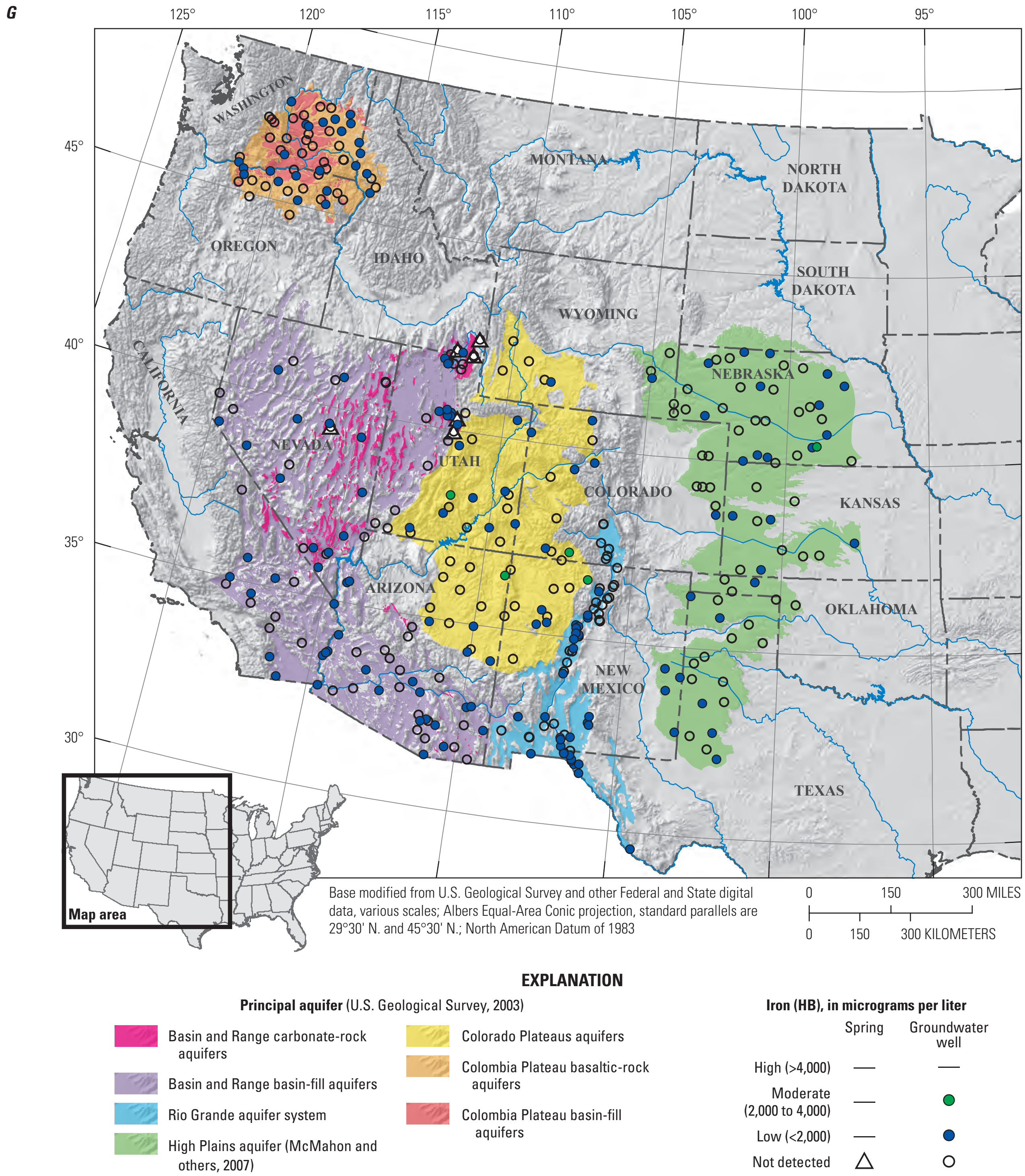
Figure 21. —Continued



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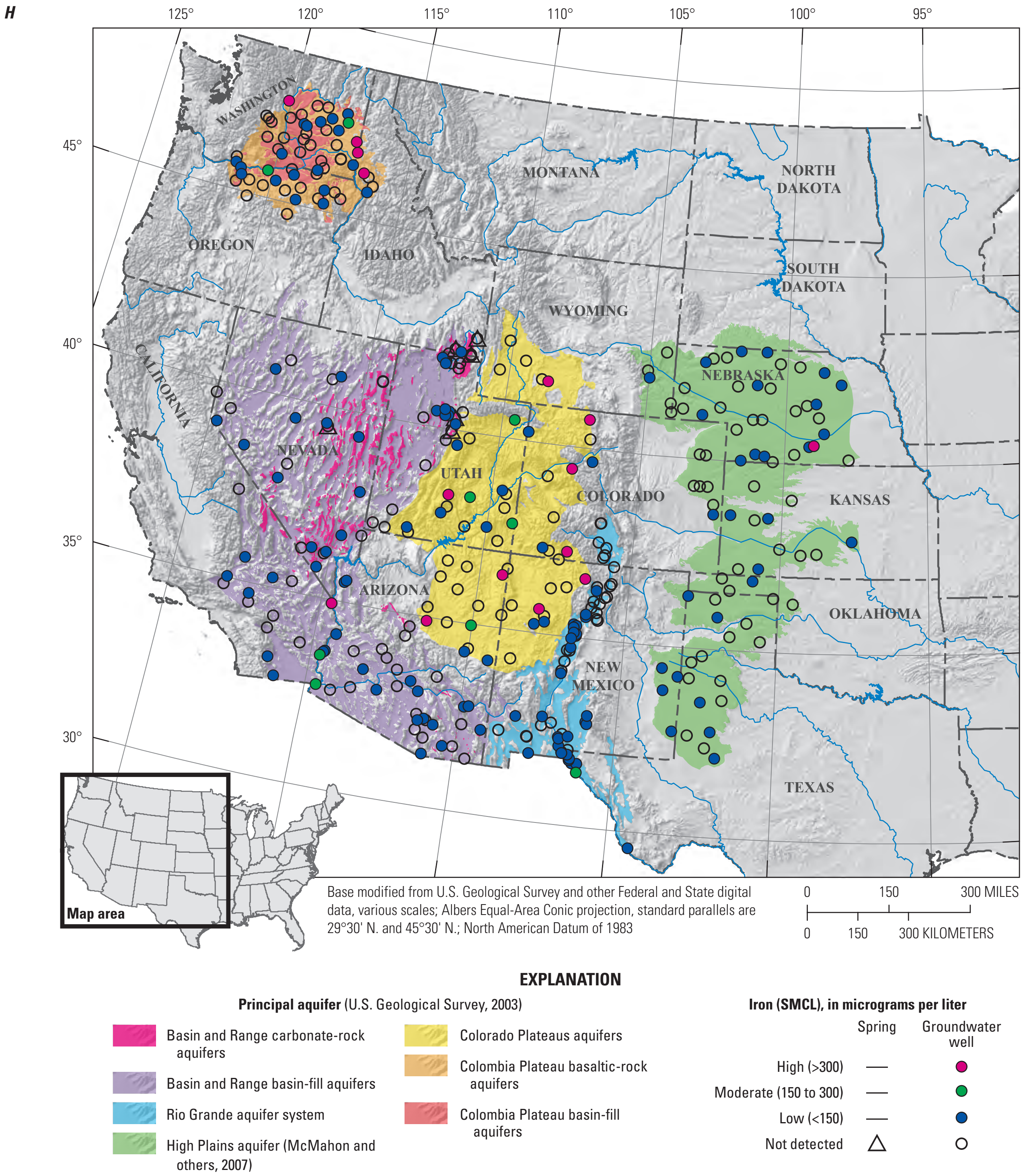

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Figure 21. —Continued

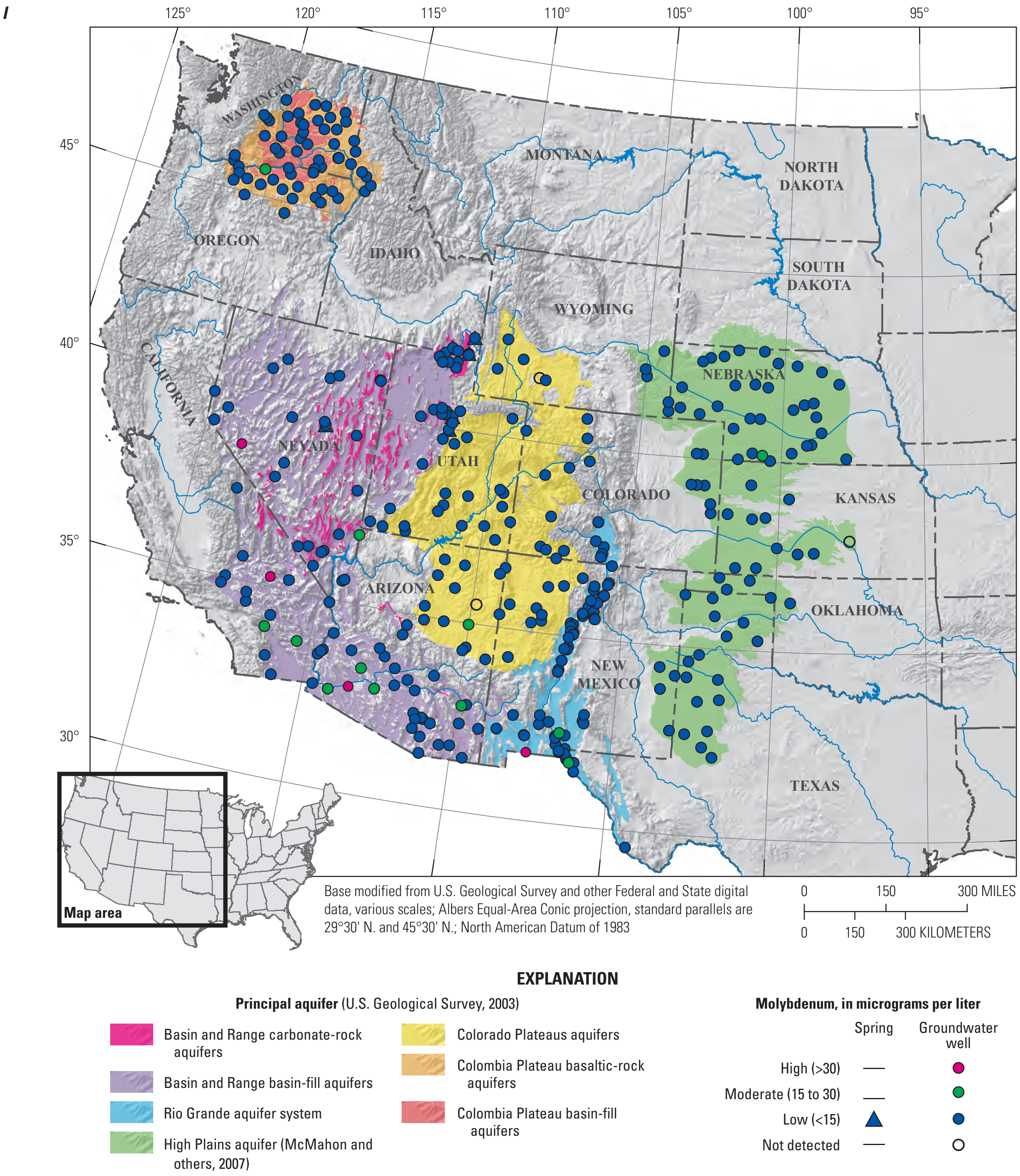

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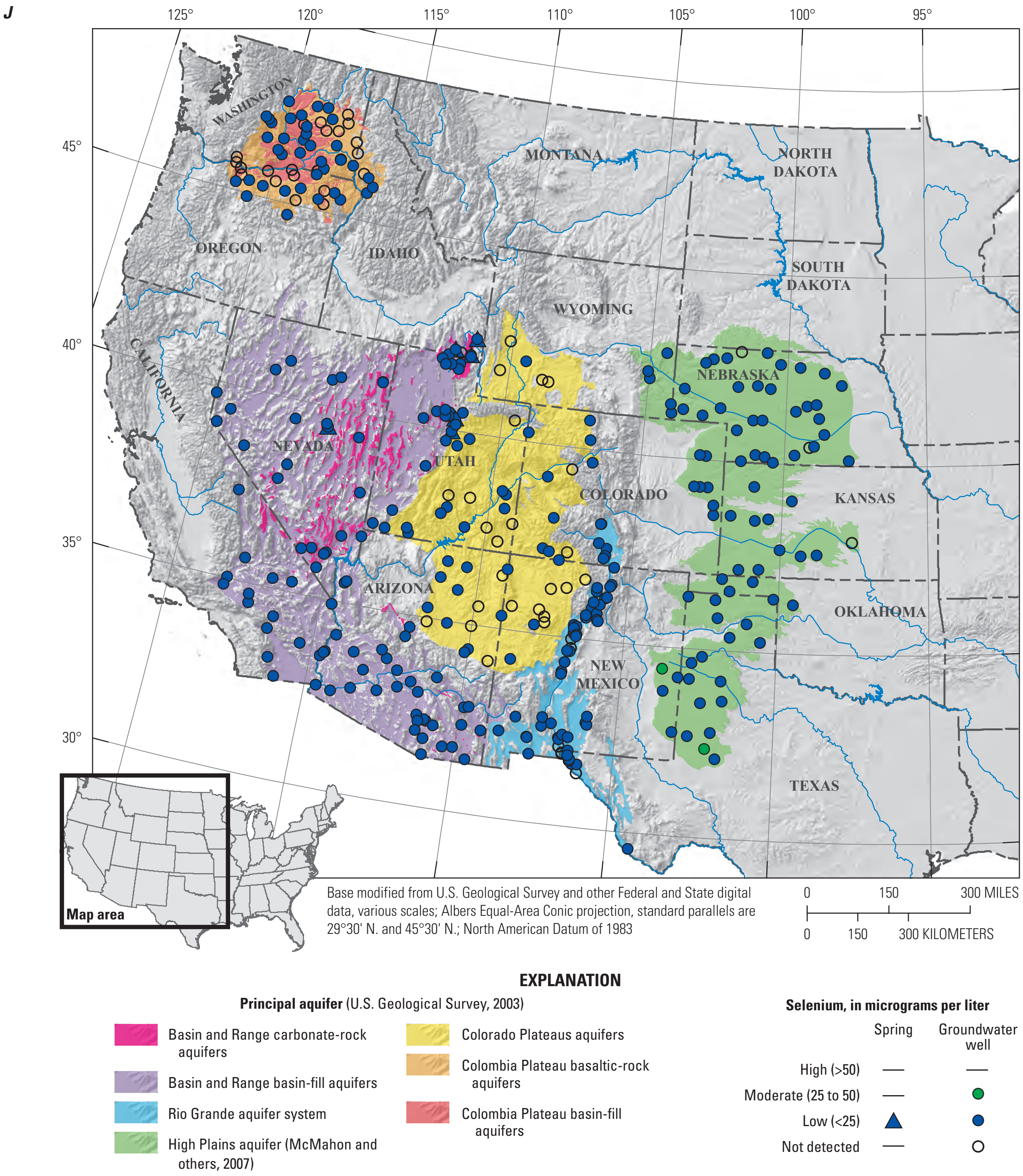
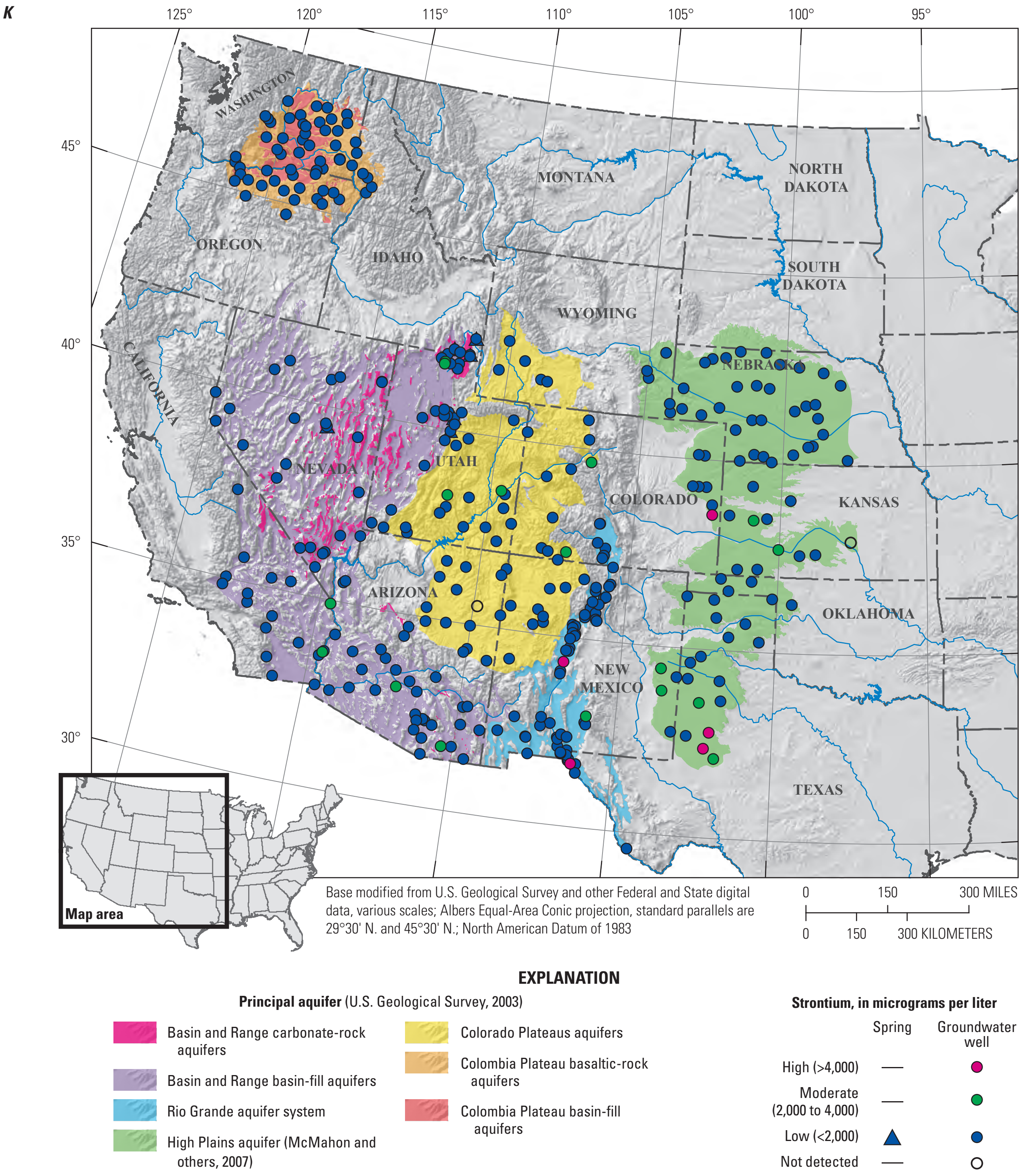
Figure 21. —Continued



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

Figure 21. —Continued



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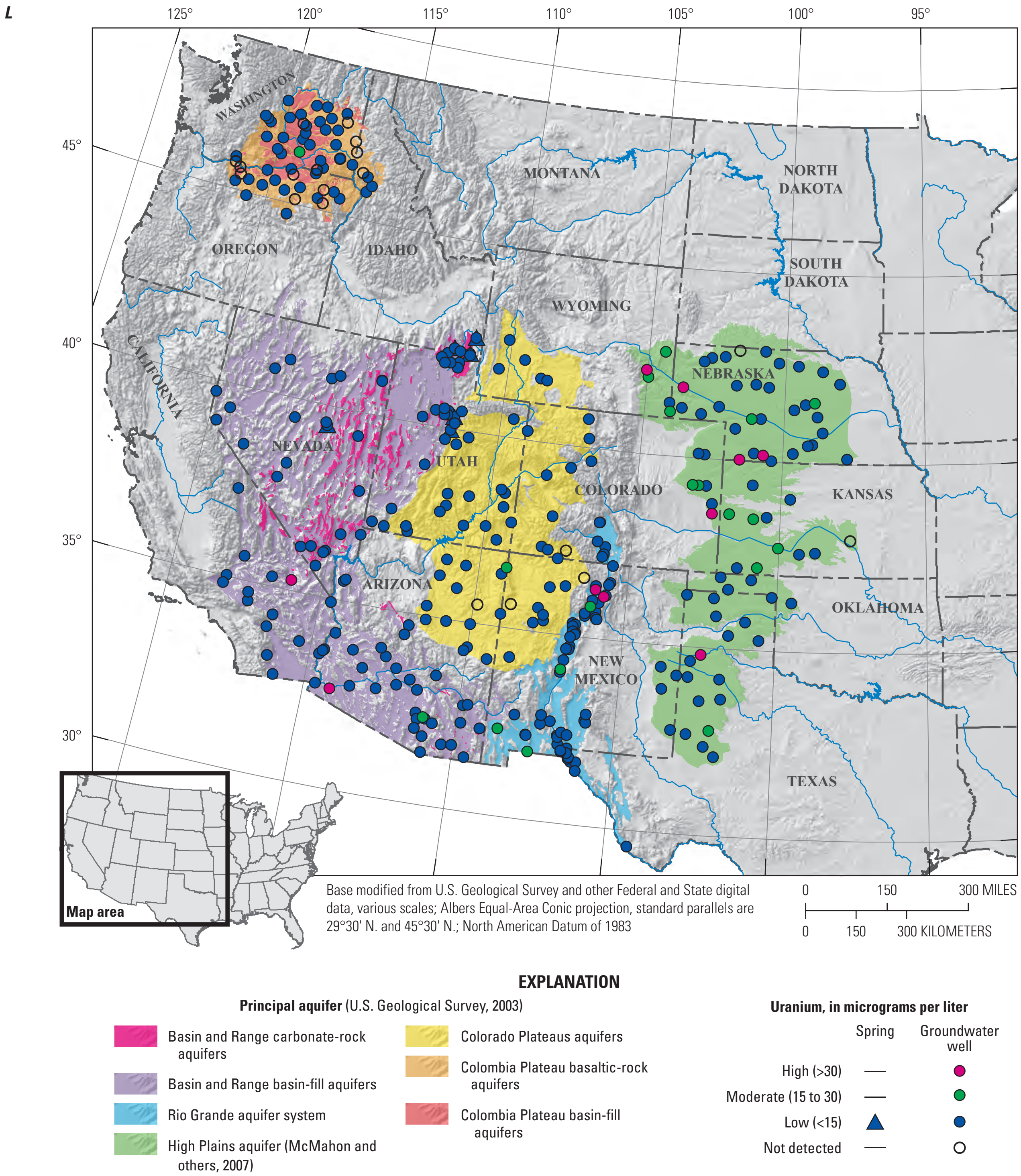


Figure 21. —Continued

The EPA MCL for arsenic in drinking water is 10 µg/L (U.S. Environmental Protection Agency, 2018a). Large regions of the continental United States have groundwater concentrations that exceed the MCL, especially in California and the southwestern states (Welch and others, 2000). Elevated concentrations of arsenic in groundwater generally are not related to high arsenic concentrations in rocks or aquifer sediments, but they are attributed to geochemical conditions that promote arsenic mobility and hydrologic conditions that favor accumulation of arsenic in groundwater (Smedley and Kinniburgh, 2002). Previous studies have identified two geochemical mechanisms associated with the occurrence of elevated arsenic in groundwater: (1) desorption from, or inhibition of sorption to, aquifer materials with increasing pH and (2) release of arsenic from dissolution of iron or manganese oxyhydroxides under iron- or manganese-reducing conditions (Welch and others, 2000; Smedley and Kinniburgh, 2002; McMahon and Chapelle, 2008, and many references therein).

High and moderate arsenic concentrations occurred more often under oxic groundwater conditions at pH values greater than 7.0 relative to anoxic groundwater conditions (fig. 22*A*). Of the 36 samples with high concentrations of arsenic, 31 were oxic. For the oxic samples, pH ranged from 7.0 to 9.3; conversely, in four of the five anoxic samples pH ranged from 8.0 to 8.9—indicating desorption from, or inhibition of sorption to, aquifer materials with increasing pH as an important mechanism for elevated arsenic concentrations. The remaining anoxic, low pH sample also had moderate and high concentrations of manganese and iron, respectively, indicating reductive dissolution of iron or manganese oxides as the potential source of elevated arsenic concentration. The primary mechanism for increasing pH of groundwater under oxic conditions are hydrolysis of silicate minerals or dissolution of calcite, which also increases TDS (Fram and Belitz, 2012). In the high pH samples, there was no difference in arsenic concentration among redox categories, suggesting that at pH values greater than 7.0, arsenic mobility could be less controlled by redox (fig. 22*A*). A similar finding was reported by Ayotte and others (2011) in a national-scale evaluation of trace elements grouped by geologic material that included unconsolidated sand and gravel, sandstone, carbonate rock, and basaltic and other volcanic-rock lithologies.

The accumulation of arsenic in groundwater generally requires favorable hydrologic conditions. Groundwater with long residence time allows for reactions to occur with aquifer materials, minimizing the amount of flushing and maximizing reaction times (Smedley and Kinniburgh, 2002). High arsenic concentrations were mostly associated with premodern or mixed groundwater age categories and elevated TDS concentrations (greater than 500 mg/L). Groundwater flow is often from the basin margins toward low-lying valley floors in long flow paths with slow flow rates, resulting in sufficient time for chemical reactions to release arsenic from the sediments (Anning and others, 2012). Arsenic concentrations often increase as groundwater moves from mountain fronts to lowlands in the center of the basins (Anning and others, 2012). Basins that have no natural surface outflow, that is, water only leaves the basins through evapotranspiration or deep groundwater underflow, are particularly vulnerable to accumulation of arsenic and other constituents from geologic sources (Welch and others, 2000; McMahon and Chapelle, 2008; Bexfield and others, 2011). Significant correlations of arsenic with explanatory factors in the Basin and Range basin-fill aquifers and Rio Grande aquifer system reflected geochemical and hydrologic conditions that favor arsenic mobility and accumulation of concentrations in groundwater (fig. 23*A*). For example, in these two PAs, arsenic was positively correlated with TDS and (or) pH and negatively correlated with aridity index and well elevation. Additionally, the positive correlation between arsenic and natural land use is consistent with the hydrogeologic nature of natural land use; natural land use in the southwestern United States tends to have relatively low rates of groundwater recharge rate and relatively high rates of evapotranspiration that likely correspond to relatively low flushing of solutes out of a basin (as compared to urban and agricultural land use with higher rates of recharge; Anning and others, 2012).

In the Basin and Range carbonate-rock aquifers, arsenic was positively correlated with TDS, and negatively correlated with aridity index and well elevation. These relations could, in part, reflect the inverse relation between TDS and well elevation in this PA (table 6*A*). Groundwater recently recharged from precipitation occurring at higher well elevations generally has higher aridity index values and relatively low TDS. Recharge occurring at these higher elevations has not had sufficient residence time for dissolution of carbonate minerals to produce the increased pH values (and TDS) that favor arsenic mobility. Premodern groundwater age also correlated with TDS in the Basin and Range carbonate-rock aquifers (table 5).

In the Columbia Plateau basaltic-rock aquifers, three of the four samples with moderate or high arsenic concentrations occurred with oxic groundwater conditions and elevated TDS values (fig. 22*A, B*). In this PA, arsenic also was positively correlated with dissolved oxygen and negatively correlated with the aridity index (fig. 23*A*). Arsenic concentrations were not correlated with potential explanatory factors in the High Plains aquifer and had slight negative correlation with TDS in the Colorado Plateaus aquifers. Elevated arsenic concentrations in the Colorado Plateaus aquifers alternatively could be associated with coal deposits; the Colorado Plateaus Province hosts large coal-bearing strata (Kirschbaum and Biewick, 2016). In 2016, the Colorado Division of Reclamation, Mining and Safety reported nearly 13 million short tons of coal production that provided more than 60 percent of Colorado's electricity generation (Colorado Division of Reclamation, 2016). Arsenic in bituminous coal occurs primarily in pyrite, a common mineral composed of iron and sulfur, which can contain a small amount of arsenic (Kolker and others, 2006). Pyrite in coal rapidly oxidizes to arsenate, which is readily leached by precipitation and groundwater (Huggins and others, 2002).

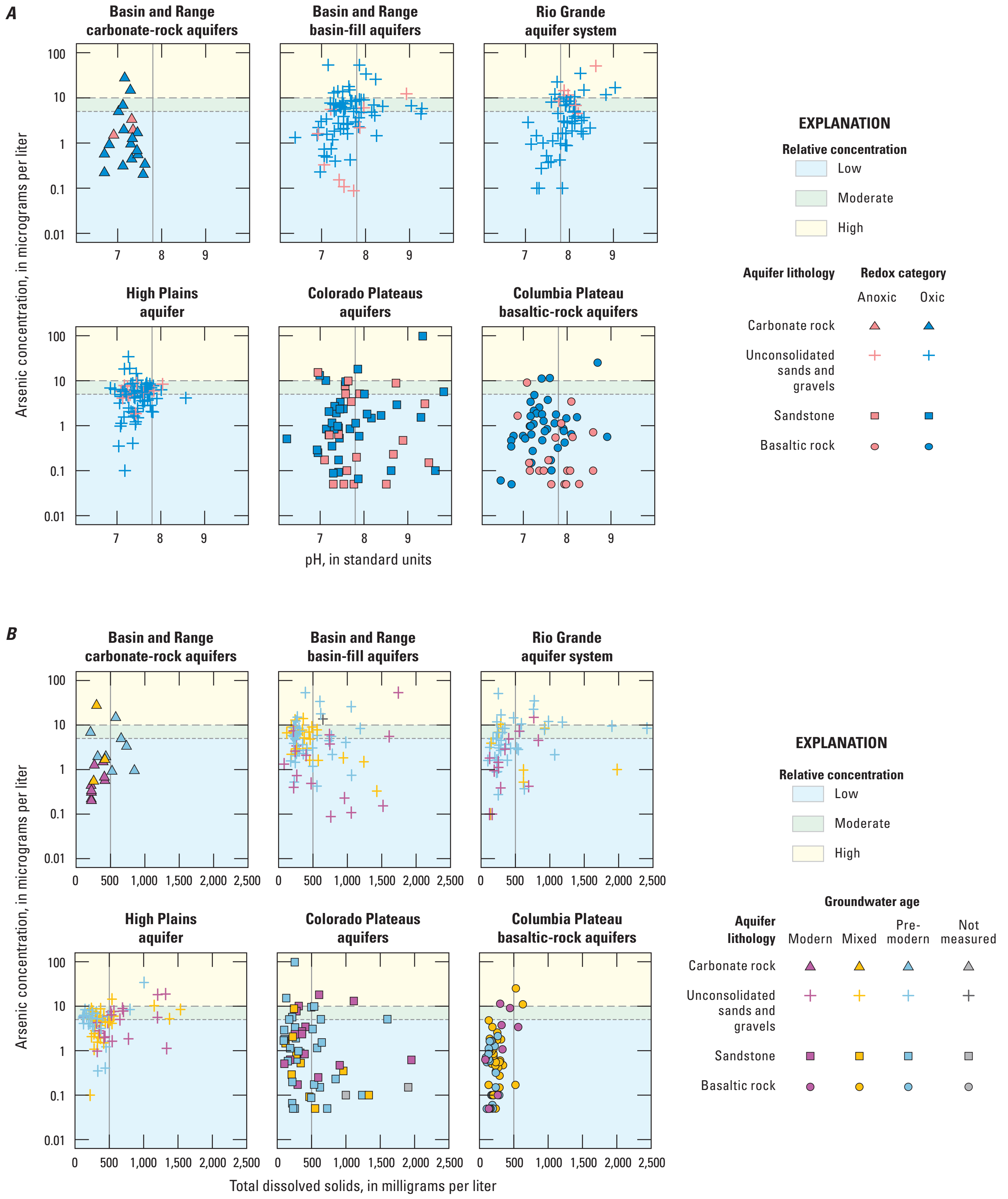


Figure 22. Arsenic concentrations by *A,* pH, redox, and aquifer lithology; and *B,* total dissolved solids, groundwater age, and aquifer lithology in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

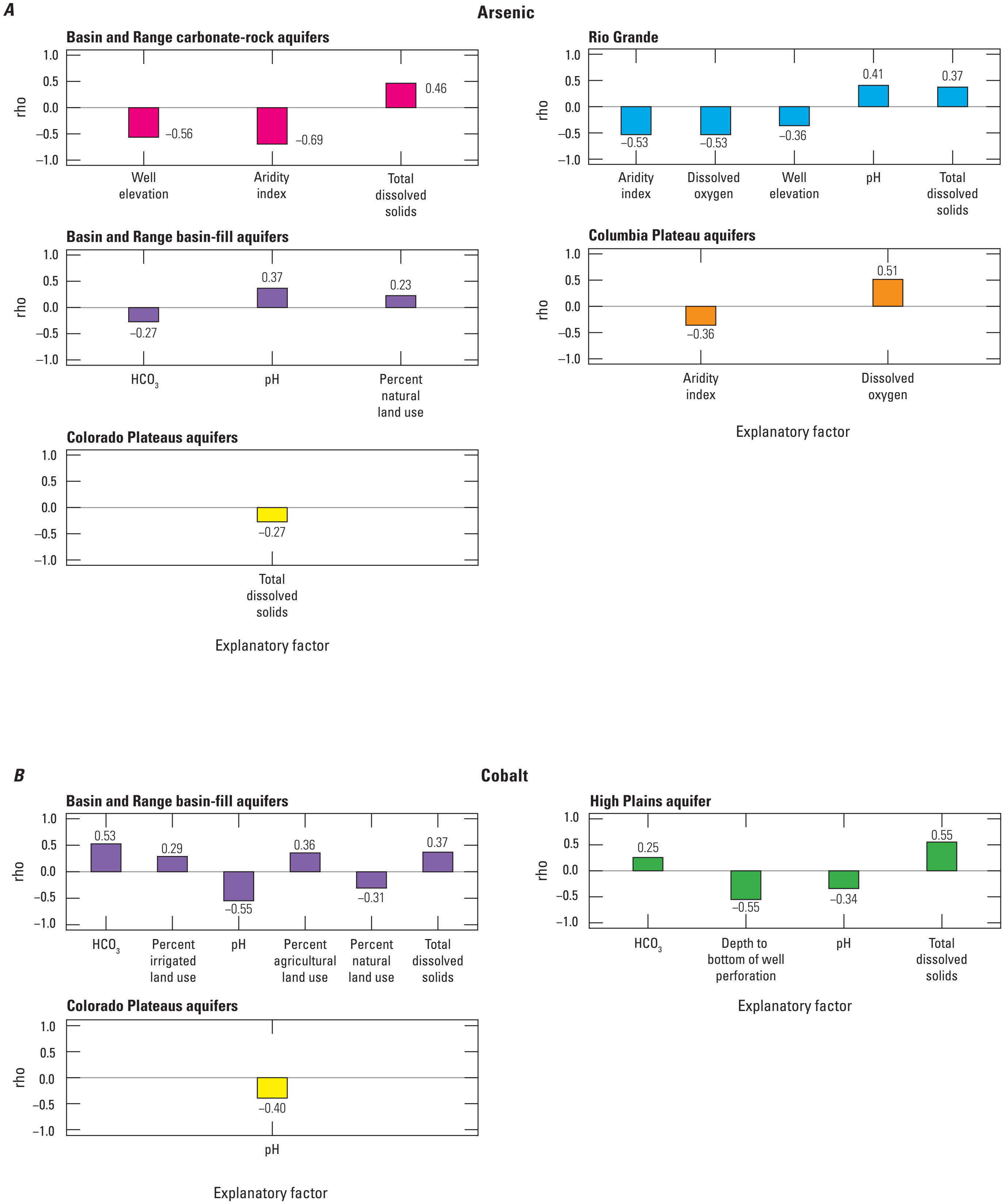
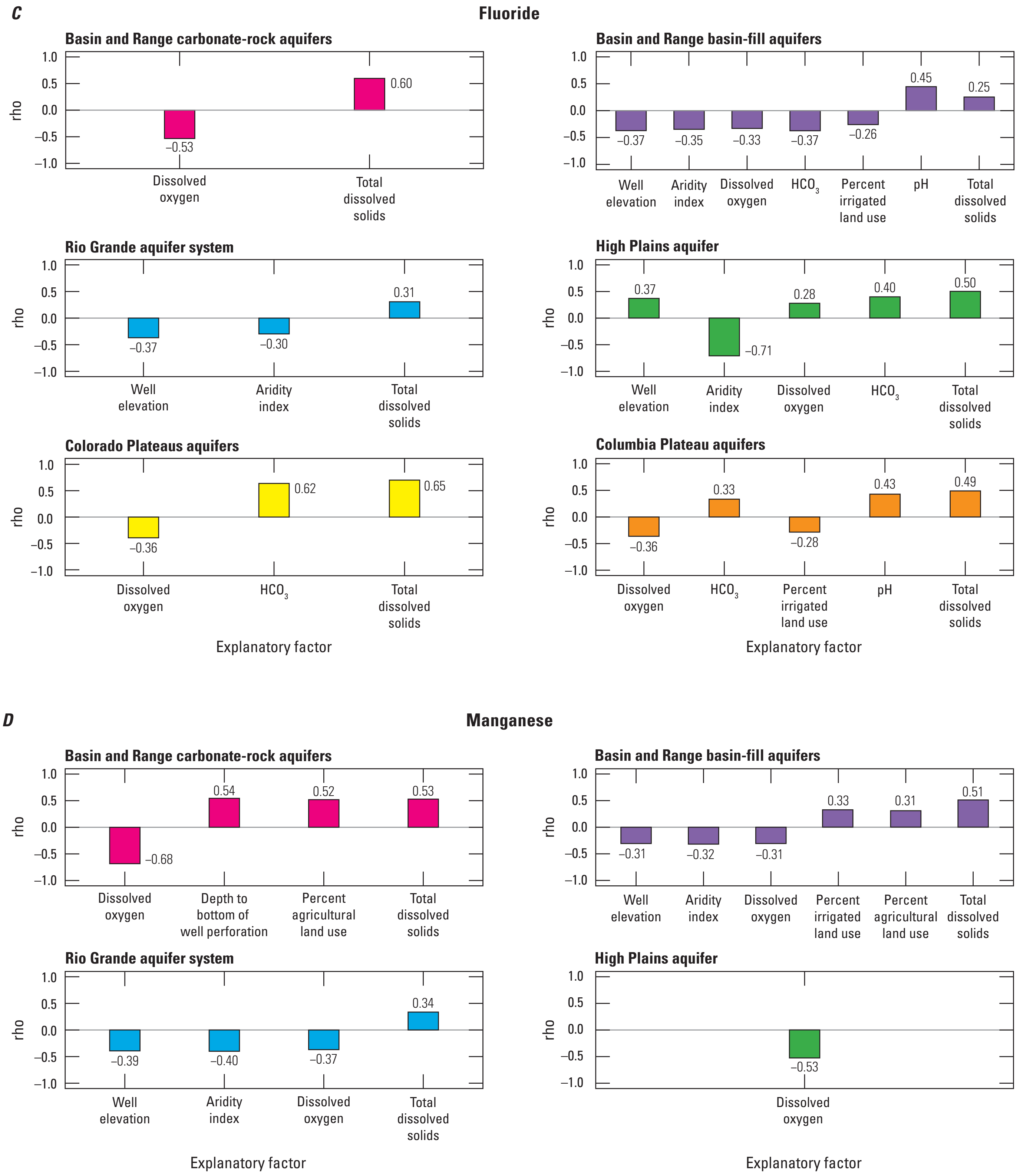


Figure 23. Spearman's rho results for trace elements *A,* arsenic; *B,* cobalt; *C,* fluoride; *D,* manganese; *E,* iron; *F,* molybdenum; *G,* selenium; *H,* strontium; and *I,* uranium in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.



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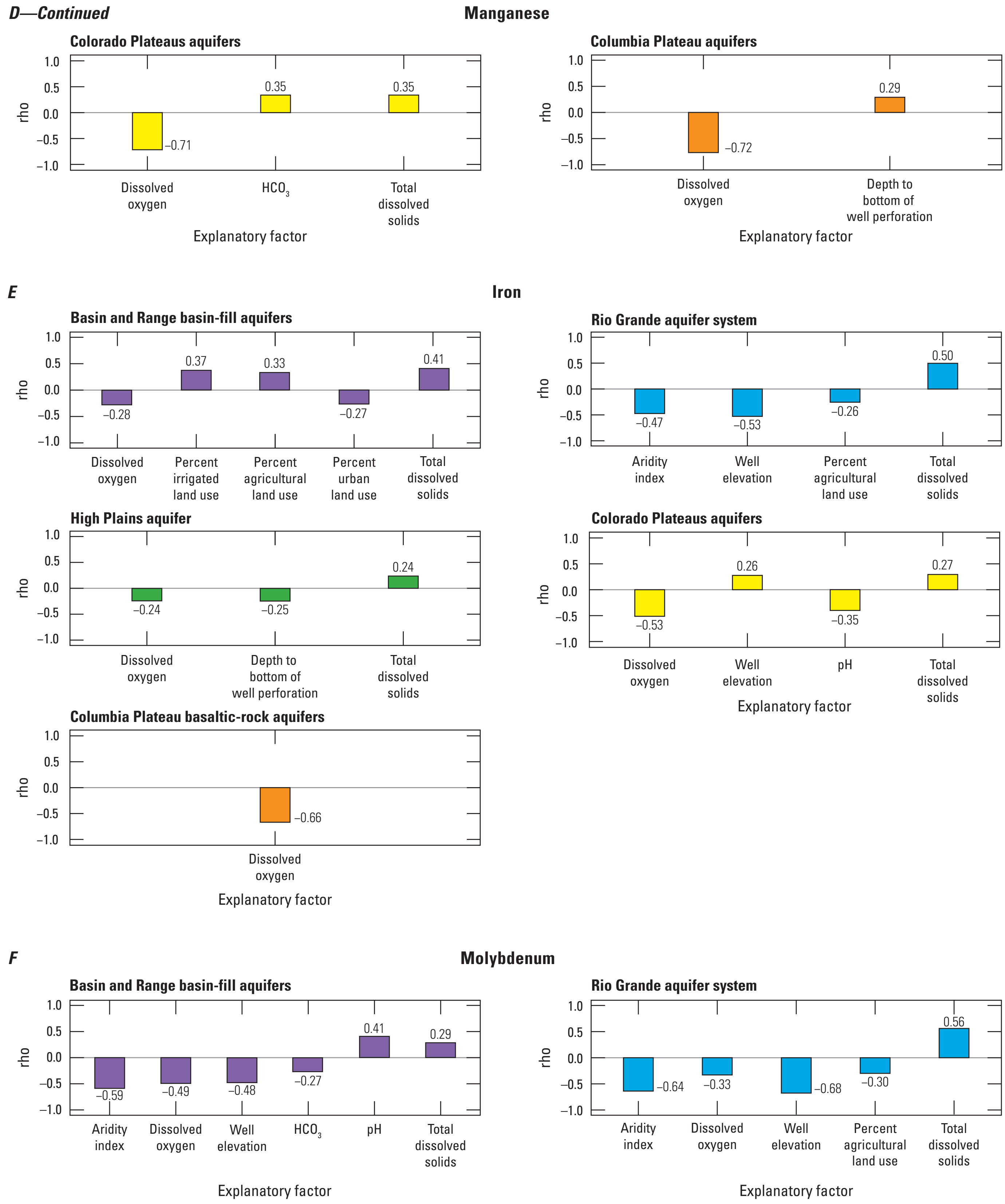
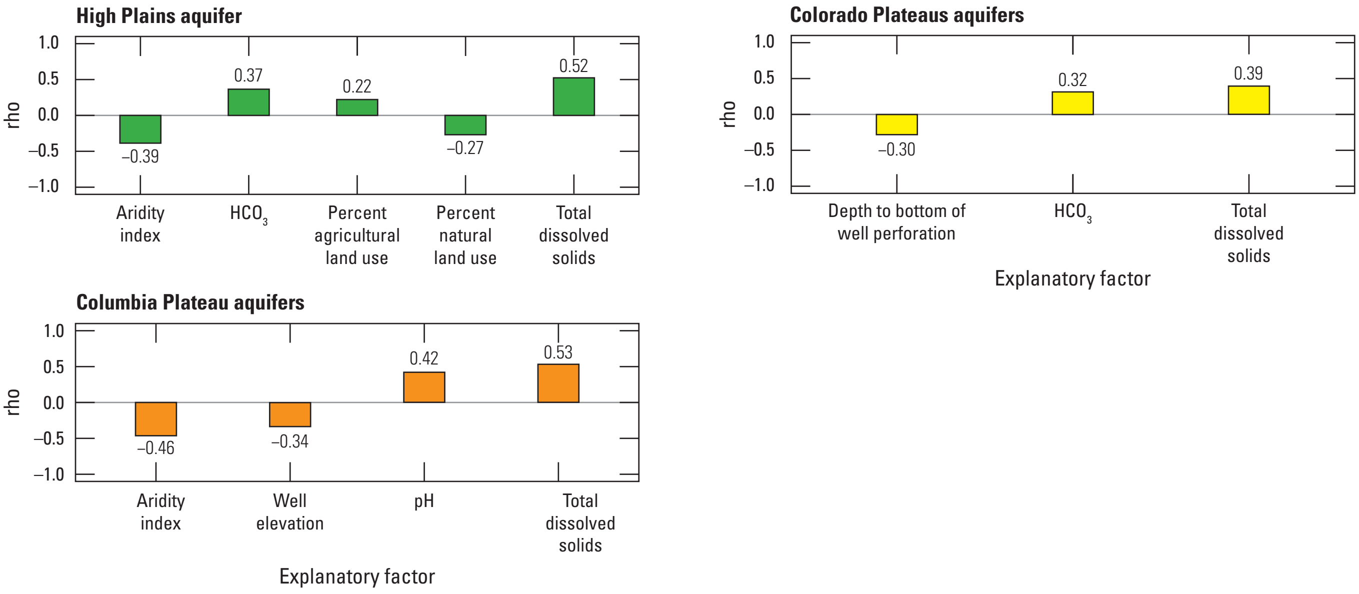
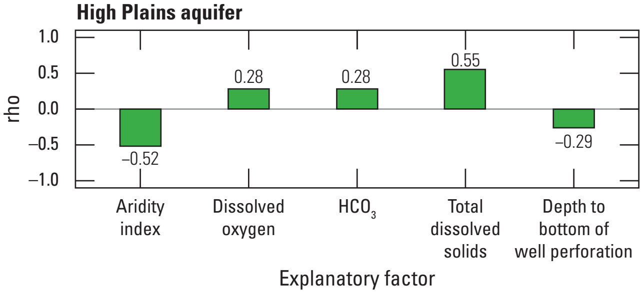


Figure 23. —Continued

F—Continued **Molybdenum**



G **Selenium**



H **Strontium**

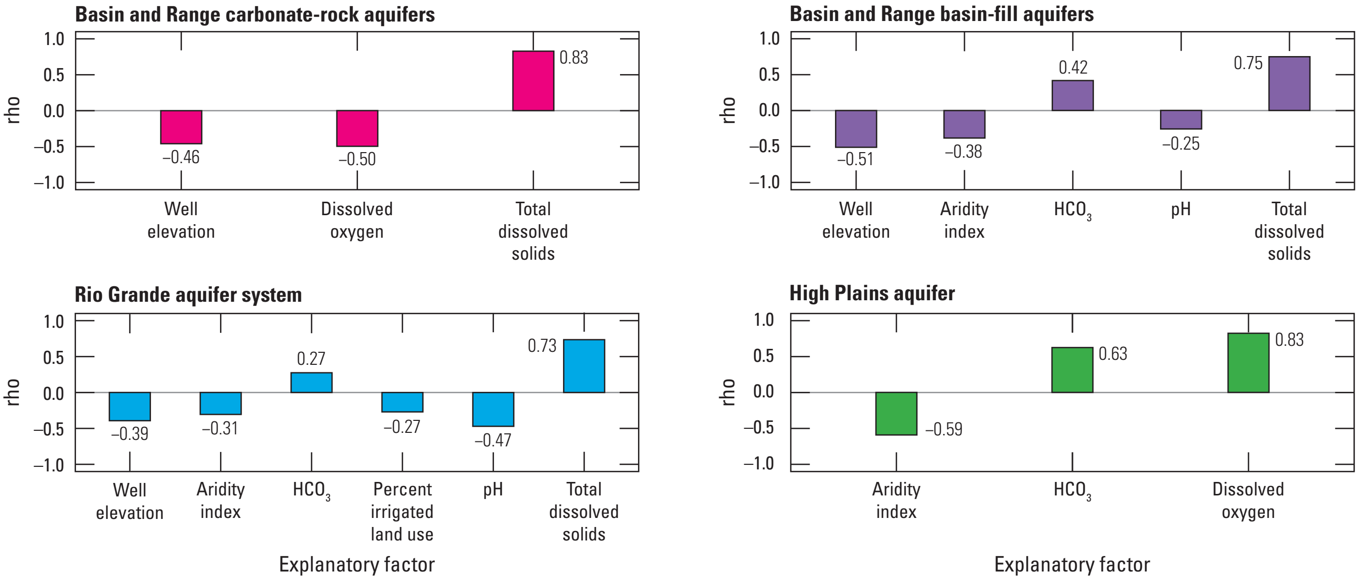
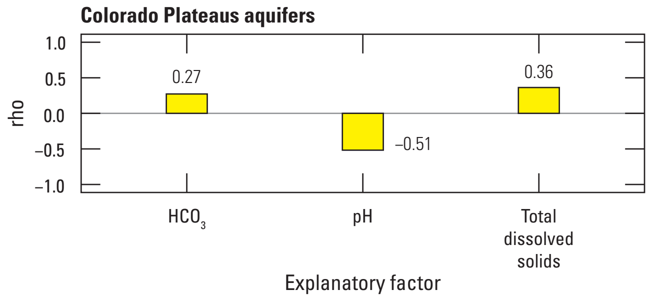


Figure 23. —Continued

H—Continued **Strontium**



I **Uranium**

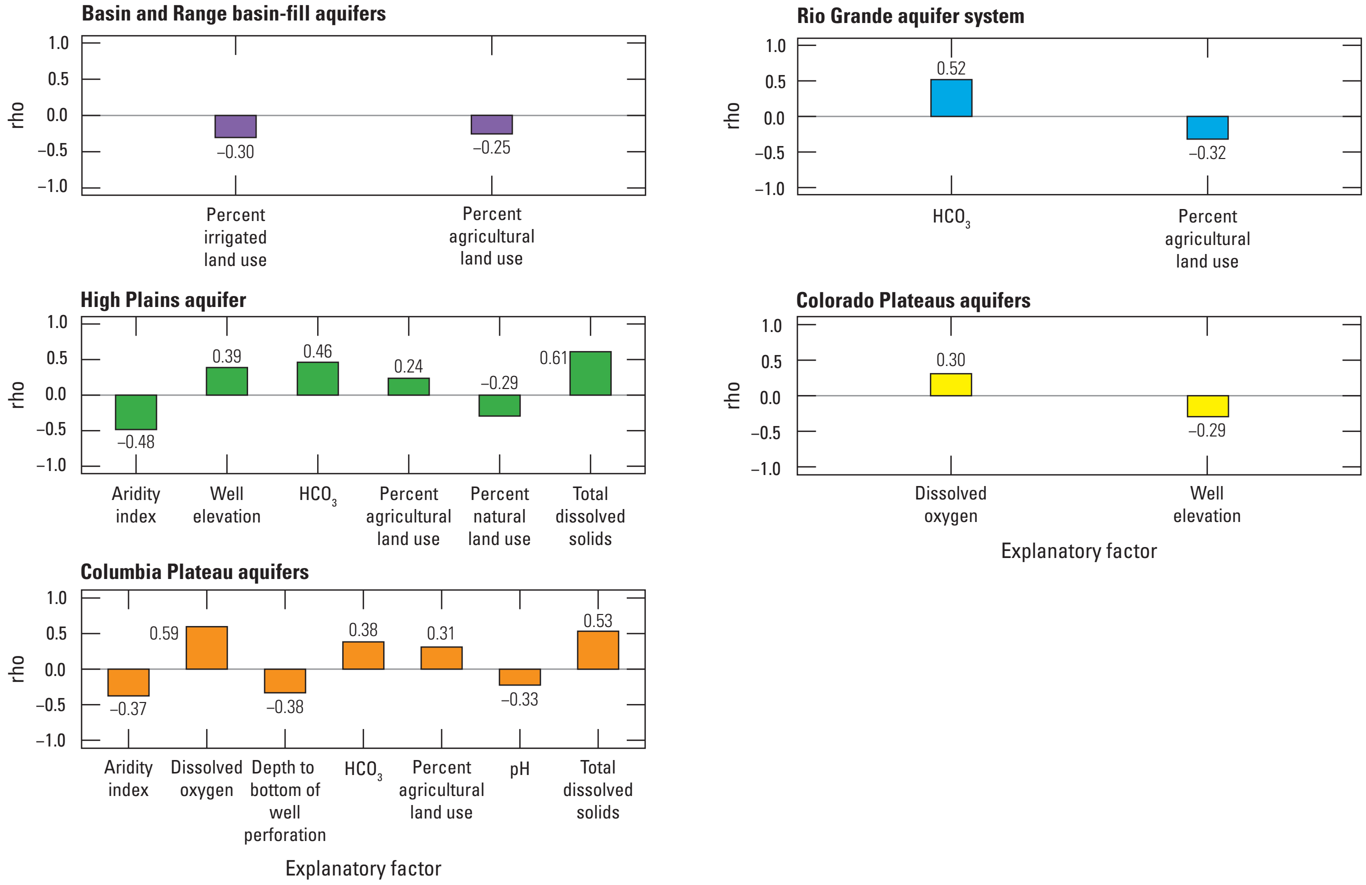


Figure 23. —Continued

Factors Affecting Cobalt

Cobalt (Co) is a naturally occurring trace element found in relatively low abundance in the Earth's crust and in natural waters. It can substitute for iron in ferromagnesian rock minerals (Hem, 1985). Cobalt was historically produced as a by-product of nickel and copper mining, but more recently, worldwide production of mined cobalt has increased because of the growth of rechargeable batteries and aerospace industries (Ma and Hooda, 2010; U.S. Geological Survey 2018b). In 2017, worldwide production of cobalt was approximately 110,000 million tons (U.S. Geological Survey, 2018b). Apart from mining and smelting activities, cobalt can enter soils from phosphorus-containing fertilizers, sewage sludges, and atmospheric deposition (Ma and Hooda, 2010). The behavior of cobalt in soils is largely influenced by the presence of manganese and iron oxides. Coprecipitation or adsorption by these oxides is an important factor in controlling cobalt in natural water (Hem, 1978, 1980). The solubility of cobalt, like other cation trace elements, decreases with increasing pH (Ma and Hooda, 2010).

Cobalt is an essential element for humans as a constituent of vitamin B_{12} (Agency for Toxic Substances and Disease Registry, 2004). Cobalt has a HBSL of 2 µg/L (U.S. Geological Survey, 2018a). The concentration of cobalt in surface and groundwater in the United States generally is low—between 1 and 10 parts per billion (ppb) in populated areas; in most drinking water, cobalt concentrations are less than 1–2 ppb (Agency for Toxic Substances and Disease Registry, 2004). Elevated cobalt concentrations were infrequent: moderate concentrations occurred in 2 percent or less of the Basin and Range basin-fill aquifers, High Plains aquifer, and Columbia Plateau basaltic-rock aquifers (tables 9*B, D, F,* respectively); high concentrations occurred in 2 percent of the Colorado Plateaus aquifers (fig. 20; table 9*E*). Cobalt was inversely correlated with pH and positively correlated with TDS and HCO_3 (fig. 23*B*).

Factors Affecting Fluoride

Fluoride (the anion of the element fluorine; F) in groundwater has natural and anthropogenic sources. Natural sources include the dissolution of fluoride-bearing minerals such as fluorite and fluorapatite (Fram and Belitz, 2012). The main anthropogenic source of fluoride in water is the fluoridation of public water supplies through the addition of sodium fluoride or hexafluorosilic acid during drinking-water treatment. The addition of fluoride to drinking water is a public health measure to reduce tooth decay. Fluorine is an important nutrient for the structure of teeth and bones in higher life forms (Hem, 1985). There are two water-quality benchmarks for fluoride, a regulatory HB benchmark of 4 mg/L and a non-regulatory SMCL benchmark of 2 mg/L (U.S. Environmental Protection Agency, 2018a, 2018b). Fluoride was evaluated herein for both benchmarks (fig. 20). Chronic exposure to fluoride in drinking water above the HB benchmark can result in skeletal bone disorders or tooth discoloration (U.S. Environmental Protection Agency, 2018a). The SMCL benchmark is a guideline for an upper boundary where high fluoride levels occur naturally and is based on balancing the beneficial effects of protection against tooth decay and undesirable effects of tooth discoloration (U.S. Environmental Protection Agency, 2018b).

High concentrations of fluoride relative to the HB benchmark (4 mg/L) were measured in less than 7 percent of samples and occurred only in the unconsolidated sand and gravel PAs—the Basin and Range basin-fill aquifers, the Rio Grande aquifer system, and the High Plains aquifer (fig. 21*B*; tables 9*B–D*). High fluoride concentrations relative to the SMCL benchmark (2 mg/L) occurred in all PAs (fig. 21*C*) with the greatest aquifer proportions (10–15 percent) occurring in unconsolidated sand and gravel aquifers (tables 9*B–D*) and the carbonate-rock aquifers (table 9*A*); high concentrations were less frequent (5 percent or less) in sandstone and basaltic-rock lithologies (Colorado Plateaus aquifers and Columbia Plateau basaltic-rock aquifers; tables 9*E, F*).

Fluoride had mostly similar significant correlations among selected potential explanatory factors across all PAs (fig. 23*C*), with the most common being concentrations of TDS, dissolved oxygen, and HCO_3. Differences in positive or negative correlations among these explanatory factors reflect relations of groundwater age, pH, and calcium and fluoride concentrations among the different aquifer lithologies (figs. 24*A, B*). Fluoride concentrations in groundwater typically are limited by the low solubility of fluorite (CaF_2) in waters containing calcium; that is, lower calcium concentrations result in higher fluoride concentrations because of the dissolution of fluorite (Nordstrom and others, 1989; Kim and Jeong, 2005). Elevated fluoride concentrations are associated with groundwater with long residence times as a result of increased interaction with aquifer materials, higher TDS concentrations, and increases in pH that result from mineral reactions contributing to the precipitation of calcite. The unconsolidated sand and gravel aquifers (Basin and Range basin-fill aquifers, Rio Grande aquifer system, and High Plains aquifer) and sandstone aquifers (Colorado Plateaus aquifers) had the highest fluoride concentrations at pH values greater than 7.0 (fig. 24*A*) and low calcium concentrations (fig. 24*B*). Groundwater compositions that primarily are controlled by the weathering of silicate minerals tend to be alkaline (as those reactions consume acidity), which is consistent with the occurrence of alkaline conditions associated with unconsolidated sand and gravel and volcanic rock lithologies of the western U.S. (DeSimone and others, 2015). In contrast, groundwater compositions that primarily are controlled by carbonate reactions, which also consume acidity, tend to have higher concentrations of HCO_3 and calcite (DeSimone and others, 2015). In the Basin and Range carbonate-rock aquifers, two samples with high concentrations relative to the SMCL benchmark were alkaline with relatively high calcium concentrations.

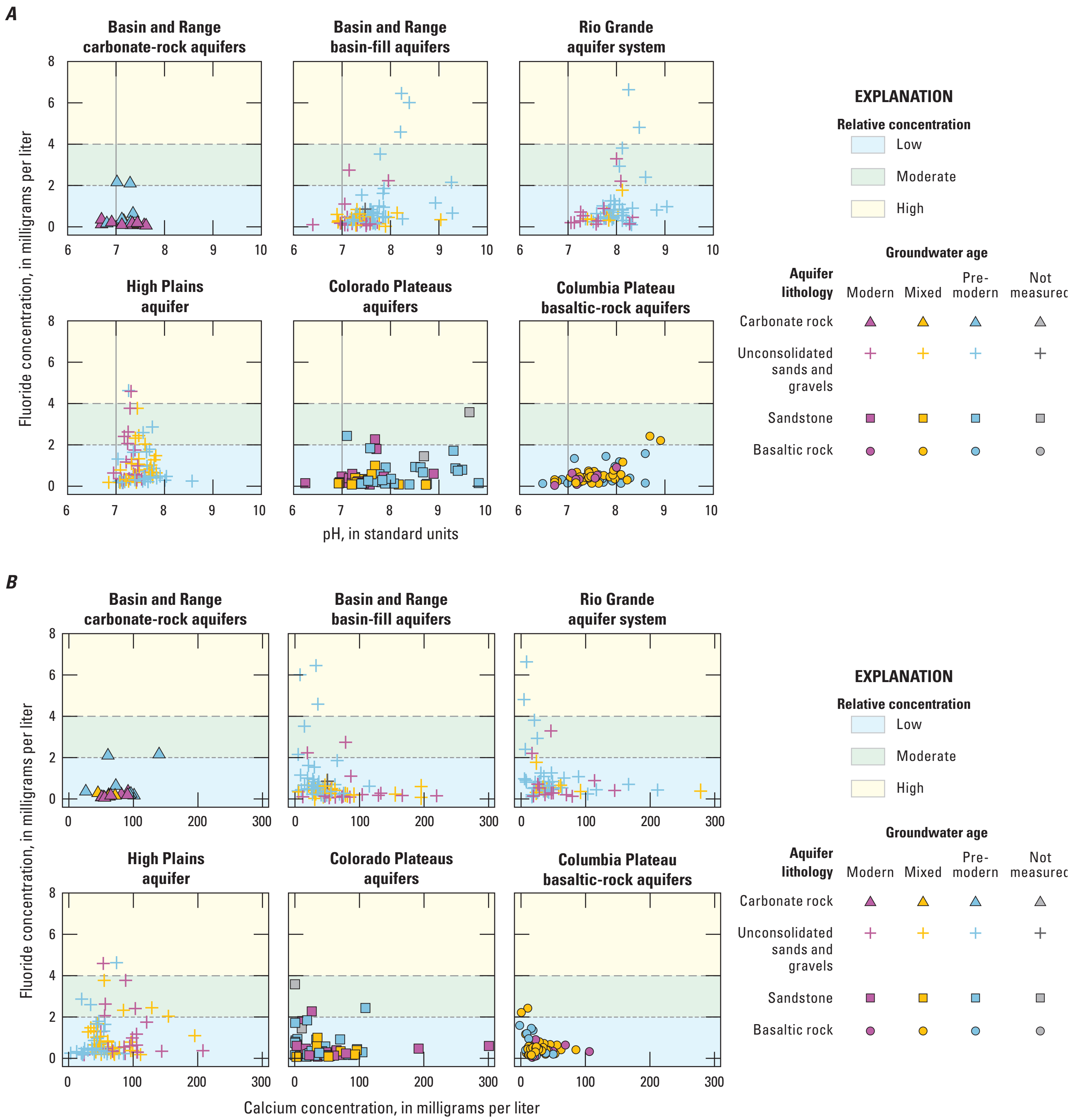


Figure 24. Fluoride concentrations by *A,* pH, aquifer lithology, and groundwater age; and *B,* calcium concentrations, aquifer lithology, and groundwater age in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Fluoride concentration was negatively correlated with well elevation and aridity index in the Basin and Range basin-fill aquifers and Rio Grande aquifer system (fig. 23*C*); these PAs had a combination of relatively high aridity and lower elevations. In the High Plains aquifer, fluoride also was negatively correlated with aridity index, but, conversely, was positively correlated with well elevation; as noted earlier, these correlationslikely reflects the climate pattern overlying the High Plains aquifer, where precipitation and elevation gradients are directionally opposite. Negative correlations with percentage of irrigated land use in the Basin and Range basin-fill aquifers and the Columbia Plateau basaltic-rock aquifers indicated that fluoride concentrations were lowest in areas of irrigated land use, where flushing of solutes associated with higher groundwater recharge likely occurs relative to natural land use.

Factors Affecting Manganese and Iron

Sources of manganese and iron in groundwater include dissolution and weathering of minerals in soils, sediments, and rocks. Manganese and iron are discussed together because manganese and iron-oxide minerals both commonly coat mineral and sediment grains, and manganese commonly substitutes for iron in silicate and oxide minerals (Fram, 2017). Both metals participate in redox processes and their solubilities are strongly dependent on groundwater redox conditions (Hem, 1985). Manganese (VI) and iron (III) occur in oxidizing conditions, whereas manganese (II) and iron (II) occur in reducing conditions. The reduced species are significantly more soluble than the oxidized species (Hem, 1978). Anthropogenic sources of manganese include municipal wastewater discharges, sewage sludge, mining and mineral processing, emissions from alloy, steel, and iron production, and combustion of fossil fuels (Howe and others, 2004). Anthropogenic sources of iron include the iron and steel industry, sewage, and dust from mining (Reimann and de Caritat, 1998).

Manganese and iron are considered essential nutrients for the human body at low levels, but exposures at high levels are toxic (U.S. Department of Human Health Services, 2012). Manganese has two benchmarks: a HBSL of 300 µg/L (Norman and others, 2018; U.S. Geological Survey, 2018a) and a SMCL of 50 µg/L (U.S. Environmental Protection Agency, 2018b). Iron also has two benchmarks: a HBSL of 4,000 µg/L (Norman and others, 2018; U.S. Geological Survey, 2018a) and a SMCL of 300 µg/L (table 2). Manganese and iron, when at concentrations above their SMCL benchmarks, are considered nuisance constituents in drinking water, causing unpleasant taste, odor, and appearance. High and moderate concentrations of manganese and iron relative to their HBSLs were both infrequent and occurred in 7 percent or less of samples from each PA (figs. 21*E, G*; tables 9*A–F*). Concentrations exceeding manganese and iron SMCL benchmarks were more common but mostly occurred in 15 percent or less of samples from each PA (figs. 21*F, H,* tables 9*A–F*).

Manganese and iron concentrations were similarly correlated with the potential explanatory factors of dissolved oxygen concentrations (negative), TDS (positive), well elevation (negative), and aridity index (negative; figs. 23*D, E*). Correlations with land use in the Basin and Range basin-fill aquifers might reflect higher concentrations of manganese occurring in agricultural and irrigated land use in this PA. Manganese is considered to be an essential micronutrient for crops, and manganese fertilizer is commonly applied to boost crop production (Mousavi and others, 2011).

Factors Affecting Molybdenum

Molybdenum (Mo) is an uncommon element in the Earth's crust but occurs frequently as an accessory mineral in many metal ores (Hem, 1985). Most molybdenum ore deposits are in the form of molybdenite (MoS_2) and are associated with porphyry granite or quartz monzonite plutons (Misra, 2000). Shale, clay schists, and granite are the primary geogenic sources in soils (Evans and Barabash, 2010). Organic-rich sediments and sedimentary deposits in sulfidic environments could have high concentrations of molybdenum (Crusius and others, 1996), however. Anthropogenic sources of molybdenum to groundwater include industrial sources and surface application as biosolids (Evans and Barabash, 2010). Molybdenum has a HBSL of 30 µg/L (Norman and others, 2018; U.S. Geological Survey, 2018a). Molybdenum is an essential trace nutrient for animals and plants (particularly legumes for nitrogen fixation); however, high levels in humans and animals can interfere with copper uptake (Vyskočil and Viau, 1999; Evans and Barabash, 2010).

High or moderate concentrations of molybdenum occurred in less than 10 percent of the Basin and Range basin-fill aquifers (table 9*B*; fig. 21*I*), whereas moderate concentrations occurred in 3 percent or less of the Rio Grande aquifer system, High Plains aquifer, Colorado Plateaus aquifers, and the Columbia Plateau basaltic-rock aquifer (tables 9*C–F*). The primary controls on molybdenum concentrations in groundwater are redox conditions, pH, and availability of molybdenum from aquifer materials (Smedley and others, 2014). Molybdenum differs from most other trace metals in that it occurs as a negatively charged species (as a molybdenate oxyanion or hydroxyanion) in soil solution at pH values greater than about 5.0, resulting in a decrease in molybdenum sorption with increasing pH (Evans and Barabash, 2010). Moderate and high concentrations of molybdenum most often occurred in the Basin and Range basin-fill and Rio Grande aquifer system, under alkaline, oxic groundwater conditions (fig. 25*A*), whereas moderate concentrations occurred under anoxic conditions in the High Plains aquifer and Columbia Plateau basaltic-rock aquifers.

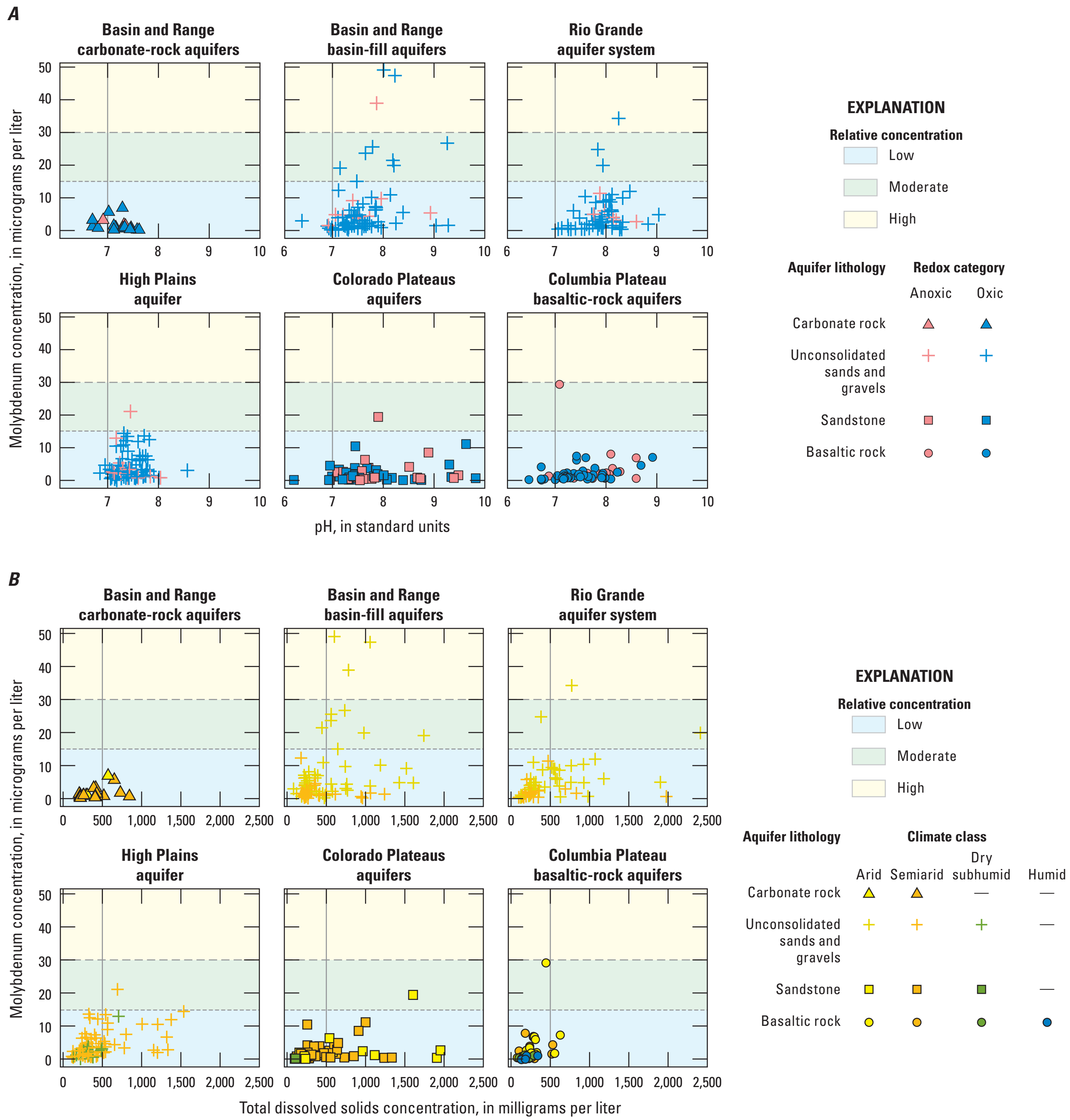


Figure 25. Molybdenum concentrations by *A,* pH, aquifer lithology, and redox; and *B,* total dissolved solids concentrations, aquifer lithology, and climate class in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Under reducing conditions, molybdenum can accumulate in groundwater through its release from aquifer materials through reductive dissolution of iron and manganese oxides (Schlieker and others, 2001; Bennett and Dudas, 2003). For the anoxic samples with moderate or near moderate molybdenum concentrations, elevated concentrations of manganese and iron co-occurred, indicating molybdenum release from aquifer materials under iron- or manganese-reducing conditions.

Molybdenum was correlated with aridity index (negative) and TDS (positive) in the Basin and Range basin-fill aquifers, Rio Grande aquifer system, High Plains aquifer, and Columbia Plateau basaltic-rock aquifers (fig. 23*F*), which likely reflects the generally elevated TDS concentrations (greater than 500 mg/L) in groundwater and aridity common to these areas of the western United States (fig. 25*B*). The positive correlation with HCO_3 in the High Plains aquifer and Colorado Plateaus aquifers likely results from the positive correlation with TDS because HCO_3 was the dominant anion in these aquifers (fig. 23*F*).

Factors Affecting Selenium

Selenium (Se) is found as selenide minerals, selenate and selenite salts, and as substitution for sulfur in sulfide minerals. It is naturally concentrated in soils that overlie bedrock with high selenium concentrations (Stillings, 2017). Selenium in groundwater results from weathering and leaching of rocks and the dissolution or oxidation of soluble salts in soils (Kunmar and Riyazuddin, 2011). Anthropogenic sources of selenium include mining, processing, use in industrial and agricultural applications, and waste (Stillings, 2017). The EPA MCL for selenium in drinking water is 50 µg/L (U.S. Environmental Protection Agency, 2018a). Selenium is an essential micronutrient in animal and human diets but is toxic at elevated levels or from long-term exposure in areas with high levels of soil selenium (Saha, 2017; U.S. Environmental Protection Agency, 2018a). Selenium occurred at moderate concentrations in 3 percent of the High Plains aquifer (table 9*D*); all other concentrations were low (fig. 21*J*). Mobilization of selenium from bedrock or soils to groundwater occurs under oxidizing, slightly alkaline conditions (McNeal and Balistrieri, 1989; Presser and Swain, 1990; Piper and others, 2000). Leaching of soil selenium is enhanced by anionic constituents such as nitrate, sulfate, and phosphate from anthropogenic sources such as fertilizer in agricultural land-use areas (Cary and Gissell-Nielsen, 1973). Selenium concentrations in the High Plains aquifer were inversely correlated with hydrologic conditions (aridity index and depth to bottom of well perforation) and positively correlated with geochemical conditions (TDS, dissolved oxygen, and HCO_3; fig. 23*G*); these relations are consistent with leaching of selenium from soils within the predominately alkaline, oxic (figs. 15*A, B*), and moderate- to elevated-TDS conditions that occur in the High Plains aquifer.

Factors Affecting Strontium

Strontium (Sr) is a fairly common element in the Earth's crust, with chemistry similar to that of calcium (Hem, 1985). Natural sources of strontium in groundwater are the weathering of silicate minerals—particularly feldspars, dissolution of carbonate and sulfate minerals, and mixing with seawater and brines (McNutt, 2000; Faure and Mensing, 2005). Strontium has a HBSL of 4,000 µg/L (Norman and others, 2018; U.S. Geological Survey, 2018a). This report evaluates concentrations of natural strontium (which are isotopically stable) and does not consider radioactive strontium-90 (^{90}Sr). Radioactive strontium-90 is widely dispersed in the environment and the food chain from atmospheric testing of nuclear weapons in the 1950s and 1960s; it occurs in radioactive waste and nuclear power production waste and is regulated in drinking water by the EPA (U.S. Environmental Protection Agency, https://ofmpub.epa.gov/tdb/pages/contaminant/contaminantOverview.do?contaminantId=10600, accessed May 22, 2020).

Strontium was detected at moderate and high concentrations in all PAs except for the Columbia Plateau basaltic-rock aquifers (fig. 21*J*). Moderate concentrations occurred in about 2–10 percent of the Basin and Range carbonate-rock aquifers, Basin and Range basin-fill aquifers, Rio Grande aquifer system, High Plains aquifer, and Colorado Plateaus aquifers (tables 9*A–E*). High concentrations occurred in 4 percent or less of the Rio Grande aquifer system and High Plains aquifer (tables 9*C, D*). Strontium was positively correlated with TDS in all PAs where moderate or high concentrations occurred, and negatively correlated with pH in the Basin and Range basin-fill aquifers, Rio Grande aquifer system, and Colorado Plateaus aquifers (fig. 23*H*). Strontium becomes increasingly soluble with increasing TDS, and relatively higher concentrations might result from the effects of competitive ions on dissolved constituents as they interact with mineral surfaces (Wright and others, 2015). Moderate and high concentrations of strontium primarily occurred at elevated TDS values (fig. 26*A*) and at pH values between 7.0 and 7.9 (fig. 26*B*).

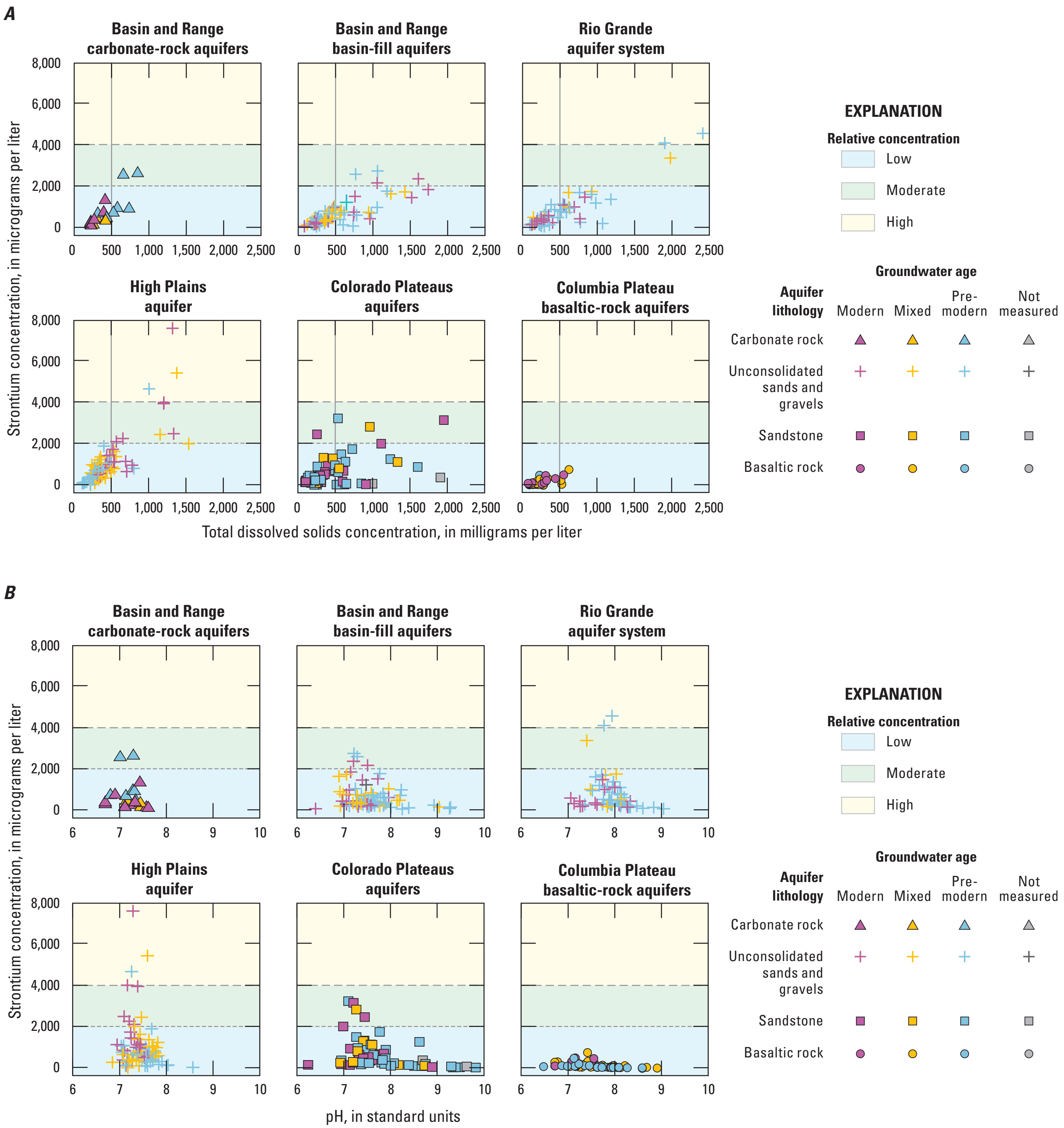


Figure 26. Strontium concentrations by *A,* total dissolved solids, aquifer lithology, and groundwater age; and *B,* pH values, aquifer lithology, and groundwater age in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Factors Affecting Thallium

Thallium (Tl) is a heavy metal and is mostly associated with potassium minerals in clays, soils, and granite (Kaplan and Mattigod, 1998; U.S. Geological Survey, 2018c). Several thallium minerals occur as sulfide or selenide complexes with antimony, arsenic, copper, lead, and silver (U.S. Geological Survey, 2018c). Thallium generally is present at low levels in the environment, but anthropogenic sources have resulted in increased concentrations near mineral smelters and coal-burning facilities (Karbowska, 2016). The MCL for thallium in groundwater is 2 µg/L (U.S. Environmental Protection Agency, 2018a). Thallium is toxic to humans, plants, animals, and microorganisms (Kazantzis, 2000; Peter and Viraraghavan, 2005), and tends to bioaccumulate (Karbowska, 2016). Thallium mobility in groundwater is largely controlled by redox conditions; it can mobilize under anoxic (reducing) and oxic (oxidizing) conditions. Thallium in soils has an affinity for iron and manganese oxyhydroxides and is mobilized by reductive dissolution of iron-manganese oxides. Conversely, in oxidizing conditions, thallium might be mobilized by gradual oxidation of thallium-bearing sulfides (Belzile and Chen, 2017). High concentration of thallium occurred in one well in the Basin and Range carbonate-rock PA (5 percent).

Factors Affecting Uranium

Uranium (U) is a radioactive trace element enriched in crystalline rocks such as granite and sediments derived from them. Sources of uranium to groundwater include dissolution of uranium-bearing minerals such as uraninite, zircon, and titanite and desorption of uranium from mineral surfaces in the presence of bicarbonate (Hem, 1985; Jurgens and others, 2010). In areas of agricultural land use, uranium contamination of soils has resulted from high or prolonged application of phosphate fertilizers, which can have high uranium concentrations (Rothbaum and others, 1979; Romero Guzmán and others, 2006). Uranium mobility in groundwater is largely controlled by redox conditions as well as pH. Uranium is highly soluble in its oxidized forms and only slightly soluble in its reduced forms; it can form bonds with other ions and remain in solution over a wider range of conditions than otherwise possible (DeSimone and others, 2015). Uranium is sometimes found in anoxic, low pH groundwater, possibly because of ion complexation or competition (Ayotte and others, 2011). The MCL for uranium is 30 µg/L (U.S. Environmental Protection Agency, 2018a). Uranium is weakly carcinogenic and chemically toxic; elevated concentrations in drinking water can cause kidney damage (Kurttio and others, 2002; U.S. Environmental Protection Agency, 2018a). The radioactive decay of uranium produces daughter products which also are of concern for human health with drinking-water benchmarks (for example, radium; U.S. Environmental Protection Agency, 2018a).

Moderate concentrations of uranium occurred in five PAs, all except for the Basin and Range carbonate-rock PA, with aquifer-scale proportions ranging from 1 to 15 percent; the highest proportion occurred in the High Plains aquifer (tables 9*B*–*F*). High concentrations of uranium, with aquifer-scale proportions ranging from 3 to 8 percent, occurred in the Basin and Range basin-fill aquifers, Rio Grande aquifer system, and High Plains aquifer; the highest proportion occurred in the High Plains aquifer (tables 9*B*–*D*). Moderate and high concentrations of uranium occurred most frequently in the unconsolidated sand and gravel aquifers, usually in association with oxic conditions, elevated TDS, and HCO_3 concentrations ranging from 155 to 484 mg/L (figs. 27*A, B*). High concentrations of uranium previously have been noted throughout the High Plains aquifer, particularly in shallow groundwater (Nolan and Weber, 2015). Low recharge rates, oxic conditions, long flow paths, and high concentrations of naturally occurring uranium in rocks and soils contribute to the accumulation of uranium in the unconsolidated sand and gravel aquifers of the western United States (DeSimone and others, 2015).

Uranium concentrations were correlated with land use, hydrologic conditions (well elevation, depth to bottom of well perforation, and aridity index), and geochemical conditions (HCO_3, pH, dissolved oxygen, and TDS; fig. 23*I*). Differences in positive or negative correlations in the PAs reflect groundwater conditions that favor the release of uranium from aquifer materials or reflect correlations among the explanatory factors (tables 6*A*–*F*).

Radionuclides

Radionuclides in groundwater primarily are from geologic sources and include uranium (note that uranium is considered with trace elements and discussed in the previous section, “Trace Elements”), radon (Rn), radium (Ra), polonium (Po), and lead (Pb). Radionuclides are produced naturally by the decay of radioactive parent materials, predominantly uranium and thorium (DeSimone and others, 2015). Radionuclides in water (with the exception of uranium) typically are considered relative to their decay energy or radioactive activity, which is measured in picocuries per liter (piC/L). Radioactive activities for three radionuclides with health-based benchmarks (gross alpha, radium, and radon-222 [radon]) were selected for evaluation by the *understanding assessment* in this report (table 2). Gross beta activity also has a health-based benchmark (4 millirems per year; U.S. Environmental Protection Agency, 2018a); gross beta activity occurred at low concentrations in all PAs and thus, was not further evaluated (table 3). Moderate concentrations of radionuclides occurred in 15 percent of the Basin and Range basin-fill aquifers and High Plains aquifer; moderate concentrations occurred in 2–13 percent of the remaining PAs (table 7). High-concentrations of radionuclides occurred in 1–5 percent of the PAs, excluding the Basin and Range basin-fill aquifers where no high concentrations occurred.

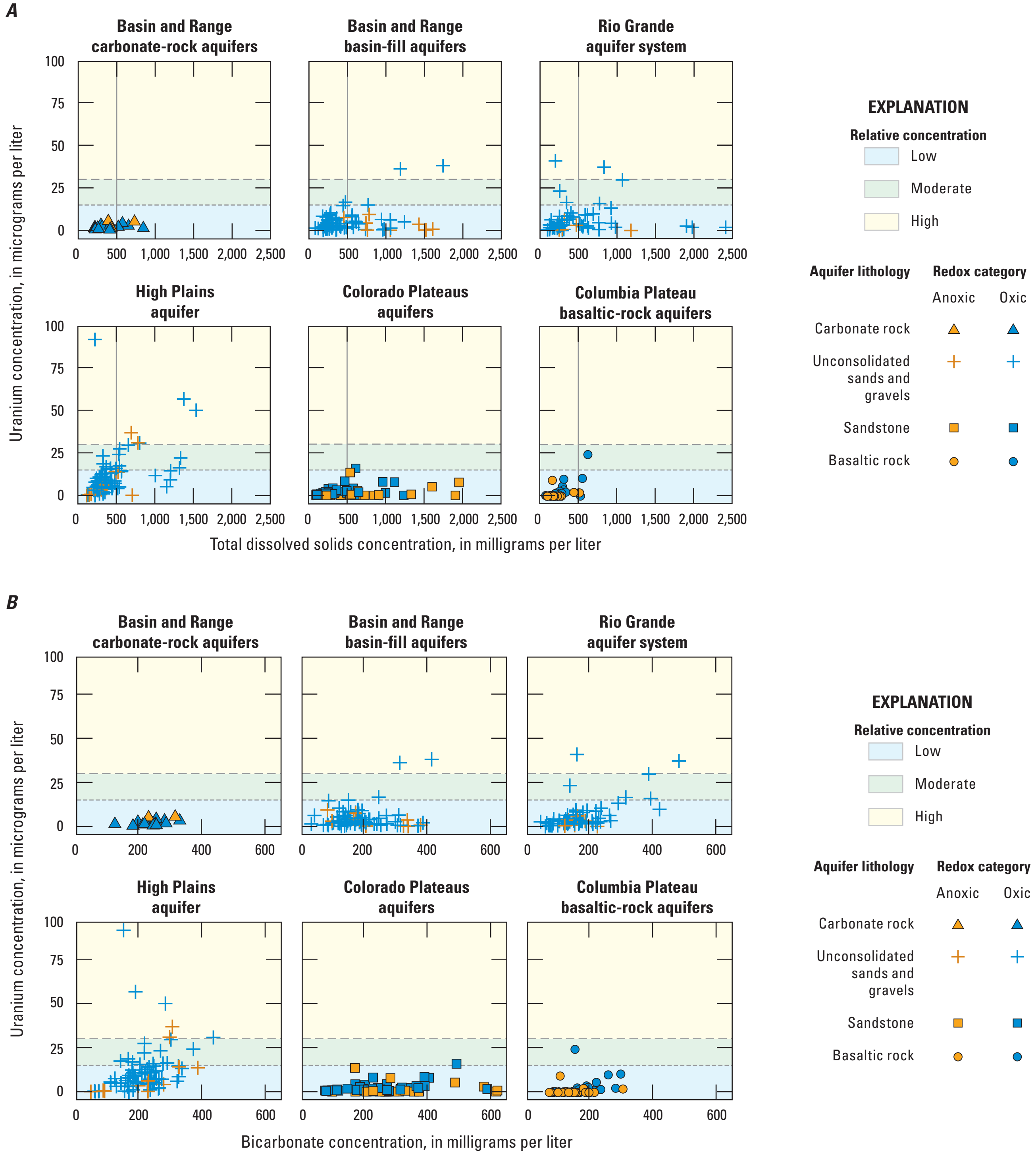


Figure 27. Uranium concentrations by *A*, total dissolved solids concentrations, aquifer lithology, and redox condition; and *B*, bicarbonate concentration, aquifer lithology, and redox conditions in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Gross Alpha Activity

Gross alpha activity is a measure of radioactive decay from uranium-238. Activity is measured as 72-hour and 30-day activities, with an MCL of 15 pCi/L (U.S. Environmental Protection Agency, 2018a). Only 30-day gross alpha activities are evaluated in this report. Moderate and high concentrations of gross alpha activity were relatively uncommon and occurred in 4 percent or less of samples from each of the PAs; there were no moderate or high concentrations in the Basin and Range carbonate-rock aquifers (fig. 28*A*; tables 9*B–F*). Gross alpha activity had positive correlations with TDS in the Columbia Plateau basaltic-rock aquifers and HCO_3 in the Rio Grande aquifer system (fig. 29*A*), which likely reflects geochemical conditions that favor release of the parent material uranium to groundwater (that is, oxic groundwater with elevated TDS and HCO_3 concentrations; figs. 27*A, B*). Gross alpha activity was positively correlated with depth to bottom of well perforation in the High Plains aquifer and could reflect naturally occurring uranium within the aquifer lithology (Hall and others, 2019) or uranium-enriched surface-water irrigation that enters deeper regional groundwater (Böhlke and others, 2007; McMahon and Böhlke, 2007).

Radium Activity

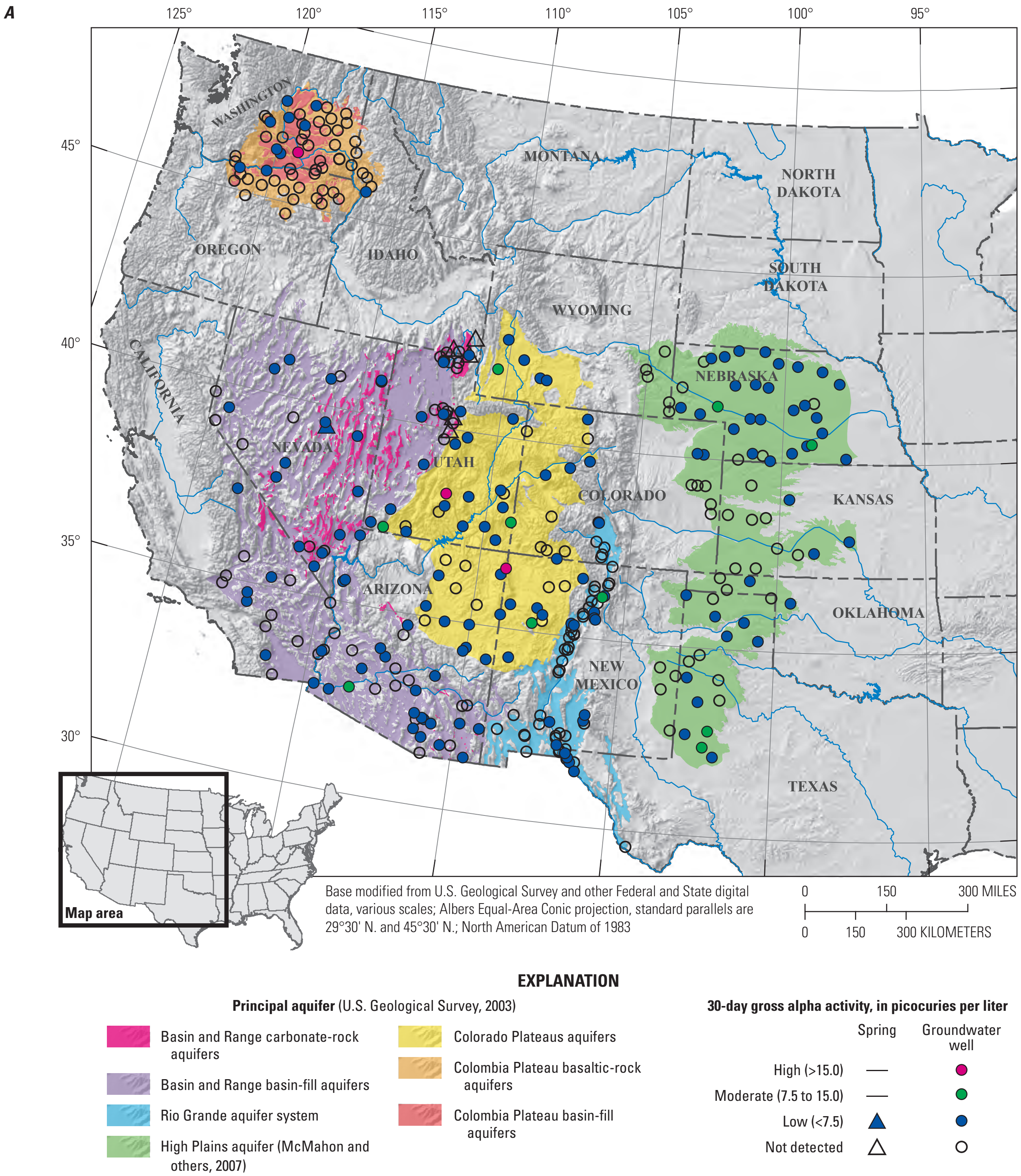
Radium (Ra) can enter groundwater by dissolution of aquifer materials, by desorption from rock or sediment surfaces, and by release from minerals during radioactive decay (DeSimone and others, 2015). Radium-226, derived from radioactive decay of uranium-238, is the most common isotope of radium. Radium-228, derived from the radioactive decay of thorium, is less common. Both isotopes are carcinogenic. The MCL for radium is 5 pCi/L and is based on their combined activity (radium-226 plus radium-228; U.S. Environmental Protection Agency, 2018a). Radium evaluation in this report is based on their combined activity. Radium in drinking water is a human-health concern because it accumulates in bone and other tissues, thereby increasing lifetime cancer risks (DeSimone and others, 2015).

Moderate and high concentrations of radium were relatively uncommon (fig. 28*B*). High concentrations only occurred in the Colorado Plateaus aquifers (4 percent of PA); moderate concentrations prop occurred in the Basin and Range carbonate-rock aquifers (6 percent), Rio Grande aquifer system (2 percent), and the Colorado Plateaus aquifers (2 percent; tables 9*A, C, E*). Geochemical conditions that favor the release of radium into groundwater include anoxic conditions, low pH, and high concentrations of TDS (DeSimone and others, 2015). Although radium-226 decays from uranium, the mechanisms that favor the mobility of uranium are quite different than those that favor radium mobility. Under oxic groundwater conditions, uranium is highly soluble in its oxidized forms and only slightly soluble when reduced. In contrast, radium in oxic, low TDS water strongly sorbs to iron and manganese oxyhydroxides and to clays formed from feldspar weathering (Szabo and Zapecza, 1991; Thomas and others, 1993). High radium concentrations occurred in two samples in the Colorado Plateuas aquifers under anoxic groundwater conditions at pH values ranging from 6.9 to 7.2 (fig. 30). Radium correlated with dissolved oxygen (negative) and with depth to bottom of well perforation (positive) in the Basin and Range carbonate-rock aquifers, indicating that lower dissolved oxygen concentrations associated with deeper wells favored the release of radium to groundwater (fig. 29*B*). The positive correlation with TDS in the Basin and Range basin-fill aquifers and negative correlation with pH in the Colorado Plateaus aquifers reflect favorable geochemical conditions for radium release.

Radon Activity

Radium-226 decays into radon-222 (radon) gas. Radon in groundwater occurs as a dissolved gas of which most is released into the air. Inhalation of radon poses a risk of lung cancer (U.S. Environmental Protection Agency, 2019b). Radon has two proposed regulatory water-quality benchmarks: (1) an MCL of 300 pCi/L and (2) an alternative maximum contaminant level (AMCL) of 4,000 pCi/L (U.S. Environmental Protection Agency, 2018c). The lower MCL was proposed to apply in states and to public water systems that do not have programs to address health risks from radon in indoor air, whereas the AMCL would apply to states with established indoor air programs (U.S. Environmental Protection Agency, 2018c). The AMCL (4,000 pCi/L) is considered in this report.

Moderate and high concentrations of radon were relatively uncommon across the PAs, occurring at aquifer-scale proportions up to 5 percent (fig. 28*C*; tables 9*A–F*). Significant correlations with potential explanatory factors occurred in four PAs—the Basin and Range carbonate-rock aquifers, Rio Grande aquifer system, High Plains aquifer, and Colorado Plateaus aquifers (fig. 29*C*). Correlations of radon with aridity index were common to the four PAs; positive correlations occurred among the the PAs with arid climates (the Basin and Range carbonate-rock aquifers, Rio Grande aquifer system, and Colorado Platueaus aquifers, fig. 14*A*), and negative correlation with aridity index occurred in the High Plains aquifer. In the Rio Grande aquifer system and Colorado Plateaus aquifers, elevated concentrations of radon were associated with geochemical conditions of low TDS and elevated HCO_3 concentrations, which occurred at higher elevations in the northern part of the Rio Grande Valley and the eastern boundary of the Colorado Plateaus aquifers associated with recharge fronts (fig. 28*C*). These correlations could reflect radon associations with source rock or recharge fronts that are represented by the selected explanatory factors.



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

Figure 28. Concentrations of *A,* 30-day gross alpha activity; *B,* radium-226 and radium-228 (combined); and *C*, radon-222 in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

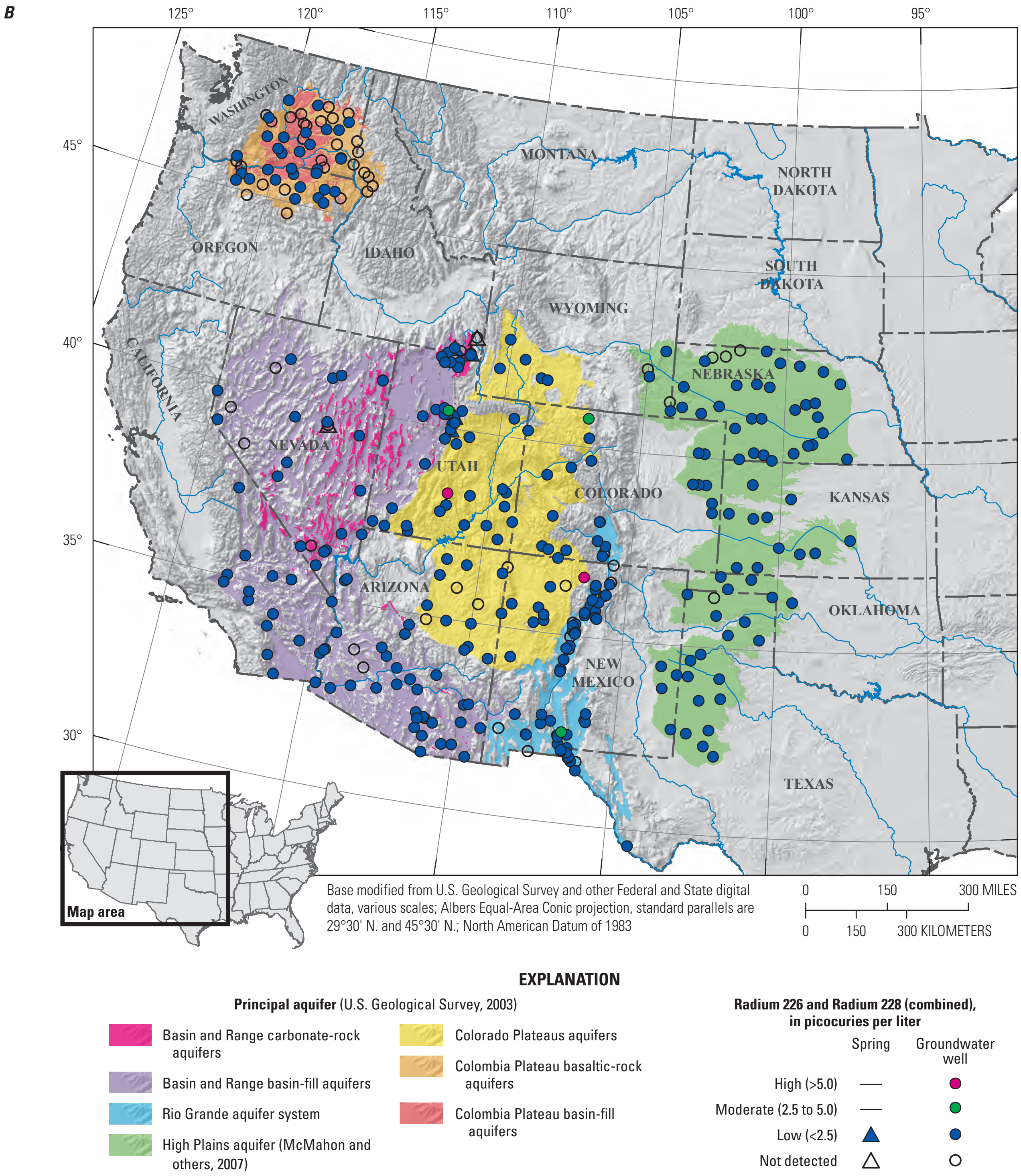


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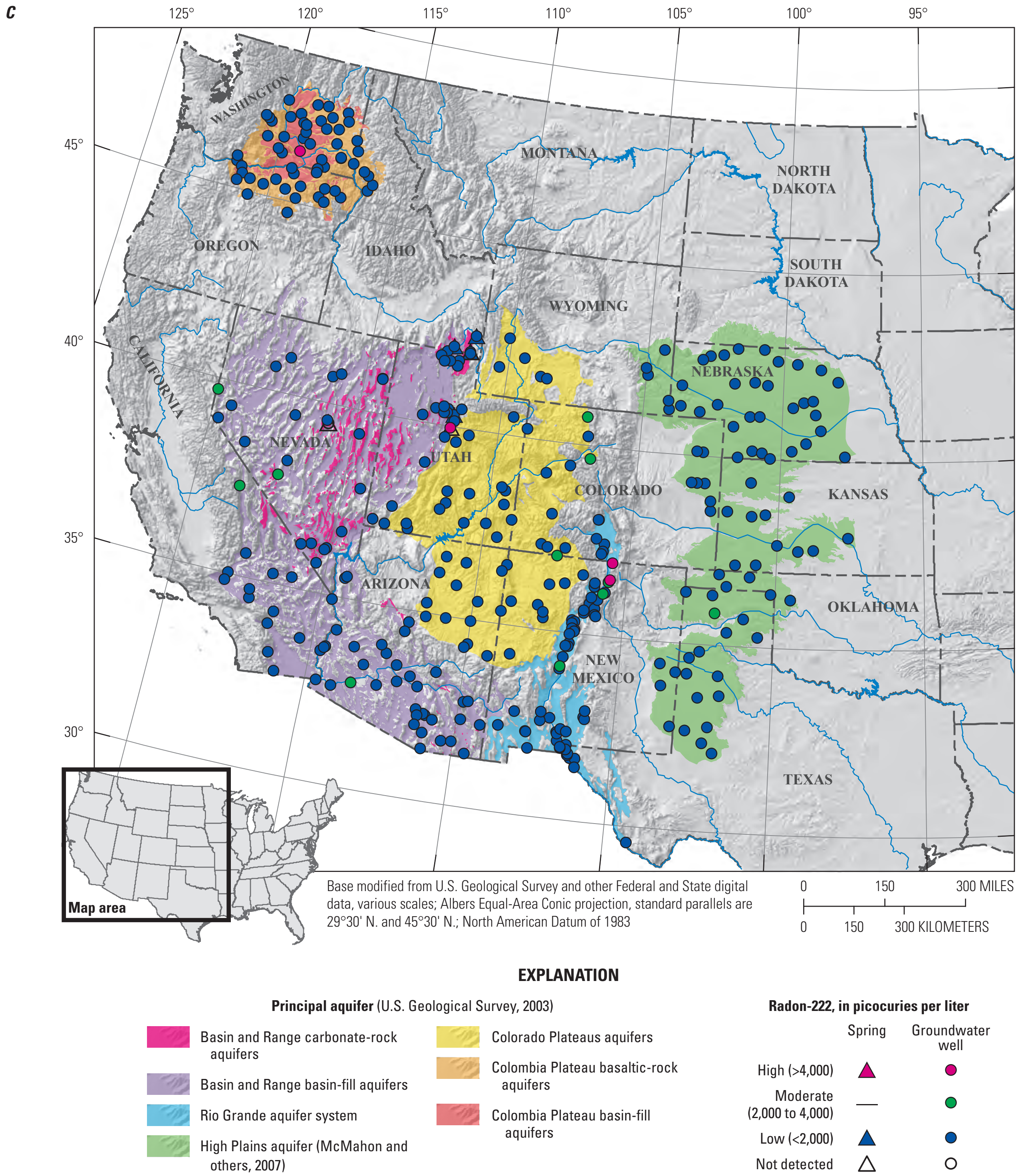
Figure 28. —Continued



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

Figure 28. —Continued

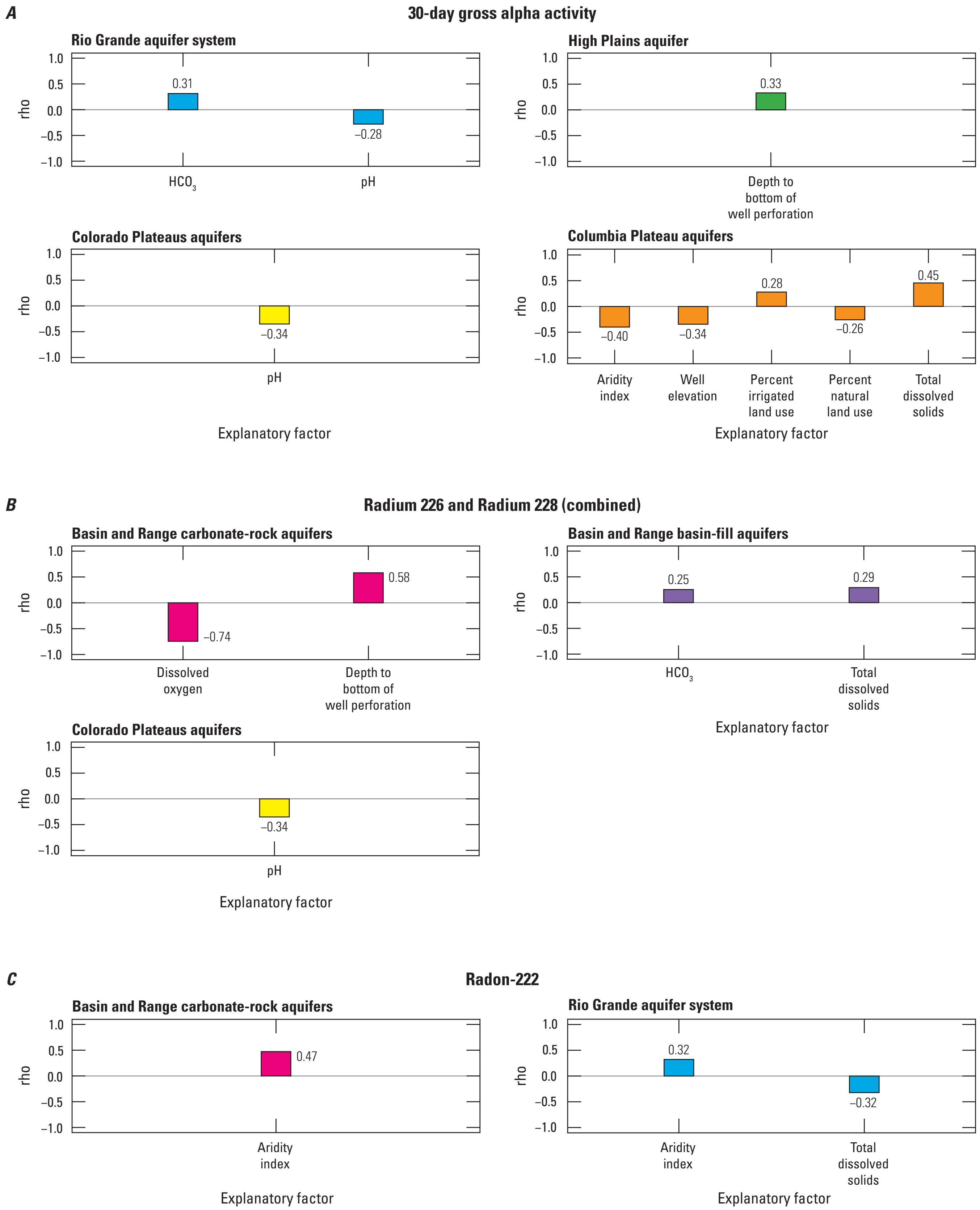


Figure 29. Spearman’s rho results for radionucludes *A,* 30-day gross alpha activity; *B,* radium-226 and radium-228 (combined); and *C,* radon-222 in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

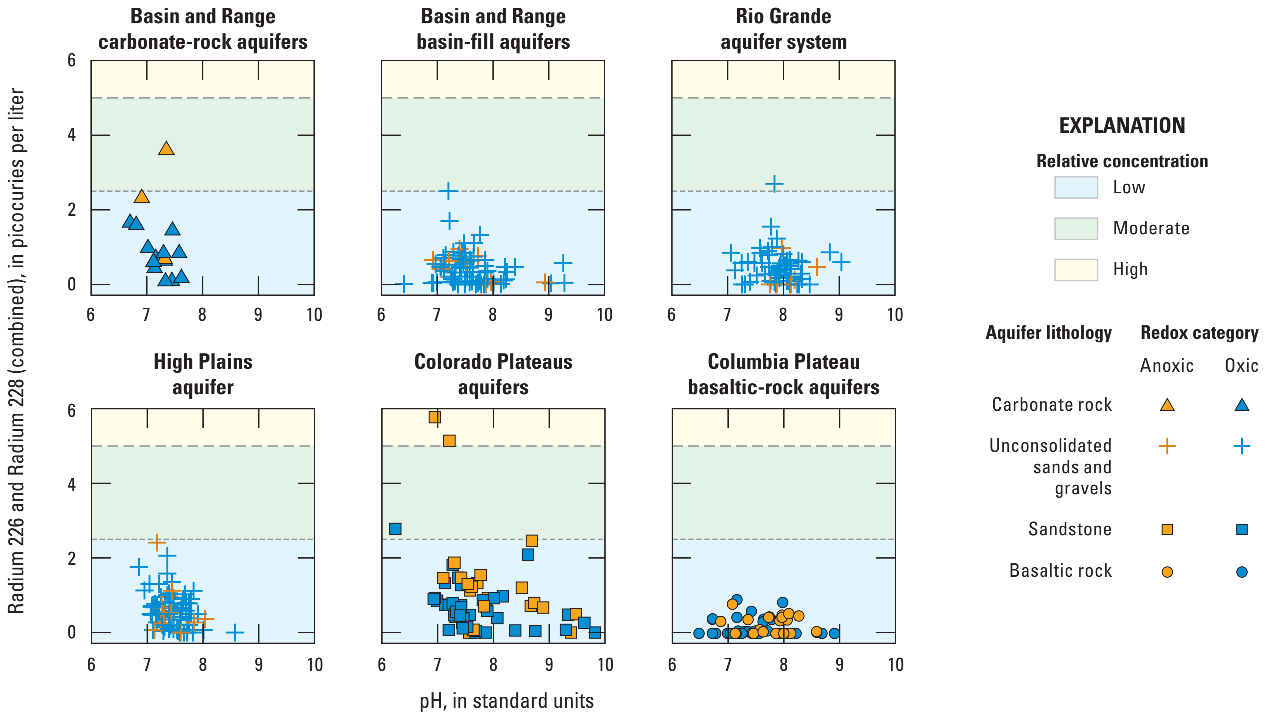


Figure 30. Relations of radium-226 and radium-228 (combined) with measured pH values by aquifer lithology and redox condition in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Salinity Indicators

Total dissolved solids, sulfate, and chloride concentrations are considered salinity indicators in this report. These constituents have SMCL benchmarks (table 2) and can affect the aesthetic properties of water, such as taste, odor, or color (U.S. Environmental Protection Agency, 2018b). The SMCL benchmark for TDS is 500 mg/L. The SMCL benchmark for sulfate and chloride is 250 mg/L. Natural sources and processes that increase TDS, chloride, and sulfate in groundwater include dissolution of minerals in soils, sediments and rock; concentration of solutes in shallow groundwater by evapotranspiration; mixing with hydrothermal fluids or saline or brackish groundwater; and mixing with saline or brackish water from the ocean, estuaries or saline lakes (Hem, 1985). Anthropogenic sources of these constituents include water used for irrigation, wastewater discharge, brines from petroleum extraction activity, or direct application (road salts, fertilizers, urban runoff) to the land surface. Sulfate and chloride are major ions that typically are important contributors to TDS.

Moderate and high concentrations of salinity indicators occurred in all six western PAs except for chloride in the Columbia Plateau basaltic-rock aquifers (fig. 31*A*). High concentrations of TDS ranged from 25 to 36 percent and generally were in the arid Southwest and in the southern part of the High Plains aquifer (fig. 32*A*; tables 9*A*–*F*). Where precipitation is relatively low and evaporation relatively high, less groundwater recharge occurs and products of rock weathering can concentrate in soils, resulting in high groundwater TDS when precipitation is sufficient to cause recharge. Parts of the arid Southwest have shallow groundwater with high evaporation rates that also contribute to elevated salinity indicators. The unconsolidated sand and gravel aquifers of the Southwest include sedimentary rocks, carbonate rocks, and evaporites that are more soluble and easily weathered than the quartz-rich sediments. Total dissolved solids were negatively correlated with several explanatory factors representing hydrologic conditions—aridity index, depth to bottom of well perforation, and well elevation—which likely are proxies for conditions associated with climate, shallow groundwater, and hydrologic position (fig. 31*B*). Natural upwelling of saline groundwater, pumping of deep groundwater, and irrigated agriculture are all potential sources of TDS in the High Plains aquifer (DeSimone and others, 2015). High TDS concentrations in the southern part of the High Plains aquifer (fig. 32*A*) likely result from mixing with saline groundwater from underlying geologic units (Nativ and Smith, 1987; Scanlon and others, 2009). Total dissolved solids were positively correlated with HCO_3 in all of the PAs except for the Basin and Range carbonate-rock aquifers; this is likely a causative correlation because HCO_3 is a primary component of TDS.

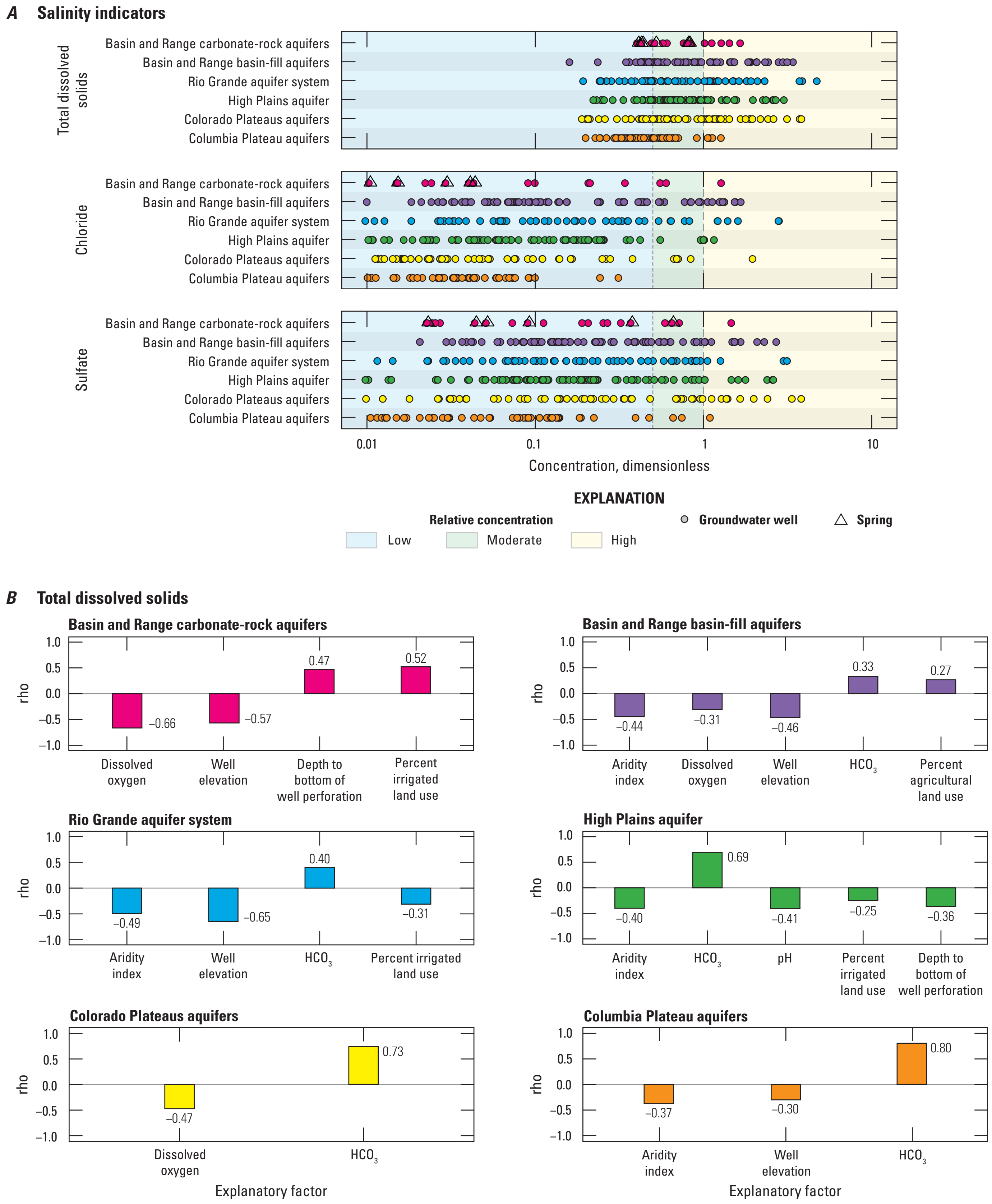
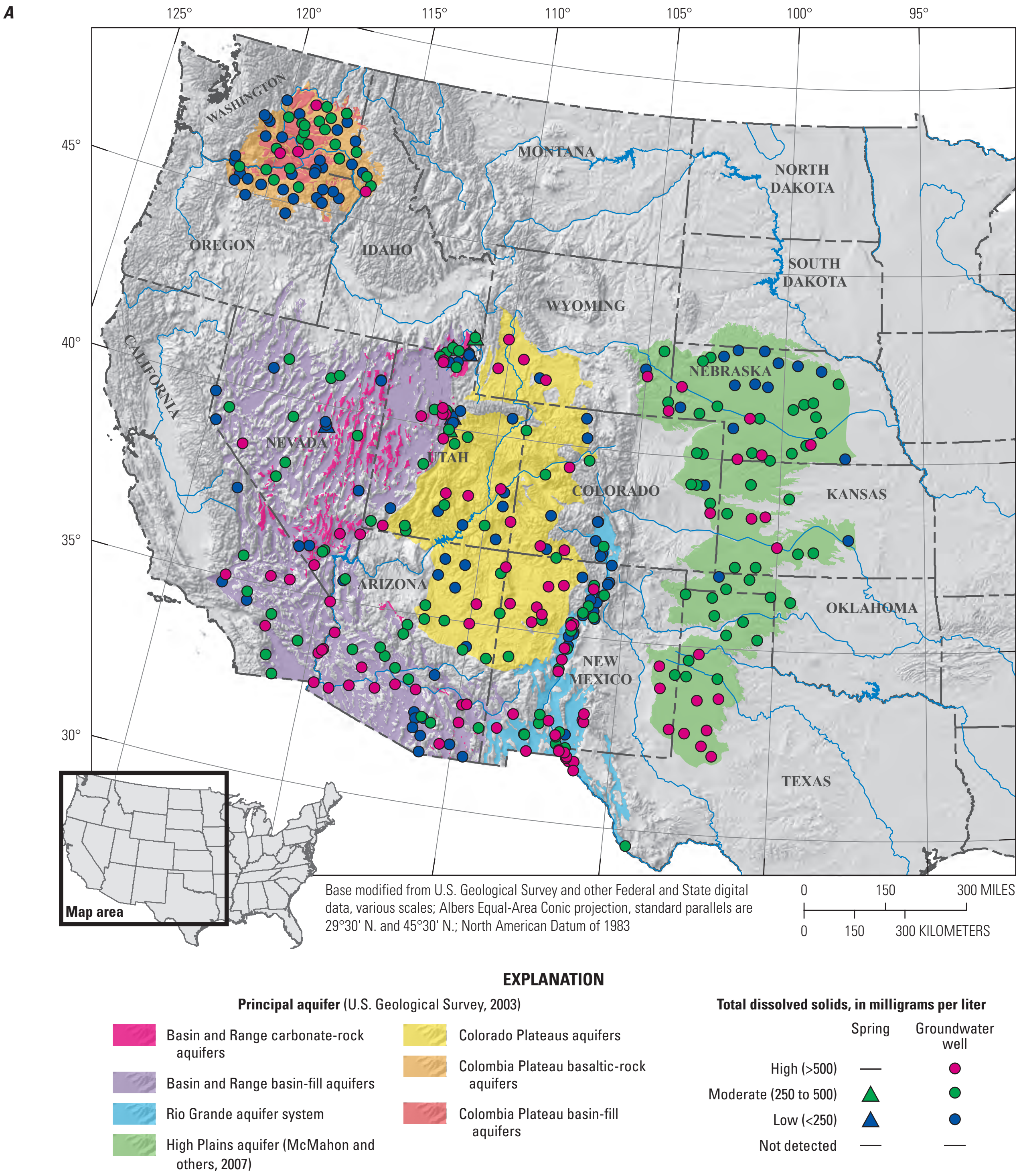
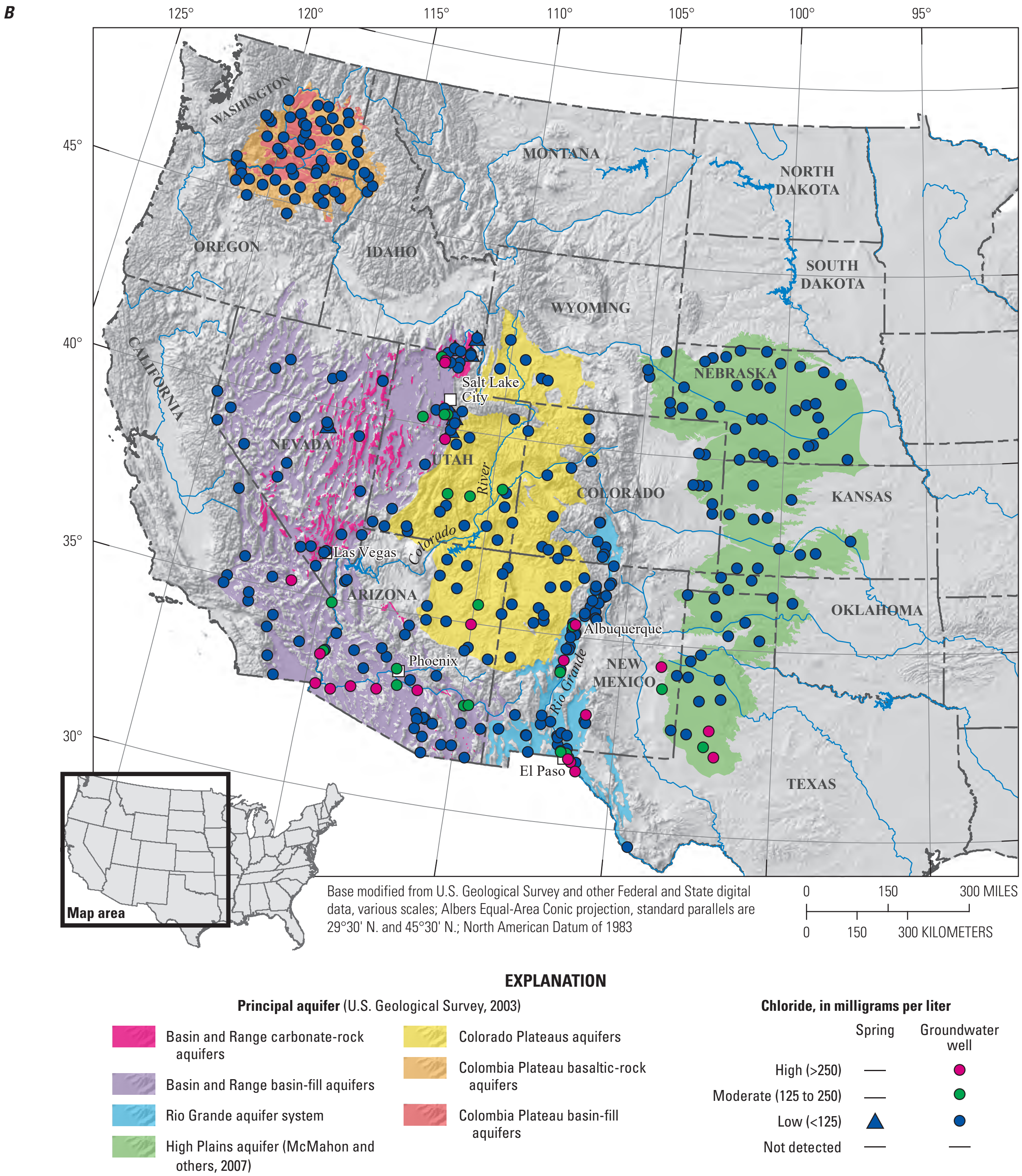


Figure 31. *A,* Concentrations of salinity indicators relative to benchmarks; and *B,* Spearman's rho results for total dissolved solids in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.



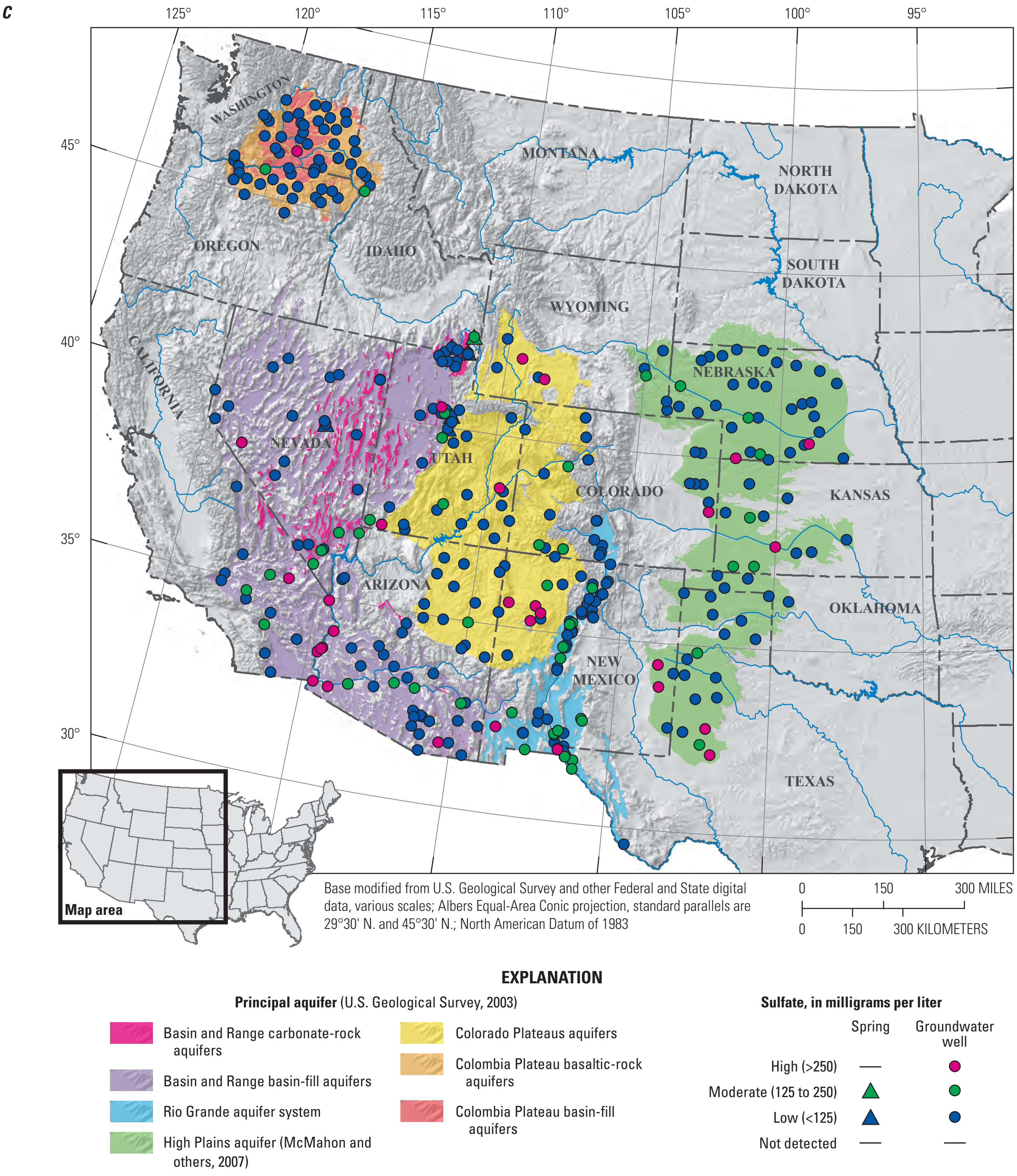
Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30' N. and 45°30' N.; North American Datum of 1983

Figure 32. Concentrations of *A,* TDS; *B,* chloride; and *C,* sulfate in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.



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

Figure 32. —Continued



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

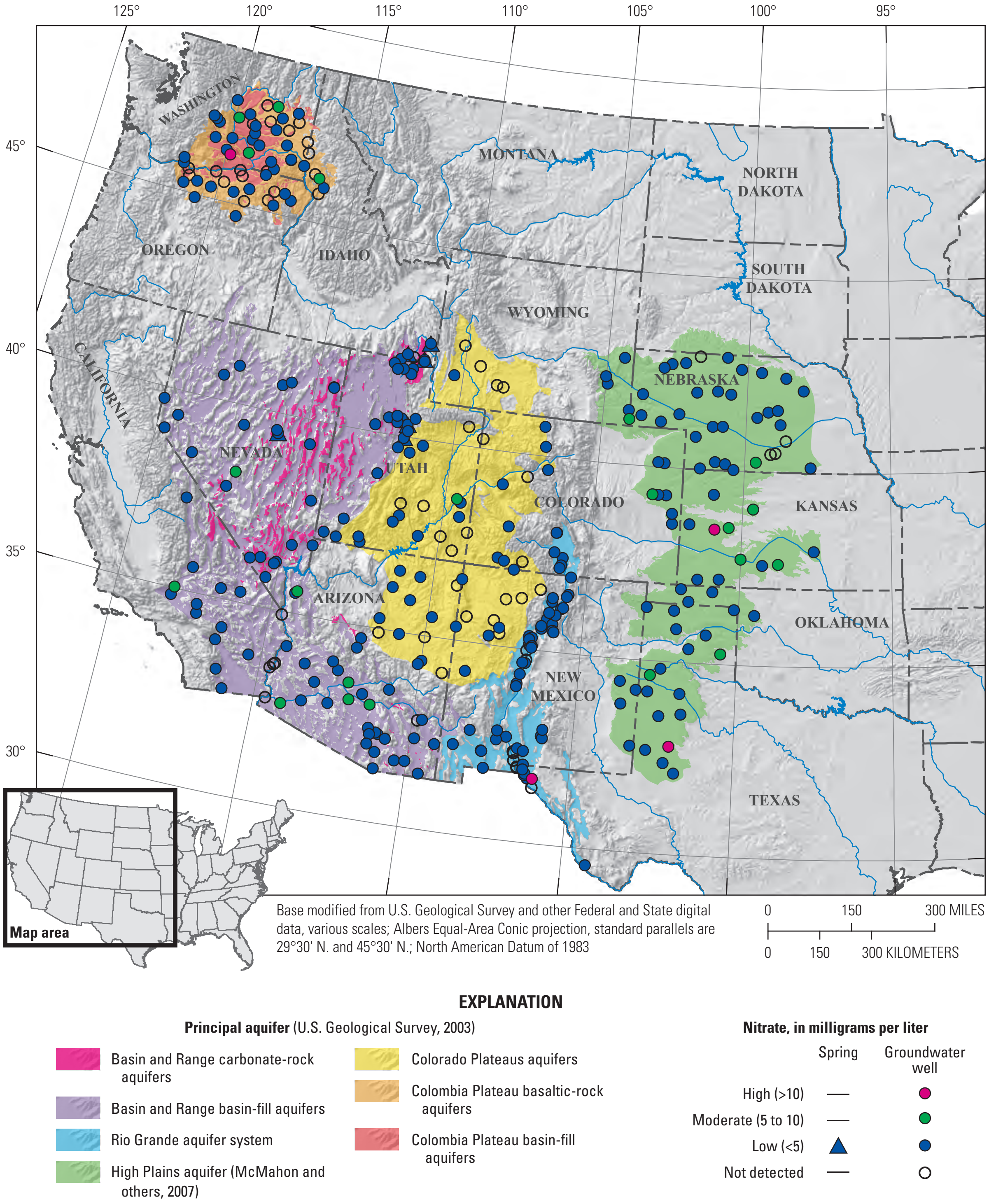
Figure 32. —Continued

As noted earlier, sulfate and chloride are major ions that typically are important contributors to TDS. In addition to the natural sources described earlier in this section, anthropogenic sources of chloride include septic, sewage, and wastewater; chloride is relatively inert, that is, it doesn't react with aquifer materials or other dissolved constituents in dilute water and is a useful tracer of human influence on water quality (DeSimone and others, 2015). High and moderate concentrations of chloride mostly coincide with urban areas in each of the PAs (for example, Salt Lake City, UT; urban areas along the Colorado River southwest of Phoenix, AZ; and urban areas along the Rio Grande River in New Mexico and Texas; fig. 32*B*). High and moderate concentrations also occurred in the southern part of the High Plains aquifer, presumably from mixing with underlying saline groundwater. Aquifer-scale proportions with high chloride ranged from about 2 percent in the Colorado Plateaus aquifers to 12 percent in the Basin and Range basin-fill aquifers (tables 9*A*–*E*). Sulfate and chloride concentrations were well correlated in all PAs (Spearman's rho values greater than or equal to 0.75). Sulfate concentrations can be affected by redox, pH, and weathering of aquifer materials. Anthropogenic sources of sulfate include dry and wet atmospheric deposition from industrial and urban emissions and leaching of accumulated solutes in soils by irrigation (Hem, 1985). Aquifer-scale proportions with high sulfate ranged from about 2 percent in the Columbia Plateau basaltic-rock aquifers to 15 percent in the Colorado Plateaus aquifers (fig. 32*C*; tables 9*A*–*F*).

Nutrients

Nutrients are elements that are important to plant growth and survival. Nutrients in water—specifically nitrogen and phosphorus compounds—have both natural and anthropogenic sources. Natural sources include dissolution of organic material in soils, animal waste, and atmospheric deposition. Anthropogenic sources can be nonpoint or point: point sources include municipal and industrial discharge and concentrated animal feeding operations, whereas non-point sources include applications of commercial fertilizers on agricultural and residential lands, cultivation of nitrogen-fixing crops, septic systems, and combustion of fossil fuels (Dubrovsky and others, 2010). Excess nutrients in waterways can promote algal blooms (eutrophication). Both oxidized and reduced forms of nitrogen, nitrate (NO_3) or nitrite (NO_2), respectively, have drinking-water benchmarks (MCLs of 10 and 1 mg/L, respectively; U.S. Environmental Protection Agency, 2018a). Nitrite only occurred at low concentrations and was not selected for further evaluation by the *understanding assessment*. Excess nitrate concentrations in drinking water can cause methemoglobinemia, or "blue baby" syndrome, in infants (U.S. Environmental Protection Agency, 2018a). Nitrate in groundwater most commonly occurs in oxic groundwater systems, and concentrations above the national background concentration in groundwater (1 mg/L) might result from anthropogenic sources (Nolan and Hitt, 2006; Dubrovsky and others, 2010). Background concentrations can vary locally; however (Dubrovsky and others, 2010), and are likely higher for the High Plains aquifer (for example, 4 mg/L in shallow groundwater; Gurdak and others, 2009).

Moderate and high concentrations of nutrients were relatively uncommon (table 7). High aquifer-scale proportions of nitrate occurred in 3 percent or less of the Rio Grande aquifer system, the High Plains aquifer, and the Columbia Plateau basaltic-rock aquifers (fig. 33; tables 9*C*, *D*, *F*). Moderate aquifer-scale proportions of nitrate ranged from 0 to 11 percent of PAs, with the highest aquifer proportions occurring in the Basin and Range basin-fill aquifers (9 percent), the High Plains aquifer (11 percent), and the Columbia Plateau basaltic-rock aquifers (7 percent; tables 9*B*, *D*, *F*). Nitrate was most strongly correlated (positive) with dissolved oxygen in the five PAs with moderate or high concentrations (fig. 34). Moderate or high concentrations occurred in oxic groundwater that was predominately of modern or mixed groundwater age (fig. 35). The positive correlation between dissolved oxygen and irrigated land use in the Columbia Plateau basaltic-rock aquifers (table 6*F*) could reflect the influence of irrigated land use within Quincy-Pasco subunit (fig. 8*B*), an area of intensive irrigated agriculture that receives more than 2.5 million acre-feet of surface water per year from the Columbia Basin Irrigation Project (Williamson and others, 1998), resulting in oxygen-rich surface-water recharge to groundwater. Land use surrounding the Quincy-Pasco subunit is predominately non-irrigated dryland agriculture or rangeland grazing (Williamson and others, 1998). In the Basin and Range basin-fill aquifers, negative correlations for nitrate with irrigated and agricultural land indicated that agriculture is likely not a source of nitrate in this PA; other nitrate sources or long lag times between irrigation and GW recharge (delayed arrival of nitrate beneath agricultural lands) not represented by the potential explanatory factors considered in this report might contribute to the moderate nitrate concentrations that occur in this PA.



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

Figure 33. Concentrations of nitrate in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

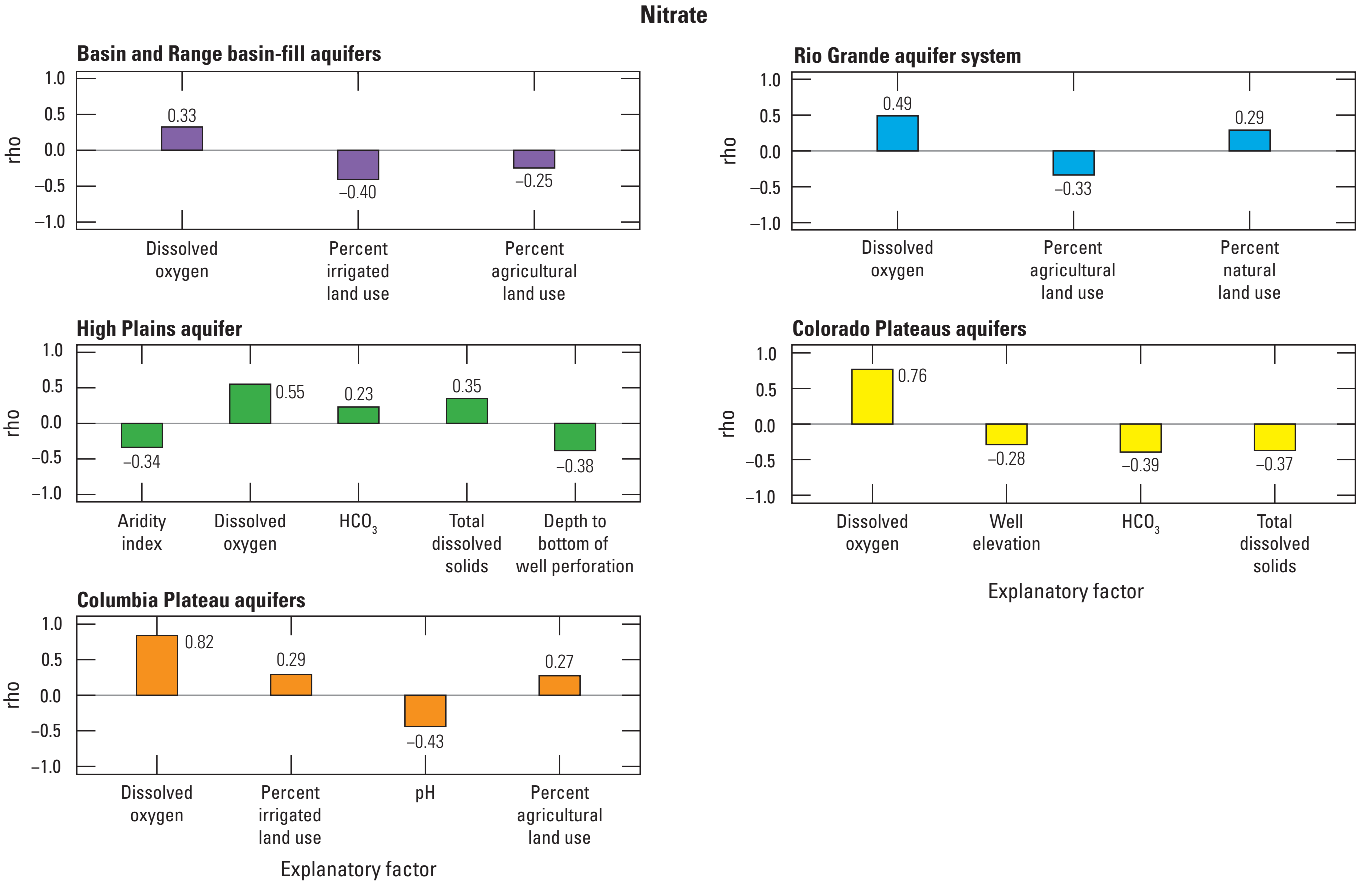


Figure 34. Spearman’s rho results for nitrate in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

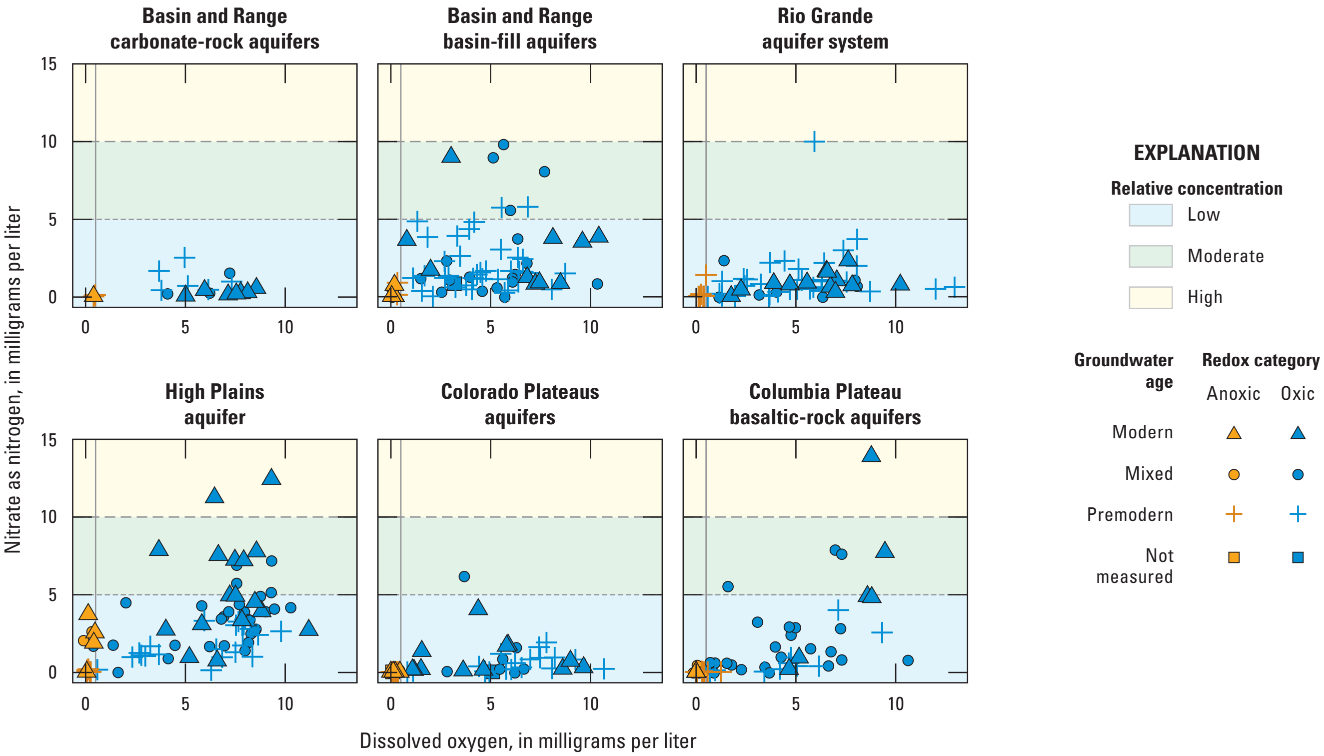


Figure 35. Relations of measured nitrate concentration with dissolved oxygen concentration, by groundwater age and redox class, for six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Organics and Special Interest Constituents

Organic constituents did not occur at high concentrations in any of the six PAs (table 10). Moderate concentrations occurred in three PAs—the Basin and Range basin-fill aquifers (VOCs), High Plains aquifer (pesticides and VOCs) and Colorado Plateaus aquifers (VOCs). Five pesticides (atrazine, bromacil, didealkylatrazine, propazine, and propoxur) and two VOCs (chloroform and bromodichloromethane) were selected for further analysis by the *understanding assessment* because they were detected relatively frequently (between 10 and 43 percent) at low concentrations in at least one principal aquifer study (fig. 36; tables 11, 12). Additionally, perchlorate—a special interest constituent—is included in this discussion. Perchlorate occurred at moderate concentrations in the two PAs in which it was collected: the Rio Grande aquifer system and the High Plains aquifer; there were no high concentrations.

Pesticides

Pesticides and pesticide compounds (hereafter, pesticides) include herbicides, insecticides, and fungicides—and their degradates—that are used to control unwanted weeds, insects, fungi, and other pests in agricultural and urban settings. The five pesticides selected for further evaluation included four herbicides (atrazine, didealkylatrazine, bromacil, and propazine) and one insecticide (propoxur). These pesticides had detection frequencies greater than 10 percent in one or more of the PAs (at low concentrations relative to health-based benchmarks; table 11; figs. 37*A–E*, respectively). Only one moderate concentration of a pesticide occurred in any PA—the herbicide atrazine in the High Plains aquifer (1 percent of PA area). The High Plains aquifer also had the highest frequency of herbicide detections of all the PAs, and four herbicides were detected at low concentrations—43 percent for atrazine, 28 percent for didealkylatrazine, 18 percent for propazine, and 10 percent for bromacil (table 11). Of these herbicides, didealkylatrazine, a degradate of atrazine, generally was detected at frequencies less than or equal to atrazine except in the Basin and Range carbonate-rock aquifers (table 11).

Table 10. Summary of aquifer-scale proportions for organic constituents with health-based benchmarks and for the special interest constituent, perchlorate, in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.1 of water quality benchmark but less than benchmark; low, concentrations less than 0.1 of benchmark and includes non-detections]

Principal aquifer	Number of samples	Percent of samples with detections	Aquifer scale proportion (percent)		
			Low	Moderate	High
Pesticides					
Basin and Range carbonate-rock aquifers	20	10	100	0	0
Basin and Range basin-fill aquifers	78	26	100	0	0
Rio Grande aquifer system	60	10	100	0	0
High Plains aquifer	79	19	99	1	0
Colorado Plateaus aquifers	59	12	100	0	0
Columbia Plateau basaltic-rock aquifers	60	25	100	0	0
Volatile organic carbons					
Basin and Range carbonate-rock aquifers	20	10	100	0	0
Basin and Range basin-fill aquifers	78	22	97	[1]3	0
Rio Grande aquifer system	60	13	100	0	0
High Plains aquifer	80	20	99	[2]1	0
Colorado Plateaus aquifers	59	46	95	[3]5	0
Columbia Plateau basaltic-rock aquifers	60	23	100	0	0
Perchlorate					
Rio Grande aquifer system	60	58	97	3	0
High Plains aquifer	79	82	89	11	0

[1] Includes single moderate concentration detections of 1,2-dichloropropane and tetrachloroethylene; respective detection frequencies were less than 10 percent.

[2] Includes a single moderate concentration detection of trichloroethylene; respective detection frequency was less than 10 percent.

[3] Includes single moderate concentration detections of dichloromethane, carbon tetrachloride, and chloroform; except for chloroform respective detection frequencies were less than 10 percent.

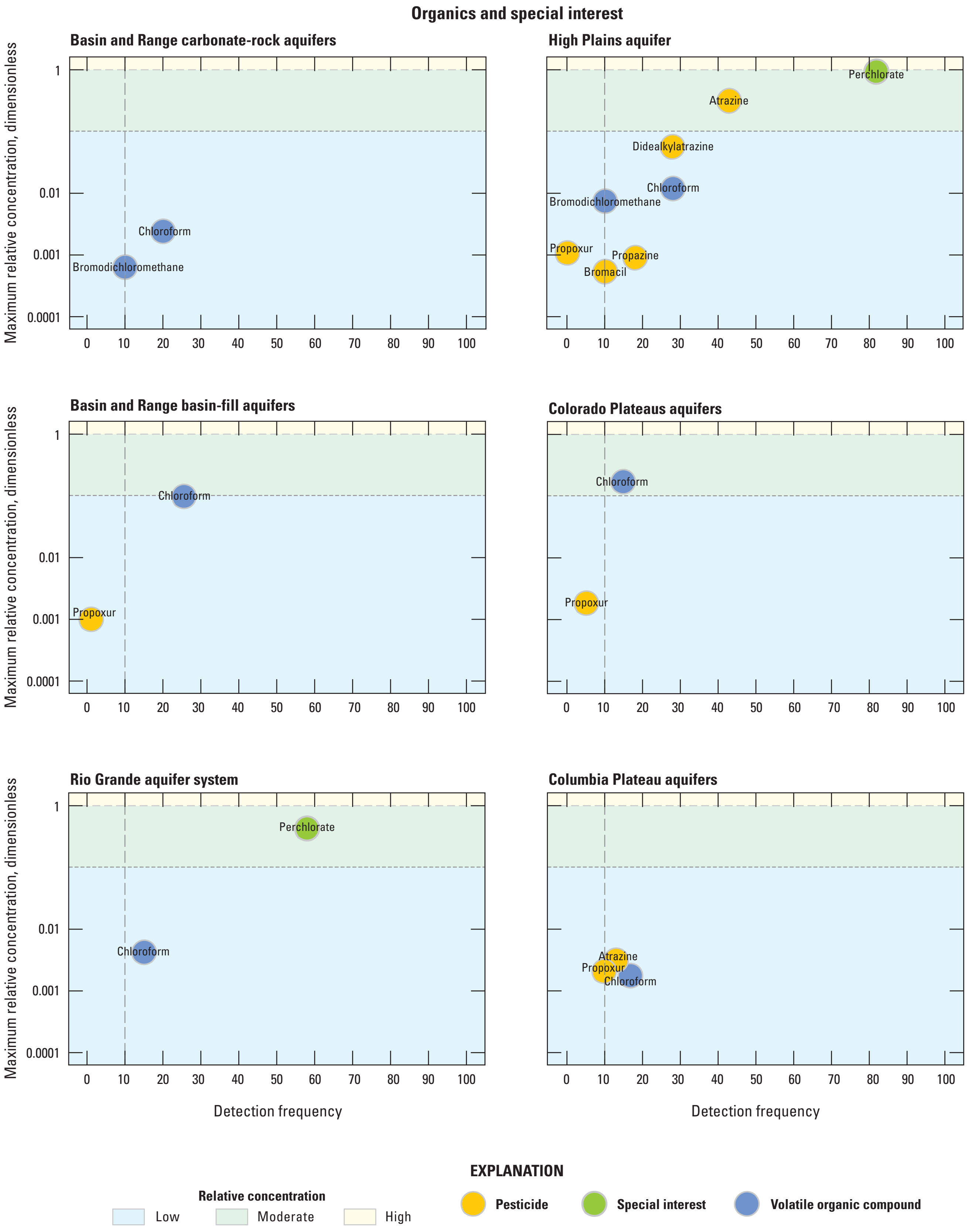


Figure 36. Detection frequency and maximum relative concentration of selected organic and special interest constituents detected in groundwater samples collected in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Table 11. Summary of aquifer-scale proportions for pesticides selected for further evaluation in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

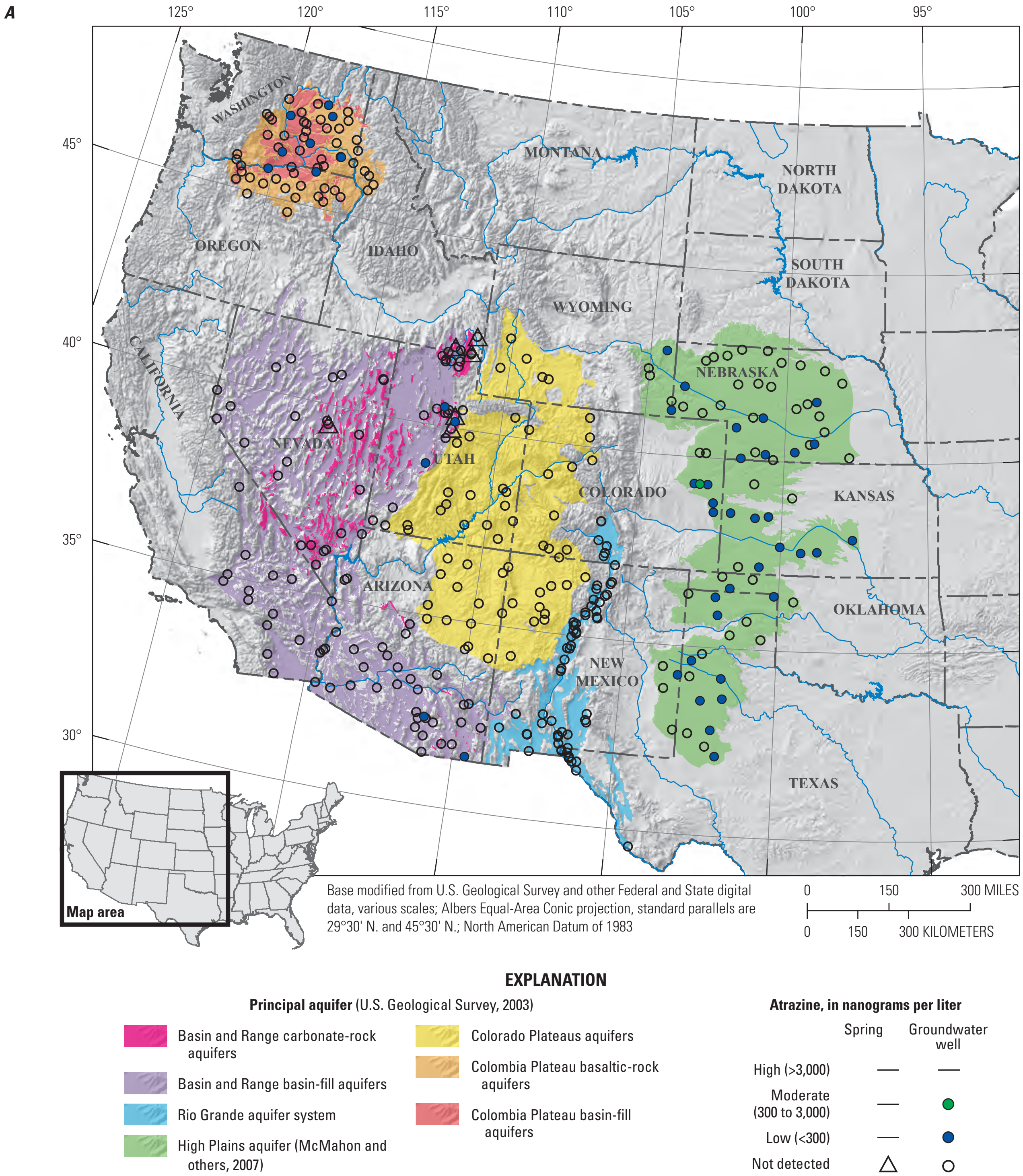
[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.1 of water quality benchmark but less than benchmark; low, concentrations less than 0.1 of bechmark and includes non-detections]

Constituent and principal aquifer	Number of samples	Percent of samples with detections	Aquifer scale proportion (percent)		
			Low	Moderate	High
Pesticides					
Atrazine (herbacide)					
Basin and Range carbonate-rock aquifers	20	0	100	0	0
Basin and Range basin-fill aquifers	78	6	100	0	0
Rio Grande aquifer system	60	0	100	0	0
High Plains aquifer	80	43	99	1	0
Colorado Plateaus aquifers	60	0	100	0	0
Columbia Plateau basaltic-rock aquifers	60	13	100	0	0
Didealkylatrazine (herbicide degradate)					
Basin and Range carbonate-rock aquifers	20	5	100	0	0
Basin and Range basin-fill aquifers	78	6	100	0	0
Rio Grande aquifer system	60	0	100	0	0
High Plains aquifer	79	28	100	0	0
Colorado Plateaus aquifers	58	2	100	0	0
Columbia Plateau basaltic-rock aquifers	60	0	100	0	0
Bromacil (herbicide)					
Basin and Range carbonate-rock aquifers	20	0	100	0	0
Basin and Range basin-fill aquifers	78	4	100	0	0
Rio Grande aquifer system	60	2	100	0	0
High Plains aquifer	79	10	100	0	0
Colorado Plateaus aquifers	58	0	100	0	0
Columbia Plateau basaltic-rock aquifers	60	8	100	0	0
Propazine (herbicide)					
Basin and Range carbonate-rock aquifers	20	0	100	0	0
Basin and Range basin-fill aquifers	78	1	100	0	0
Rio Grande aquifer system	60	0	100	0	0
High Plains aquifer	79	18	100	0	0
Colorado Plateaus aquifers	58	0	100	0	0
Columbia Plateau basaltic-rock aquifers	60	2	100	0	0
Propoxur (insecticide)					
Basin and Range carbonate-rock aquifers	20	0	100	0	0
Basin and Range basin-fill aquifers	78	1	100	0	0
Rio Grande aquifer system	60	0	100	0	0
High Plains aquifer	79	1	100	0	0
Colorado Plateaus aquifers	58	5	100	0	0
Columbia Plateau basaltic-rock aquifers	60	10	100	0	0

Table 12. Summary of aquifer-scale proportions for volatile organic compounds (VOCs) selected for further evaluation in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

[**Relative concentration categories**: high, concentrations greater than water quality benchmark; moderate, concentrations greater than or equal to 0.1 of water quality benchmark but less than benchmark; low, concentrations less than 0.1 of bechmark and includes non-detections]

Constituent and principal aquifer	Number of samples	Percent of samples with detections	Aquifer scale proportion (percent)		
			Low	Moderate	High
VOCs					
Chloroform					
Basin and Range carbonate-rock aquifers	20	20	100	0	0
Basin and Range basin-fill aquifers	78	26	100	0	0
Rio Grande aquifer system	60	15	100	0	0
High Plains aquifer	80	28	100	0	0
Colorado Plateaus aquifers	59	15	98	2	0
Columbia Plateau basaltic-rock aquifers	60	17	100	0	0
Bromodichloromethane					
Basin and Range carbonate-rock aquifers	20	10	100	0	0
Basin and Range basin-fill aquifers	78	5	100	0	0
Rio Grande aquifer system	60	3	100	0	0
High Plains aquifer	80	10	100	0	0
Colorado Plateaus aquifers	59	8	100	0	0
Columbia Plateau basaltic-rock aquifers	60	2	100	0	0
Dibromochloromethane					
Basin and Range carbonate-rock aquifers	20	0	100	0	0
Basin and Range basin-fill aquifers	78	1	100	0	0
Rio Grande aquifer system	60	2	100	0	0
High Plains aquifer	80	4	100	0	0
Colorado Plateaus aquifers	59	5	100	0	0
Columbia Plateau basaltic-rock aquifers	60	3	100	0	0
Bromoform					
Basin and Range carbonate-rock aquifers	20	0	100	0	0
Basin and Range basin-fill aquifers	78	1	100	0	0
Rio Grande aquifer system	60	2	100	0	0
High Plains aquifer	80	6	100	0	0
Colorado Plateaus aquifers	59	2	100	0	0
Columbia Plateau basaltic-rock aquifers	60	5	100	0	0



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

Figure 37. Concentrations of selected pesticides *A,* atrazine; *B,* didealkylatrazine; *C,* bromacil; *D,* propazine and *E*, propoxur in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

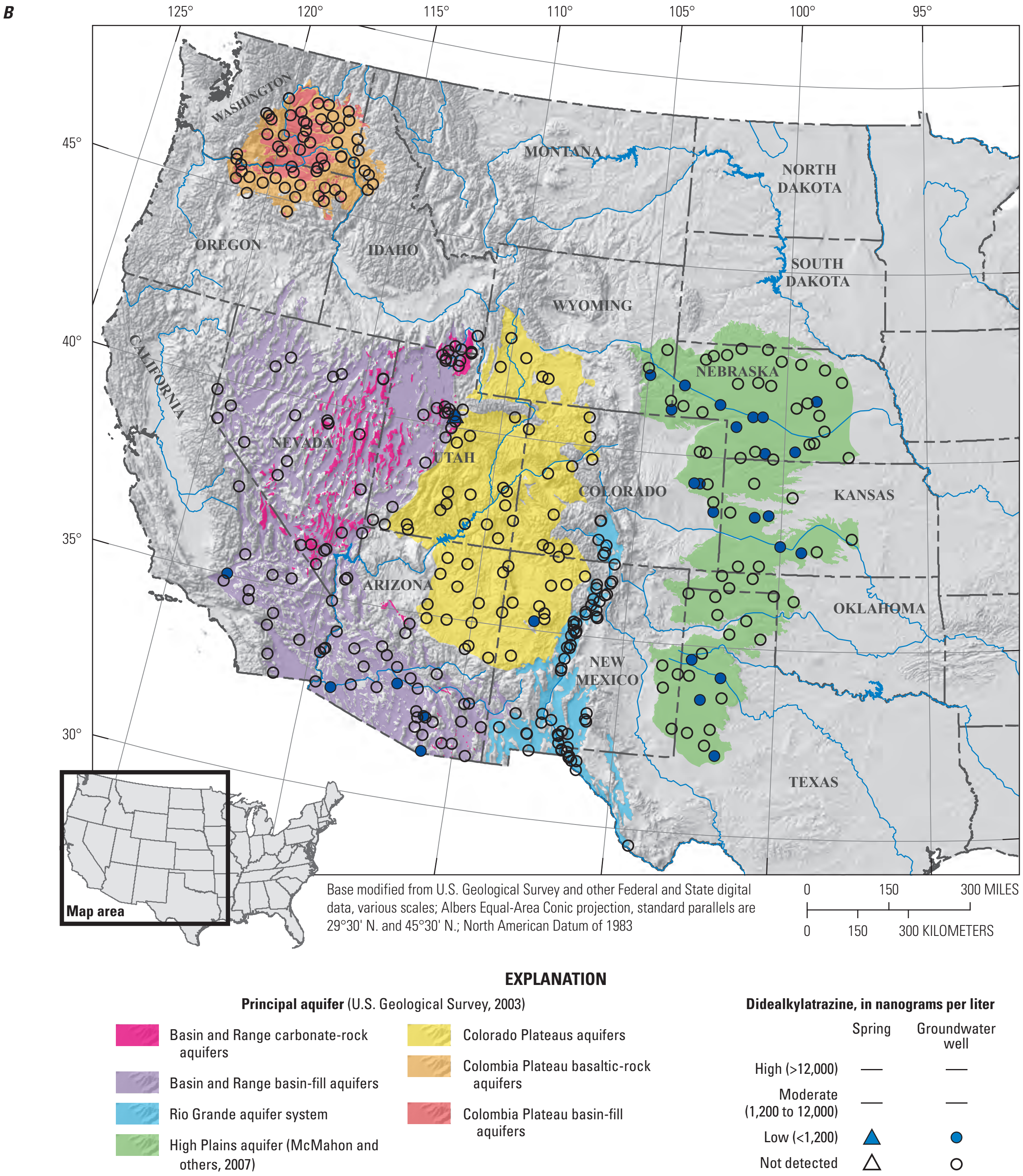


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Figure 37. —Continued

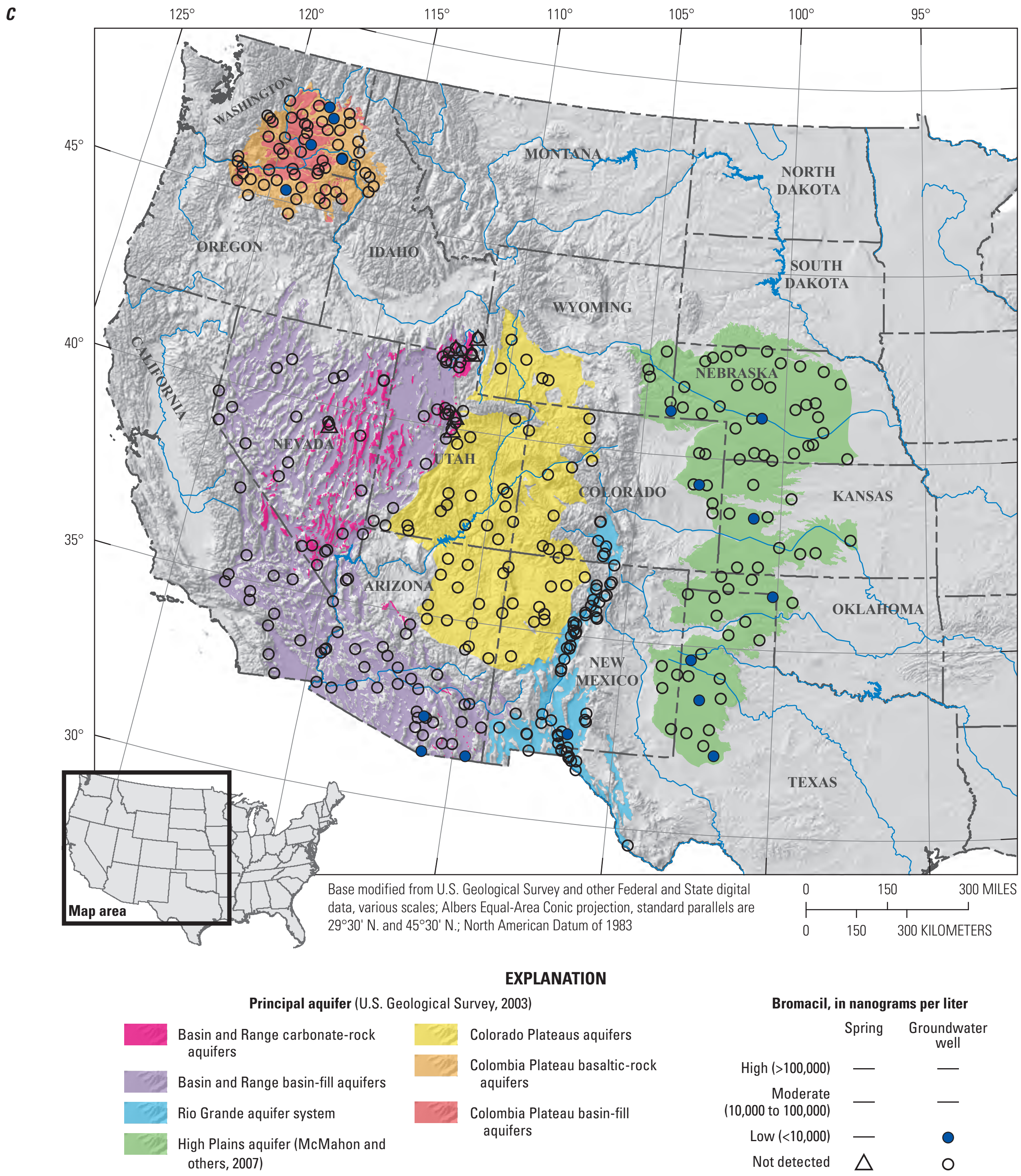

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Figure 37. —Continued

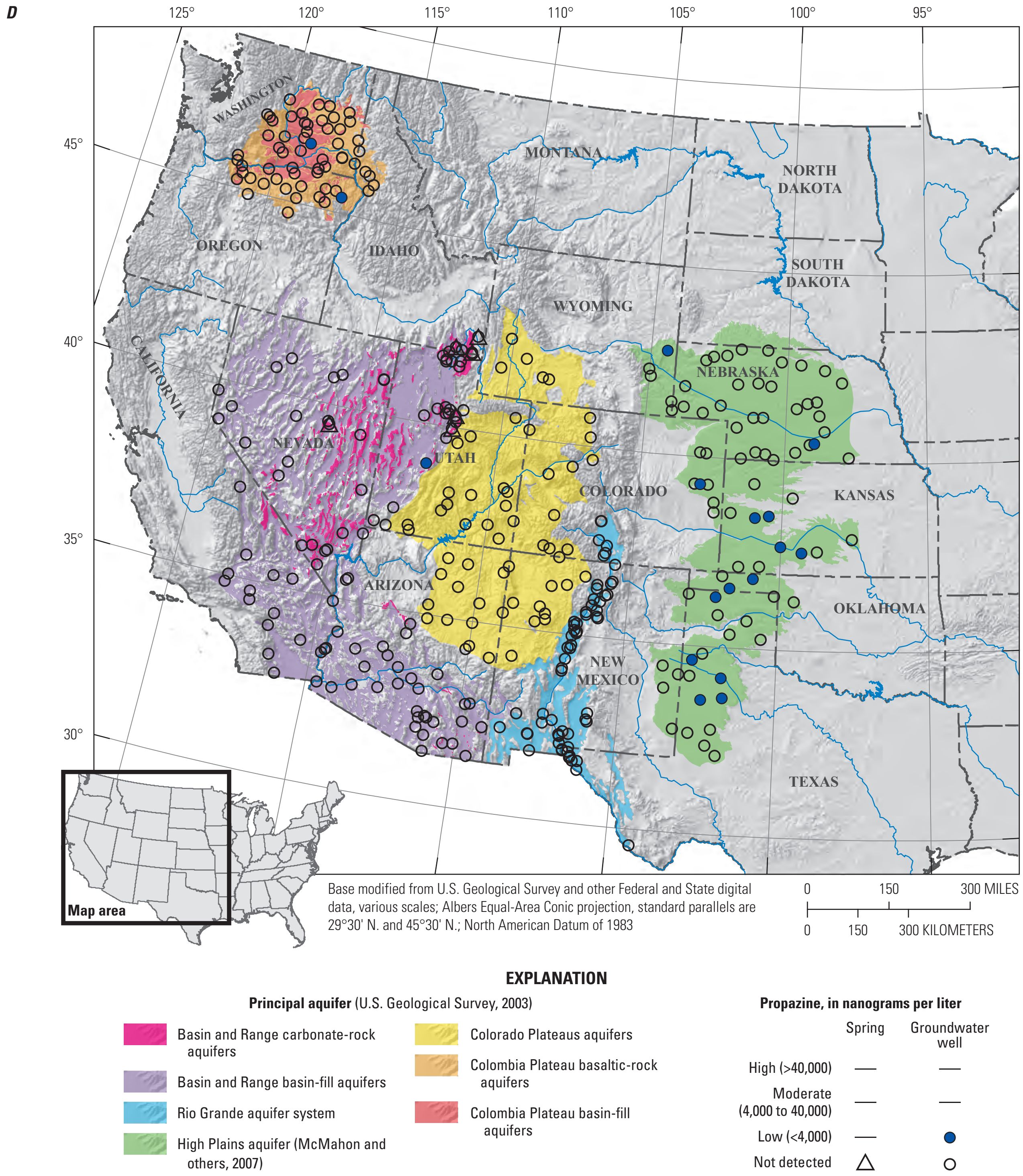

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Figure 37. —Continued

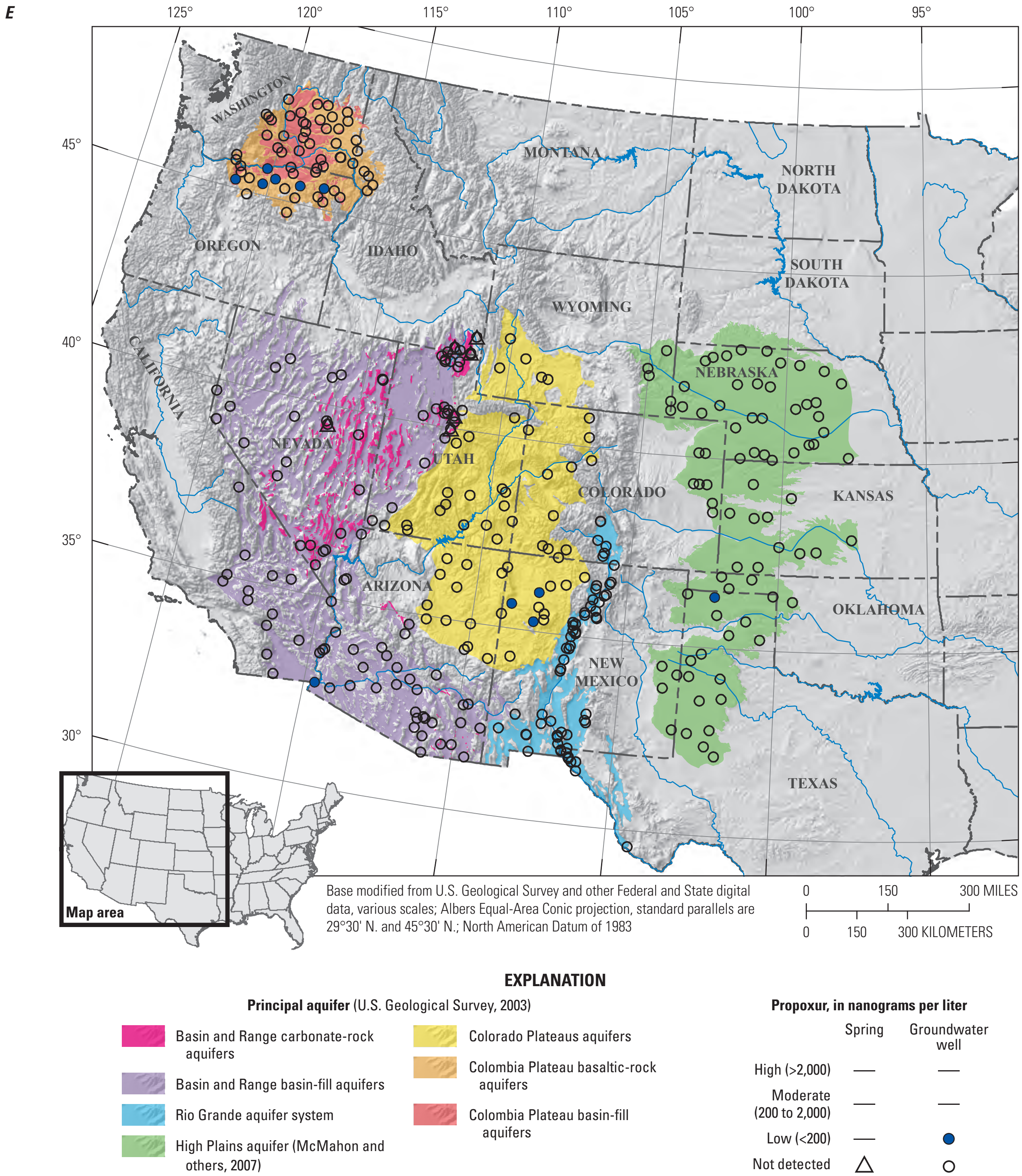

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Figure 37. —Continued

Degradate concentrations in groundwater might exceed parent compound concentrations for the triazine (which include atrazine) and chloroacetanilide (which include metolachlor) herbicides (Kolpin and others, 1998, 2000; Scribner and others, 2000). Herbicide degradates are often more water soluble than their parent compounds; therefore, herbicide degradates are leached more rapidly through the soil into the groundwater, causing the degradate concentrations to be higher (Scribner and others, 2000). In this report, the herbicide degradate didealkylatrazine was the only degradate included for the *understanding assessment* (because it occurred at detection frequencies greater than 10 percent); however, other atrazine degradate compounds were detected (table 3). For example, in the Columbia Plateau basaltic-rock aquifers, low concentrations of atrazine (13-percent detections) and one of its degradate, 2-hydroxyatrazine (2 percent) were detected.

Correlations with pesticide compounds and potential explanatory factors occurred only in the High Plains aquifer and the Columbia Plateau basaltic-rock aquifers (fig. 38). Herbicides in the High Plains aquifer were positively correlated with geochemical factors (TDS and HCO_3 concentrations) as well as percentage of urban land use, and inversely correlated with natural land use. The inverse correlation with natural land use likely reflects that herbicides generally are not applied or used in natural land use areas. It is likely that surface application of herbicides, particularly in agricultural areas, results in their transport and leaching to the shallow groundwater. Atrazine and didealkylatrazine were also negatively correlated with depth to bottom of well perforation, indicating they occur more commonly in shallow groundwater. The insecticide propoxur did not have significant correlations with any of the potential explanatory factors considered in this report.

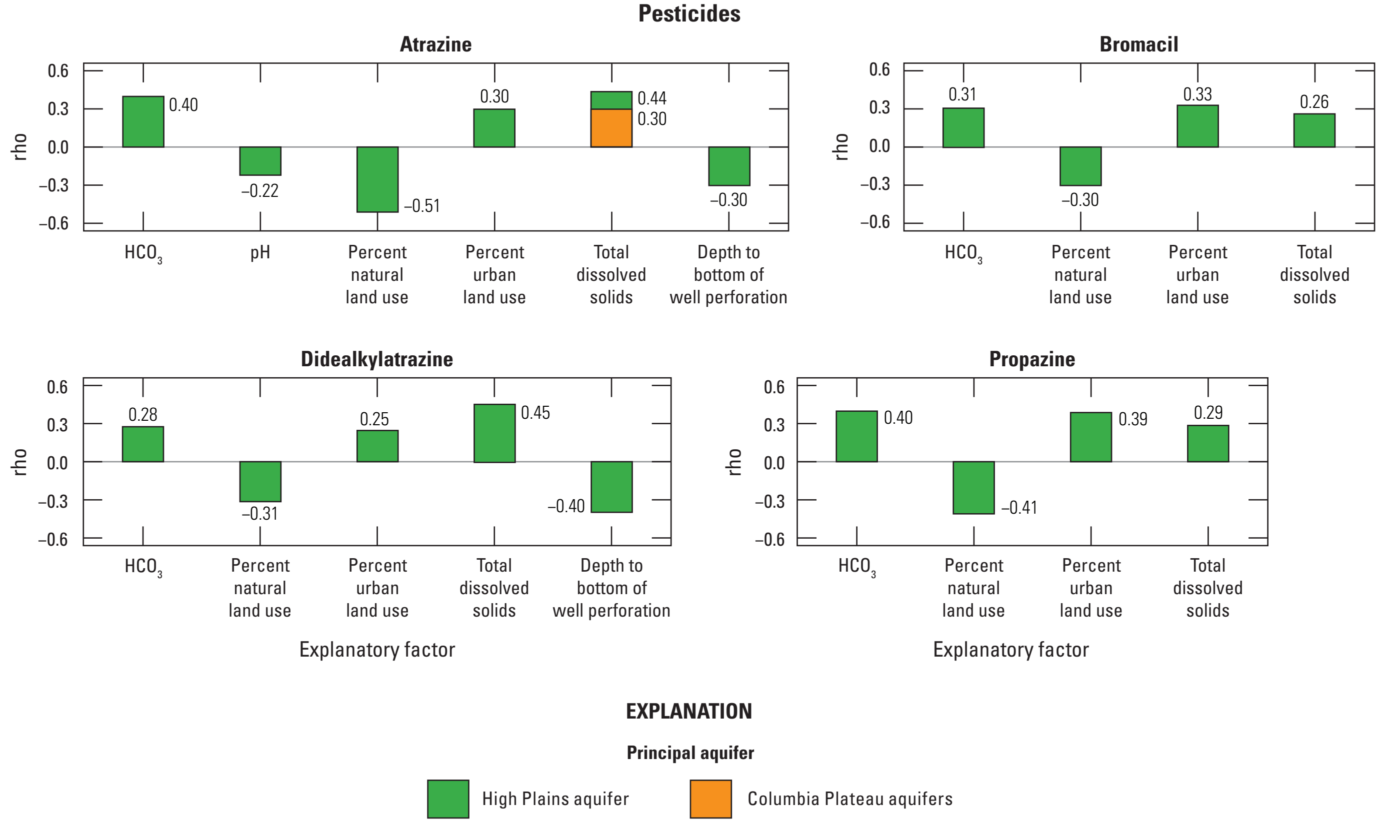


Figure 38. Spearman's rho results for pesticides in two western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Volatile Organic Compounds (VOCs)

Volatile organic compounds are characterized by their tendency to volatilize or evaporate and are present in many household, commercial, industrial, and agricultural products; common VOCs include solvents, gasoline hydrocarbons, and trihalomethanes (THMs; which may originate as water chlorination by-products). Although moderate concentrations of VOCs occurred in several of the PAs (table 10), these were often single occurrences of one or more compounds and were not included in the understanding assessment. Only two VOCs—chloroform and bromodichloromethane—which are both THMs, were included in the *understanding assessment* because they were detected at frequencies greater than or equal to 10 percent (fig. 36). Trihalomethanes, also known as disinfection by-products, are produced from the use of chlorine to disinfect drinking water; they include chlorinated and brominated compounds, most commonly chloroform, bromodichloromethane, dibromochloromethane, and bromoform (Ivahnenko and Barbash, 2004). Chloroform is the most commonly detected VOC in groundwater and drinking water in the United States; detection frequencies typically are higher in PSWs than in domestic wells (11 percent compared to 5 percent) and might be attributed to higher pumping rates for PSWs and their proximity to developed areas (Zogorski and others, 2006). Trihalomethanes in drinking water are associated with acute and chronic human-health problems including nausea, headaches, and damage to liver and kidneys from prolonged exposure (Agency for Toxic Substances and Disease Registry, 1997, 2018). The MCL for combined THMs is 80 µg/L (U.S. Environmental Protection Agency, 2018a).

Chlorinated drinking water and wastewater is an important source of chloroform and other THMs to groundwater (Ivahnenko and Barbash, 2004). Major sources of chlorinated water to groundwater include irrigation of lawns, golf courses and parks; leaking drinking-water distribution and sewer pipes; artificial recharge of wastewater; regulated discharges of cooling process blowdown water from electric power-generating plants; combined sewer overflows; unintended backflow of chlorinated water to supply wells; and domestic well disinfection with bleach (California Department of Health, 1990; Agency for Toxic Substances and Disease Registry, 1997; Zogorski and others, 2006). Several natural sources of chloroform include volcanic gases (Isidorov and others, 1990), soil fungi (McCulloch, 2003), and marine algae (Gribble, 1994; Laturnus and others, 2002). McCulloch (2003) estimated that natural sources of chloroform contribute about 90 percent of the total global chloroform flux (McCulloch, 2003). A national-scale study of VOCs in groundwater and drinking-water supply wells was inconclusive regarding the contribution of natural sources of chloroform to groundwater (Zogorski and others, 2006).

Chloroform was detected at low concentrations in all PAs (fig. 39*A*) with detection frequencies ranging from 15 percent in the Colorado Plateaus aquifers and Rio Grande aquifer system to 28 percent in the High Plains aquifer (table 12). Only one moderate concentration of chloroform occurred, which was in the Colorado Plateaus aquifers. The high detection frequencies at low concentrations were consistent with the national-scale findings of Zogorski and others (2006) in which chloroform concentrations generally occurred at less than 1 µg/L.

Bromodichloromethane also was detected at low concentrations in all of the PAs (fig. 39*B*), with the highest detection frequency (10 percent) occurring in the High Plains and the Basin and Range carbonate-rock PAs (table 12). Low concentration of the remaining two THMs considered—dibromochloromethane and bromoform—had detection frequencies ranging from 1 percent to about 6 percent in the PAs except for the Basin and Range carbonate-rock aquifers where they were not detected (table 12). Although dibromochloromethane and bromoform were not selected for the *understanding assessment* evaluation, detection frequencies are included in table 12 because of their generation from chlorination. The trend in detection frequencies and concentrations of THMs (decreasing from chloroform to bromodichloromethane to dibromochloromethane to bromoform) is consistent with studies of the formation of multiple THMs during water chlorination that have shown that concentrations and detection frequencies decrease with increasing bromide concentration (Minear and Bird, 1980; Clark and others, 1996; Chellam, 2000).

Chloroform and bromodichloromethane had negative correlation with aridity index in the High Plains, whereas in the Columbia Plateau aquifer only chloroform was negatively correlated with aridity index (figs. 40*A, B*). The most significant correlations for chloroform in the remaining PAs were negative correlations with pH in the Basin and Range carbonate-rock aquifers, Rio Grande aquifer system, and Colorado Plateaus aquifers. These relations indicate that causative and non-causative correlations might not directly relate to THM production in groundwater and could be associated with the recharge of chlorinated water to groundwater in urban land use areas or shallow groundwater depths within the PAs instead.

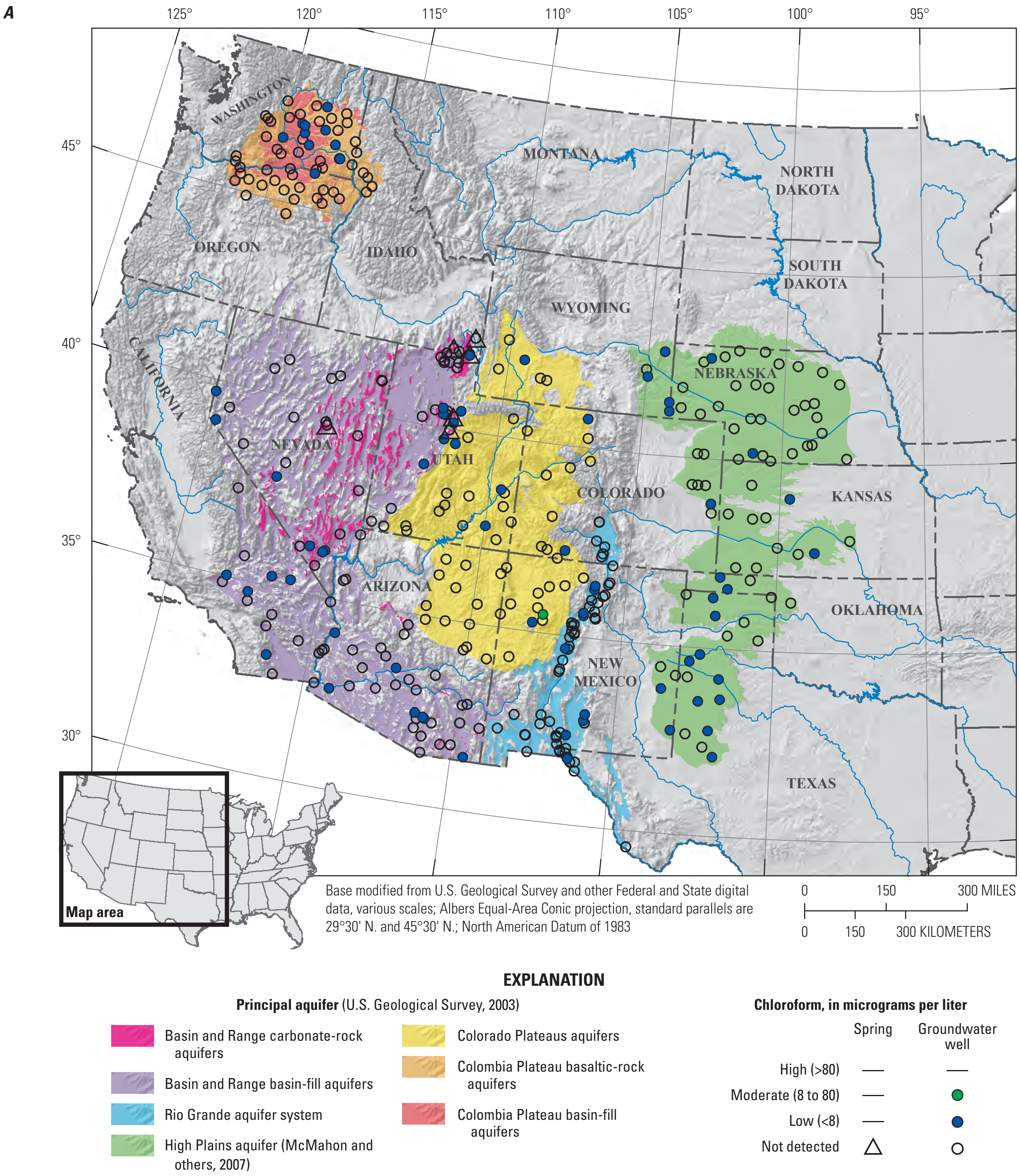
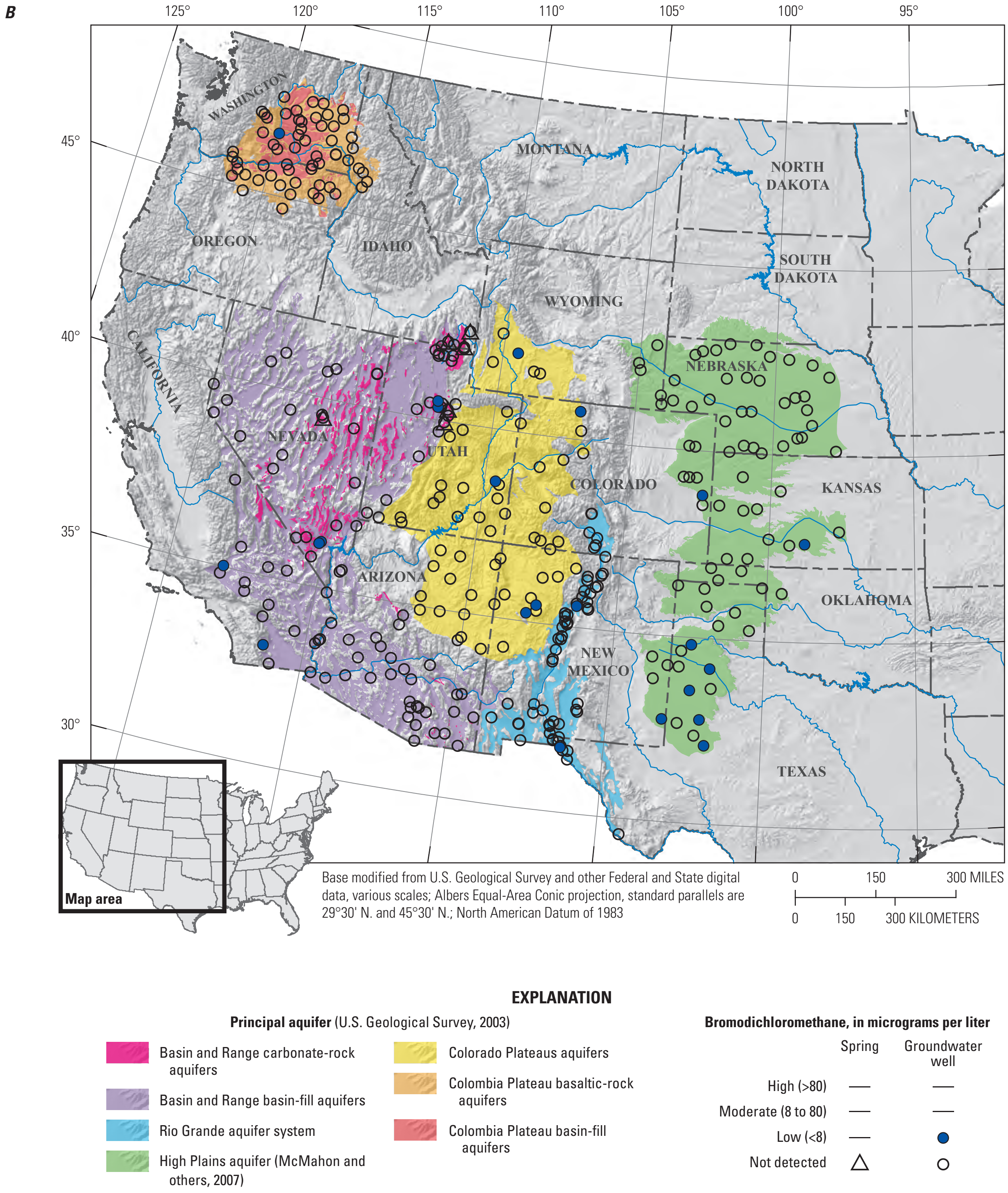


Figure 39. Concentrations of selected volatile organic compounds *A,* chloroform; and *B,* bromodichloromethane in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.



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

Figure 39. —Continued

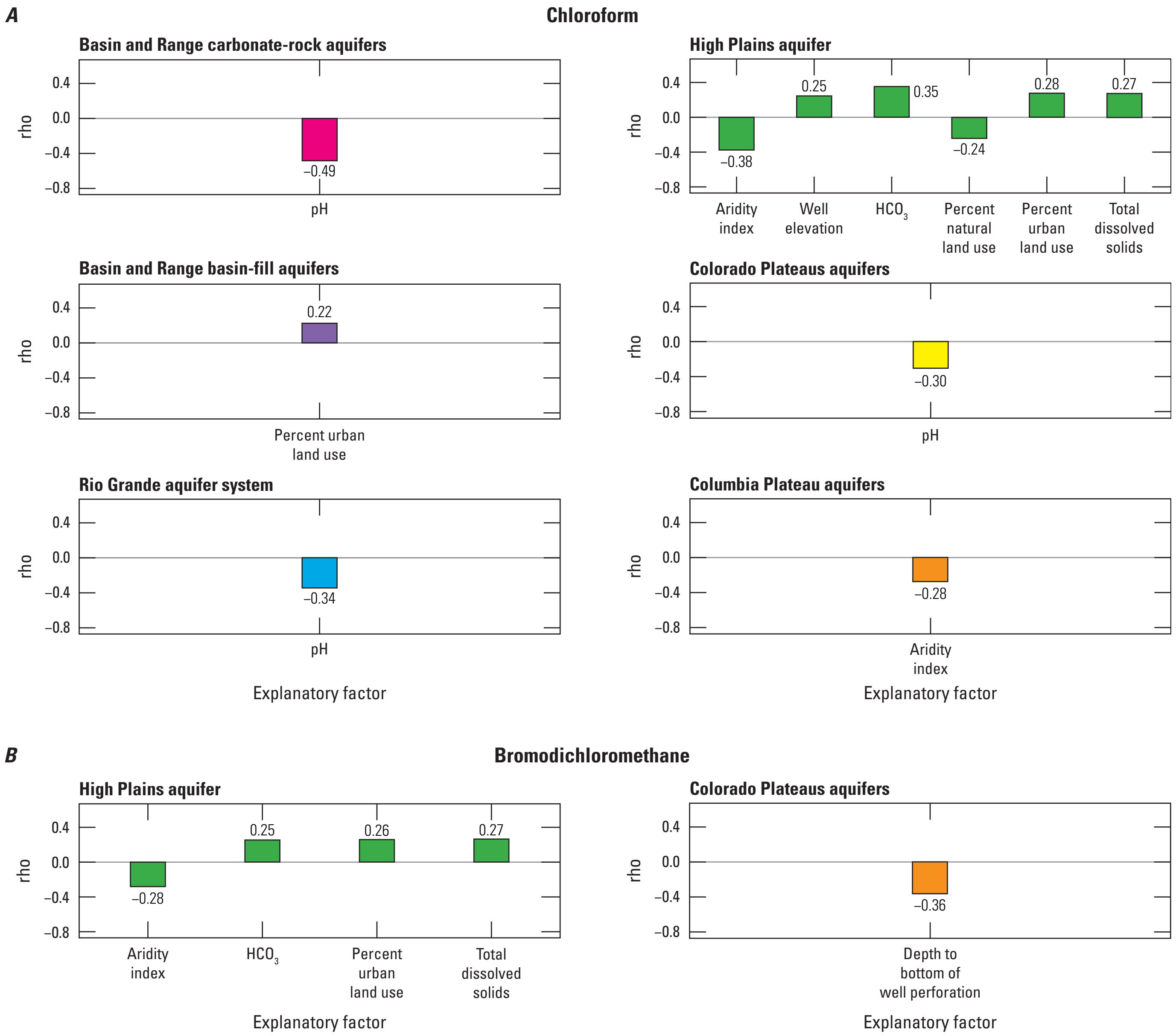


Figure 40. Spearman's rho results for *A,* chloroform; and *B,* bromodichloromethane in six western U.S. principal aquifers sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Special Interest Constituent: Perchlorate

Perchlorate in drinking water is a human-health concern because it can disrupt the normal function of the thyroid gland; as of 2018, there is no MCL for perchlorate (U.S. Environmental Protection Agency, 2018d), but it has a HBSL of 15 µg/L (Norman and others, 2018; U.S. Geological Survey, 2018a). Perchlorate in groundwater has synthetic and natural sources (Hatzinger and others, 2018). Synthetic sources include rocket propellants, road flares, fireworks, blasting agents, sodium chlorate, and perchloric acid (Aziz and Hatzinger, 2008). Natural sources include the apparent atmospheric formation and accumulation in vadose-zone soils in arid environments (Dasgupta and others, 2005). Anthropogenic sources include the historical application of the naturally occurring imported Chilean nitrate fertilizer. In the surficial deposits of the Atacama Desert of Chile, perchlorate co-occurs with sodium nitrate ($NaNO_3$) at an average concentration of around 0.1 percent (by mass) of total soluble salt (Ericksen, 1981, 1983; Dasgupta and others, 2006). During the first half of the 20th century, processed nitrate deposits from the Atacama Desert were widely used in the United States as fertilizer. Post 2002, changes in manufacturing processes reduced the perchlorate concentrations to less than (or about) 0.01 percent (Dasgupta and others, 2006); however, previous applications are a potential source of perchlorate in groundwater and drinking water in the United States (Hatzinger and others, 2018). Perchlorate not associated with Chilean fertilizer has been detected in soil, groundwater, and mineral deposits from arid regions of the southern High Plains in Texas and New Mexico (Jackson and others, 2004, 2006; Dasgupta and others, 2005; Rajagopalan and others, 2006; Scanlon and others, 2008) and the middle Rio Grande Basin of New Mexico (Plummer and others, 2006). The postulated source of this perchlorate is long-term accumulation of atmospheric dry deposition and precipitation (Rajagopalan and others, 2006, 2009; Rao and others, 2007) forming in the atmosphere through photochemical reactions (Bao and Gu, 2004; Dasgupta and others, 2005; Kang and others, 2008; Sturchio and others, 2009). The perchlorate accumulations can be mobilized and transported from the vadose zone to the water table. Irrigation also could be associated with transport of perchlorate to groundwater from crops treated with Atacama nitrate fertilizer (Böhlke and others, 2009; Sturchio and others, 2014; Hatzinger and others, 2018). Perchlorate also can form in chlorine solutions used for drinking-water disinfection (Greiner and others, 2008).

Perchlorate samples only were collected in the High Plains aquifer and the Rio Grande aquifer system (fig. 41) and no high concentrations were observed. Moderate aquifer-scale proportions of perchlorate occurred in 11 percent of the High Plains aquifer and 3 percent of the Rio Grande aquifer system (table 10). Detected concentrations of perchlorate in collected samples were common, occurring in 82 percent of the High Plains aquifer and 58 percent of the Rio Grande aquifer system. In the High Plains aquifer, the most significant perchlorate correlations were with dissolved oxygen, TDS, and aridity index (fig. 42). Moderate concentrations of perchlorate predominately occurred in wells in the southern part of the High Plains aquifer, associated with drier climate and elevated TDS concentrations in shallower wells. Although dissolved oxygen was positively correlated with perchlorate, the correlation is likely non-causative because the High Plains aquifer was predominately oxic (fig. 15*A*). In the Rio Grande aquifer system, concentrations of perchlorate were negatively correlated with percentage of agricultural and irrigated land use and positively correlated with TDS and HCO_3. Determining the source of perchlorate (natural or synthetic) was not possible using the potential explanatory factors applied in this study; however, considering the location of moderate concentrations occurring in the most arid regions of these two PAs and significant correlations with hydrologic conditions and land use, the sources of perchlorate are more likely attributed to natural atmospheric formation and accumulation in the vadose zone and Atacama nitrate fertilizer rather than synthetic sources or those associated with drinking-water disinfection. In the Rio Grande aquifer system, Plummer and others (2006) proposed that low concentrations of perchlorate were likely associated with natural accumulation in the vadose zone and subsequent transport to the water table. In the High Plains aquifer, accumulation in the vadose zone and subsequent transport to groundwater from crops treated with Atacama nitrate fertilizer could account for the occurrence of low and moderate perchlorate concentrations.

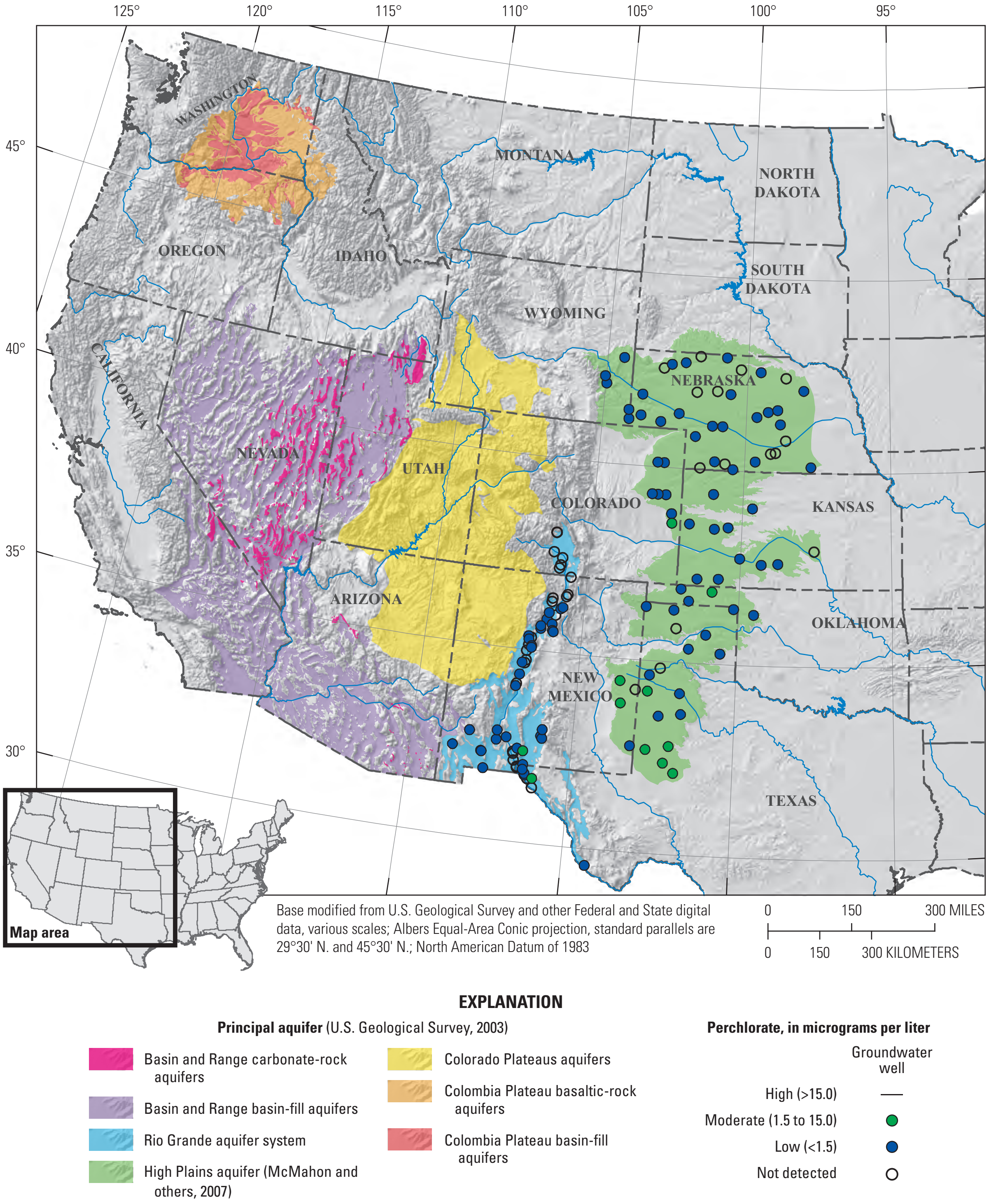


Figure 41. Concentrations of special interest constituent perchlorate in the Rio Grande aquifer system and High Plains aquifer sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

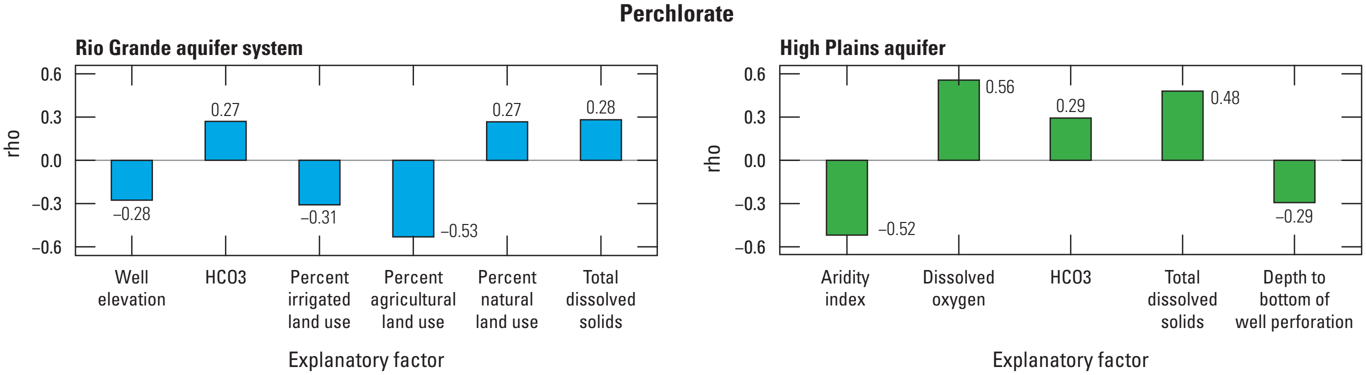


Figure 42. Spearman's rho results for special interest constituent perchlorate in the Rio Grande aquifer system and High Plains aquifer sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Summary

The U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Project has been evaluating the water quality of source water (that is, untreated water) from principal aquifers that are important sources of drinking water. Groundwater quality at public-supply well depths was evaluated for inorganic and organic constituents in six principal aquifers (PAs) of the western United States that are important sources of public supply:

- the Basin and Range carbonate-rock aquifers
- the Basin and Range basin-fill aquifers
- the Rio Grande aquifer system
- the High Plains aquifer
- the Colorado Plateaus aquifers
- the Columbia Plateau basaltic-rock aquifers.

To provide context for water-quality data, constituent concentrations of untreated groundwater were compared with available water-quality benchmarks. The quality of water received by consumers can be different because after withdrawal, groundwater might be treated prior to delivery. The benchmarks that were considered were federal regulatory health-based benchmarks (U.S. Environmental Protection Agency Maximum Contaminant Levels [MCLs]), non-regulatory health-based benchmarks (health-based screening levels [HBSLs] developed by the U.S. Geological Survey), and non-regulatory secondary benchmarks (U.S. Environmental Protection Agency secondary maximum contaminant levels [SMCLs]). The PA studies evaluated water quality by sampling spatially distributed public-supply wells (PSWs) or springs using an equal-area grid sampling approach. This approach provides a spatially unbiased estimate of the aquifer-scale proportion that is equal to the observed detection frequency of a constituent concentration relative to a given threshold or benchmark (Belitz and others, 2010). This approach was used to estimate the percentage of a principal aquifer that has low, moderate, or high concentrations of constituents relative to their benchmarks. Two types of assessments were made: (1) *status:* an assessment that describes the quality of the groundwater resource; and (2) *understanding:* an evaluation of the natural and human factors affecting the quality of groundwater, including an explanation of statistically significant associations between water quality and selected explanatory factors. The assessments were based on water-quality data collected from 352 PSWs and 6 springs. Potential explanatory factors considered in the *understanding assessment* were depth to bottom of well perforation, groundwater age category, land use, aquifer lithology, hydrologic conditions, and geochemical conditions. Constituents selected for assessment included inorganic constituents with moderate or high concentrations and organic constituents with detection frequencies greater than 10 percent. Inorganic constituents were grouped and described by four classes—trace elements, radionuclides, nutrients, and salinity indicators. Organic constituents were grouped and described by two classes, pesticides and volatile organic compounds (VOCs), and additionally included perchlorate, a special interest constituent.

Trace elements with health-based benchmarks were the largest group with moderate and high concentrations in all of the PAs—aquifer-scale proportions were Rio Grande aquifer system (27 percent), Basin and Range basin-fill aquifers (22 percent), High Plains aquifer (16 percent), Basin and Range carbonate-rock aquifers (15 percent), Colorado Plateaus aquifers (13 percent), and Columbia Plateau basaltic-rock aquifers (5 percent). The trace elements arsenic, fluoride, and manganese were those that most frequently occurred at moderate and high concentrations. Of these trace elements, arsenic was most frequently high, particularly in the unconsolidated sand and gravel aquifers of the arid Southwest. Elevated concentrations of arsenic were attributed to geochemical conditions that promote arsenic mobility and hydrologic conditions that favor accumulation of arsenic in groundwater. High and moderate arsenic concentrations were associated with oxic conditions, elevated pH values (greater than 7), and premodern groundwater age.

Three radionuclides with health-based benchmarks—30-day gross alpha activity, radium (radium-226 plus radium-228), and radon-222 (radon)—were selected for evaluation by the *understanding assessment* in this report. High radionuclide concentrations occurred in four PAs—the Basin and Range carbonate-rock aquifers (5 percent of PA), Rio Grande aquifer system (5 percent), Colorado Plateaus aquifers (5 percent), and Columbia Plateau basaltic-rock aquifers (3 percent). High concentrations of 30-day gross alpha were associated with geochemical factors favoring the release of the parent material uranium in groundwater (oxic groundwater with elevated total dissolved solids [TDS] and bicarbonate [HCO_3] concentrations), whereas high concentrations of radium-226 and radium-228 generally occurred with anoxic or mixed groundwater conditions at pH values ranging from 7.4 to 7.7. High concentration of radon above the 4,000 pCi/L proposed benchmark occurred in 5 percent or less of the Basin and Range carbonate-rock aquifers, Rio Grande aquifer system, Colorado Plateaus aquifers, and Columbia Plateau basaltic-rock aquifers.

Moderate and high aquifer-scale proportions of salinity indicators (TDS, sulfate, and chloride) occurred in all six western PAs (excluding chloride in the Columbia Plateau basaltic-rock aquifers). The proportion of each PA having high concentrations of TDS ranged from 25 to 37 percent and generally was highest in the most arid regions of the unconsolidated sand and gravel PAs (the Rio Grande aquifer system and the Basin and Range basin-fill aquifers) and in the southern part of the High Plains aquifer. These arid to semi-arid regions are associated with low precipitation and high evaporation rates, which result in less groundwater recharge to dilute the products of rock weathering. Portions of the Southwest also have shallow groundwater with high evaporation rates that further contribute to elevated TDS concentrations. High concentrations of TDS in the southern part of the High Plains aquifer might result from mixing with saline groundwater from underlying geologic units. Irrigated agriculture also is a potential source of TDS in the High Plains aquifer.

Moderate and high concentrations of the nutrient nitrate (as nitrogen) were relatively uncommon in the western PAs; aquifer-scale proportions with moderate concentrations ranged from 0 to 11 percent, with the highest aquifer proportions occurring in the High Plains aquifer (11 percent), Basin and Range basin-fill aquifers (9 percent), and Columbia Plateau basaltic-rock aquifers (7 percent). High concentrations were present in 3 percent or less of the Rio Grande aquifer system, High Plains aquifer, and Columbia Plateau basaltic-rock aquifers. Nitrate was most strongly correlated (positive) with dissolved oxygen in the five PAs with moderate or high concentrations, which also tended to occur in modern or mixed age groundwater.

Organic constituents did not occur at high concentrations in any of the six PAs. Moderate concentrations occurred in three PAs—the Basin and Range basin-fill aquifers, High Plains aquifer, and Colorado Plateaus aquifers. Five pesticides (the herbicides atrazine, bromacil, didealkylatrazine, and propazine, and the insecticide propoxur) and two VOCs (chloroform and bromodichloromethane) were selected for further analysis by the *understanding assessment* because they were detected relatively frequently (between 10 and 43 percent) in at least one PA. The High Plains aquifer had the highest detection rates, at low concentrations, of the pesticide constituent group—atrazine (43 percent), didealkylatrazine (28 percent), propazine (18 percent) and bromacil (10 percent). Atrazine also was detected in 1 percent of the High Plains aquifer at moderate concentrations. Atrazine and its degradate didealkylatrazine had significant negative correlations with well depth; presumably, surface application of the parent compound is followed by degradation and both compounds are transported or leached to shallow groundwater in the High Plains aquifer. The insecticide propoxur was detected at low concentrations in Columbia Plateau basaltic-rock aquifers (10 percent of PA), Colorado Plateaus aquifers (5 percent), High Plains aquifer (1 percent), and the Basin and Range basin-fill aquifer (1 percent); concentrations were not correlated with any of the potential explanatory factors considered in this report.

Only two VOC constituents—chloroform and bromodichloromethane—which are trihalomethanes, were selected for the *understanding assessment*. Chloroform was detected at low concentrations in all PAs at frequencies that ranged from 15 percent of samples in the Colorado Plateaus aquifers and Rio Grande aquifer system to 28 percent in the High Plains aquifer. The high detection frequencies at low concentrations were consistent with the findings of previous national-scale studies. Bromodichloromethane also was detected at low concentrations in all PAs, occurring at frequencies up to 10 percent in the High Plains aquifer and the Basin and Range carbonate-rock aquifers. Several potential explanatory factors were correlated with chloroform and bromodichloromethane (TDS, urban land use, and well depth), which likely reflect associations with the recharge of chlorinated water to groundwater in urban land use areas and shallow groundwater depths.

The special interest constituent perchlorate was only sampled in the High Plains aquifer and Rio Grande aquifer system. No high concentrations were observed. Moderate concentrations were observed in 11 percent of the High Plains aquifer and 3 percent of the Rio Grande aquifer system.

Detections at low concentrations were common, occurring at frequencies of 82 percent in the High Plains aquifer and 58 percent in the Rio Grande aquifer system. Moderate concentrations of perchlorate predominately occurred in the southern part of the High Plains aquifer, associated with shallow well depths (depth to bottom of well perforation), elevated TDS concentrations, and arid climates. In the Rio Grande aquifer system, perchlorate was negatively correlated with agricultural and irrigated land use and was positively correlated with TDS and HCO_3. The distribution of detections at low concentration in the Rio Grande aquifer system likely reflects natural perchlorate accumulation (atmospheric deposition and accumulation in the vadose zone with subsequent leaching into shallow groundwater). Perchlorate detections in the High Plains aquifer also might reflect natural accumulation or could potentially be associated with transport of perchlorate to groundwater from crops treated with Atacama nitrate fertilizer.

Acknowledgments

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Appendix 1. Quality-Control Data and Analysis

Samples

Quality-control (QC) samples are routinely collected with environmental groundwater samples. Quality-control samples help to identify data that best represent environmental conditions and data that might have been affected by contamination or bias during sample collection, processing, storage, transportation, or laboratory analysis (Bennett and Fram, 2014). The third cycle of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Project began in 2013, and during this cycle, groundwater samples were collected from four types of groundwater networks—principal aquifer study networks (six of which are the focus of this report), land-use study networks, major aquifer study networks, and enhanced trends networks. The NAWQA groundwater sampling has collected and evaluated three types of QC samples: (1) blank samples to assess positive bias from contamination during sample collection or sample analysis, (2) replicate samples to assess variability, and (3) matrix-spike tests to assess positive or negative bias. Quality-control results for five of the six principal aquifer study networks described in this report have been previously published in USGS data-series reports corresponding to collection periods of groundwater samples for the respective PAs (table 1.1); QC results for these five principal aquifer studies, therefore, are not discussed herein. Quality-control results for the Colorado Plateaus aquifers principal aquifer study will be included in a subsequent data-series report and also are described in this appendix.

Table 1.1. Principal aquifer study unit and respective U.S. Geological Survey (USGS) data-series reports that summarize quality-control results for groundwater samples collected by the National Water-Quality Assessment Project sampled by the U.S. Geological Survey National Water-Quality Assessment Project, 2013–2017.

Principal aquifer study unit	Sample collection year	USGS Data series report
Basin and Range basin-fill aquifers	2013	Arnold, T.L., DeSimone, L.A., Bexfield, L.M., Lindsey, B.D., Barlow, J.R., Kulongoski, J.T., Musgrove, M., Kingsbury, J.A., and Belitz, K., 2016, Groundwater quality data from the National Water-Quality Assessment Project, May 2012 through December 2013 (ver. 1.1, November 2016): U.S. Geological Survey Data Series 997, 56 p., https://doi.org/10.3133/ds997.
Basin and Range carbonate-rock aquifers	2013 and 2015	Arnold, T.L., Bexfield, L.M., Musgrove, M., Stackelberg, P.E., Lindsey, B.D., Kingsbury, J.A., Kulongoski, J.T., and Belitz, K., 2018, Groundwater-quality and select quality-control data from the National Water-Quality Assessment Project, January through December 2015, and previously unpublished data from 2013 to 2014: U.S. Geological Survey Data Series 1087, 68 p., https://doi.org/10.3133/ds1087.
Rio Grande aquifers system	2014	Arnold, T.L., Bexfield, L.M., Musgrove, M., Lindsey, B.D., Stackelberg, P.E., Barlow, J.R., DeSimone, L.A., Kulongoski, J.T., Kingsbury, J.A., Ayotte, J.D., Fleming, B.J., and Belitz, K., 2017, Groundwater-quality data from the National Water-Quality Assessment Project, January through December 2014 and select quality-control data from May 2012 through December 2014: U.S. Geological Survey Data Series 1063, 83 p., https://doi.org/10.3133/ds1063.
High Plains aquifer	2015 and 2016 (sites in Texas)	Arnold, T.L., Bexfield, L.M., Musgrove, M., Stackelberg, P.E., Lindsey, B.D., Kingsbury, J.A., Kulongoski, J.T., and Belitz, K., 2018, Groundwater-quality and select quality-control data from the National Water-Quality Assessment Project, January through December 2015, and previously unpublished data from 2013 to 2014: U.S. Geological Survey Data Series 1087, 68 p., https://doi.org/10.3133/ds1087.
Columbia Plateau basaltic-rock aquifers	2016	Arnold, T.L., Bexfield, L.M., Musgrove, M., Erickson, M.L., Kingsbury, J.A., Degnan, J.R., Tesoriero, A.J., Kulongoski, J.T., and Belitz, K., 2020, Groundwater-quality and select quality-control data from the National Water-Quality Assessment Project, January through December 2016, and previously unpublished data from 2013 to 2015: U.S. Geological Survey Data Series 1124, 135 p., https://doi.org/10.3133/ds1124.
Colorado Plateaus aquifers	2017	Included in this report.

Blanks

Blank samples are used to determine if water samples could have been contaminated during sample collection, field processing transport, or laboratory analysis (Mueller and others, 2015). Blank samples are collected using blank water that has been certified by the USGS National Water Quality Laboratory (NWQL) to be free of detectable concentrations of the constituents of interest. Three types of blank samples were collected: equipment, field, and source-solution blanks. Equipment blanks generally are collected in a controlled environment (such as a laboratory) before field sampling begins to evaluate equipment and cleaning protocols for established data-quality requirements. A field blank is treated with the same sample collection, field processing, preservation, transportation, and laboratory handling procedures as an environmental sample to evaluate the potential of these procedures to be a source of contamination. A source-solution blank is a sample of the water used to collect the equipment and field blanks and is intended to verify that the blank water does not contain the constituents of interest. Five trace elements—barium, cobalt, copper, strontium, and zinc were detected at low concentrations in equipment blanks and field blanks, whereas only copper was detected in a source-solution blank (table 1.2). Copper and zinc are known to sometimes occur in field and equipment blanks because of their presence in the fittings and equipment used to collect groundwater samples (Olsen and others, 2010). Copper, zinc, and barium were not selected for analysis by the *understanding assessment*. Detections of trace elements in blank samples were less than 5 percent of their health-based benchmarks and were not considered to have affected the interpretation of the environmental samples collected in Colorado Plateaus principal aquifer study. Two major ions—calcium and chloride—were detected at low concentrations in field blanks; blank concentrations were two to three orders of magnitude below those of most environmental samples and thus were unlikely to significantly affect groundwater results. The volatile organic compounds (VOCs) isopropyl alcohol and carbon disulfide were detected in one field blank and one equipment blank, respectively (table 1.2), with no detections of these constituents in environmental samples. No pesticide compounds or nitrate were detected in any of the field blanks or equipment blanks (table 1.2).

Table 1.2. Constituents detected in groundwater blank samples from the Colorado Plateaus aquifers, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.

[µg/L, micrograms per liter; <, less than; nv, no value in category; mg/L, milligrams per liter; na, not applicable; E, estimated; ng/L, nanograms per liter]

Constituent	Reporting level	Number of field blank detection/ total number of field blank sample	Concentration(s) detected in field blank sample(s)	Number of equipment blank detection/ total number of equipment blank sample	Concentration(s) detected in equipment blank sample(s)	Number of source solution blank detection/ total number of source solution blank sample	Concentration(s) detected in source solution blank sample(s)
				Trace elements (µg/L)			
Barium	<0.1	1/5	0.21	2/5	0.13; 0.14;	0/4	nv
Cobalt	<0.03	2/5	0.052; 0.081	1/5	0.081	0/4	nv
Copper	<0.2	4/5	0.27; 0.27; 0.7; 0.84	3/5	0.29; 0.97; 1.5	1/4	0.28
Stontium	<0.5	2/5	0.57; 1.76	1/5	0.57	0/4	nv
Zinc	<2	1/5	8.1	1/5	5.2	0/4	nv
				Nutrients (mg/L)			
Nitrate as N	<0.04	0/5	nv	na	na	na	na
				Major and minor ions (mg/L)			
Calcium	<0.022	2/5	0.097; 0.097	na	na	na	na
Chloride	<0.02	1/5	0.08	na	na	na	na
				Volatile organic compounds (VOCs; µg/L)			
Isopropyl alcohol	<0.6	1/5	1.84	0/6	nv	0/10	nv
Carbon disulfide	<0.1	0/5	nv	1/6	E 0.02	0/10	nv
				Pesticides (ng/L)			
na	na	0/4	nv	0/1	nv	0/1	nv

Replicates

Replicates are samples that are collected at the same time (sequential) as environmental samples and then processed, preserved, transported, and analyzed identically. Replicate samples assess water-quality data variability. Two methods were used to assess variability over the broad range of measured constituents—standard deviation (SD) for low concentrations and relative standard deviation (RSD) for high concentrations (Anderson, 1987; Mueller and Titus, 2005). The RSD is the SD divided by the mean concentration for each replicate pair, expressed as a percentage. A concentration of 5 times the constituent's reporting limit (RL) defined the boundary between assessing the replicate concentration by SD or RSD. Replicate samples for all constituents were evaluated as follows:

- If concentrations were detected (that is, above the RL) in both the environmental and replicate sample pair, the SD or RSD was calculated. The SD was calculated for a constituent if the mean concentration was less than 5 times the RL (low concentration). The RSD was calculated for a constituent if the mean concentrations was greater than or equal to 5 times the RL (high concentration). For low concentrations, the SD variability was considered acceptable if the SD was less than half of the RL. For high concentrations, the RSD variability was considered acceptable for RSDs less than 10 percent:

- If both values were non-detections (that is, less than the RL), the variability was considered zero and acceptable.

- If one value in the sample pair was a non-detection and the other was a reported concentration less than the RL, a value of zero was substituted for the non-detection, resulting in the maximum estimate of variability for the sample pair.

- If one value in the sample pair was reported as a non-detection and the other was a reported concentration greater than the RL, the variability for the sample pair was considered unacceptable.

A small number of replicate sample pairs were collected in the Colorado Plateaus aquifers. Table 1.3 summarizes results for the single replicate analysis for inorganic and radioactive constituents for the Colorado Plateaus aquifers. The SD and RSD values were acceptable for inorganic and radioactive constituents. Table 1.4 summarizes the replicate pair analysis for organic constituents in groundwater samples—there were two pesticide and one VOC replicate sample pairs. No pesticide or VOC constituents were detected in the replicate sample pairs and results were considered acceptable.

Table 1.3. Summary of replicate samples for inorganic and radioactive constituents in groundwater samples collected from the Colorado Plateaus aquifers, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.

[Constituents for which all replicate samples were non-detection are not listed. **Abbreviations**: SD; percent standard deviation; RSD, percent relative standard deviation; RL, reporting limit; >, greater than; <, less than; ≤, less than or equal to; nv, no value in category]

Constituent	Number of non-detection or ≤ coded replicate samples/ number of replicate samples	Number of SDs >1/2 RL/number of replicate samples with concentrations <5 times the RL	Number of RSDs >10 percent/ number of replicate samples with concentrations >5 times the RL
Trace elements			
Aluminum	1/1	nv	0/1
Antimony	1/1	nv	0/1
Arsenic	0/1	nv	0/1
Barium	0/1	nv	0/1
Beryllium	1/1	nv	0/1
Boron	0/1	0/1	nv
Cadmium	1/1	nv	0/1
Cobalt	1/1	nv	0/1
Copper	0/1	nv	0/1
Iron	0/1	nv	0/1
Lead	1/1	nv	0/1
Lithium	0/1	nv	0/1

Table 1.3. Summary of replicate samples for inorganic and radioactive constituents in groundwater samples collected from the Colorado Plateaus aquifers, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Constituents for which all replicate samples were non-detection are not listed. **Abbreviations**: SD; percent standard deviation; RSD, percent relative standard deviation; RL, reporting limit; >, greater than; <, less than; ≤, less than or equal to; nv, no value in category]

Constituent	Number of non-detection or ≤ coded replicate samples/number of replicate samples	Number of SDs >1/2 RL/number of replicate samples with concentrations <5 times the RL	Number of RDDs >10 percent/number of replicate samples with concentrations >5 times the RL
Manganese	1/1	nv	0/1
Molybdenum	0/1	nv	0/1
Nickel	0/1	0/1	nv
Selenium	0/1	nv	0/1
Silver	1/1	nv	0/1
Strontium	0/1	nv	0/1
Thallium	1/1	nv	0/1
Uranium (natural)	0/1	nv	0/1
Vanadium	0/1	nv	0/1
Zinc	1/1	nv	0/1
Nutrients			
Nitrate plus nitrate, as nitrogen[1]	0/1	nv	0/1
Major and minor ions and total dissolved solids (TDS)			
Calcium	0/1	nv	0/1
Chloride	0/1	nv	0/1
Flouride	0/1	nv	0/1
Magnesium	0/1	nv	0/1
Potassium	0/1	nv	0/1
Sodium	0/1	nv	0/1
Sulfate	0/1	nv	0/1
Silica (as SiO_2)	0/1	nv	0/1
TDS	0/1	nv	0/1
Radioactive constituents			
Gross alpha radioactivity, 30-day count	0/1	0/1	nv
Radium-226[2]	0/1	0/1	nv
Radium-228[2]	0/1	0/1	nv
Radon-222	0/1	nv	0/1

[1] Nitrite plus nitrate (as nitrogen) is referred to as nitrate in the text for clarity.

[2] In this work, radium-226 and radium-228 activities are combined and reported as radium activity, but quality control is presented for individual constituents.

Matrix Spikes

A matrix spike is the addition of a known concentration of constituent(s) (spike) to a replicate environmental sample that enables the laboratory to determine the effect of the groundwater matrix on the sample analysis. Known constituents added in matrix spikes are the same as those analyzed in the environmental sample and allow for an analysis of bias from matrix interference on a compound-by-compound basis. Low matrix-spike recovery can indicate that the compound might not be detected in some samples if it were present at very low concentrations. Low and high matrix-spike recoveries are of potential concern if a concentration in groundwater is close to the health-based benchmark. A low recovery could result in a falsely measured concentration less than the health-based benchmark, whereas a high recovery could result in a falsely measured concentration greater than the health-based benchmark (Bennett and Fram, 2014). The NAWQA Project considers median matrix-spike recoveries of 70–130 percent as acceptable, and results for constituents outside of this range were flagged as having unacceptable recoveries. Matrix spikes were performed for VOCs and pesticide compounds because the analytical methods for these constituents can be susceptible to matrix interference.

A single spike sample for pesticide compounds was collected in the Colorado Plateaus aquifers. Groundwater samples were spiked with 214 pesticides to calculate matrix-spike recoveries. Except for 38 pesticide compounds, matrix-spike recoveries were between 70 and 130 and considered acceptable (table 1.5). Of the 38 pesticides that had unacceptable matrix-spike recoveries, only one compound (didealkylatrazine) was detected at low concentrations in less than 2 percent of the Colorado Plateaus principal aquifer study (table 3). The matrix-spike recovery of didealkylatrazine was 149 percent, indicating that measured concentrations of this pesticide compound in the environmental sample could have been lower than the reported concentration. Didealkylatrazine was not selected for the status and understanding assessment; detections frequencies of less than 10 percent or maximum measured concentrations less than 0.1 of a given regulatory or non-regulatory health-based benchmark were not included in the assessments for organic constituents.

A single spike sample for VOCs was collected in the Colorado Plateaus aquifers, and the resulting matrix-spike recoveries are summarized in table 1.6. Groundwater samples were spiked with 86 VOCs to calculate matrix-spike recoveries. Except for 8 VOC constituents, matrix-spike recoveries were between 70 and 130 percent. The seven VOC constituents that had unacceptable matrix-spike recoveries—isophorone, n-pentane, tert-butyl alcohol, methyl *tert*-butyl ether, 2-propen-1-ol, alpha-Terpineol, chloropicrin, and butane—were not detected in any samples collected from the Colorado Plateaus aquifers.

Table 1.4. Summary of replicate samples for organic constituents in groundwater samples collected from the Colorado Plateaus aquifers, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.

[Constituents for which all replicate pairs were non-detects are not listed. **Abbreviations**: SD, percent standard deviation; >, greater than; RL, reporting limit; <, less than; —, no detections]

Constituent	Number of non-detections/number of replicate pairs	Number of SDs >1/2 RL/ number of replicate pairs with concentrations <5 times the RL
	Pesticides	
—[1]	2/2	0/2
	Volatile organic compounds (VOCs)	
—[1]	1/1	0/1

[1] No detections of pesticide or volatile organic compound constituents in the replicate pair analysis; all replicate pairs consisidered acceptable for pesticides and volatile organic compounds.

Table 1.5. Quality-control summary for matrix-spike recoveries of pesticides in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
2-(1-Hydroxyethyl)-6-methylaniline	1	25
2,3,3-Trichloro-2-propene-1-sulfonic acid (TCPSA)	1	80
2,4-Dichlorophenoxyacetic acid (2,4-D)	1	83
2-[(2-Ethyl-6-methylphenyl)amino]-1-propanol	1	90
2-Aminobenzimidazole	1	75
2-Amino-N-isopropylbenzamide	1	101
2-Chloro-2,6-diethylacetanilide	1	94
2-Chloro-N-(2-ethyl-6-methylphenyl)acetamide	1	99
2-Hydroxyatrazine (OIET)	1	66
2-Isopropyl-6-methyl-4-pyrimidinol	1	113
3,4-Dichlorophenylurea (DCPU)	1	85
3-Hydroxycarbofuran	1	92
3-Phenoxybenzoic acid	1	79
4-Chlorobenzylmethyl sulfoxide	1	106
4-Hydroxy molinate	1	86
4-Hydroxychlorothalonil	1	78
4-Hydroxyhexazinone A	1	86
Acephate	1	69
Acetochlor	1	102
Acetochlor oxanilic acid	1	93
Acetochlor sulfonic acid	1	87
Acetochlor sulfynilacetic acid	1	88
Alachlor oxanilic acid	1	103
Alachlor sulfonic acid	1	132
Alachlor sulfynilacetic acid	1	106
Aldicarb	1	80
Aldicarb sulfone	1	89
Aldicarb sulfoxide	1	98
Ametryn	1	105
Asulam	1	43
Atrazine	1	88
Azinphos-methyl	1	95
Azinphos-methyl oxon	1	84
Azoxystrobin	1	92
Bentazon	1	105
Bifenthrin	1	26
Bromacil	1	77
Bromoxynil	1	96

Table 1.5. Quality-control summary for matrix-spike recoveries of pesticides in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
Butralin	1	97
Butylate	1	93
Carbaryl	1	115
Carbendazim	1	100
Carbofuran	1	91
Carboxy molinate	1	78
Chlorimuron-ethyl	1	34
Chlorosulfonamide acid	1	10
Chlorpyrifos	1	86
Chlorpyrifos oxon	1	52
Chlorsulfuron	1	53
cis-Permethrin	1	66
Cyanazine	1	71
Dechlorofipronil	1	95
Dechlorometolachlor	1	92
Deethylatrazine (CIAT)	1	89
Deethylhydroxyatrazine (OIAT)	1	89
Deiodo flubendiamide	1	87
Deisopropyl prometryn	1	75
Deisopropylatrazine (CEAT)	1	69
Deisopropylhydroxyatrazine (OEAT)	1	84
Demethyl fluometuron (DMFM)	1	99
Demethyl hexazinone B	1	94
Desamino metribuzin	1	85
Desamino-diketo metribuzin	1	93
Desulfinylfipronil	1	92
Desulfinylfipronil amide	1	109
Diazinon	1	94
Diazoxon	1	75
Dichlorvos	1	57
Dicrotophos	1	97
Didealkylatrazine (CAAT)	1	149
Didemethyl hexazinone F	1	70
Diflubenzuron	1	91
Diflufenzopyr	1	36
Diketonitrile-isoxaflutole	1	112
Dimethenamid	1	98
Dimethenamid oxanilic acid	1	76

Table 1.5. Quality-control summary for matrix-spike recoveries of pesticides in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
Dimethenamid sulfinylacetic acid	1	72
Dimethenamid sulfonic acid	1	94
Dimethoate	1	98
Dimethoate oxon (Omethoate)	1	74
Disulfoton	1	72
Disulfoton oxon	1	87
Disulfoton oxon sulfone	1	83
Disulfoton oxon sulfoxide	1	100
Disulfoton sulfone	1	70
Disulfoton sulfoxide	1	115
Diuron	1	97
EPTC	1	86
EPTC degradate R248722	1	102
Ethoprophos	1	100
Etoxazole	1	81
Fenamiphos	1	97
Fenamiphos sulfone	1	79
Fenamiphos sulfoxide	1	99
Fentin	1	72
Fipronil	1	89
Fipronil amide	1	97
Fipronil sulfide	1	90
Fipronil sulfonate	1	74
Fipronil sulfone	1	92
Flubendiamide	1	94
Flumetsulam	1	105
Fonofos	1	88
Halosulfuron methyl	1	58
Hexazinone	1	96
Hexazinone Transformation Product C	1	90
Hexazinone Transformation Product D	1	87
Hexazinone Transformation Product E	1	70
Hexazinone Transformation Product G	1	75
Hydroxy didemethyl fluometuron	1	74
Hydroxy monodemethyl fluometuron	1	50
Hydroxyacetochlor	1	88
Hydroxyalachlor	1	95
Hydroxydiazinon	1	96

Table 1.5. Quality-control summary for matrix-spike recoveries of pesticides in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
Hydroxymetolachlor	1	100
Hydroxyphthalazinone	1	88
Hydroxysimazine	1	97
Hydroxytebuthiuron	1	69
Imazamox	1	90
Imazaquin	1	87
Imazethapyr	1	85
Imidacloprid	1	81
Indoxacarb	1	69
Isoxaflutole	1	75
Isoxaflutole acid metabolite RPA 203328	1	70
Kresoxim-methyl	1	77
Lactofen	1	52
Linuron	1	92
Malaoxon	1	50
Malathion	1	76
Metalaxyl	1	96
Metconazole	1	88
Methamidophos	1	115
Methidathion	1	90
Methomyl	1	82
Methomyl oxime	1	54
Methoxyfenozide	1	91
Metolachlor	1	92
Metolachlor hydroxy morpholinone	1	107
Metolachlor oxanilic acid	1	80
Metolachlor sulfonic acid	1	108
Metribuzin	1	86
Metribuzin DK	1	105
Molinate	1	86
Myclobutanil	1	85
N-(3,4-Dichlorophenyl)-N’-methylurea (DCPMU)	1	100
Naled	1	0
Nicosulfuron	1	43
Norflurazon	1	77
Novaluron	1	96
O-Ethyl-O-methyl-S-propylphosphorothioate	1	97
O-Ethyl-S-methyl-S-propyl phosphorodithioate	1	94

Table 1.5. Quality-control summary for matrix-spike recoveries of pesticides in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
O-Ethyl-S-propylphosphorothioate	1	85
Orthosulfamuron	1	21
Oryzalin	1	88
Oxamyl	1	60
Oxamyl oxime	1	106
Oxyfluorfen	1	86
Paraoxon	1	95
Paraoxon-methyl	1	91
Pendimethalin	1	83
Phorate	1	77
Phorate oxon	1	67
Phorate oxon sulfone	1	67
Phorate oxon sulfoxide	1	74
Phorate sulfone	1	96
Phorate sulfoxide	1	99
Phthalazinone	1	58
Piperonyl butoxide	1	89
Profenofos	1	66
Prometon	1	84
Prometryn	1	82
Propanil	1	99
Propargite	1	70
Propazine	1	95
Propiconazole	1	83
Propoxur	1	112
Propyzamide	1	102
Prosulfuron	1	34
Pyraclostrobin	1	80
Pyridaben	1	82
Pyriproxyfen	1	80
sec-Acetochlor oxanilic acid	1	66
sec-Alachlor oxanilic acid	1	76
Siduron	1	95
Simazine	1	86
Sulfentrazone	1	71
Sulfometuron-methyl	1	55
Sulfosulfuron	1	62
Sulfosulfuron ethyl sulfone	1	72

Table 1.5. Quality-control summary for matrix-spike recoveries of pesticides in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
Tebuconazole	1	95
Tebufenozide	1	91
Tebupirimfos	1	91
Tebupirimfos oxon	1	95
Tebuthiuron	1	94
Tebuthiuron Transformation Product 104	1	103
Tebuthiuron Transformation Product 106	1	85
Tebuthiuron Transformation Product 108	1	82
Tebuthiuron Transformation Product 109	1	82
Terbacil	1	87
Terbufos	1	69
Terbufos oxon	1	39
Terbufos oxon sulfone	1	76
Terbufos oxon sulfoxide	1	87
Terbufos sulfone	1	99
Terbufos sulfoxide	1	104
Terbuthylazine	1	97
Tetraconazole	1	106
Thiobencarb	1	95
trans-Permethrin	1	70
Triallate	1	74
Tribuphos	1	84
Triclopyr	1	79
Trifloxystrobin	1	78

Table 1.6. Quality-control summary for matrix-spike recoveries of volatile organic compounds (VOCs) in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
1,1-Dichloro-2-propanone	1	76
1,4-Dioxane	1	95
2,2-Dichloro-1,1,1-trifluoroethane (HCFC-123)	1	94
2-Nitropropane	1	86
Acetonitrile	1	75
Chlorodifluoromethane (HCFC-22)	1	91
Dichlorofluoromethane	1	96
Dimethoxymethane	1	91
Ethyl acetate	1	87
Hexane	1	96
Isophorone	1	65
Methyl acetate	1	84
Nitrobenzene	1	72
n-Nitroso-diethylamine (NDEA)	1	92
n-Pentane	1	175
tert-Butyl alcohol (TBA)	1	151
1,1,1,2-Tetrachloroethane	1	93
1,1,1-Trichloroethane (TCA)	1	95
1,1,2-Trichloroethane	1	107
1,1-Dichloroethane	1	98
1,1-Dichloroethylene	1	101
1,2,3-Trichloropropane (1,2,3-TCP)	1	93
1,2,4-Trichlorobenzene	1	93
1,2,4-Trimethylbenzene	1	101
1,2-Dibromo-3-chloropropane (DBCP)	1	90
1,2-Dibromoethane (EDB)	1	93
1,2-Dichlorobenzene	1	103
1,2-Dichloroethane	1	100
1,2-Dichloropropane (1,2-DCP)	1	93
1,4-Dichlorobenzene	1	105
Benzene	1	101
Bromochloromethane	1	99
Bromodichloromethane (THM)	1	99
Bromomethane	1	91
Carbon disulfide	1	97
Chlorobenzene	1	104
Chloromethane (Methylchloride)	1	92
cis-1,2-Dichloroethylene	1	102

Table 1.6. Quality-control summary for matrix-spike recoveries of volatile organic compounds (VOCs) in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
cis-1,3-Dichloropropene	1	97
Dibromochloromethane (THM)	1	95
Dichloromethane (methylene chloride)	1	97
Ethylbenzene	1	101
m- and p-Xylene	1	106
Naphthalene	1	95
n-Propylbenzene	1	98
o-Xylene	1	101
sec-Butylbenzene	1	97
Styrene	1	94
Methyl *tert*-butyl ether (MTBE)	1	402
Tetrachloroethylene (PCE)	1	104
Carbon tetrachloride (tetrachloromethane)	1	94
Toluene	1	99
trans-1,2-Dichloroethylene	1	102
trans-1,3-Dichloropropene	1	96
Bromoform (tribromomethane) (THM)	1	92
Trichloroethylene (TCE)	1	100
Chloroform (trichloromethane) (THM)	1	100
Vinyl chloride (Chloroethylene)	1	103
1,3-Butadiene	1	110
2-Ethoxyethyl acetate	1	74
2-Propen-1-ol	1	67
alpha-Terpineol	1	69
Butanal	1	123
Chloropicrin	1	15
trans-Crotonaldehyde	1	119
1,1-Difluoroethane	1	78
1,2,3,4-Tetrahydronapthalene (Tetralin)	1	94
1,2-Dichloro-1,1,2,2-tetrafluoroethane (CFC-114)	1	74
1,3-Dioxolane	1	78
Butanol	1	79
1-Chloro-1,1-difluoroethane	1	73
1-Methoxy-4(2-propenyl)benzene	1	90
1-Octanol	1	107
2,6-Dimethyl-4-heptanone	1	116
2-Ethyl-1-hexanol	1	99
Isobutyl acetate	1	88

Table 1.6. Quality-control summary for matrix-spike recoveries of volatile organic compounds (VOCs) in samples collected from groundwater at public supply depths in the Colorado Plateaus, U.S. Geological Survey National Water-Quality Assessment Principal Aquifer Studies, June 2017 to December 2017.—Continued

[Acceptable recovery range is between 70 and 130 percent; bolded values have unacceptable recoveries]

Constituent (synonym or abbreviation)	Number of matrix spike samples collected	Recovery (percent)
4-Methyl-2-pentanol	1	99
5-Methyl-2-hexanone	1	115
Butane	1	315
Cyclohexanone	1	99
Isopropyl acetate	1	87
Isopropyl alcohol	1	88
n-Pentanal	1	114
Propyl acetate	1	86

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