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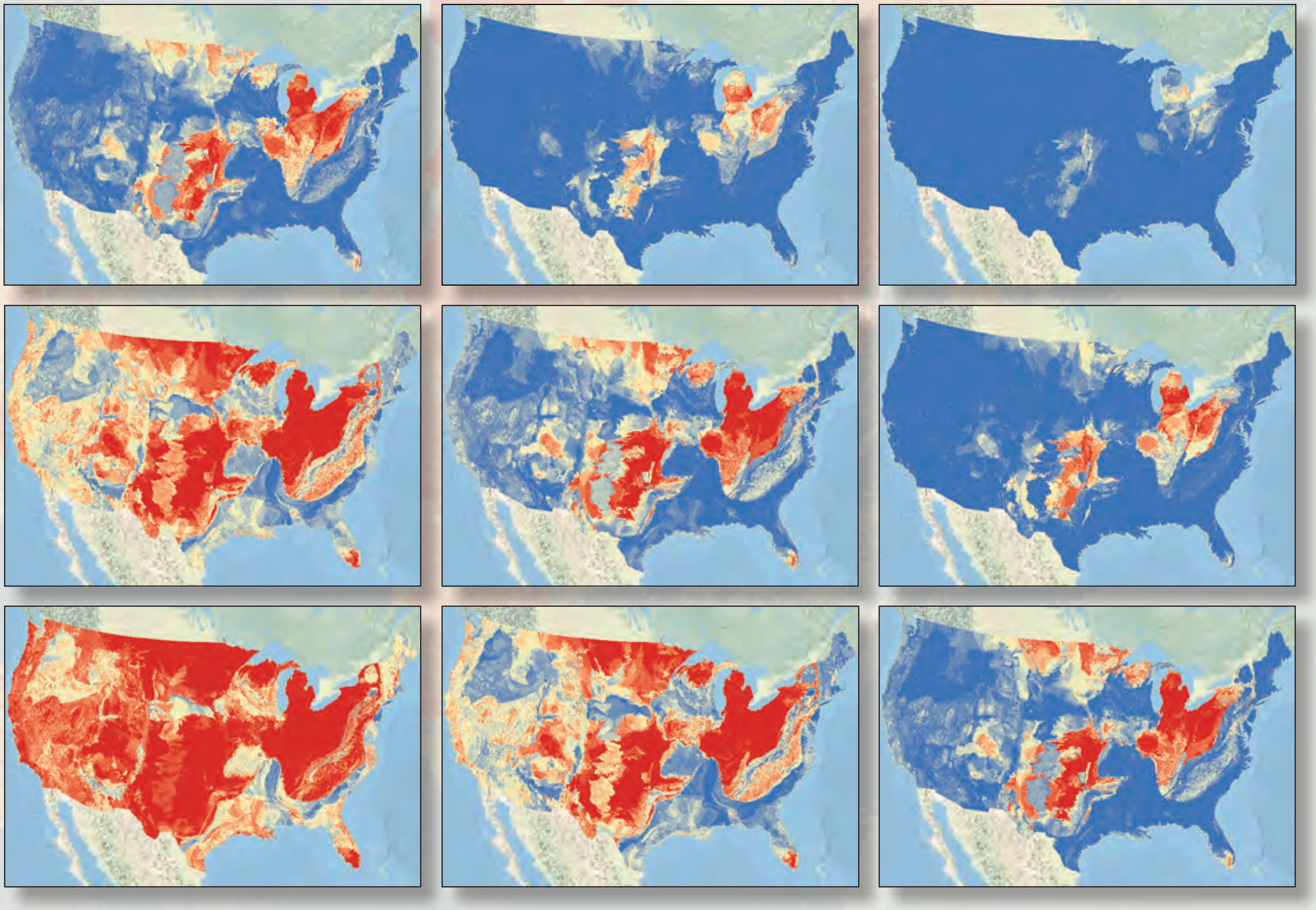
Brackish Groundwater in the United States



Professional Paper 1833

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

Cover. Predicted percentage probabilities of exceeding dissolved-solids concentrations of 1,000, 3,000, and 10,000 milligrams per liter for depths 500, 1,500, and 3,000 feet below land surface in the conterminous United States.

Brackish Groundwater in the United States

By Jennifer S. Stanton, David W. Anning, Craig J. Brown, Richard B. Moore,
Virginia L. McGuire, Sharon L. Qi, Alta C. Harris, Kevin F. Dennehy,
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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons (Bgal)	0.003785	cubic kilometer (km^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
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)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
	Energy	
kilowatthour (kWh)	3,600,000	joule (J)

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

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Celsius (°C) may be converted to degrees kelvin (K) as follows:

$$K = °C + 273.15$$

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) or moles per liter (mol/L); one mole contains 6.022 × 1023 atoms or molecules of a substance.

Ionic mobility represents the velocity of an ion in a potential electrical gradient of 1 volt per centimeter.

Abbreviations

CSV	comma separated value
BGW	brackish groundwater
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
ln(*depth*)	natural logarithm of well depth
ln(*DS*)	natural logarithm of dissolved-solids concentration
$P(CO_2)$	partial pressure of carbon dioxide
R^2	coefficient of determination
USGS	U.S. Geological Survey

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Executive Summary

For some parts of the Nation, large-scale development of groundwater has caused decreases in the amount of groundwater that is present in aquifer storage and that discharges to surface-water bodies. Water supply in some areas, particularly in arid and semiarid regions, is not adequate to meet demand, and severe drought is affecting large parts of the United States. Future water demand is projected to heighten the current stress on groundwater resources. This combination of factors has led to concerns about the availability of freshwater to meet domestic, agricultural, industrial, mining, and environmental needs. To ensure the water security of the Nation, currently [2016] untapped water sources may need to be developed.

Brackish groundwater (abbreviated as “BGW” for the purposes of this report), which is defined for this assessment as groundwater having a dissolved-solids concentration ranging from 1,000 to 10,000 milligrams per liter (mg/L), is an unconventional water source that may offer a partial solution to current [2016] and future water demands. In support of the national census of water resources, the U.S. Geological Survey completed the national brackish groundwater assessment to better understand the occurrence and characteristics of BGW in the United States as a potential water resource. This BGW assessment was authorized by section 9507(c) of the Omnibus Public Land Management Act of 2009 (42 U.S.C. 10367), passed by Congress in March 2009. Section 9507(c) states that the Secretary of the Interior, in consultation with State and local water resource agencies, shall conduct a study of available data and other relevant information (1) to identify significant BGW resources in the United States; (2) to consolidate available data related to those groundwater resources; and (3) to submit a report that will describe significant brackish aquifers, data gaps, and current use and summarize information available at the time of passage of the act.

Analyses completed as part of this assessment relied on previously collected data from multiple sources; no new data were collected. Compiled data included readily available information about groundwater chemistry, horizontal and vertical extents and hydrogeologic characteristics of principal aquifers (regionally extensive aquifers or aquifer systems that have the potential to be used as a source of potable water), and groundwater use. Although these data were obtained from a wide variety of sources, the compiled data are biased toward shallow and fresh groundwater resources; data representing groundwater that is at great depths and is saline were not as readily available.

One of the most important contributions of this assessment is the creation of a database containing chemical characteristics and aquifer information for the known areas with BGW in the United States. Previously published digital data relating to BGW resources were limited to a small number of State- and regional-scale studies. Data sources for this assessment ranged from single publications to large datasets and from local studies to national assessments. Geochemical data included concentrations of dissolved solids, major ions, trace elements, nutrients, and radionuclides as well as physical properties of the water (pH, temperature, and specific conductance). Additionally, the database provides selected well information (location, yield, depth, and contributing aquifer) necessary for evaluating the water resource.

The assessment was divided into national-, regional-, and aquifer-scale analyses. National-scale analyses included evaluation of the three-dimensional distribution of observed dissolved-solids concentrations in groundwater, the three-dimensional probability of BGW occurrence, and the geochemical characteristics of saline (greater than or equal to 1,000 mg/L of dissolved solids) groundwater resources. To describe BGW resources in the context of generalized hydrogeologic characteristics, the United States was divided into 10 BGW regions: Coastal Plains, Eastern Midcontinent, Southwestern Basins, Western Midcontinent, Eastern Mountains and Uplands, Northwestern Volcanics, Western Mountain Ranges, Alaska, Hawaii, and U.S. Territories. Each regional-scale analysis included a summary of the percentage of observed volume in the region that was occupied by BGW within the mixture of air, water, and rock for multiple depth intervals. Aquifer-scale analyses focused primarily on the four regions (Coastal Plains, Eastern Midcontinent, Southwestern Basins, and Western Midcontinent) that contained the largest amounts of observed BGW. Aquifer-scale analyses included a generalized description of hydrogeologic characteristics from previously published work; the distribution of dissolved-solids concentrations; considerations for developing BGW resources, including a summary of other chemical characteristics that may limit the use of BGW and the ability of sampled wells producing BGW to yield useful amounts of water; and the amount of saline groundwater being used in 2010.

Brackish Groundwater in the United States

Subsurface BGW for the Nation was represented three dimensionally by using geochemical data from across the country and a geographic information system. A coarse, three-dimensional grid was used to estimate the subsurface volume that contains BGW in the mixture of air, water, and rock; however, the actual amount of usable BGW in these observed areas is highly uncertain, largely because of information gaps about the subsurface materials containing this water resource. Across the Nation, about 29 percent of the grid cell volume between 0 and 3,000 feet (ft) below land surface contains BGW in the areas where dissolved-solids concentration data were available. At the depth intervals studied, BGW was identified in every State except New Hampshire and Rhode Island. The most extensive occurrence of BGW is observed in a wide band in the central United States that extends from Montana and North Dakota in the north to Texas and Louisiana in the south. States along the Atlantic coast have the most extensive observation coverage; however, most of the groundwater in those States is fresh with little BGW except along the coastline. Other notable areas with extensive BGW are in Florida, eastern Ohio, West Virginia, Kentucky, western Pennsylvania, western New York, central Michigan, southern Illinois, northwestern and southern Iowa, northwestern Missouri, west-central Alabama, southern Mississippi, eastern and western Colorado, south-central and southeastern New Mexico, southwestern and northeastern Arizona, most of Utah, northwestern Nevada, and central and southeastern California.

To estimate the occurrence of BGW where chemical data were not available, a regression analysis approach was used. Dissolved-solids concentrations in groundwater were related to variables that may affect dissolved-solids concentrations. Results from this analysis indicated that the actual volume of subsurface materials that contain some BGW at depths between 500 and 3,000 ft below land surface may be as much as 14 times larger than the amount represented by the groundwater chemistry data compiled for this assessment.

The chemical composition of BGW across the Nation varies widely because of differences in geologic setting and associated hydrologic and geochemical processes. This diversity in composition, processes, and water use needs in different parts of the United States have important implications for the feasibility and cost of using BGW. Much of the variation of BGW chemistry can be summarized with reference to four major groups determined by the cluster analyses of the major cations, major anions, silica, dissolved-solids concentration, pH, and temperature of the water:

1. *Group 1.*—The water in group 1 is a sodium-bicarbonate-dominant water type (sodium is the dominant cation and bicarbonate is the dominant anion) in which sulfate contributes about one-third of the total anion equivalents and has a mean pH of 8.1, which is higher than that of other geochemical groups.
2. *Group 2.*—The water in group 2 is a calcium-sulfate-dominant water type in which sodium and magnesium each contribute about one-quarter of the total cation equivalents.
3. *Group 3.*—The water in group 3 is a sodium-chloride-dominant water type and has a high mean concentration of dissolved-solids (8,440 mg/L) relative to other geochemical groups.
4. *Group 4.*—The water in group 4 is a mixture of cations and anions and has a low mean concentration of dissolved-solids (1,360 mg/L) and a high percentage of silica (1.7 percent of the total moles of cations and anions) relative to other geochemical groups.

Study of the chemistry of BGW is essential for understanding the relation of the chemistry of a BGW resource to climate and geology as well as factors affecting the potential use of BGW for various purposes. For example, concentrations of arsenic and boron in different regions or water types may limit use of untreated BGW for drinking water or irrigation. Other constituents may have concentrations above which the amount of mineral precipitation (scaling) could affect the cost or exceed feasibility of use or treatment of BGW using current technology. Thermodynamic analyses indicate BGW samples commonly would be oversaturated with respect to calcite ($CaCO_3$), barite ($BaSO_4$), or chalcedony (SiO_2), which could cause problems for resource development by precipitating solids (scaling) during conveyance, storage, or treatment. A substantial fraction (48 to 74 percent) of samples from the four geochemical groups were oversaturated with respect to barite, particularly those samples from volcanic aquifers of the southwestern United States and unconsolidated aquifers in the northern Great Plains. Barite scaling is a costly problem for reverse osmosis, the most common form of desalination treatment, because flux decline and membrane damage are common in barite-saturated waters. Oversaturation of chalcedony is most common in group 4 samples (81 percent), which have higher silica concentrations compared with other groups. Removal of silica from BGW before reverse osmosis treatment is difficult, and removal from the reverse osmosis membrane after it forms a scale may not be possible.

The median Langelier saturation index value for all of the BGW groups was positive, indicating deposition of calcite should be more prevalent than corrosion of infrastructure exposed to most BGW. Relative amounts of potential scaling by different mineral phases estimated by geochemical modeling of hypothetical reverse osmosis treatment demonstrate the importance of understanding geochemical variation for assessment and development of BGW resources.

Regional- and Aquifer-Scale Brackish Groundwater

To describe BGW resources in the context of general hydrogeologic characteristics, the United States was divided into 10 BGW regions. Most BGW was observed within the Western Midcontinent region. The remaining areas known to be underlain by BGW primarily are in the Coastal Plains, Eastern Midcontinent, and Southwestern Basins regions. Although the hydrogeologic conditions within each of the BGW regions are generally similar, variability exists among the principal aquifers within each of these regions; therefore, BGW characteristics are evaluated at the principal aquifer-scale where possible.

Coastal Plains Region

Median dissolved-solids concentrations of groundwater collected from wells (represented by one sample per well) in the Coastal Plains region increased slightly with well depth. The percentage of sampled wells (for depths between 0 and 3,000 ft below land surface) producing BGW varied among principal aquifers of this region. More than 20 percent of the sampled wells in the Intermediate and Coastal lowlands aquifer systems produced BGW. For other principal aquifers, the percentage of wells producing BGW ranged from 4 to 14 percent. The median depth of sampled wells producing BGW ranged from 45 ft in the surficial aquifer system to 760 ft in the Southeastern Coastal Plain aquifer system.

About 23 percent of the observed grid cell volume in the Coastal Plains region contained BGW for areas where dissolved-solids concentrations were available. The percentage of observed grid cell volume containing BGW ranged from 7 to 53 percent among principal aquifers in this region; the Intermediate aquifer system contained the largest percentage. BGW observed within this region was mostly between 50 and 1,500 ft below land surface.

Constituents most likely to be present in BGW in this region at concentrations that are greater than selected primary U.S. Environmental Protection Agency drinking-water standards are arsenic (in the surficial aquifer system and in sand and gravel aquifers of alluvial or glacial origin) and nitrate (in sand and gravel aquifers of alluvial or glacial origin). Boron, fluoride, and iron in untreated BGW are the selected constituents most likely to be problematic for livestock consumption in some aquifers. Arsenic, boron, fluoride, and iron are potential concerns where untreated BGW from most of the principal aquifers is used for irrigation. Most of the sampled wells producing BGW that have concentrations of these constituents that exceed selected drinking-water, livestock, or irrigation standards are in southern Texas.

About 24 percent of sampled wells producing BGW had a yield of greater than (>) 100 gallons per minute (gal/min), and less than (<) 1 percent of wells producing BGW had a yield >1,000 gal/min. The largest median yields of wells producing BGW were in the Floridan, Intermediate, Southeastern Coastal Plain, and Northern Atlantic Coastal Plain or Castle Hayne aquifer systems. Although data were sparse for depths >1,000 ft below land surface, available data indicate that wells in the deep intervals in this region are able to yield at least 10 gal/min and may be able to yield 1,000 gal/min or more in some areas.

Eastern Midcontinent Region

Median dissolved-solids concentrations in the Eastern Midcontinent region increased slightly with depth to about 1,500 ft below land surface. Below that depth, the median dissolved-solids concentration increased by two orders of magnitude. Four of the principal aquifers mostly within this region (Marshall aquifer, Silurian-Devonian aquifers, Mississippian aquifers, and New York and New England carbonate-rock aquifers) had dissolved-solids concentrations in the BGW range (between 1,000 and 10,000 mg/L) in 13 percent or more of the wells sampled. For the other principal aquifers, the percentage of sampled wells producing BGW ranged from 0 to 11 percent. At depths >1,500 ft below land surface, most observed groundwater had dissolved-solids concentrations greater than the BGW range.

In the Eastern Midcontinent region, BGW was present in about 16 percent of the observed grid cell volume between 0 and 3,000 ft below land surface. The percentage of observed volume containing BGW ranged from 0 to about 26 percent among principal aquifers in this region; the Pennsylvanian aquifers, the Marshall aquifer, and the Silurian-Devonian aquifers had the highest percentages.

Constituents most likely to be present in BGW in this region at concentrations greater than selected drinking-water standards are arsenic (Ozark Plateaus aquifer system, sand and gravel aquifers of alluvial or glacial origin, and the Valley and Ridge aquifers), fluoride (Ordovician aquifers), and nitrate (sand and gravel aquifers of alluvial or glacial origin). The BGW samples with exceedances for drinking-water standards are most common in the western part of the region. Fluoride and iron concentrations in untreated BGW are the constituents most likely to be problematic for livestock consumption in some aquifers. Boron and fluoride are potential concerns for most of the principal aquifers where untreated BGW is used for irrigation.

In this region, median yields were larger for sampled wells producing freshwater (20 gal/min) than for those producing BGW (10 gal/min). Of the sampled wells producing BGW, about 44 percent had yields >10 gal/min, 7 percent had yields >100 gal/min, and only 1 percent had yields >1,000 gal/min. The largest median yields of sampled wells producing BGW were in the Marshall aquifer, the Cambrian-Ordovician aquifer system, and the Silurian-Devonian aquifers. Available data indicate that wells in the deeper intervals in this region are able to yield at least 100 gal/min and may be able to yield 1,000 gal/min or more in some areas.

Southwestern Basins Region

Median dissolved-solids concentrations and the percentage of sampled wells that produced BGW in the Southwestern Basins region were greatest for the depth intervals of <50 ft and 1,500 to 3,000 ft below land surface. Among the principal aquifers considered to have substantial amounts of BGW within this region, the percentage of sampled wells producing BGW was mostly similar, ranging from about 20 percent in the Central Valley aquifer system to 33 percent in the Rio Grande aquifer system. The median depth of sampled wells producing BGW ranged from 29 ft below land surface in the sand and gravel aquifers of alluvial or glacial origin to 429 ft below land surface in the Central Valley aquifer system.

For areas where dissolved-solids information was available, 31 percent of the grid cell volume contained BGW. Most of the observed BGW is present between 50 and 1,500 ft below land surface. Except for the volcanic-rock aquifers in southern Nevada, the percentage of grid cell volume containing BGW between 0 and 3,000 ft below land surface ranged from about 30 to 40 percent among principal aquifers in this region; the sand and gravel aquifers of alluvial or glacial origin, Rio Grande aquifer system, and Central Valley aquifer system contained the largest percentages.

Arsenic, nitrate, and uranium were the constituents in this region that are most likely to be present in concentrations greater than selected drinking-water standards. The Basin and Range basin-fill aquifers contained the largest percentage of sampled wells producing BGW that exceed selected standards for livestock consumption, but untreated BGW from other principal aquifers is generally safe for livestock. Arsenic, boron, and fluoride are potential concerns for untreated BGW used for irrigation for most of the principal aquifers in this region.

Well yields were reported for 19 percent of the sampled wells producing BGW in this region. About 80 percent of those wells had a yield >100 gal/min, and most (almost 60 percent) of the BGW wells had a reported yield >1,000 gal/min. The median reported yields for sampled wells with water in the BGW range were about twice as large as the median yields for wells with freshwater. Reported yields indicate that shallow and deep wells that produce BGW yield adequate amounts of water for many uses.

Western Midcontinent Region

Median dissolved-solids concentrations in the Western Midcontinent region decreased slightly with depth from near surface (<50 ft below land surface) to 50 to 500 ft below land surface, then increased with depth. The percentage of sampled wells producing BGW was largest (49 percent) for depths ranging from 500 to 1,500 ft below land surface. At depths >1,500 ft below land surface, about 85 percent of sampled wells produced either brackish or highly saline (>10,000 mg/L of dissolved solids) groundwater.

The percentage of sampled wells producing BGW varied among principal aquifers of this region from 6 to 80 percent. The aquifers with 50 percent or more of the wells producing BGW were the Blaine aquifer, the Upper Cretaceous aquifers, the Lower Tertiary aquifers, the Pecos River Basin alluvial aquifer, the Lower Cretaceous aquifers, and the Seymour aquifer. For other principal aquifers, the percentage of wells producing BGW ranged from 6 to 44 percent. The median depth to BGW ranged from 46 ft below land surface in the Seymour aquifer to 1,890 ft below land surface in the Paleozoic aquifers.

In the Western Midcontinent region, BGW was present in about 50 percent of the observed grid cell volume (including air, water, and rock) for depths between 0 and 3,000 ft below land surface. BGW observed within this region mostly exists from 50 to 1,500 ft below land surface. At depths >1,500 ft below land surface, most groundwater is brackish or highly saline. The estimated percentage of volume containing BGW ranged from 12 to 87 percent among the principal aquifers in this region; the Seymour aquifer contains the largest percentage.

Constituents with concentrations above selected drinking-water standards in at least 25 percent of the sampled wells producing BGW in 1 or more of the 19 principal aquifers in this region are arsenic, fluoride, nitrate, and uranium. Constituents with concentrations that are greater than the selected livestock standards in at least 10 percent of the sampled wells producing BGW are boron, fluoride, iron, and selenium. Where untreated BGW is used for irrigation, constituents of concern in at least 10 percent of the BGW samples are arsenic, boron, fluoride, iron, and selenium. BGW samples that exceed selected standards are distributed throughout the region.

In this region, about 44 percent of sampled wells with BGW had yields >10 gal/min, 7 percent had yields >100 gal/min, and 1 percent had yields >1,000 gal/min. The largest median yields of sampled wells producing BGW were in the Arbuckle-Simpson aquifer, the Pecos River Basin alluvial aquifer, the Blaine aquifer, and the Central Oklahoma aquifer. Data about sampled wells indicate that deep wells in this region are able to yield at least 10 gal/min and may be able to yield 100 gal/min or more in some areas.

Data Gaps and Limitations

The national brackish groundwater assessment provides an updated summary of the occurrence of BGW and a more complete characterization of BGW resources using data from a wide variety of sources; however, as with other studies covering large areas, the lack of consistent and comprehensive data prevents a full characterization of the resource. Although the sample database is large, there are many gaps that restrict the ability to describe the distribution, chemical characteristics, hydrogeologic characteristics, and use of the Nation's BGW. Estimates of volumes containing some BGW are given in this report, but results do not represent the actual amount of BGW available for use. An evaluation of sustainable BGW development was not within the scope of this assessment. Results should be used with consideration of the data gaps and limitations.

Little is known about the hydraulic characteristics of the BGW zones of the principal aquifers, making it difficult to assess the volume of BGW that can be extracted. Because BGW has not been a focus of studies in the past, there are few wells completed in BGW zones. An effort to more fully characterize these potential resources would require a more extensive compilation of existing data, new well drilling, and increased hydraulic analysis (aquifer testing) of these parts of the aquifers, all of which would provide critical information concerning the feasibility of producing and treating water from these largely untapped potential resources.

This assessment does not evaluate the potential for BGW to be replenished if the resource is developed, examine the effects of extracting and treating BGW on the surrounding environment, or account for legal considerations for developing BGW. The potential effects of withdrawals from the BGW part of the aquifers on adjoining, overlying, or underlying water resources (fresh and saline) have mostly been unexplored. Studies about the ability of BGW zones to yield sufficient quantities of water should also consider how BGW quality might change after long-term withdrawals. If a particular system were to be developed, prior use of numerical models and time-series water quality sampling would allow detailed evaluation of the potential for movement of and changes in the chemical composition of the BGW resource.

This assessment provides basic information about the occurrence and characteristics of BGW and a foundation for focusing future research on areas where BGW might be developed as a resource. An understanding of the occurrence of BGW, amount of BGW in storage, chemical and hydraulic characteristics of BGW, and use of BGW would be improved through the collection of new data, compilation of additional existing data, and use of additional tools for assessing the resource.

Groundwater discharge and rainfall-runoff collect and evaporate from this brackish playa lake in Saline Valley, California. Photograph by David Anning, U.S. Geological Survey.

Introduction

The U.S. Geological Survey (USGS) and partner agencies have completed thousands of assessments during the past century to determine the availability of groundwater across the Nation. These studies have identified and characterized the aquifers that serve as important sources of fresh groundwater supply. Results from these assessments indicate that, for some parts of the Nation, large-scale development has caused decreases in the amount of groundwater that is present in storage and that discharges to surface-water bodies (Reilly and others, 2008). Water supply in some areas, particularly in arid and semiarid regions (High Plains [McGuire, 2014] and Central Valley [Faunt and others, 2015]), is not adequate to meet demand, and severe drought is affecting large parts of the United States, particularly in the western part of the country (National Drought Mitigation Center, U.S. Department of Agriculture, and National Oceanic and Atmospheric Association, 2015). This combination of factors has led to concerns about the availability of freshwater to meet domestic, agricultural, industrial, mining, and environmental needs.

Future water demand is projected to heighten the stress on groundwater resources. By 2050, population growth and increased power generation could cause water demand in the United States to increase by 12.3 percent if per capita water use and power generation technologies remain the same (Roy and others, 2012); furthermore, this increased water demand coupled with projected climate change could produce moderate to extreme risk to water-supply sustainability for most of the United States (fig. 1*A*; Roy and others, 2012). The regions of highest risk would be in the southwestern and central parts of the United States, Texas, parts of the Mississippi River Valley, and Florida. Without the effects of climate change, fewer areas in the United States would be at extreme risk, but moderate- to high-risk areas could extend across the Southwest, the Northwest, parts of the Mississippi River Valley, and Florida (fig. 1*B*; Roy and others, 2012). Although past patterns of population, power generation, and water use may not indicate future demand, demand will likely continue to grow.

For many of these moderate- to high-risk areas, surface-water supplies are already fully appropriated, making groundwater the only water source that can help meet this additional demand; however, groundwater availability is not without its own set of concerns. In many areas, rates of groundwater discharge through pumping already exceed rates of groundwater recharge (Reilly and others, 2008). In addition, a recent study that examined the implications of projected climate change on groundwater recharge for the end of the 21st century indicated average decreases of 10 to 20 percent in total recharge across southwestern aquifers (Meixner and others, 2016). To ensure the water security of the Nation, untapped water sources may need to be developed in some areas. Brackish groundwater (abbreviated as “BGW” for the purposes of this report) is a nontraditional water source that may offer a partial solution to current [2016] and future water challenges.

In general, BGW is groundwater that has a dissolved minerals concentration (referred to hereafter as “dissolved-solids concentration”) greater than freshwater, and sometimes the term “brackish groundwater” is used interchangeably with “saline groundwater;” however, a variety of classification schemes have been used to quantitatively describe waters that have different dissolved-solids concentrations (table 1). Most classification schemes consider BGW to have a dissolved-solids concentration between 1,000 and 10,000 milligrams per liter (mg/L); for this assessment, the dissolved-solids concentration of BGW ranges from 1,000 to 10,000 mg/L. Saline groundwater often refers to any groundwater having a dissolved-solids concentration of at least 1,000 mg/L, including groundwater in the brackish salinity range as well as more highly saline groundwater. The U.S. Environmental Protection Agency (EPA) has set a nonmandatory secondary maximum contaminant level for dissolved solids in drinking water at 500 mg/L, above which water may be distasteful or may cause corrosion and staining (U.S. Environmental Protection Agency, 2015a). For purposes of controlling underground waste disposal, the EPA defines freshwater, or potable water, as having a dissolved-solids concentration <3,000 mg/L and potential drinking water from underground sources as having a dissolved-solids concentration <10,000 mg/L (U.S. Environmental Protection Agency, 2015b).

Slightly saline groundwater can replace freshwater for some uses without treatment. Depending on the concentration of specific constituents, water with dissolved-solids concentrations of as much as about 1,500 mg/L can be used for irrigating most crops (NRS Engineering Water Solutions, 2008; Bauder and others, 2014). With careful management, water with higher concentrations can be used to grow salt-tolerant crops at reduced yields (Rhoades and others, 1992). Livestock generally can drink water with dissolved-solids concentrations of as much as 3,000 mg/L, though some species can tolerate higher concentrations (Lardy and others, 2008; NRS Engineering Water Solutions, 2008). Groundwater with dissolved-solids concentrations of as much as 3,000 mg/L is consumed from rural domestic wells without treatment in areas such as eastern Montana, where freshwater is unavailable (Joanna Thamke, U.S. Geological Survey, oral commun., 2014); however, BGW usually is not considered suitable for drinking. Water with dissolved-solids concentrations higher than the brackish range (greater than 10,000 mg/L) can be used for purposes such as cooling during power generation, aquaculture, and a variety of uses in the oil and gas industry (drilling, enhancing recovery, and hydraulic fracturing). In general, though, the cost to use saline groundwater increases with dissolved-solids concentration (Barlow, 1963; Bureau of Reclamation, 2003; Pearce, 2008).

Desalination allows use of saline groundwater for purposes such as drinking water that require lower dissolved-solids concentrations. In 2010, there were 649 active desalination plants in the United States with a capacity to treat 402 million gallons per day (Mgal/d; Shea, 2010). Of the desalination plant capacity in the United States in 2005, 67 percent was

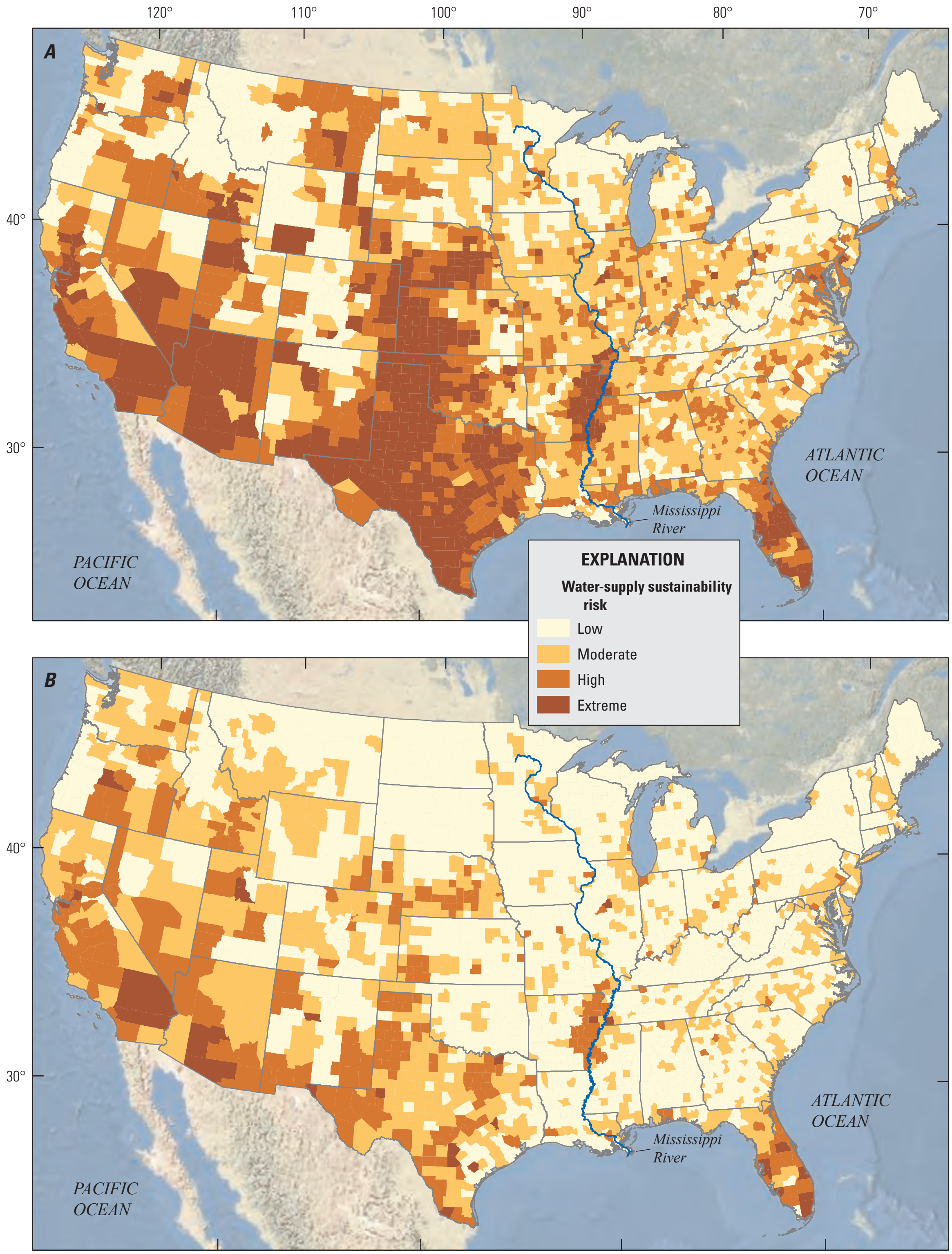

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Figure 1. Water-supply sustainability risk index for the conterminous United States in 2050 linking water demand *A*, to population growth, increases in power generation, and climate change and *B*, to population growth and increases in power generation. Modified from Roy and others (2012).

Table 1. Groundwater classification schemes, from previously published reports and this report, for the United States.

Dissolved-solids concentration, in milligrams per liter	Robinove and others (1958)	Winslow and others (1968)	Freeze and Cherry (1979)	Rhoades and others (1992)	Reese (1994)	Yobbi (1996)	Bureau of Reclamation (2003)	National Ground Water Association (2010)	Meyer and others (2011)	Stanton and others (2017)[1]
0	Fresh	Fresh	Fresh	Nonsaline	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh
500				Slightly saline		Slightly saline (brackish)				
1,000	Slightly saline	Slightly saline	Brackish		Brackish		Mildly brackish	Slightly saline (brackish)	Brackish	Slightly saline (brackish)
1,500				Moderately saline						
2,000										
2,500										
3,000	Moderately saline	Moderately saline				Moderately saline (brackish)		Moderately saline (brackish)		Moderately saline (brackish)
3,500										
4,000										
4,500										
5,000							Moderately brackish			
5,500										
6,000										
6,500										
7,000				Highly saline						
7,500										
8,000										
8,500										
9,000										
9,500										
10,000	Very saline	Very saline	Saline		Slightly saline	Very saline (salt water)		Highly saline	Saline	Highly saline
15,000				Very highly saline			Heavily brackish			
20,000										
25,000										
30,000										
35,000	Briney	Brine		Brine	Saline	Briney	Seawater	Seawater		
40,000								Unclassified		
45,000										
50,000										
≥100,000			Brine							

[1] This report.

for municipal purposes, 18 percent was for industry, 9 percent was for power, and the remaining 6 percent was for other uses (National Research Council, 2008). A series of surveys completed between 1971 and 2010 identified 324 desalination facilities in the United States that each produced at least 25,000 gallons per day for municipal supply (Mickley, 2012). Survey results determined that more than 80 percent of the municipal desalination plants are inland groundwater facilities—primarily in Florida, California, and Texas (fig. 2)—and most municipal desalination has been for treatment of groundwater in the brackish salinity range (Mickley, 2012; Mike Mickley, Mickley and Associates, written commun., 2013). The dissolved-solids concentration of feedwater rarely is >10,000 mg/L, and most facilities treat source waters with concentrations of <3,000 mg/L (Texas Water Development Board, 2010; Mike Mickley, Mickley and Associates, written commun., 2015) because the cost to desalinate increases with greater dissolved-solids concentrations. Advances in technology have reduced the cost and energy requirements of desalination, making treatment a more viable option for purposes requiring lower dissolved-solids concentrations (National Research Council, 2008). This viability is reflected in the rapid increase in the number of facilities since 1971 (fig. 3; Mickley, 2012).

BGW is becoming a larger component of the water supply as a supplement or replacement for freshwater. Data from the USGS Water-Use Program (Maupin and others, 2014) indicate that an estimated 3,290 Mgal/d of saline groundwater (dissolved-solids concentration of greater than or equal to [≥] 1,000 mg/L) was used in the United States in 2010 (fig. 4), which is about 4 percent of the total groundwater use. Most of the reported use was in Alaska, California, Florida, Oklahoma, Texas, Utah, and Wyoming. Total reported saline groundwater use, primarily for mining (including oil and gas), has increased by about 400 percent since 1985 (fig. 5). Although these results represent the best available information, saline groundwater use is underreported, and actual use may be much larger (see the “Data Gaps and Limitations” section).

Using saline groundwater for purposes that do not require a high-quality supply or after desalination can either provide an alternative water source in areas where freshwater is not available or ease pressure on existing freshwater resources. Using saline water for closed-loop thermoelectric powerplants can potentially save a substantial amount of freshwater because each modern powerplant can use as much water as a community of about 12,000 people (Maulbetsch and DiFilippo, 2008). Similarly, hydraulic fracturing requires large volumes of water. In the Marcellus Shale, for example, 3 to 5 million gallons of water is typically used for fracturing a single horizontal gas well (Boschee, 2014). Reusing the saline flowback and produced water not only preserves freshwater resources for other uses but also can substantially reduce operation costs by decreasing the amount of freshwater that is purchased and the amount of produced water that must be transported, treated, and disposed.

Evaluating Brackish Groundwater

Identification of new water-supply sources has been a focus of water research and policy for the past century but is understandably biased toward freshwater sources. In support of the national census of water resources, the USGS completed the national brackish groundwater assessment to gain a better understanding of the occurrence and hydrogeologic and chemical characteristics of BGW in the United States. This assessment was authorized by section 9507 in subtitle F of title IX (also known as the Secure Water Act) of the Omnibus Public Land Management Act of 2009 (42 U.S.C. 10367), passed by Congress in March 2009. More specifically, section 9507(c) states that the Secretary of the Interior, in consultation with State and local water resource agencies, shall complete a study of available data and other relevant information to (1) identify significant BGW resources in the United States; (2) consolidate available data related to those groundwater resources; and (3) submit a report that will describe significant brackish aquifers, data gaps, and current use and summarize information available at the time of passage of the act.

Groundwater in the brackish salinity range is an appropriate focus for assessment because the cost to use or treat saline water generally increases as the dissolved-solids concentration increases (Barlow, 1963; Bureau of Reclamation, 2003; Pearce, 2008). In addition to other factors, BGW in many locations is available at shallower depths than highly saline groundwater, resulting in lower drilling and pumping costs. As a result, most of the saline groundwater being used is likely in the brackish salinity range. The EPA formally defined potential underground sources of drinking water as having a dissolved-solids concentration <10,000 mg/L (U.S. Environmental Protection Agency, 2015b). Although groundwater reservoirs with dissolved-solids concentrations greater than the brackish salinity range (1,000 to 10,000 mg/L) may still be useful for some purposes, these bodies of water have been approved for injecting wastewater of low quality, such as brines and industrial byproducts, and may be less suitable for development. As a final consideration, few data are available to define groundwater resources that have dissolved-solids concentrations greater than the brackish salinity range.

To evaluate the usefulness of BGW as a resource, hydrogeologic and chemical characteristics should be considered; however, lack of information about these characteristics for BGW zones is an obstacle to expanding the development of these resources (Land and Johnson, 2004; National Research Council, 2008; Texas Water Development Board, 2015). Important features to understand include depth to the interface between fresh groundwater and BGW, areal extent, thickness, amount in storage, and hydraulic properties that indicate the ability of the aquifer to yield usable amounts of water (specific yield, storage coefficient, permeability, and hydraulic conductivity). It is also useful to understand the groundwater flow system such as areas of recharge and discharge and the connection between BGW and fresh groundwater or surface water. Important chemical features include other chemical

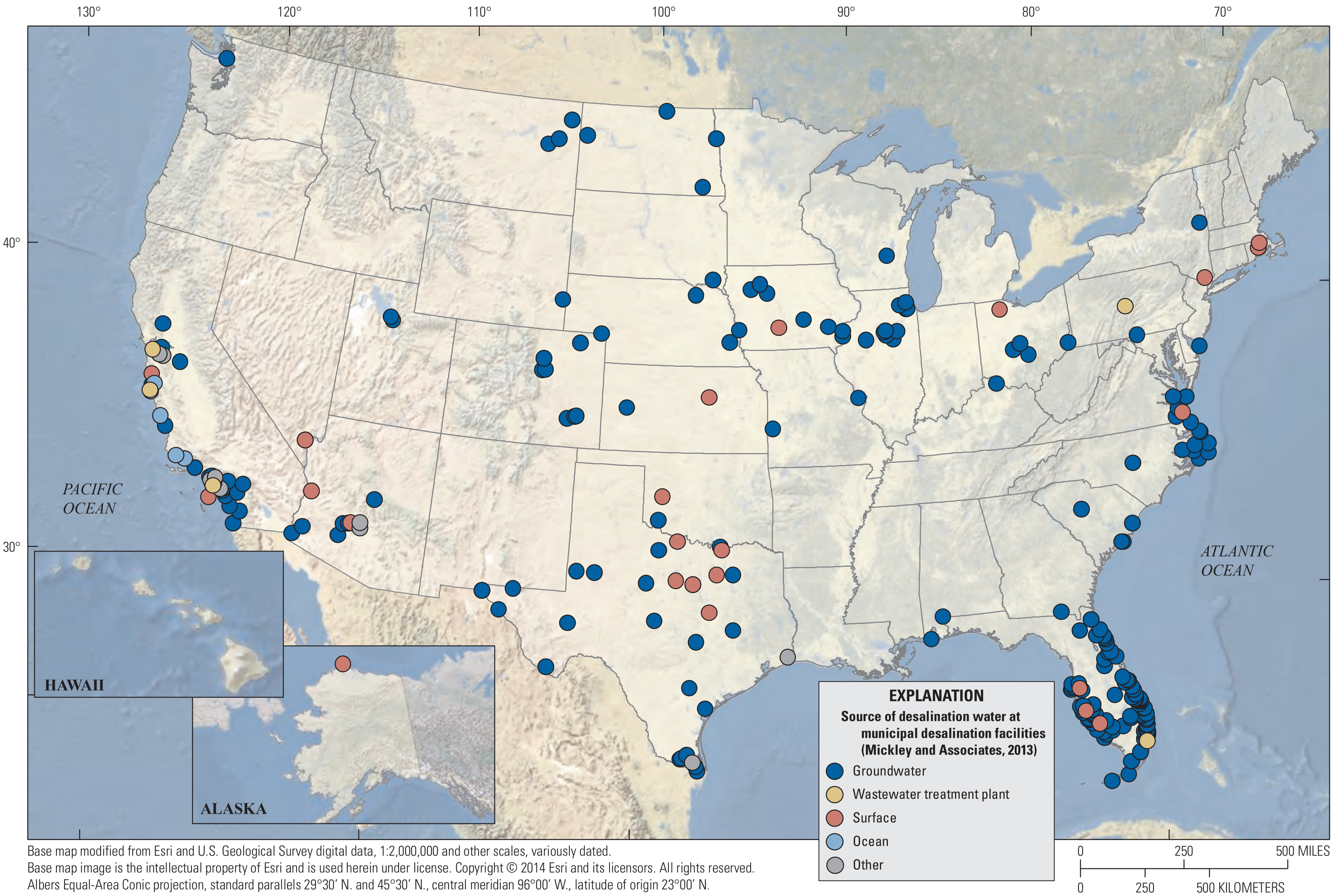

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Figure 2. Locations and sources of desalination water at municipal desalination facilities in the United States in 2010.

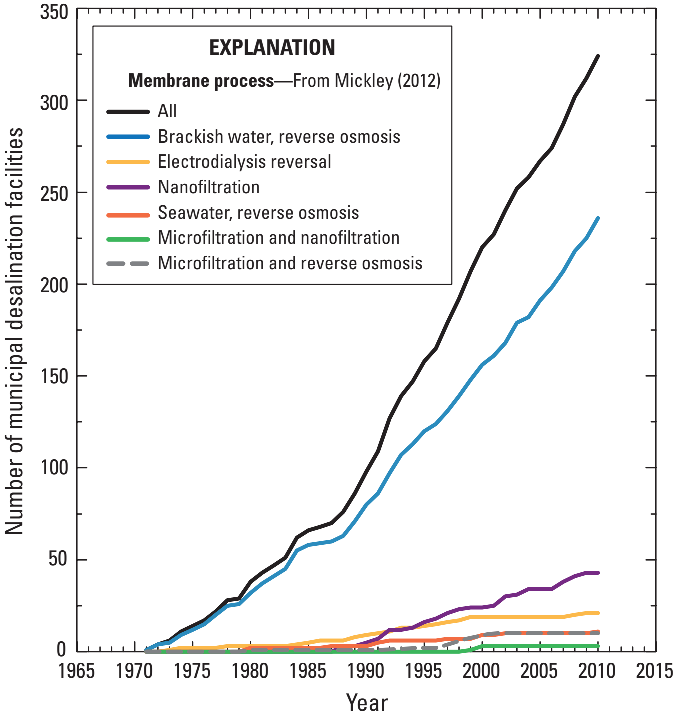

Figure 3. Number of municipal desalination facilities, by type of membrane process, from 1971 through 2010.

constituents that affect the usability and treatability of the BGW resource for different purposes. Whereas highly saline groundwater is likely to be dominated by chloride salts, BGW can have a wide variety of chemical characteristics (for example, different relative amounts of chloride, sulfate, bicarbonate, sodium, calcium, magnesium, trace elements, and metals) that can affect costs associated with its use.

A national assessment that compiled data on mineralized groundwater was last completed in the 1960s (Feth, 1965a). That assessment produced maps showing depth to the shallowest groundwater known to contain at least 1,000 mg/L of dissolved solids and general chemical types of groundwater. The Feth (1965a) assessment indicated that BGW is likely plentiful across the United States. Although that preliminary report has served as the primary source of information about the national occurrence of BGW, it was based on data from only about 1,000 locations. Since that time, substantially more hydrogeologic and geochemical data have been collected, and more sophisticated data analysis tools are available for more robust analyses of large datasets than could be achieved 50 years ago. The assessment in this report takes advantage of these additional data and updated analytical tools to improve the understanding of the hydrogeologic and chemical characteristics of BGW to support economic development of these BGW resources and provide a scientific basis for associated regulatory and policy decisions.

Purpose and Scope

This report summarizes the results of the national brackish groundwater assessment. The goal of the assessment was to develop a better understanding of the occurrence and characteristics of BGW resources within the United States and its territories. For this report, saline groundwater is defined as having a dissolved-solids concentration of at least 1,000 mg/L, BGW is defined as having a dissolved-solids concentration ranging from 1,000 to 10,000 mg/L, and highly saline groundwater is defined as having a dissolved-solids concentration >10,000 mg/L (table 1). This report focuses on groundwater within 3,000 feet (ft) of land surface because few data were readily available below that depth.

Results are presented at national, regional, and aquifer scales. Aquifer-scale results primarily are summarized for hydrogeologic units that have been identified by the USGS as principal aquifers (regionally extensive aquifers or aquifer systems that have the potential to be used as a source of potable water; fig. 6; Reilly and others, 2008) because they represent the major aquifers of the United States. In addition to the database and geographic analysis of BGW as defined by dissolved-solids content, this report also explores some implications of varying chemical composition of BGW; for example, the relative concentrations of various constituents included in the dissolved-solids content. Distributions of individual constituents, constituent ratios, and mineralization potentials are used to illustrate features that could be useful for assessment and development of BGW resources.

Data gaps and limitations for fully characterizing BGW have been identified. The information in this report generally is limited to a compilation of information from readily available national-, regional-, and some State-scale digital datasets; does not include all data that are available; and is not equally representative of all geochemical characteristics. Nonetheless, results within this report probably are a reasonable representation of the resource used and represent the most comprehensive compilation of BGW data as of 2013. As such, this report provides a foundation for possible future work that can more comprehensively and accurately assess BGW resources. Results presented are not appropriate for defining site-specific or local conditions.

Previous National- and Regional-Scale Studies

Most of the groundwater assessments completed in the United States were focused on freshwater aquifers; however, interest in the development of saline groundwater for use as a source of water supply has been longstanding. Several national-scale investigations of saline groundwater resources were completed in the 1950s and 1960s. A primary source of information about the occurrence of saline groundwater is a nationwide compilation of data on mineralized groundwater

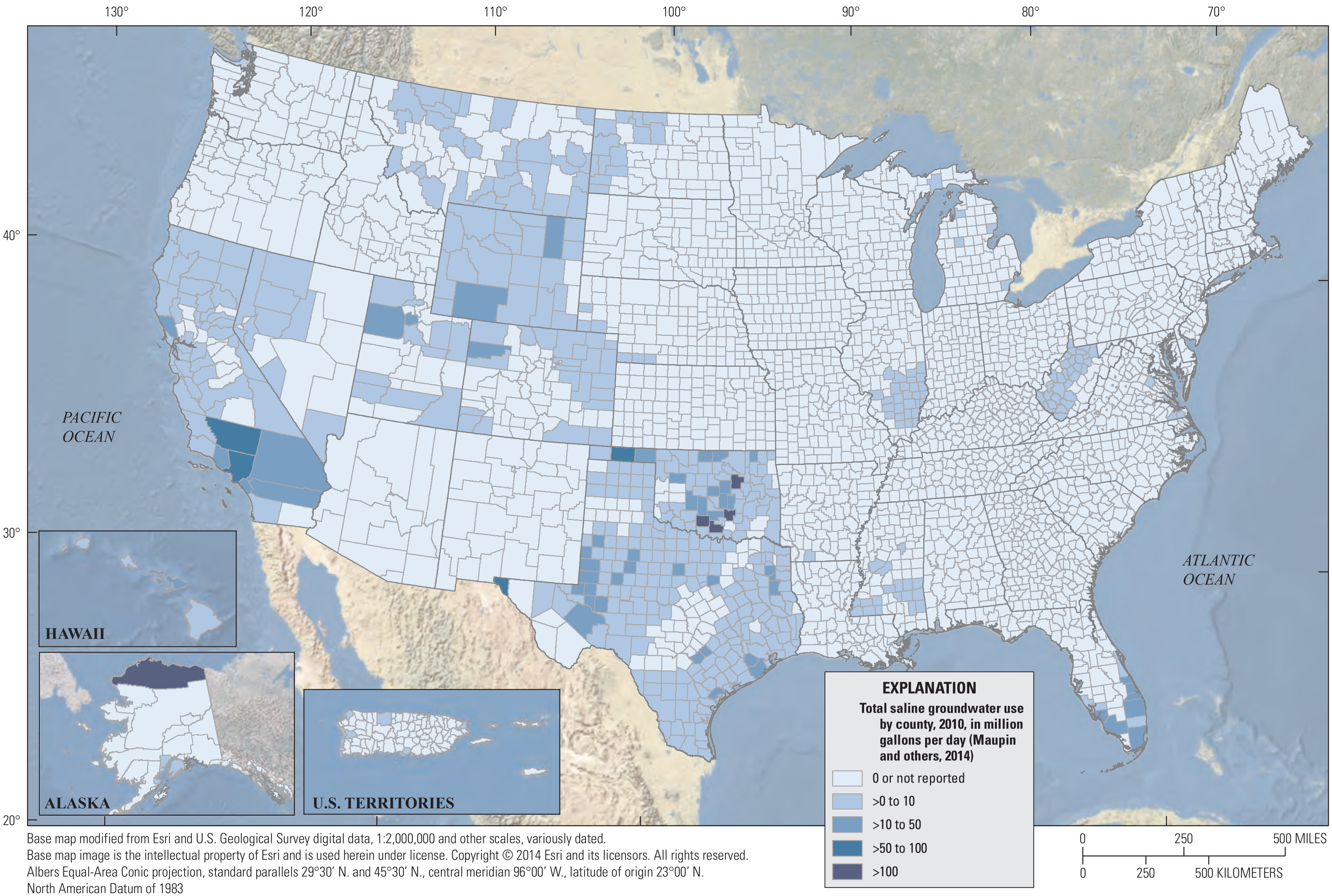

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Figure 4. Saline groundwater use, by county, in the United States and selected U.S. territories in 2010.

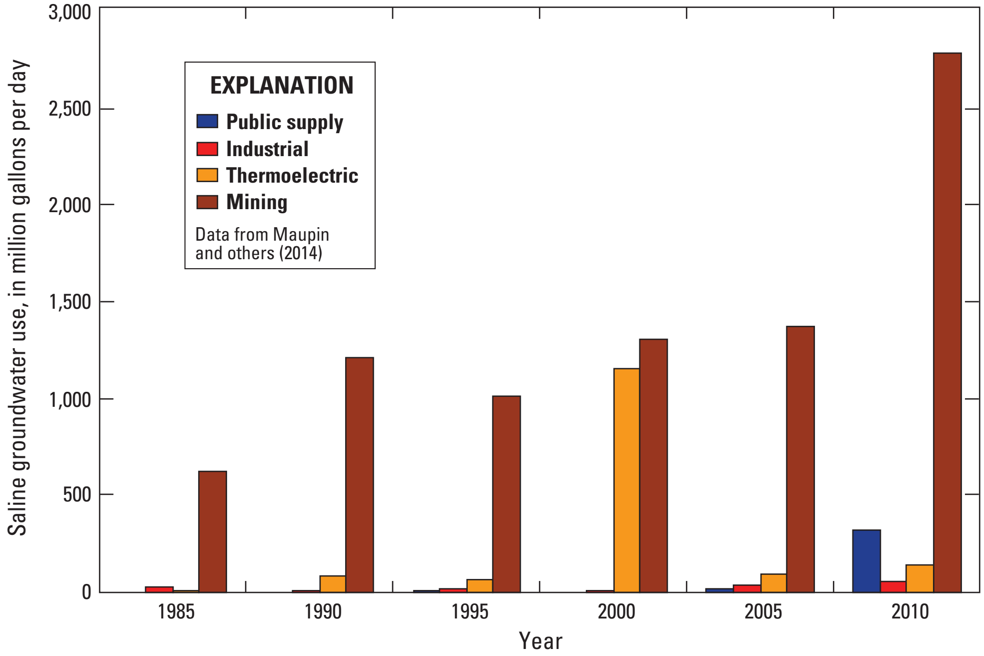


Figure 5. Saline groundwater use by water use category, 1985 through 2010.

that was completed in the 1960s (Feth, 1965a). That assessment contributed a preliminary map showing depth to the shallowest observed groundwater containing at least 1,000 mg/L of dissolved solids and a map of the major dissolved minerals of that water. Before that, a survey of saline groundwater resources was released as part of the U.S. Department of the Interior's Saline Water Conversion Program to assist with meeting the goal to develop processes for converting seawater and other saline waters into useful water (Krieger and others, 1957). That survey produced generalized, mostly qualitative descriptions of the known occurrence of saline groundwater (>1,000 mg/L of dissolved solids) for geologic formations on the basis of a minimal number of selected data, generally <20 saline groundwater samples per State from multiple data sources and previously published or unpublished reports. Feth (1965b, p. 1) compiled a reference list of about 500 reports documenting saline groundwater conditions that "is by no means exhaustive, but it is representative of the types of information available and will serve to lead the reader into the literature."

Later, Feth (1981) and Richter and Kreitler (1991) summarized various models and mechanisms used to explain the national spatial and temporal variability of dissolved solids in groundwater. Feth (1981) provided a national synthesis of chloride in natural waters, noting that the ratio of various other anions to chloride can be used as a tool to diagnose the source of mineralized water. Richter and Kreitler (1991) supplemented work completed by Feth (1965a) and Dunrud and Nevins (1981) to create maps of the approximate extent of halite deposits, locations of oil fields, estimates of the extent of seawater intrusion to coastal aquifers, and saline springs and seeps to identify areas where mineralized groundwater exists. Richter and Kreitler (1991) also provided a State-by-State summary of the occurrence of each source of groundwater salinization.

The USGS regional aquifer-system analysis studies were completed between 1978 and 1995 to define the geohydrology of the Nation's regionally extensive aquifers or aquifer systems. Maps showing dissolved-solids concentrations were published for many of these aquifer systems and were compiled for the USGS "Ground Water Atlas of the United States" (Miller, 2000). In most cases, these published maps incorporated data from numerous State- and local-scale studies that were available during the regional aquifer-system analysis study. In some cases, regional aquifer-system analysis studies included geochemical characterization and modeling, which assisted with understanding, interpolating, and extrapolating data on the occurrence of BGW (for example, Busby and others, 1995).

More recently, Androwski and others (2011) used previously published USGS reports to complete a national assessment of the total volume of the saline (dissolved-solids concentrations between 1,000 and 35,000 mg/L) part of selected aquifers in the conterminous United States that could be available for desalination. The primary sources of dissolved-solids and aquifer-dimension information for that assessment were digitized maps from the USGS "Ground Water Atlas of the United States" (Miller, 2000). No additional dissolved-solids data were collected or compiled for the assessment. Sandia National Laboratories assessed the relative availability and cost of using shallow (<2,500 ft below land surface) BGW (1,000 to 10,000 mg/L of dissolved solids) as a water source for thermoelectric power generation in 17 Western States (Tidwell and others, 2014). Sources of information for estimating the availability of BGW include published volumetric estimates of BGW in Arizona (McGavock, 2009), New Mexico (Huff, 2004a), and Texas (LBG–Guyton Associates, 2003); USGS water use information (Kenny and others, 2009); and locations of wells in the USGS National Water Information

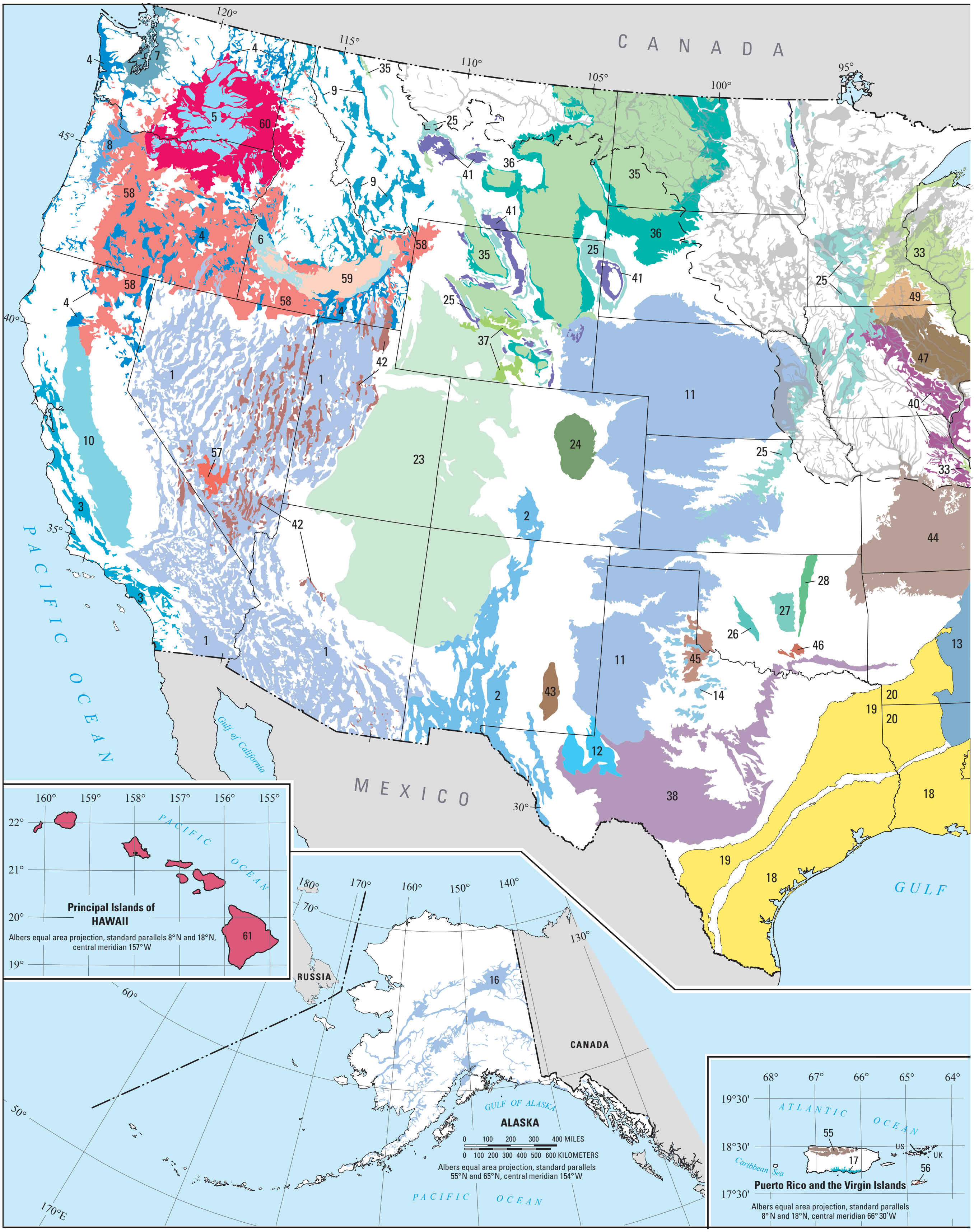
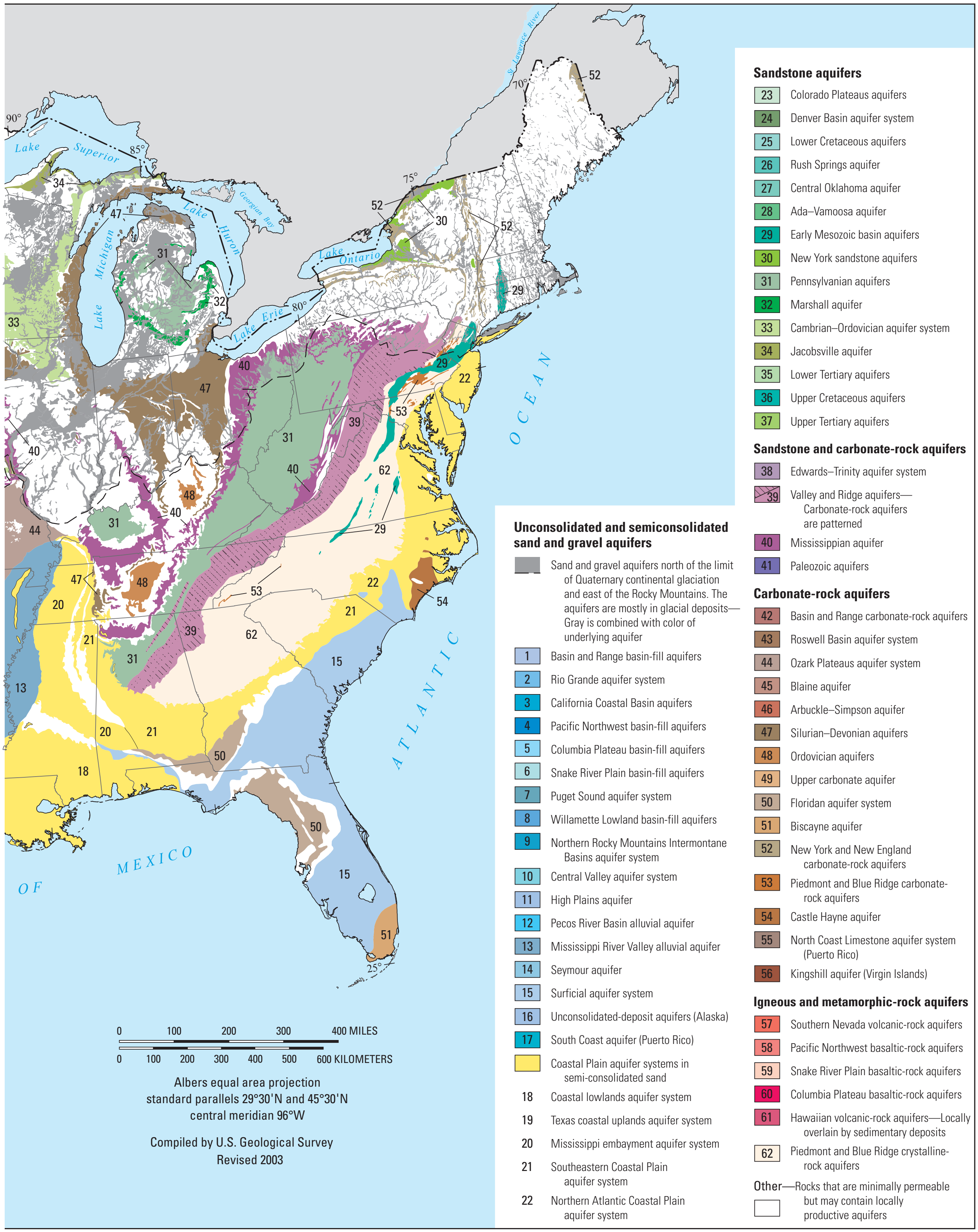


Figure 6. Principal aquifers of the United States; modified from Reilly and others (2008).



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central meridian 96°W

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Revised 2003

System (U.S. Geological Survey, 2016b) that produce BGW. The Texas Water Development Board implemented the Brackish Resources Aquifer Characterization System study to provide a detailed characterization of aquifers containing BGW (Meyer and others, 2011) and develop numerical groundwater flow models for estimating brackish aquifer productivity in Texas (Texas Water Development Board, 2015).

Three pilot studies were recently completed (2010–12) as part of the USGS Groundwater Resources Program to assess saline groundwater resources at regional scales (Osborn and others, 2013; Williams and others, 2013; Gillip, 2014). The goals of the pilot studies were to determine data availability for assessing the occurrence and characteristics of saline groundwater and to test and develop methodologies for assessing the resource. The regions studied were the southern midcontinent, the southeastern United States, and the Upper Cretaceous aquifers of the Mississippi embayment.

Southern Midcontinent Pilot Study

The hydrogeology, occurrence, and volume of saline water in the High Plains aquifer, the Coastal lowlands aquifer system, the Texas coastal uplands aquifer system, the Mississippi embayment aquifer system, the Edwards-Trinity aquifer system, the Great Plains aquifer system, the Western Interior Plains aquifer system, the Ozark Plateaus aquifer system, the Mississippian aquifer, and the Cambrian-Ordovician aquifer of the southern midcontinent of the United States were evaluated to provide information about saline groundwater resources (Osborn and others, 2013, figs. 2, 3, 17, 18, 25, and 26). Those aquifers underlie six States in the southern midcontinent (Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas), adjacent areas (including all or parts of Alabama, Colorado, Florida, Illinois, Kentucky, Mississippi, Nebraska, New Mexico, South Dakota, Tennessee, and Wyoming), and some offshore areas of the Gulf of Mexico. For this study, saline groundwater of the aquifers was evaluated by digitizing previously published maps of the distribution of dissolved-solids concentrations, aquifer thickness, sand percentage, and porosity (primarily from the USGS Regional Aquifer-System Analysis Program); defining salinity zones; and computing the volume of saline water in storage. Based on those data, the estimated combined volume of BGW (1,000 to 10,000 mg/L of dissolved solids) from the aquifer systems was 21,600 million acre-feet. The aquifer systems with the largest estimated amounts of BGW were the Coastal lowlands (7,200 million acre-feet) and Great Plains (6,700 million acre-feet) aquifer systems (Osborn and others, 2013, table 16).

Upper Cretaceous Aquifers of the Mississippi Embayment Pilot Study

The Upper Cretaceous Nacatoch Sand and Tokio Formation of the Mississippi embayment aquifer system in Arkansas were chosen for a second pilot study (Gillip, 2014, fig. 1). Few physical and chemical measurements were available for determining the hydrogeologic characteristics and chemical quality of the water of these deeper aquifers because shallower aquifers are used for water supply; therefore, borehole geophysical logs were used to estimate those characteristics. More specifically, geologic structure, thickness, clean-sand percentage of the total formation thickness, and dissolved-solids concentrations were estimated from resistivity logs. Those data were then used to estimate the amount of groundwater available for several salinity ranges. Based on those results, the Nacatoch Sand was estimated to contain more than 80 million acre-feet of water with a dissolved-solids concentration ranging from 1,000 to 10,000 mg/L, and the Tokio Formation was estimated to contain more than 18 million acre-feet of water with a dissolved-solids concentration ranging from 1,000 to 10,000 mg/L.

Southeastern United States Pilot Study

The assessment of the southeastern United States was the most detailed of the three pilot studies (Williams and others, 2013; Lester Williams, U.S. Geological Survey, written commun., 2013). Groundwater resources were evaluated horizontally and vertically in terms of their dissolved-solids concentrations for each of the major hydrogeologic units of the Southeastern Coastal Plain and Floridan principal aquifer systems (Williams and others, 2013, fig. 1) to create maps and cross sections depicting fresh, brackish (1,000 to 10,000 mg/L of dissolved solids), and highly saline groundwater occurrence. Results were based on geologic, geophysical, and water quality data from 1,267 well locations. Dissolved-solids concentrations primarily were estimated from geophysical logs by using the resistivity porosity method (Archie, 1942). The study identified different types of BGW zones, ranging from relatively narrow bands in clastic rocks in the downdip areas of the Southeastern Coastal Plain aquifer system to broad, thick bodies of BGW in permeable carbonate rocks of the Upper and Lower Floridan aquifers. Volumes of available groundwater from those BGW zones were not calculated as part of the pilot study.

Data and Methods Used for Analyses

This section describes the data and methods used as part of the national brackish groundwater assessment. In general, the assessment was divided into national-, regional-, and aquifer-scale analyses. National-scale analyses included evaluations of the three-dimensional distribution of observed dissolved-solids concentrations in groundwater, the probability of exceeding selected dissolved-solids concentrations at multiple depths, and the geochemical characteristics of saline groundwater resources (including BGW).

To provide a context of hydrogeologic characteristics for the description of BGW resources, the United States was divided into 10 BGW regions (fig. 7)—Coastal Plains, Eastern

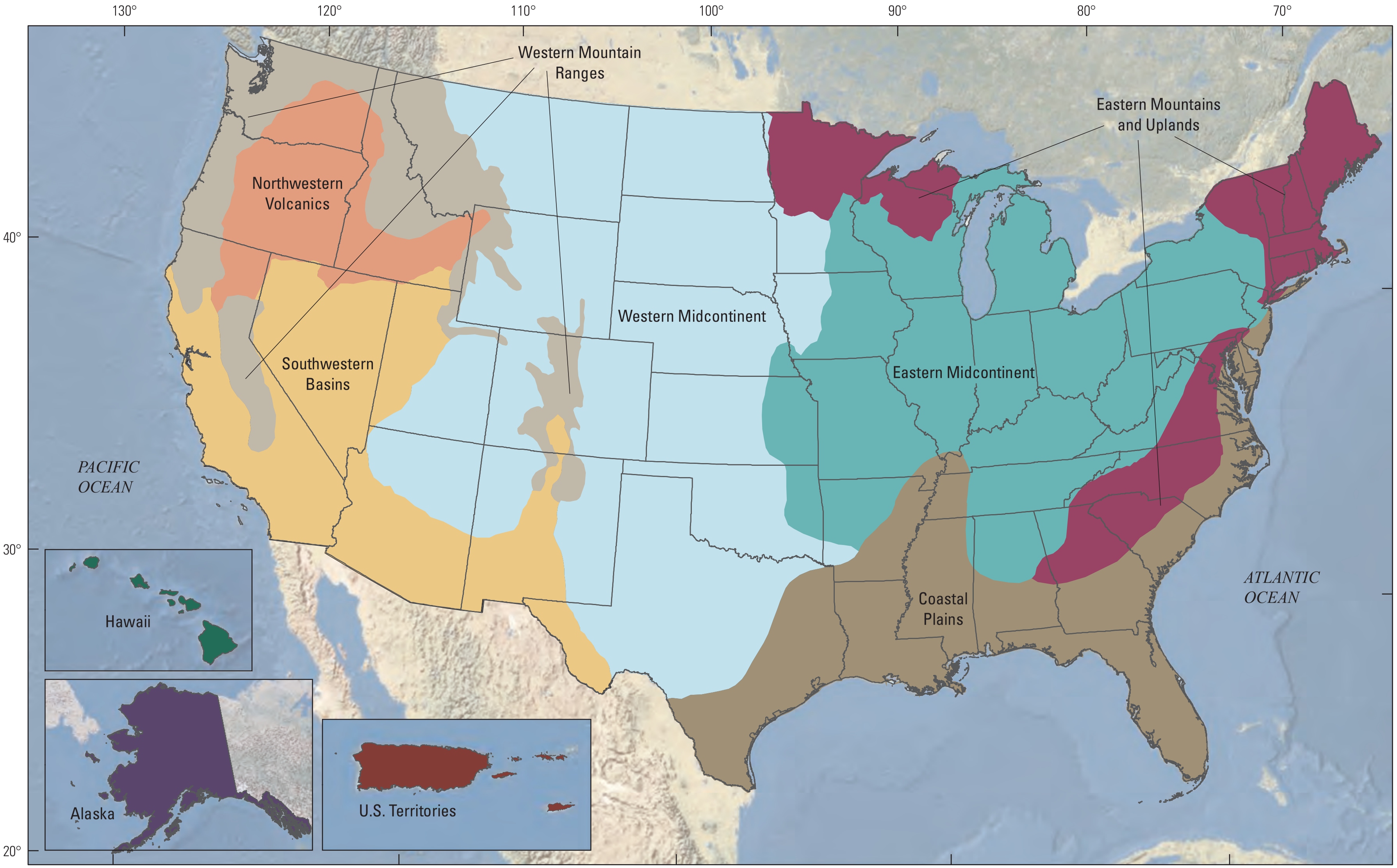

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Figure 7. Brackish groundwater regions in the United States and selected U.S. territories; modified from Heath (1984).

Midcontinent, Southwestern Basins, Western Midcontinent, Eastern Mountains and Uplands, Northwestern Volcanics, Western Mountain Ranges, Alaska, Hawaii, and U.S. Territories (Puerto Rico and U.S. Virgin Islands). Regions used for this report are based on groundwater regions defined by Heath (1984) but have been simplified and revised to reflect hydrogeologic characteristics that are related to the occurrence of BGW. For example, the Central region as described by Heath (1984) was not divided into glaciated and nonglaciated regions for this assessment; instead, the region was divided into Eastern Midcontinent and Western Midcontinent regions on the basis of the extent of the seas that covered the middle part of the United States during the Cretaceous Period. Areas outside the conterminous United States—Alaska, Hawaii, and the U.S. territories—were treated as individual regions. Although there is local variation, each region generally has similar composition, structure, and arrangement of geologic units. Groundwater conditions, such as the presence of primary or secondary porosity, hydraulic properties of aquifers, and the distribution of recharge and discharge areas, also are commonly similar within each region (Heath, 1984). Each regional-scale analysis included a summary of the percentage of observed grid cell volume in the region that was occupied by BGW within the mixture of air, water, and rock for multiple depth intervals.

The distribution of dissolved-solids concentrations and occurrence of BGW also are briefly described for the principal aquifers (fig. 6) within the four regions with the largest amounts of observed BGW (Coastal Plains, Eastern Midcontinent, Southwestern Basins, and Western Midcontinent). The principal aquifers are major aquifers of the United States and defined as regionally extensive aquifers or aquifer systems that have the potential to be used as sources of potable water. Several of the regional boundaries were adjusted to minimize principal aquifers being split into multiple regions. Despite these adjustments, principal aquifer boundaries do not exactly match region boundaries; therefore, for purposes of this report, each principal aquifer was assigned to the region that contained most of its areal extent.

Aquifer-scale analyses included the following aquifer-scale characterization:

- A generalized description of hydrogeologic characteristics from previously published studies;
- A description of the distribution of dissolved-solids concentrations;
- A discussion of considerations for developing BGW, including a summary of other chemical characteristics that may limit its use and the ability of wells producing BGW to yield useful amounts of water; and
- An estimate of the amount of saline groundwater used in 2010.

This assessment improves on previous national-scale studies in several tangible ways. Previous national assessments of the occurrence of BGW (Feth, 1965a; Androwski and others, 2011) relied on a small fraction of the dissolved-solids data compared with the data that were compiled for this assessment. A more complete set of information was assembled from a wide variety of sources and includes data collected after publication of the previous assessments. This assessment includes the characterization of BGW resources beyond just their physical occurrence. In addition to the resource location, detailed chemical characteristics (such as major-ion and trace-element concentrations) and generalized hydrogeologic characteristics (such as aquifer material, depth, generalized flow patterns, and hydraulic properties) are summarized. Improved characterization is needed for understanding and predicting BGW occurrences in areas with few data. It also is necessary for assessing characteristics of a resource that could affect its utility for certain purposes given limitations relative to production and treatment. Although detailed assessments of aquifers containing BGW have previously been completed at the State and regional scales, the methods differed among those studies. This assessment describes BGW on the basis of measures applied consistently and systematically across the Nation.

Data Sources

Analyses completed as part of this assessment relied on previously collected data. Data compiled for this assessment included readily available information about groundwater chemistry, horizontal and vertical extents and hydrogeologic characteristics of principal aquifers, and water use. These data were obtained from a variety of sources; however, data representing deep, saline groundwater were not as readily available, and the compiled data are biased toward shallow, freshwater resources.

Groundwater chemistry data were compiled from 33 sources (table 2; Qi and Harris, 2017). It was not possible to compile all data available for the Nation, and data selected for this assessment were mostly limited to large datasets that were available in a digital format. As a result, data on local-scale BGW resources may not be represented. Horizontal and vertical extents of principal aquifers were obtained primarily from previously published USGS reports that were part of the regional aquifer-system analysis studies (Sun, 1986), regional groundwater availability studies (U.S. Geological Survey, 2016a), or the “Ground Water Atlas of the United States” (Miller, 2000). For the assessment in this report, principal aquifer boundaries compiled from previous publications and geologic formation information provided by the original data sources were used to estimate the contributing aquifer for wells in the geochemistry database if an aquifer code was not provided from the original data source. This was completed by comparing well-depth and geologic formation information with the horizontal and vertical boundaries of the principal aquifers. Generalized hydrogeologic characteristics were obtained from numerous reports covering various scales, but reports for national- and regional-scale studies were preferred more than local-scale studies. Water use data were obtained from the USGS Water-Use Program (Maupin and others, 2014).

Table 2. Geochemical data sources.

[CD, compact disk; RASA, regional aquifer-system analysis]

Source agency	Geographic area	Name of dataset	Reference
Southwest Technology Development Institute	Arizona	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
Arizona Geological Survey	Arizona	Elevated salinity data from groundwater wells in Arizona	Gootee and others (2012, table 1).
Arizona Department of Environmental Quality	Arizona	Statewide groundwater quality data	Aiko Condon (Arizona Department of Environmental Quality, written commun., 2013).
Arkansas Department of Environmental Quality	Arkansas	Water Quality Monitoring Data	Arkansas Department of Environmental Quality (2013).
California Department of Conservation, Division of Mines and Geology	California	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
U.S. Geological Survey	Central Midwest	Central Midwest (RASA Program)	Christi Hansen (U.S. Geological Survey, written commun., 2013).
Colorado Geological Survey	Colorado	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
Colorado Department of Agriculture	Colorado	Agricultural chemicals and groundwater protection water quality database	Colorado Department of Agriculture (2013).
U.S. Geological Survey, in cooperation with other government and private entities	Colorado	Water-quality data repository	U.S. Geological Survey (2013).
U.S. Geological Survey	Continental United States	Standard or partial analyses of water (by U.S. Geological Survey except as noted) in parts per million except specific conductance and pH	Feth (1965a, table 2).
Nevada Bureau of Mines and Geology and Great Basin Center for Geothermal Energy	Great Basin	Great Basin groundwater geochemical database	Nevada Bureau of Mines and Geology and Great Basin Center for Geothermal Energy (2013).
Idaho Department of Water Resources	Idaho	Environmental Data Management System	Idaho Department of Water Resources (2013).
Illinois Environmental Protection Agency	Illinois	Water quality data from the Ambient Network of Community Water Supply Wells (CWS Network)	Joe Konczyk (Illinois Environmental Protection Agency, written commun., 2014).
Iowa Department of Natural Resources	Iowa	General groundwater quality database of Iowa	Iowa Department of Natural Resources, Geological Survey (2007).
Kansas Geological Survey	Kansas	Brine analyses	Kansas Geological Survey (2006).
Montana Bureau of Mines and Geology	Montana	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
Montana Groundwater Information Center	Montana	Montana Ground-Water Characterization Program database	Montana Groundwater Information Center (2013).
University of Nebraska-Lincoln, School of Natural Resources	Nebraska	Groundwater-level continuous monitoring network	Aaron Young (University of Nebraska, written commun., 2014).
Nevada Bureau of Mines and Geology	Nevada	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
Southwest Technology Development Institute	New Mexico	Geo-Heat Center western states geothermal databases CD	Boyd (2002).

Table 2. Geochemical data sources.—Continued

[CD, compact disc; RASA, regional aquifer-system analysis]

Source agency	Geographic area	Name of dataset	Reference
New Mexico Bureau of Geology & Mineral Resources	New Mexico	Groundwater monitoring database	Stacy Timmons (New Mexico Bureau of Geology and Mineral Resources, written commun., 2014).
New Mexico Environment Department-Ground Water Quality Bureau	New Mexico	Groundwater monitoring data (as part of the groundwater permitting program)	John Hall (New Mexico Groundwater Quality Bureau, written commun., 2014).
New Mexico Interstate Stream Commission lower Rio Grande Hydrologic Data Compendium	New Mexico	Groundwater monitoring database	Tom Burley (U.S. Geological Survey, written commun., 2014).
North Dakota State Water Commission	North Dakota	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
Ohio Environmental Protection Agency	Ohio	Ground Water Quality Characterization Program	Ohio Environmental Protection Agency (2013).
Oregon Department of Geology and Mineral Industries	Oregon	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
Texas Water Development Board	Texas	Groundwater database	Texas Water Development Board (2013).
Texas Water Development Board	Texas	Brackish Resources Aquifer Characterization System (BRACS)	Texas Water Development Board (2015).
Utah Geological Survey	Utah	Water chemistry database	Anderson and others (2012, appendix A).
Utah Geological Survey	Utah	Geo-Heat Center western states geothermal databases CD	Boyd (2002).
U.S. Geological Survey	United States	National geochemical database	Smith (2006).
U.S. Geological Survey	United States	National Produced Waters Geochemical Database v2.1	Blondes and others (2014).
U.S. Geological Survey	United States	National Water Information System	U.S. Geological Survey (2016).

Geochemical Data Selection

A notable contribution of this BGW assessment is its compilation of readily available, digital geochemical data from numerous sources for the assessment of the occurrence and characteristics of the Nation’s BGW. These data are provided with this report in comma-delimited text (CSV) and geographic information system (GIS) formats (Qi and Harris, 2017). Previously published BGW digital data were limited to a small number of State and regional studies. Data sources for this assessment ranged from single publications to large datasets and from local studies to national assessments (table 2); the compiled datasets include geochemical data (dissolved-solids concentrations, major ions, trace elements, nutrients, and radionuclides) and physical properties of the water (pH, temperature, and specific conductance). Although some data sources did not specifically indicate that conductance values were measured at or temperature-adjusted to 25 degrees Celsius (°C), this assumption was made, and conductance is referred to as “specific conductance” throughout this report. Additionally, the final dataset provides selected well information (location, yield, depth, and contributing aquifer) necessary for evaluating the resource. Some characteristics that might be of interest were not commonly reported in the previously published datasets and, therefore, are not included with data compiled for this assessment; for example, dissolved organic compounds, dissolved gases, and suspended solids are not included.

Geochemical data were first assembled into a relational database housed in a Microsoft SQL Server database management system. Two subsets of the available wells were selected from the relational database and formatted into CSV files and an Esri ArcGIS geodatabase for use in analyses—(1) a “dissolved-solids” dataset, containing data for more than 380,000 wells, that included information for assessing the distribution of dissolved-solids concentrations and other chemical constituents, including some major ions and trace elements that may limit the usability of BGW; and (2) a “major-ions” dataset, containing data for almost 124,000 wells, that satisfied specific criteria for relatively complete chemical analyses that could be used for classifying geochemical water types and for geochemical (thermodynamic) modeling. Data from these datasets were screened for obvious inconsistencies; however, because of the large number of records, individual data values were not investigated for validity if they seemed anomalous. Instead, data considered potentially erroneous were removed before analysis. This section provides an overview of the steps taken to process the geochemical data used for analyses. Specific details are provided with the digital geospatial data published in support of this report (Qi and Harris, 2017).

Data for sampled wells selected for analyses were required to include geographic-location coordinates or information that could be used to derive coordinates and either a well-depth measurement or contributing aquifer information. Samples from qualifying wells were selected for the dissolved-solids dataset if the sample data included either a dissolved-solids concentration or a specific conductance measurement; they were selected for the major-ions dataset if the sample data included a value for pH, temperature, alkalinity, calcium, chloride, magnesium, potassium, sodium, and sulfate. The most recent sample meeting the subset requirements was selected. Although the same well may exist in the companion dissolved-solids dataset, a different sample was often selected for the same well among the two datasets.

Several of the data sources included in the database are compilations, and some samples are duplicated within and among the sources. If a well seemed to be a duplicate on the basis of location (within 1,000 ft of another well) and depth (within a 5-percent difference), then the sample date, dissolved-solids concentration, specific conductance, calcium, chloride, potassium, sodium, and magnesium values were compared. If the sample results matched for those values, one of the samples was removed from the data used for analyses.

For some groundwater samples, results from multiple methods or fractions were reported for a chemical constituent; in these cases, only a single value was selected for analyses. For example, an individual well and sample date may have included calcium concentrations measured from filtered and unfiltered groundwater samples. In such a case, a prioritization scheme was used to select the best result available for a sample. In general, filtered samples were selected rather than unfiltered samples, and common laboratory methods were selected rather than uncommon laboratory or field methods. For pH and specific conductance, field methods were selected rather than laboratory methods.

In 54 percent of the samples, the concentration of dissolved-solids was reported by a laboratory from either an analysis of residue on evaporation or the summation of the individual constituent concentrations. For samples having neither of these values available, the dissolved-solids concentration (*DSC*) was estimated from specific conductance and from equations derived as part of this assessment by using a provisional version of the dataset. The equations were determined by using regression on samples for which specific conductance and dissolved-solids concentrations were reported. The following equation was derived for cases in which specific conductance was <50,000 microsiemens per centimeter at 25 degrees Celsius (µS/cm), which is the approximate specific conductance (*SC*) for seawater (see figure 3–1 for a graphical depiction of the equation):

$$DSC = -55 + 0.689SC \qquad (1)$$

where

DSC is the dissolved-solids concentration, in milligrams per liter; and

SC is the specific conductance, in microsiemens per centimeter at 25 degrees Celsius.

Although the coefficient of determination (R^2) of 0.94 for this equation indicates a strong relation between *DSC* and *SC*, the equation is less reliable for low *SC* values; for example, the equation produces negative dissolved-solids concentrations when *SC* is <80 µS/cm. To account for the decreased reliability at low *SC* values, dissolved-solids concentrations computed with this equation for *SC* <300 µS/cm were censored in the database as <150 mg/L. Where *SC* was >50,000 µS/cm, the relation was not linear, and a quadratic form was used. The equation follows, and it had an R^2 of 0.92:

$$DSC = 27{,}720 - 0.0869SC + 6.204\times10^{-6}SC^2 \qquad (2)$$

The empirical relations summarized in equations 1 and 2 have uncertainties that are partly related to data quality and partly caused by variation in the theoretical relation between specific conductance and dissolved-solids concentration for different salt solutions (ion ratios). These sources of error are evaluated in appendix 2 of this report.

Several simple checking routines were used to identify systematic errors in the data and remove those values that were deemed incomplete or unreliable. Most of the original data sources provided data qualifier codes; the codes were standardized to the USGS National Water Information System codes (U.S. Geological Survey, 2016b) where possible for consistency. In some cases, wells were removed from the datasets used for analyses if the well construction information was inconsistent; for example, if the total well depth was shallower than depth to the bottom of a well screen or if well depth or bottom of well screen was a negative value (above land surface), then the well was removed. Wells also were removed if the well’s latitude and longitude coordinates caused it to be plotted far outside its State code. The value of an individual constituent measurement was removed if the data qualifier code indicated the value was suspect. The concentration measurement of a major ion, trace element, or nutrient was removed if it was higher than the dissolved-solids concentration of the same sample. Samples that were questionable because they had a dissolved-solids concentration that either did not agree with other dissolved-solids concentrations from different analytical methods for the same sample (that is, if the ratio between the values was >1.12 or <0.90) or was less than the dissolved-solids concentration associated with rainwater, were removed from the dissolved-solids dataset. Samples were not used for geochemical characterization if the charge imbalance was >10 percent. Although these checking routines and the resulting selection of data improved the quality of the information used for analyses, some errors are still likely to exist within the datasets (see the “Data Gaps and Limitations” section).

Analytical Methods

This section describes methods applied to data compiled for this assessment to assess the vertical and horizontal distribution of dissolved-solids concentrations in groundwater, predict the occurrence of BGW for areas where data were not available, describe the geochemical characteristics of saline groundwater (including BGW), and estimate saline groundwater use for principal aquifers.

Three-Dimensional Mapping of Observed Dissolved-Solids Concentrations

A three-dimensional representation of subsurface BGW for the Nation was created by using geochemical data from across the country and a GIS. A discretized three-dimensional representation of BGW and of other chemical and physical characteristics in aquifers allows for estimation of volumes with BGW available and changes in described properties with depth. Three-dimensional representations of BGW also aid in establishing initial and boundary conditions for flow and transport modeling in saline (variable-density) systems.

Maps and tables of the distribution of dissolved-solids concentrations and other chemical constituents were developed from data from individual wells and data that were summarized by using a coarse-resolution three-dimensional grid. The coarse-resolution three-dimensional grid was used to account for dense well clustering. The spatial distribution of sampled wells within the dissolved-solids dataset is uneven and includes dense well clustering in several areas, whereas other areas lack wells. If uneven spatial densities of data are not accounted for, then data summaries for the Nation or other large areas can be biased toward the conditions of those areas with more wells. In addition, high spatial densities of data can present difficulties in illustrating spatial variations for larger regions because of overlapping data points. To overcome these issues, the approach used was to develop a large grid and then characterize BGW conditions within each grid cell as the maximum dissolved-solids concentration observed for wells within the cell. Aquifer, regional, and national summaries were then tabulated by using the single value representing each grid cell (that is, the maximum observed concentration), thereby limiting spatial bias and facilitating display of the data. To provide a three-dimensional understanding of the spatial distribution of BGW, the grid has four layers with different depth intervals: <50 ft below land surface, 50 to 500 ft below land surface, 500 to 1,500 ft below land surface, and 1,500 to 3,000 ft below land surface. Cells within a given grid layer have identical depth intervals, and all cells regardless of grid layer have the identical lateral dimensions—6.2 miles (mi) by 6.2 mi, or 10 kilometers (km) by 10 km.

Grid cell dimensions were selected considering several factors. The thickness of the grid layers was chosen to increase with depth because the number of wells in the geochemical database decreases with depth. In addition, there generally is less information on subsurface geology and hydraulic properties for deeper intervals below land surface. The 6.2-mi by 6.2-mi lateral dimensions of the grid cells were selected on the basis of the following factors: (1) the lateral dimensions of a cell needed to be smaller than the widths of principal aquifers such that most grid cells represent only one aquifer and not multiple aquifers or part aquifer and part nonaquifer, (2) the lateral dimensions needed to be small enough that lateral transitions and other spatial patterns in BGW conditions could be observed, (3) the lateral dimensions needed to be large enough that most cells would have one or more wells within them, and (4) the lateral dimensions of the grid used to show the observed occurrence of BGW needed to be readily scalable to the lateral dimensions of the grid used to model the probability of BGW occurrence (see the “Predicting Brackish Groundwater Occurrence and Distribution” section).

Each well was assigned to a grid cell and depth interval on the basis of its latitude, longitude, and maximum depth value (either bottom of screened interval, total well depth, or hole depth). If the maximum depth was >3,000 ft below land surface, the well was assigned to the 1,500- to 3,000-ft below land surface depth interval, provided that the top of the screen was <3,000 ft below land surface.

The maximum observed dissolved-solids concentration was used to represent BGW conditions within each grid cell and layer because the national brackish groundwater assessment seeks to identify the occurrence of BGW, and reporting a mean or median concentration could underreport the occurrence of BGW in some areas. Despite the approach of using the maximum concentration observed, it is still likely that some areas with BGW are not identified because most of the wells in the data compiled for this assessment were drilled for the purpose of obtaining the freshest and best quality water available in the area, and drillers may have purposely avoided developing BGW resources. Use of the maximum observed concentration to represent each grid cell in subsequent tabulations and summaries implicitly assumes that if part of the grid cell contains BGW, then the entire cell contains BGW; consequently, grid cell volumes of BGW may be overestimated.

Predicting Brackish Groundwater Occurrence and Distribution

Dissolved-solids concentrations in groundwater across the contiguous United States were statistically evaluated by multivariate regression analysis (SAS Institute, Inc., 2008) with respect to hydrogeologic factors that may affect dissolved-solids concentrations. As such, the model is a stochastic (statistical) rather than a process-oriented model. Methods other than multivariate regression analysis, such as logistic regression and random forest, were also considered but not selected. For the present application of probability estimation, multivariate regression analysis seemed most appropriate.

After calibration, the model was used to produce maps of the probability of exceeding certain dissolved-solids concentrations that are relevant to potential BGW use (1,000, 3,000, and 10,000 mg/L) at specific depths (500, 1,500, and 3,000 ft below land surface). Existing data compiled for this assessment were used for the analysis, and dissolved-solids concentration (natural logarithm transformed) was the dependent variable. Numerous variables that are distributed geographically across the Nation are available to test as model predictors; however, only data that were available in digital formats and covered the entire contiguous United States were used for this analysis. More than 25 variables (table 3) were examined, including categorical variables (for example, bedrock geologic units) and continuous numerical variables (for example, potential evapotranspiration).

For the purpose of data exploration, several subsets of the data were examined individually. These subsets were (1) all well data with depth values, (2) all wells representing groundwater ≥500 ft below land surface, (3) all wells representing groundwater ≥1,000 ft below land surface, and (4) all wells representing groundwater ≥3,000 ft below land surface. The subset of wells ≥500 ft below land surface provided the model with the highest R^2 and had coefficients for statistically significant predictors that were similar to the model developed by using only samples from depths greater than either 1,000 or 3,000 ft below land surface. The model produced by using the data from all depths was less predictive and involved factors that did not seem to be predictive at greater depths. For this reason, the final predictive model was developed by using the data from depths ≥500 ft below land surface.

Some of the data (14.6 percent of the full dataset and 2.6 percent for the data obtained ≥500 ft below land surface) were censored to be less than a detection limit of 150 mg/L (see the “Geochemical Data Selection” section). These censored data were set to 98.0 mg/L, which is the median of the uncensored data <150 mg/L (93.34 mg/L is the mean). This level of 2.6 percent for censoring samples is well below the 5 to 10 percent above which Lubin and others (2004) would expect a bias. Additionally, the application of the model used thresholds of 1,000, 3,000, and 10,000 mg/L for estimating exceedance probabilities. These concentrations are in the brackish salinity range and are well above the 150-mg/L detection limit; thus, a potential bias from the censored data is considered minimal.

In building the model, it was first established that using values of the natural logarithm of dissolved-solids concentration [ln(*DS*)] as the dependent variable produced residuals that were nearly normally distributed, whereas residuals produced by using the untransformed dissolved-solids concentrations as the dependent variable were not normally distributed; therefore, ln(*DS*) was used as the dependent variable. Well depth was used as a surrogate for well-screen intervals because of the lack of screened-interval data. Like ln(*DS*), values of the natural logarithm of well depth [ln(*depth*)] were more nearly normally distributed than were the depths themselves, and ln(*depth*) was chosen as the predictor variable. A simple linear regression of ln(*DS*) in relation to ln(*depth*) indicated that the depth term described 40 percent of the variance in the dependent variable. This was also by far the strongest predictor [186.5 for the *t* value (SAS Institute, Inc., 2008) for the predictor ln(*depth*)] in the final model; the next highest (absolute) *t* value was 51.6 (evaporite salt and anhydrite/gypsum deposits; appendix 1). Residuals from this simple relation between ln(*DS*) and ln(*depth*) were nearly normal (slightly bimodal). Because of this dominant relation, the addition of indicator variables that were categorical and dichotomous in a multiple-variable regression can be viewed as producing simple modifications of this relation (for example, modifying the intercept). Interactions between ln(*depth*) and other predictor variables also were tested. When the predictor was a dichotomous indicator variable and the interaction term was determined to be significant, the interaction term modified the slope of the relation between ln(*DS*) and ln(*depth*).

Predictions were estimated from the final model for depths of 500, 1,500, and 3,000 ft below land surface, where most of the BGW exists. This model is not intended for predicting dissolved-solids concentrations at shallow depths such as 50 or 100 ft below land surface; for example, predicting the occurrence of BGW formed by shallow processes, such as may happen beneath present-day [2016] playas within closed basins, is an application beyond the scope of this assessment.

Testing for normality of the residuals is important for evaluating the performance of a regression model. The testing approach used for this assessment was described in Moore and others (2002, p. 47) and is restated here. The cumulative distribution function of the residuals was determined by using SAS/INSIGHT software (SAS Institute, Inc., 2008). The statistic *D* of the Kolmogorov-Smirnov test (SAS Institute, Inc., 2008), which represents the maximum vertical distance between the two distribution functions, was then used to test the null hypothesis that the population distribution of the residuals is normally distributed. In the normality test, the null hypothesis was rejected in this case because, at some point, the normal distribution fell outside the 95-percent confidence band. Although the Kolmogorov-Smirnov statistic *D* test indicated that the residuals were not normally distributed at the 95-percent confidence level, the graphical distribution was nearly normal, thus for practical purposes, the model was considered

Table 3. Predictor variables tested in national regression model for dissolved solids.

[X, strong continuous variable; can be positive or negative; NA, not applicable; PRISM, Parameter-Elevation Relationships on Independent Slope Model]

Variables tested for predicting dissolved-solids concentrations	Predictor is significant in the model[1]	Strong[2] predictor categories	Variable interactive with depth[3]	Reference
Depth below land surface (natural logarithm transformed)[4]	Yes	X	No	Data compiled for this assessment.
Subsurface evaporite deposits[5]	Yes	Area underlain by gypsum/anhydrite; or area underlain by salt and gypsum/anhydrite	Yes	Anning and Flynn (2014), Johnson (2008).
Bedrock geology[5]	Yes	Missourian and Virgilian Series of the Pennsylvanian-aged deposits, Wolfcampian and Loeonardian of the Permian-aged deposits, Cretaceous-aged Taylor Group, Oligocene-aged Continental Rock Group	Yes	King and Beikman (1974), Schruben and others (1998).
Principal aquifers[5]	Yes	Coastal lowlands aquifer system, Edwards-Trinity aquifer system, Texas coastal uplands or Mississippi embayment aquifer system, Ozark Plateaus aquifer system, Cambrian-Ordovician aquifer system, High Plains aquifer, Central Oklahoma aquifer	Yes	Reilly and others (2008).
Level III ecoregions of the continental United States[5]	Yes	Central Great Plains, Cross Timbers (semiarid plains), Southern Michigan/Northern Indiana Drift Plains, Western Allegheny Plateau, Flint Hills (south-central semiarid prairies), Atlantic Coastal Pine Barrens, Southeastern Plains	Yes	Commission for Environmental Cooperation (2009).
Base-flow index grid for the conterminous United States[4]	Yes	X	No	Wolock (2003a).
Percent irrigated lands[4]	Yes	NA	No	Pervez and Brown (2010).
Soil characteristics for the conterminous United States (soil group,[5] available water capacity,[4] minimum permeability,[4] minimum soil depth[4])	Yes	NA	No	Wolock (1997).
Topographic wetness index[4]	Yes	NA	No	Wolock and McCabe (1999), David Wolock (U.S. Geological Survey, written commun., 2015).
Regional water table[4]	Yes	NA	No	Fan and others (2013).
Proximity to the sea coast[5]	Yes	NA	Yes	Calculated as part of this assessment.
National Land Cover Database 2011[5]	Yes	Evergreen forest, pasture/hay	Yes	Homer and others (2015).
Surficial geology categories[5]	Yes	NA	Yes	Cress and others (2010).

Table 3. Predictor variables tested in national regression model for dissolved solids.—Continued

[X, strong continuous variable; can be positive or negative; NA, not applicable; PRISM, Parameter-Elevation Relationships on Independent Slope Model]

Variables tested for predicting dissolved-solids concentrations	Predictor is significant in the model[1]	Strong[2] predictor categories	Variable interactive with depth[3]	Reference
Hydrologic landscape regions of the United States[5]	Yes	NA	Yes	Wolock (2003c).
Groundwater regions[5]	Yes	NA	Yes	Heath (1984).
Generalized geology[5]	Yes	NA	Yes	Reed and Bush (2005).
Percentage distance from watershed divide to stream[4]	No	NA	No	Richard Moore (U.S. Geological Survey, written commun., 2015).
Land-surface elevation[4]	No	NA	No	U.S. Geological Survey (2014).
Bouguer gravity anomaly[4]	No	NA	No	Phillips and others (1993).
Isostatic residual gravity anomaly[4]	No	NA	No	Phillips and others (1993).
Potential evapotranspiration[4]	No	NA	No	Wolock and McCabe (1999), David Wolock (U.S. Geological Survey, written commun., 2014).
30-year normal precipitation[4]	No	NA	No	PRISM Climate Group (2012).
Annual recharge[4]	No	NA	No	Wolock (2003b).
Distance to stream[4]	No	NA	No	Calculated as part of this assessment.
Watershed Boundary Dataset (WBD) Closed Basins[5]	No	NA	No	U.S. Environmental Protection Agency and U.S. Geological Survey (2012).
Precipitation minus potential evapotranspiration (recharge)[4]	No	NA	No	David Wolock (U.S. Geological Survey, written commun., 2015).

[1] If predictor is categorical, then these data indicate if the predictor contains significant categories.

[2] Strong predictor variables are arbitrarily defined as those with *t* values (SAS Institute, Inc., 2008) greater than 16 or less than –16.

[3] Indicates if variable has been proven to be most significant in the model as a (natural logarithm transformed) variable interactive with depth. Interaction is determined by testing in the model the product of the categorical variable (0 = not present; 1 = present) and depth below land surface (natural logarithm transformed).

[4] Continuous variable.

[5] Categorical variable.

appropriate for estimating probabilities greater than or equal to a given dissolved-solids concentration. The spatial distribution of residuals also was reviewed to identify systematic patterns of high or low values. Though the spatial distribution was considered generally acceptable, several patches of high or low residuals indicated that the available predictor variables used in the model did not fully capture the spatial distribution of dissolved solids in groundwater at all locations; for example, high or low residuals existed along some ecoregion boundaries, possibly suggesting the need for data that are more localized than the data for EPA level III ecoregions.

In total, 30 percent of the dissolved-solids data from across the Nation were randomly selected to be sequestered for use as a verification dataset. Sequestered data were used for verification of the models calibrated by using the primary dataset. The primary dataset contained data from 269,621 wells. The sequestered verification dataset contained data from 115,466 wells. The number used in the final model (data from wells ≥500 ft below land surface) was reduced to 54,896 in the primary dataset and 23,504 in the sequestered verification dataset. For the sequestered verification dataset, a simple linear regression was used to examine dissolved-solids results calculated by using the calibrated model in relation to the measured dissolved-solids concentrations of the sequestered samples. The equation developed from the multilinear regression model (with the primary nonsequestered data) was used to predict dissolved-solids concentrations for the sequestered data. A simple linear regression of these predictions in relation to the observed values indicated that the sequestered data are explained remarkably well by the model developed from just the nonsequestered data—the intercept determined by this simple linear regression is near zero, and the slope is 1; furthermore, the R^2 and root mean square error of this simple linear regression are virtually the same as they were for the original model developed from the nonsequestered data (both have a R^2 of 0.79 [dimensionless] and root mean square error of 1.15 [dimensionless]). This illustrates that the calibrated multilinear regression model predicted the sequestered data nearly as well as it did the calibration dataset. If this were not the case, then the R^2 of this simple linear regression would be significantly lower than that of the original multilinear regression, and the root mean square error would be significantly higher than that of the original multilinear regression.

The regression model is very stable. This stability can be demonstrated by examining the change in coefficients when the sequestered data (23,504 wells) are included along with the calibration dataset as input to a model run. Such a model run returns minimal changes to model coefficients derived from the original calibrated model. It seems probable that the robustness of the model is driven by the richness of the data, with sampled wells available throughout the Nation from numerous data sources, and the strong ubiquitous underlying relation between ln(*DS*) and ln(*depth*).

Geochemical Characterization

Geochemical characterizations included cluster analyses of major-ion compositions, distributions of selected constituents, and theoretical (thermodynamic) modeling of solution properties and hypothetical BGW treatment processes. Theoretical calculations were performed with the PHREEQC computer program (Parkhurst and Appelo, 1999; Charlton and Parkhurst, 2011).

The focus of the geochemical characterization was on saline (brackish and highly saline) groundwater (≥1,000 mg/L of dissolved solids); consequently, 100,245 well samples in the major-ions dataset that had a dissolved-solids concentration <1,000 mg/L were excluded from most of the analyses except for use in figures 16 and 3–1, in which fresh groundwater values were plotted for comparison with saline samples. Highly saline water was included in the analysis because it can produce BGW with similar relative constituent concentrations when diluted with freshwater. To ensure reasonable accuracy of the geochemical data used, an additional 6,748 samples were excluded from the analysis because their charge balance was not within 10 percent as calculated by the PHREEQC program. In addition, 1,725 samples were excluded because they were missing well-depth, temperature, pH, alkalinity, or silica data and 2 samples with anomalously high silica concentrations were removed because they caused undue effects on the clustering. After these selection criteria were applied, 14,979 samples were available for the analysis.

A cluster analysis that implemented the *k*-means algorithm (MacQueen, 1967; SAS Institute, Inc., 2008) was used to find geochemically distinct groups of samples having similar values for selected geochemical parameters within each group but dissimilar values among groups. In the *k*-means algorithm, the analyst specifies the number of groups (*k*) into which the observations will be partitioned. The value for *k* is selected primarily on the basis of the relation between *k* and R^2, which is a measure of how much variability in the dataset is explained by assigning observations to *k* compared to assigning observations to a single group (*k*=1). For this assessment, a plot of R^2 against *k* (fig. 8) shows that R^2 increases rapidly with increases in *k* until *k*=4. For *k*≥5, increases in *k* correspond to diminishing increases in R^2; consequently, *k*=4 was selected as the optimal *k*, and the *k*-means algorithm was used to assign individual samples to one of the four groups (see the "Geochemical Characteristics of Brackish Groundwater" section).

Two stages of transformations were applied to the data in preparation for the cluster analysis. In the first stage, to emphasize differences in geochemical characteristics related to constituent ratios (for example, to normalize for variations in dissolved-solids concentrations), the equivalent concentration of each of the major ions was converted into its respective fraction of the total cation or anion equivalents in the sample, and the molar concentration of silica was converted to its fraction of the total moles per liter of major cations and anions. Dissolved-solids concentrations determined from the sum of dissolved constituent concentrations in the PHREEQC program were logarithmically (base 10; $\log_{10}$) transformed. Sample measurements of pH and temperature were not adjusted in the initial transformation. In the second transformation stage,

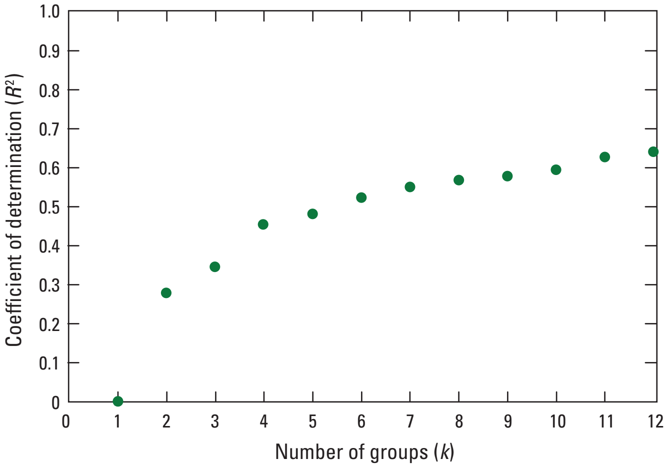

Figure 8. Relation between the coefficient of determination and the number of groups (*k*) that the dataset observations are partitioned into in the *k*-means algorithm.

observations for a given parameter were normalized to the mean and standard deviation determined for all samples in the dataset; this was done to give each variable equal weight in the cluster analysis.

Maps showing the spatial distribution of the four major geochemical groups of saline groundwater defined by cluster analysis were developed by using a grid approach similar to that used for dissolved-solids concentrations. In about 28 percent of the grid cells, there were two or more wells; in these cases, about 41 percent of those grid cells had wells representing two or more different groups. For the 11 percent of grid cells where there were multiple groups, the group with the largest observation count was selected to represent each grid cell; in the case of a tie, the group with the highest observed dissolved-solids concentration was selected. Although the cluster analysis did not exclude samples on a geographical basis, <1 percent of the samples were in areas outside the conterminous United States.

The PHREEQC program was used to (1) determine constituent speciation, ionic strength, osmotic pressure, and other thermodynamic properties of saline groundwater samples in the major-ions dataset, (2) calculate mineral saturation indices for the groundwater samples where saturation index = log(ion activity product / solubility product), and (3) simulate processes including a hypothetical treatment process resembling reverse osmosis to evaluate conditions related to water use and mineral precipitation potential during BGW treatment. The Pitzer aqueous model database (Plummer and others, 1988; Parkhurst and Appelo, 2013) was used with the PHREEQC program because it is well suited for high-salinity waters. PHREEQC simulations were used to explore how dilution with freshwater would change geochemical characteristics of saline groundwater that might be important to the use and treatment of BGW such as concentrations of selected constituents relative to health-based benchmarks and mineral precipitation potential. For simulating a hypothetical treatment process resembling reverse osmosis, pure water was removed from the simulated solution to produce concentration factors of 1 (0 percent of the water removed), 2, 4, 8, and 16 (about 94 percent of water removed).

Reverse osmosis is the most common form of desalination treatment in the United States. Reverse osmosis systems include a thin, semipermeable barrier that transmits water under pressure while excluding solutes. The hypothetical treatment process resembling reverse osmosis was simulated with the PHREEQC program in the same way as evaporation (Huff, 2004b; McMahon and others, 2015). In reverse osmosis, dissolved ions on the influent side of the membrane become increasingly concentrated as the influent stream flows through each membrane vessel and stage, which increases the potential for mineral precipitation (scale formation). Simulations of reverse osmosis were completed under closed atmospheric conditions with respect to the partial pressure of carbon dioxide [$P(CO_2)$] to assess water chemistry in sealed tanks or distribution lines with no exchange of carbon dioxide with the atmosphere. Simulations were completed at 25 °C and a pressure of 20 atmospheres (atm), which are generally representative of reverse osmosis operating conditions (Greenlee and others, 2009). Mineral precipitation potentials for barite ($BaSO_4$), calcite ($CaCO_3$), chalcedony (SiO_2), gypsum ($CaSO_4 \cdot 2H_2O$), and halite (NaCl) were calculated for each concentration factor by requiring the minerals to attain equilibrium for the geochemical conditions at that concentration factor. Actual solid phases and assemblages formed during reverse osmosis may differ.

Several variables were used to help assess the suitability of the water types for different uses: (1) the osmotic pressure, (2) the sodium-adsorption ratio, (3) the mineral saturation indices, and (4) the Langelier saturation index (Langelier, 1936). These variables are discussed in detail in appendix 2.

Estimating Saline Groundwater Use for Principal Aquifers

In addition to mapping the occurrence of BGW, another objective of this assessment, as directed by the Secure Water Act, was to determine the amount of BGW being used. County-level water use data for 2010 from the USGS Water-Use Program (Maupin and others, 2014) and the dissolved-solids dataset provided information for determining the proportion of saline groundwater use that could be attributed to each principal aquifer. Groundwater use for just the brackish salinity range (1,000 to 10,000 mg/L of dissolved solids) was not possible to assess because USGS data are compiled for two categories: fresh groundwater (<1,000 mg/L of dissolved solids) and saline groundwater (≥1,000 mg/L of dissolved solids); however, most uses of saline water have lower operating costs for water with smaller dissolved-solids concentrations (Barlow, 1963; Bureau of Reclamation, 2003; Pearce, 2008), and it may be a reasonable assumption that much of the USGS-defined saline groundwater used falls within the brackish salinity range.

The amount of saline groundwater use attributed to each of the principal aquifers had to be estimated because data from the USGS Water-Use Program are compiled by county and, in some areas, several principal aquifers are present below each county. This estimation was done by calculating, for each county, the proportion of saline groundwater samples produced from each principal aquifer and then multiplying that proportion by the total saline groundwater use for that county. For each county, the number of saline samples was totaled by aquifer and divided by the total number of saline samples within the county to determine the proportion of all saline samples in the county produced by each principal aquifer. Only samples for which the dissolved-solids concentration was ≥1,000 mg/L and the principal aquifer was known were included in calculations. The 2010 saline water use for each water use category for each county was then weighted by the proportion of the saline water-producing wells in that county that were completed in each aquifer; for example, if the proportion of the saline water-producing wells in a county that were completed in the Western Interior Plains aquifer system was 0.3, then the associated county saline water use was multiplied by 0.3 for that aquifer. All water use values for each water use category for each aquifer were then summed to determine the total saline groundwater use for each principal aquifer.

To better understand some of the limitations of water use reported by the USGS Water-Use Program (see the "Data Gaps and Limitations" section), possible BGW use was assessed by using dissolved-solids concentrations and the type codes for well-water use from data compiled for this assessment. Using the number of wells in a county that produced BGW and the associated coded information on well water use, four categories were developed to represent the likelihood of BGW use within each county:

- Where BGW use was not observed (county contained fewer than five samples with observed BGW, <5 percent of the samples were brackish, or there were no samples in the dataset);

- Where BGW was present but use was unknown (county contained at least five samples with observed BGW and that number was >5 percent of the total samples; <5 percent of sampled wells that produced BGW had a known use);

- Where BGW was present and it was being used beneficially (county contained at least five samples with observed BGW and that number was >5 percent of the total samples; >5 percent of sampled wells that produced BGW had a known water use and were defined as being used for beneficial purposes); and

- Where BGW was present and it was not being used beneficially (county contained at least five samples with observed BGW and that number was >5 percent of the total samples; >5 percent of sampled wells that produced BGW had a known water use but the use was not defined as beneficial).

Wells defined as providing beneficially used water had a water use that was not for dewatering or monitoring and the well had not been identified as being plugged or destroyed.

Brackish Groundwater in the United States

The following sections describe, from a national perspective, the observed distribution of dissolved solids and occurrence of BGW, the predicted occurrence of BGW, and the geochemical characteristics of BGW.

Observed Distribution of Dissolved Solids and Occurrence of Brackish Groundwater

BGW was identified beneath nearly every State and U.S. territory within the uppermost 3,000 ft below land surface and represents a substantial, but largely untapped, resource. Although data are sparse in some areas, the data compiled for the national brackish groundwater assessment provide considerable information on the distribution of BGW laterally and vertically throughout much of the Nation's subsurface. The occurrence and distribution of BGW was characterized on the basis of nearly 336,000 samples, of which about 20 percent indicated the presence of BGW (dissolved-solids concentration between 1,000 and 10,000 mg/L) and about 2 percent indicated the presence of highly saline groundwater (dissolved-solids concentration >10,000 mg/L; table 4).

Grid cells containing well samples (observations) represent about 2.03 million square miles (mi^2), which is about 53 percent of the Nation's land area. Areas lacking information tend to be in the mountainous areas of the Western States, Alaska, and most areas at great depths, especially >1,500 ft below land surface. Across the Nation, there is about 604,000 mi^2 where the maximum dissolved-solids concentration observed between the land surface and 3,000 ft below the land surface was in the brackish range; this area represents about 16 percent of the total land area of the Nation. An additional 120,000 mi^2, or 3 percent of the total land area, is underlain by highly saline groundwater. Some of the areas where the maximum observed concentration is in the highly saline range may also contain brackish groundwater; however, these areas are not included in the 604,000-mi^2 result.

Grid cells containing well samples (observations) represent about 15 percent of the Nation's subsurface volume within the uppermost 3,000 ft below land surface. Nearly 89,000 cubic miles (mi^3) of subsurface materials underneath the Nation to 3,000-ft below land surface depth (including air, water, and rock) contained some BGW (table 4). This is about 29 percent of the grid cell volume containing observations but only 4.3 percent of the Nation's total subsurface volume to 3,000-ft below land surface. More than 99 percent of the observed grid cell volume of BGW exists within the conterminous United States largely because the other States and territories are either small or, in the case of Alaska, lack observations. In addition to the volume of BGW, about 29,000 mi^3 of subsurface materials across the Nation contained highly saline groundwater.

The actual amount of usable BGW in these observed areas is highly uncertain largely because of information gaps about the subsurface materials containing this resource. Scientific investigation through the years, however, has determined that much of this volume is rock, that some of this volume is air in the unsaturated zone, and that not all water in this volume can actually be drained from the subsurface materials. Taking into account the likely volumes of saturated material and typical values of aquifer porosity, the actual volume of BGW is unlikely to exceed 25 percent of the total volume of

Table 4. Summary of observed brackish and highly saline groundwater in brackish groundwater regions of the United States.

[Grid cells are categorized as "fresh," "brackish," or "highly saline" based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization, "fresh" cells could also contain unobserved brackish or highly saline groundwater, "brackish" cells could also contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and "highly saline" cells could also contain observed or unobserved fresh and/or brackish groundwater. <, less than; NA, brackish or highly saline groundwater not observed in listed depth interval of the brackish groundwater region]

Brackish groundwater region (fig. 7)	Depth interval, in feet below land surface	Statistics for sampled wells				Total observed and unobserved volume, in cubic miles	Estimated grid cell volume represented by sampled wells[1]					
							Fresh, brackish, and highly saline groundwater[2]		Brackish groundwater		Highly saline groundwater	
		Number of sampled wells	Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median dissolved-solids concentration, in milligrams per liter		Volume, in cubic miles	Observed volume, as a percentage of total volume	Volume, in cubic miles	Observed volume, in percent	Volume, in cubic miles	Observed volume, in percent
United States and U.S. territories												
Total United States, including territories	0 to 50	68,589	18	<1	334	34,076	8,637	25	1,900	22	118	1
	50 to 500	216,871	18	<1	360	306,684	147,586	48	40,268	27	2,224	2
	500 to 1,500	39,844	27	4	500	681,520	98,069	14	30,384	31	6,508	7
	1,500 to 3,000	10,500	30	41	3,692	1,022,241	48,866	5	16,146	33	19,689	40
	0 to 3,000	335,804	20	2	376	2,044,521	303,157	15	88,697	29	28,540	9
Brackish groundwater regions												
Coastal Plains	0 to 50	12,745	6	<1	150	3,681	1,487	40	171	12	17	1
	50 to 500	39,828	14	<1	290	33,125	25,601	77	5,374	21	392	2
	500 to 1,500	12,405	19	1	382	73,611	28,226	38	7,166	25	607	2
	1,500 to 3,000	1,802	18	18	510	110,417	8,643	8	2,194	25	2,106	24
	0 to 3,000	66,780	13	1	281	220,834	63,958	29	14,904	23	3,121	5
Eastern Midcontinent	0 to 50	15,974	6	<1	253	5,960	2,288	38	214	9	2	<1
	50 to 500	46,490	6	<1	262	53,644	35,970	67	5,469	15	448	1
	500 to 1,500	3,905	15	19	428	119,208	15,810	13	2,808	18	2,771	18
	1,500 to 3,000	2,292	15	65	57,728	178,813	11,561	6	1,887	16	7,360	64
	0 to 3,000	68,661	7	4	279	357,625	65,629	18	10,377	16	10,581	16
Southwestern Basins	0 to 50	3,448	35	9	810	3,671	426	12	132	31	42	10
	50 to 500	21,141	22	<1	465	33,043	12,281	37	3,843	31	316	3
	500 to 1,500	8,553	21	<1	444	73,429	14,055	19	4,088	29	197	1
	1,500 to 3,000	958	39	3	912	110,144	3,444	3	1,196	35	197	6
	0 to 3,000	34,100	24	2	493	220,287	30,205	14	9,259	31	753	3

Table 4. Summary of observed brackish and highly saline groundwater in brackish groundwater regions of the United States.—Continued

[Grid cells are categorized as "fresh," "brackish," or "highly saline" based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization "fresh" cells could also contain unobserved brackish or highly saline groundwater, "brackish" cells could also contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and "highly saline" cells could also contain observed or unobserved fresh and/or brackish groundwater. <, less than; NA, brackish or highly saline groundwater not observed in listed depth interval of the brackish groundwater region]

Brackish groundwater region (fig. 7)	Depth interval, in feet below land surface	Statistics for sampled wells				Total observed and unobserved volume, in cubic miles	Estimated grid cell volume represented by sampled wells[1]					
							Fresh, brackish, and highly saline groundwater[2]		Brackish groundwater		Highly saline groundwater	
		Number of sampled wells	Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median dissolved-solids concentration, in milligrams per liter		Volume, in cubic miles	Observed volume, as a percentage of total volume	Volume, in cubic miles	Observed volume, in percent	Volume, in cubic miles	Observed volume, in percent
Brackish groundwater regions—Continued												
Western Midcontinent	0 to 50	23,502	38	<1	761	8,820	2,695	31	1,330	49	49	2
	50 to 500	74,344	35	<1	641	79,382	48,804	61	24,167	50	951	2
	500 to 1,500	12,470	49	5	1,175	176,405	31,481	18	15,854	50	2,837	9
	1,500 to 3,000	5,270	39	46	7,113	264,607	23,956	9	10,640	44	9,982	42
	0 to 3,000	115,586	37	3	746	529,214	106,935	20	51,990	49	13,819	13
Eastern Mountains and Uplands	0 to 50	8,141	<1	<1	150	1,548	1,185	77	19	2	1	<1
	50 to 500	15,987	2	<1	150	13,932	14,258	100	480	3	36	<1
	500 to 1,500	534	3	1	150	30,959	2,311	7	88	4	29	1
	1,500 to 3,000	9	11	NA	150	46,439	99	<1	11	11	NA	NA
	0 to 3,000	24,671	2	<1	150	92,878	17,853	19	599	3	67	<1
Northwestern Volcanics	0 to 50	1,304	3	<1	217	1,598	171	11	9	5	<1	<1
	50 to 500	9,063	2	<1	241	14,384	4,633	32	263	6	7	<1
	500 to 1,500	1,487	1	<1	213	31,964	4,314	13	117	3	7	<1
	1,500 to 3,000	104	2	NA	272	47,946	713	1	22	3	NA	NA
	0 to 3,000	11,958	2	<1	234	95,891	9,832	10	411	4	14	<1
Western Mountain Ranges	0 to 50	2,672	2	<1	150	2,096	312	15	13	4	2	1
	50 to 500	8,042	3	<1	153	18,868	5,018	27	438	9	23	<1
	500 to 1,500	336	9	2	194	41,929	1,375	3	161	12	44	3
	1,500 to 3,000	42	60	19	3,014	62,894	296	<1	165	56	44	15
	0 to 3,000	11,092	3	<1	153	125,788	7,001	6	776	11	113	2

Table 4. Summary of observed brackish and highly saline groundwater in brackish groundwater regions of the United States.—Continued

[Grid cells are categorized as “fresh,” “brackish,” or “highly saline” based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization “fresh” cells could also contain unobserved brackish or highly saline groundwater, “brackish” cells could also contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and “highly saline” cells could also contain observed or unobserved fresh and/or brackish groundwater. <, less than; NA, brackish or highly saline groundwater not observed in listed depth interval of the brackish groundwater region]

Brackish groundwater region (fig. 7)	Depth interval, in feet below land surface	Statistics for sampled wells				Total observed and unobserved volume, in cubic miles	Estimated grid cell volume represented by sampled wells[1]					
							Fresh, brackish, and highly saline groundwater[2]		Brackish groundwater		Highly saline groundwater	
		Number of sampled wells	Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median dissolved-solids concentration, in milligrams per liter		Volume, in cubic miles	Observed volume, as a percentage of total volume	Volume, in cubic miles	Observed volume, in percent	Volume, in cubic miles	Observed volume, in percent
Brackish groundwater regions—Continued												
Alaska	0 to 50	567	2	NA	150	5,512	47	1	3	6	NA	NA
	50 to 500	1,120	4	<1	164	49,610	569	1	76	13	16	3
	500 to 1,500	18	17	6	181	110,245	80	<1	22	27	7	9
	1,500 to 3,000	1	NA	NA	937	165,368	11	<1	NA	NA	NA	NA
	0 to 3,000	1,706	4	<1	159	330,735	707	<1	100	14	24	3
Hawaii	0 to 50	21	57	19	1,912	61	4	7	2	60	1	20
	50 to 500	184	14	2	305	548	201	37	53	26	10	5
	500 to 1,500	119	8	3	177	1,218	322	26	51	16	7	2
	1,500 to 3,000	13	NA	NA	155	1,827	88	5	NA	NA	NA	NA
	0 to 3,000	337	14	3	272	3,653	614	17	106	17	18	3
U.S. Territories; Puerto Rico	0 to 50	172	27	9	621	33	20	61	6	30	3	13
	50 to 500	536	13	2	456	294	211	72	72	34	20	9
	500 to 1,500	15	20	NA	293	654	80	12	22	27	NA	NA
	1,500 to 3,000	9	33	NA	435	981	55	6	33	60	NA	NA
	0 to 3,000	732	16	3	478	1,961	366	19	133	36	22	6
U.S. Territories; U.S. Virgin Islands	0 to 50	43	86	12	1,464	1	2	100	1	50	1	50
	50 to 500	136	79	4	1,416	11	39	100	33	83	7	17
	500 to 1,500	2	50	NA	1,540	25	15	59	7	50	NA	NA
	0 to 1,500	181	81	6	1,450	38	56	100	41	73	8	14

[1] Volumes include air, water, and rock occupied in the subsurface to 3,000 feet below land surface. Volumes are computed based on grid cell dimensions and on well construction and sample information associated with each grid cell. Estimates reported here reflect grid cell volumes only for areas where well observations are available.

[2] In some cases estimated volumes exceed total observed and unobserved volumes because of imperfect agreement between region boundaries and the edge of the model grid.

subsurface materials observed to contain BGW; and the usable volume is likely to be substantially less than this when considering the economic, legal, cultural, and environmental consequences that can be associated with extracting groundwater. Our approach also assumes that if some BGW is observed in a grid cell, then all groundwater in the cell is brackish, which may overestimate its occurrence volumetrically. In addition, groundwater storage properties vary spatially, and, in some areas, <1 percent of the total volume may contain extractable BGW. As a final consideration, no matter how estimated, it must be kept in mind that the volume of BGW observed likely represents only a fraction of the total amount available because 85 percent of the Nation's subsurface lacks directly observed groundwater based on the data.

Although large uncertainties are associated with the amount of BGW actually available, the potential for BGW to serve as a substantial water resource to the United States can still be assessed at a coarse scale. Suppose, hypothetically and conservatively, that the extractable BGW represents only 1 percent of the grid cell volume that contains BGW. This would be equivalent to nearly 890 mi^3, or about 3.0 billion acre-feet of water. To put this volume in perspective, water use estimates for 2010 indicate that about 3.7 million acre-feet per year of saline water and 85 million acre-feet per year of fresh groundwater were used in the United States (Maupin and others, 2014); thus, a conservative low estimate for the volume of BGW available is more than 800 times the amount of saline groundwater used each year and more than 35 times the amount of fresh groundwater used. Consequently, it is reasonable to consider BGW to be a substantial water resource available for potential use by the Nation. In addition, highly saline groundwater may be viable for some uses, and BGW not observed in this assessment likely represents an even larger water resource than the amount observed. This topic is discussed in more detail in the "Predicting Brackish Groundwater Occurrence and Distribution" section. Despite the potential for BGW use, this assessment does not evaluate the potential for BGW to be replenished if the resource is developed, examine the effects of extracting and treating BGW on the surrounding environment, or take into account legal considerations for developing BGW. These factors also would affect the potential for the resource to be developed.

BGW was identified in every State except New Hampshire and Rhode Island within the uppermost 3,000 ft below land surface (fig. 9). States along the Atlantic coast have the most extensive coverage by observations; however, groundwater in these States is largely freshwater, and little BGW occurs except along the coastline. Other notable areas with extensive BGW are in Florida, eastern Ohio, West Virginia, Kentucky, western Pennsylvania, western New York, central Michigan, southern Illinois, northwestern and southern Iowa, northwestern Missouri, west-central Alabama, southern Mississippi, eastern and western Colorado, south-central and southeastern New Mexico, southwestern and northeastern Arizona, large parts of Utah, northwestern Nevada, and central and southeastern California.

The maximum observed dissolved-solids concentration in groundwater across most of the Nation tends to be similar over distances of many tens of miles, if not hundreds of miles (fig. 9). This similarity indicates that the predominant hydrologic and geologic factors controlling dissolved-solids concentrations also vary at a similar scale and helps to validate the use of the 6.2-mi lateral grid cell dimensions. In New York, for example, maximum observed dissolved-solids concentrations for grid cells in the 50- to 500-ft-below land surface depth interval are largely less than or equal to 500 mg/L, except for an east-west band of grid cells that exists in the central latitudes of the State. The central part of that band mostly has maximum observed dissolved-solids concentrations of 1,000 to 3,000 mg/L, and that area is fringed by grid cells with concentrations of 500 to 1,000 mg/L. Similarly, for the same depth interval in central Texas, there is a core area with maximum observed dissolved-solids concentrations of 3,000 to 10,000 mg/L, which is flanked by several cells in the 1,000 to 3,000-mg/L range, and on the fringe are grid cells mostly in the 500 to 1,000-mg/L range. Details of the hydrologic and geologic factors affecting dissolved-solids concentrations and generating spatial patterns such as the ones noted here are described in more detail in the "Regional-Scale and Aquifer-Scale Brackish Groundwater" section.

In general, dissolved-solids concentrations are higher and saline groundwater is observed more frequently at greater depths below land surface (table 4). Across the United States, for example, about 73 percent of the grid cells with an observation in the 1,500- to 3,000-ft below land surface depth interval yielded brackish or highly saline groundwater. In contrast, only about 23 percent of the grid cells in the <50-ft below land surface depth interval had brackish or highly saline groundwater. Similarly, dissolved-solids concentrations tend to increase with well-screen depth; for example, the median dissolved-solids concentration observed across the United States is 334 mg/L for all wells completed in the <50-ft below land surface depth interval and 3,692 mg/L for all wells completed in the 1,500- to 3,000-ft below land surface depth interval. Maps of the maximum observed dissolved-solids concentration also show the general trend of increasing and a higher frequency of saline groundwater occurrence with increased depth; for example, the map for the 1,500- to 3,000-ft below land surface depth interval (fig. 9*D*) shows a much greater frequency of cells with maximum observed dissolved-solids concentrations of >3,000 mg/L than the map for the 50- to 500-ft below land surface depth interval (fig. 9*B*).

The observed minimum depth to BGW was determined on the basis of the maximum observed dissolved-solids concentration data available for the four depth intervals of grid cells (fig. 10). Although dissolved-solids concentrations generally increase with depth, in some areas BGW is not observed above the highly saline groundwater. For this reason, depth to highly saline groundwater is shown on the map if BGW is not present. This map provides a concise visual summary of the observed spatial distribution of BGW (fig. 10); however, it does not include as much information on spatial

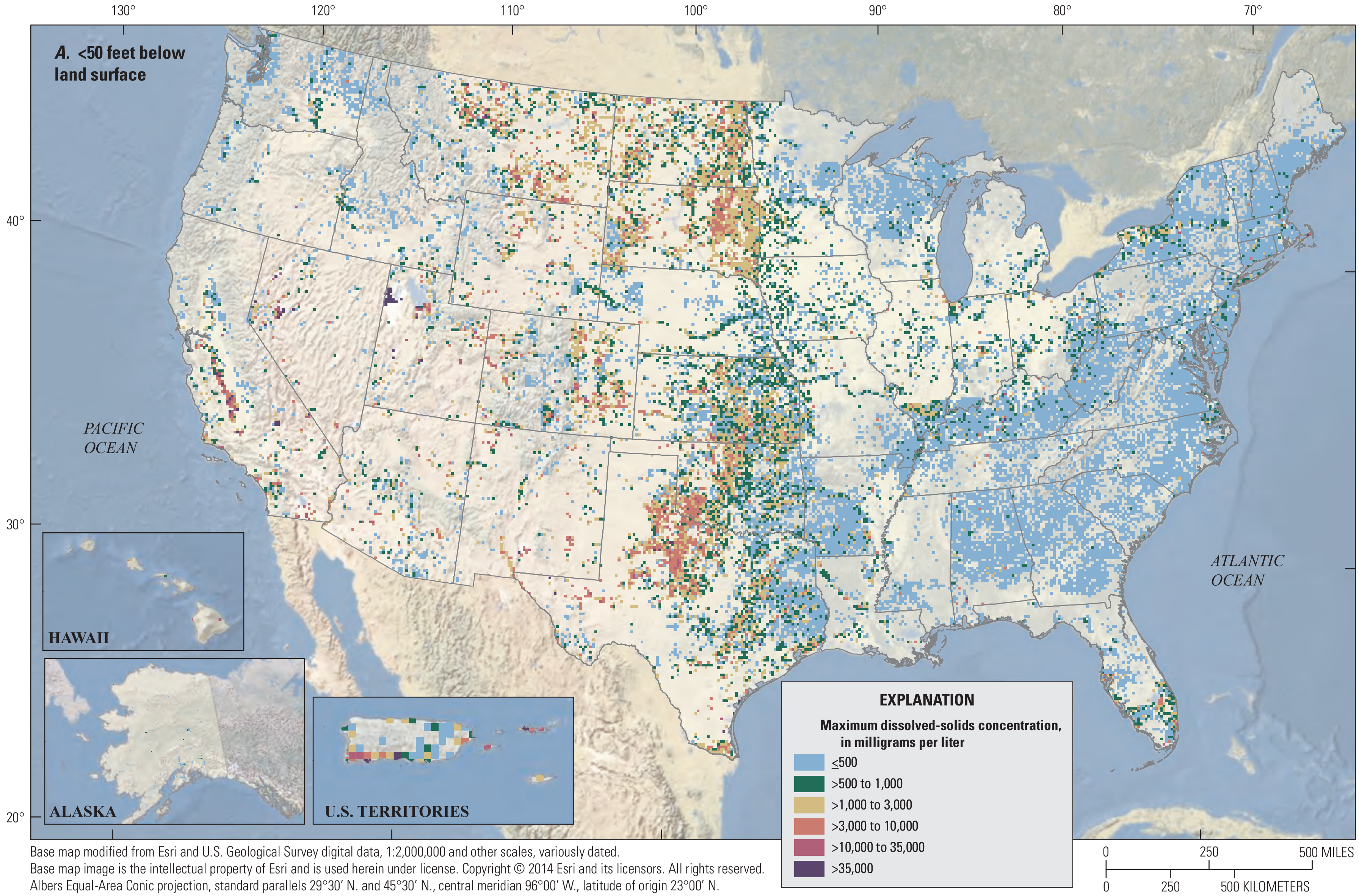

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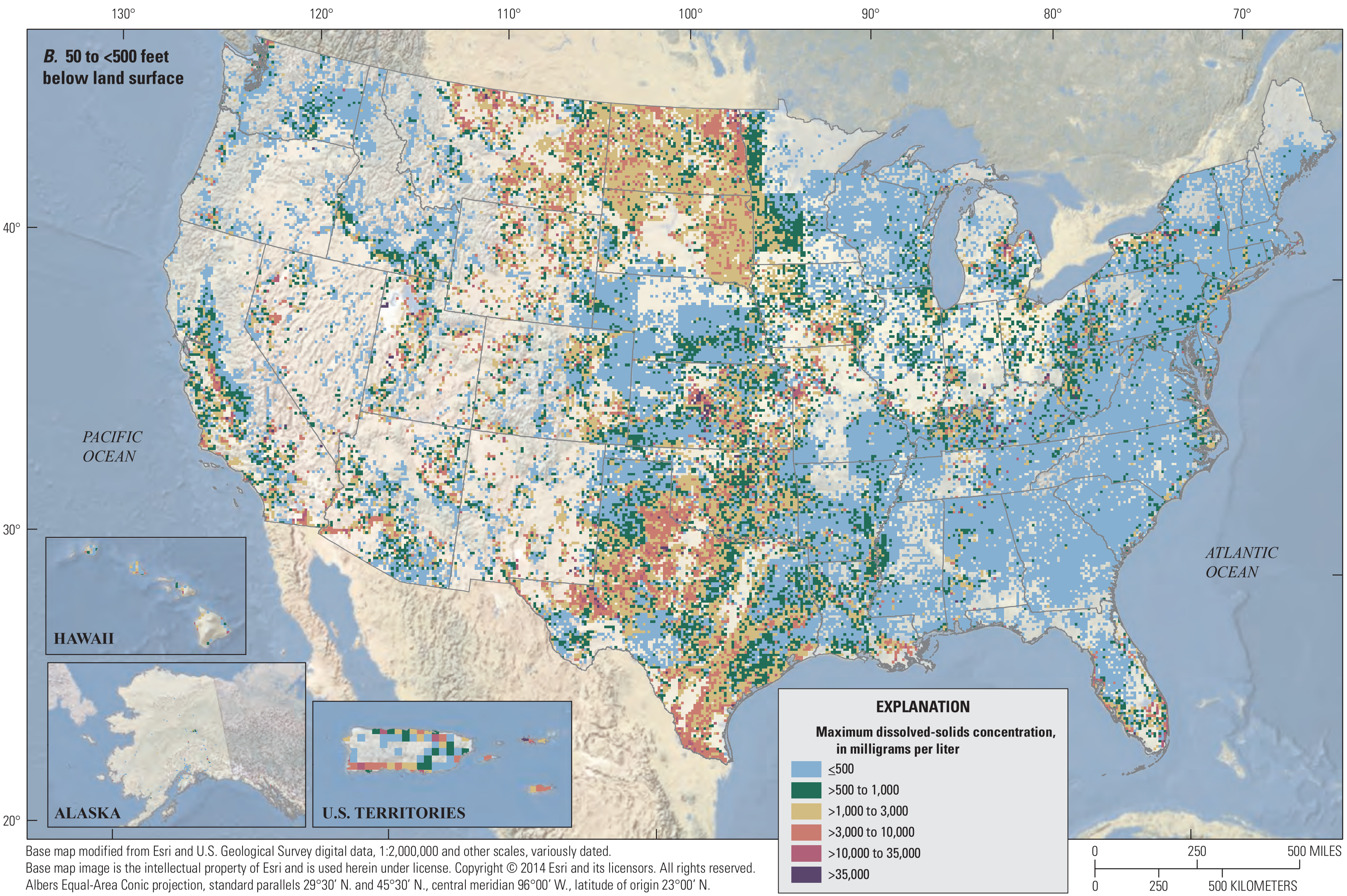
Figure 9. Maximum dissolved-solids concentrations observed in the United States and selected U.S. territories. *A*, depths less than (<) 50 feet below land surface; *B*, depths 50 to <500 feet below land surface; *C*, depths 500 to <1,500 feet below land surface; and *D*, depths 1,500 to 3,000 feet below land surface. Large versions of these maps are available at https://doi.org/10.3133/pp1833.



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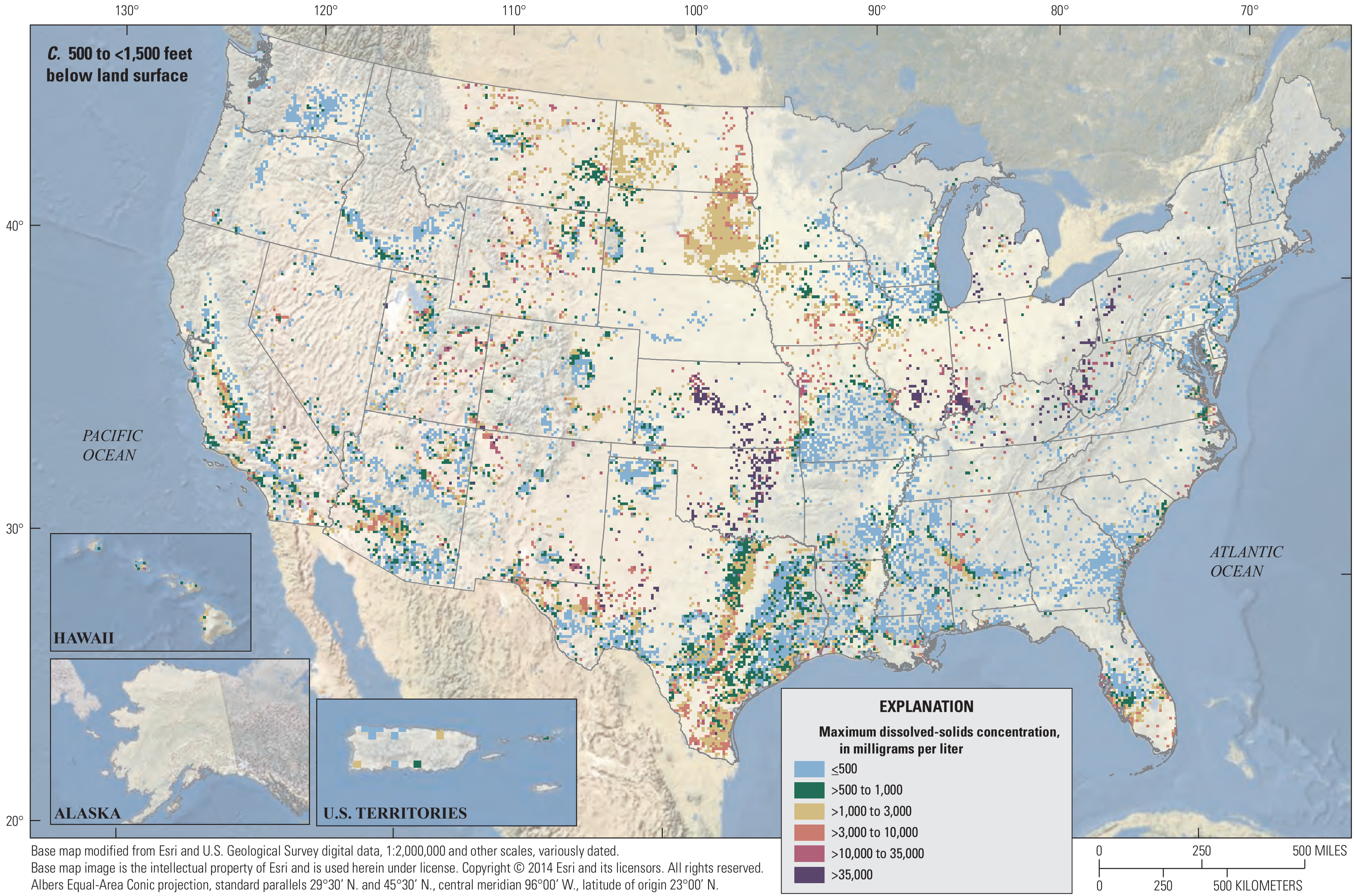

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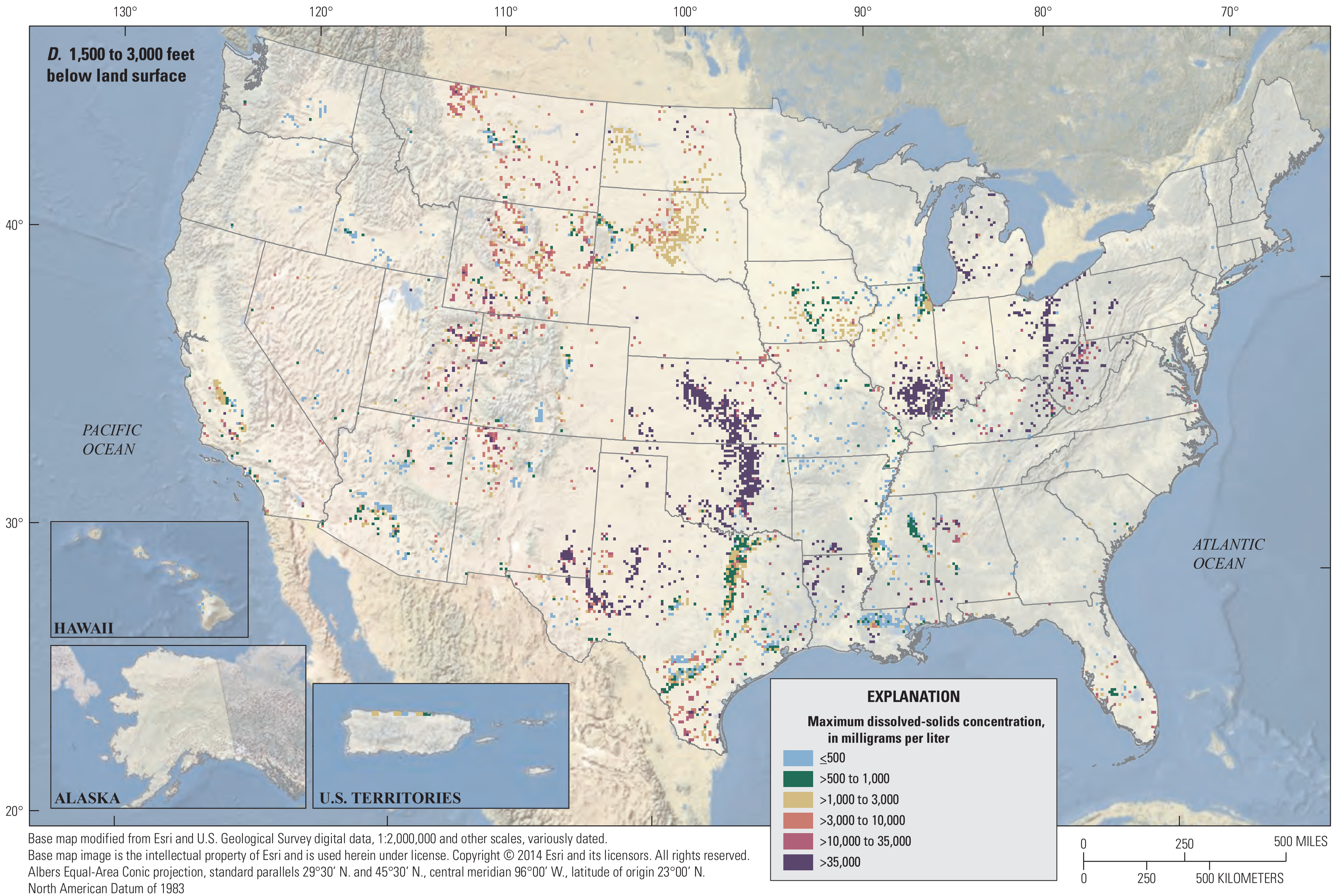

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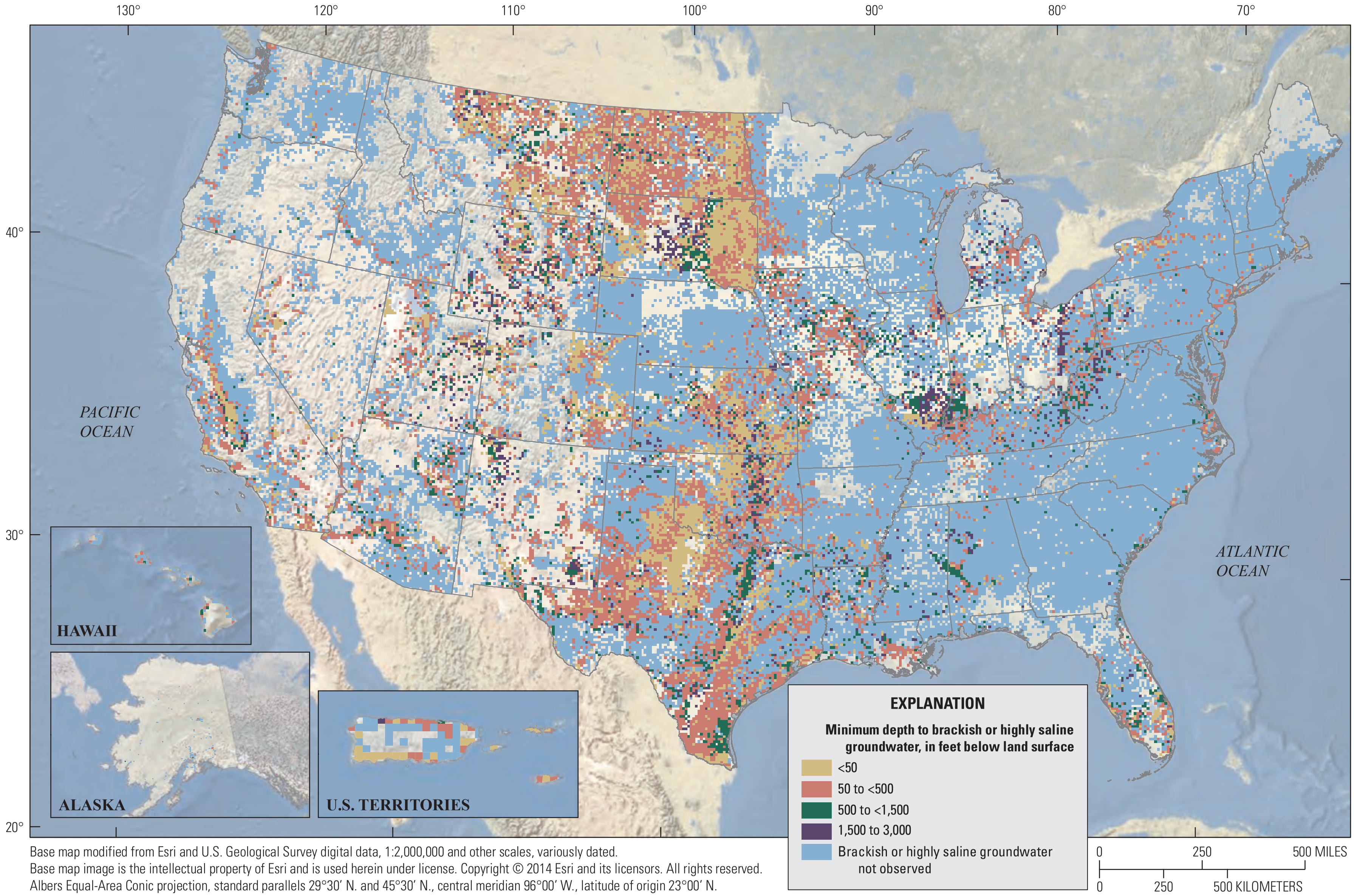

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Figure 10. Observed minimum depth to brackish or highly saline groundwater in the United States and selected U.S. territories. A large version of this map is available at https://doi.org/10.3133/pp1833.

variations in dissolved-solids concentration as do the maps of dissolved-solids concentrations shown in figure 9. Much of the observed occurrence of BGW is in a wide band across the central United States that starts in the north in Montana and North Dakota and extends south down to Texas and Louisiana. Gradual lateral transitions in the depth to BGW are present in several large areas within the central band containing this water resource.

Overall, the observed minimum depth to BGW (fig. 10) is similar to that shown in Feth (1965a, pl. 1); however, there are two notable differences. The largest areal differences result from differences in methods of map construction. In this assessment, observed and interpolated conditions are presented separately. Feth (1965a) used hydrogeologic knowledge to manually interpolate conditions between observation points and drew boundaries of BGW areas to their conceived extent rather than to their observed extent. Differences because of these separate approaches to map construction are extensive across the Coastal Plains and Eastern Midcontinent regions and also apparent in parts of the Western Midcontinent region (see the “Regional-Scale and Aquifer-Scale Brackish Groundwater” section). Several small areal differences also exist between the two maps as a result of this assessment’s reporting of results at a higher spatial resolution than the results of Feth (1965a) and filling in spatial gaps as a result of having about 50 additional years of data.

Estimated Occurrence of Brackish Groundwater

The occurrence of BGW is associated with processes such as dissolution of minerals in the saturated and unsaturated zones, mixing with geologic (connate) seawater or brine, intrusion of modern coastal seawater, leaching from saline soils, or contamination from road salt, brine from oil and gas wells, or other sources related to human activity. These processes are affected by characteristics such as groundwater flow rates and hydraulic connection among various water sources or sinks. In addition, climate conditions can affect the occurrence of BGW in shallow systems. In areas where potential evaporation is greater than precipitation, groundwater recharge and movement through the aquifer is minimal, causing salts to accumulate in soils. Large rainstorms or irrigation resulting in groundwater recharge can then move those salts into shallow groundwater.

To determine relations between dissolved-solids concentrations and hydrogeologic processes and characteristics and to subsequently estimate the occurrence of BGW where geochemistry data were not available, a regression analysis approach was used. In this analysis, measured dissolved-solids concentrations in groundwater across the contiguous United States were related to variables that may affect dissolved-solids concentrations (table 3). The strongest single predictor variable associated with increased dissolved-solids concentrations is the natural logarithm of well depth [ln(*depth*)]. Geologic variables, individually and collectively, also are dominant predictors in the model. The second strongest single predictor is the presence of evaporites (halite, gypsum and anhydrite, or both) buried at depth. Behind this in predictive strength come a variety of ecoregions and mapped geologic units based on where they crop out on the land surface (King and Beikman, 1974; Schruben and others, 1998); some ecoregions and geologic units are strong positive predictive variables associated with greater dissolved-solids concentrations, and some geologic units are strong negative predictive variables associated with lower dissolved-solids concentrations.

Principal aquifers can be strong negative predictors. In the model, the principal aquifers that are strong negative predictors are associated with less of an increase in dissolved-solids concentrations with depth than are areas outside of these principal aquifers. Strong negative predictors are individual interaction terms between various principal aquifers and ln(*depth*), indicating that fresher water tends to be present at greater depths within these aquifers. Although the relation between dissolved solids and depth is lessened within these principal aquifers, they can still contain substantial amounts of brackish water. The EPA level III ecoregions, which are regions that have similar climate, geology, and soils, can serve as either positive or negative predictors of dissolved-solids concentrations. The groundwater base-flow index is also a strong negative predictor, indicating that a greater flushing of groundwater is associated with lower dissolved-solids concentrations. Other variables tested in the model are presented in table 3. Final predictor variables, model coefficients, and associated statistics are provided in appendix 1.

Exceedance probability maps (fig. 11) were generated for specified depths (500, 1,500, and 3,000 ft below land surface) and exceedance probabilities (1,000, 3,000, and 10,000 mg/L). An exceedance probability of 1,000 mg/L was selected because that is the lowest dissolved-solids concentration limit of the brackish salinity range, the exceedance probability of 10,000 mg/L was selected because that is the upper limit of the brackish salinity range, and the exceedance probability of 3,000 mg/L represents a practical limitation where the potential use of the BGW becomes more restrictive or expensive.

Although about 47,000 mi^3 of observed grid cell volume contained BGW at depths between 500 and 3,000 ft below land surface according to data compiled for this assessment (table 4), the actual volume likely to contain such water is much larger. Model predictions for the occurrence of BGW in this same depth interval suggest that the volume containing BGW may be as much as 14 times larger (593,000 mi^3) than what was observed with data compiled for this assessment; however, it is unknown whether all areas predicted to contain BGW have enough groundwater to yield usable amounts.

Three of the probability maps shown along the diagonal from upper left to lower right in figure 11 display similar patterns. The areas with ancient basins with evaporite deposits appear in orange or red, indicating a higher probability of exceeding a certain threshold concentration. In general, at these locations, groundwater is slightly saline (1,000 to 3,000 mg/L of dissolved solids) at 500 ft below land

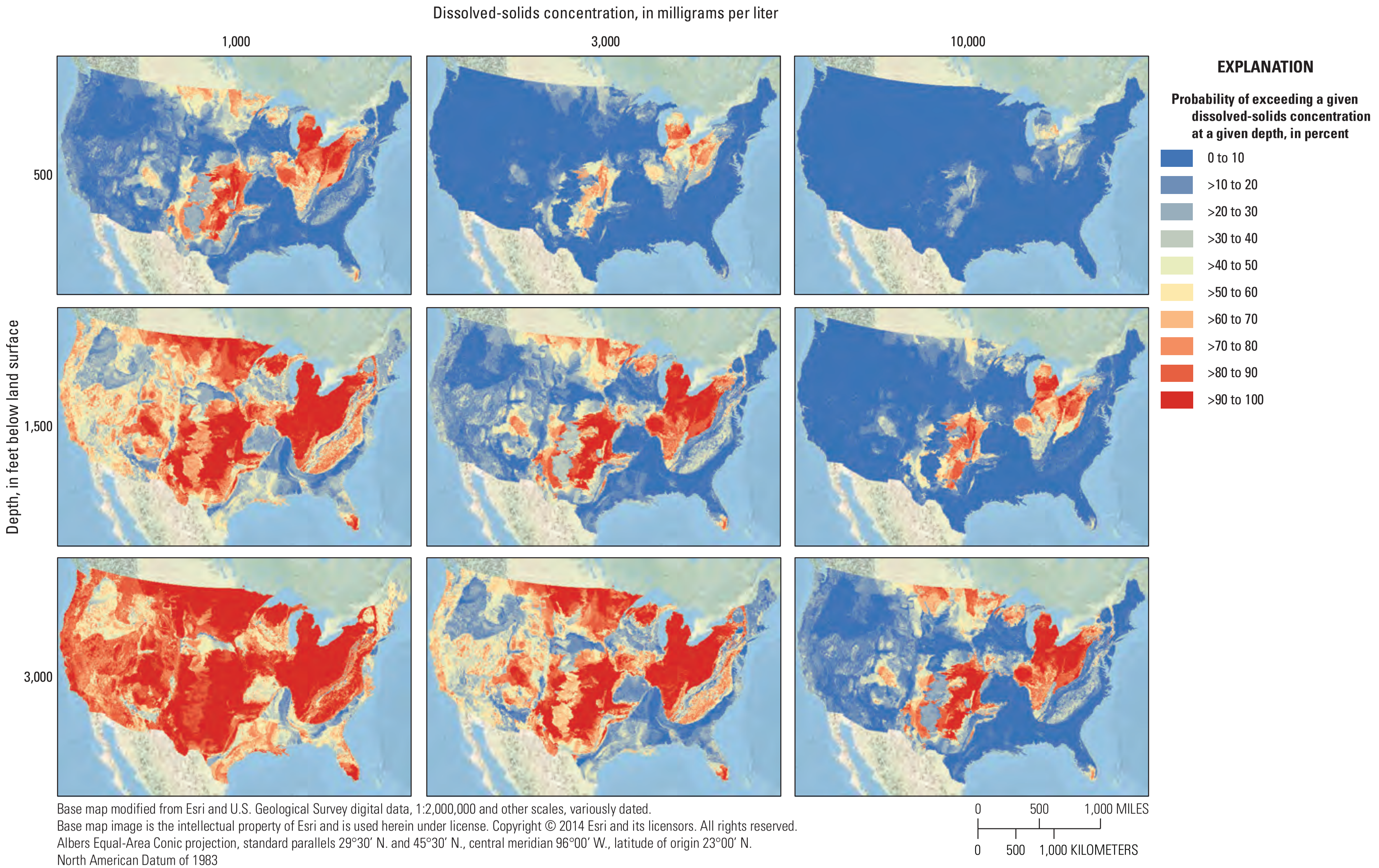

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Figure 11. Predicted percentage probabilities of exceeding dissolved-solids concentrations of 1,000, 3,000, and 10,000 milligrams per liter for depths 500, 1,500, and 3,000 feet below land surface in the conterminous United States.

surface, transitioning into a higher salinity BGW (3,000 to 10,000 mg/L of dissolved solids) by 1,500 ft below land surface, and exceeding the brackish salinity range (>10,000 mg/L of dissolved solids) by 3,000 ft below land surface.

Three model runs developed to estimate the probability of exceeding 1,000 mg/L of dissolved solids at 500, 1,000, and 3,000 ft below land surface were used to compute a generalized map of predicted depth to BGW below land surface (fig. 12) for comparison with work completed by Feth (1965a). Depths to BGW are based on a 50-percent or greater probability of exceeding a dissolved-solids concentration of 1,000 mg/L at specified depth; for example, where there is a 50-percent or greater probability of exceeding 1,000 mg/L of dissolved solids at 500 ft below land surface, the map is shaded in light blue (fig. 12), indicating that BGW is likely to exist at 500 ft below land surface. Where there is a <50-percent probability of finding BGW at 3,000 ft below land surface, the map is shaded in dark blue, indicating that BGW is not likely to be present even at 3,000 ft below land surface.

When compared with the map of depth and distribution of mineralized waters by Feth (1965a, pl. 1), some major features of the predicted depth to BGW in figure 12 are in agreement and many minor features appear to differ. Differences are expected because the latest effort is based on a statistical evaluation of a much larger dataset that represents 50 additional years of data collection. The newer dataset and analysis provide a more comprehensive look into the BGW resource. Both maps indicate that BGW in most of the large area of the Mississippi embayment, the Chesapeake Bay area and coastal areas of Delaware and New Jersey, and much of South Dakota and Nebraska is deeper than 1,000 ft below land surface (fig. 12). Similarly, the areas identified as <500 ft below land surface to BGW by this assessment are also largely in agreement with the Feth (1965a, pl. 1) map. Exceptions include the northern part of the Michigan Peninsula, western New York State, and northern Pennsylvania, where the Feth (1965a, pl. 1) map indicates that it is deep to BGW on the basis of "analogy with other areas where geologic and hydrologic conditions are comparable." Another exception includes the southern part of California's Central Valley, where the Feth (1965a, pl. 1) map indicates that it is shallow to BGW, but the analysis in this report indicates deeper BGW. This is likely because wells with shallow depths (<500 ft below land surface) were not included in the model. Some large areas, such as New England, where BGW is not shown on the Feth (1965a) maps, are consistent with figure 12. Many smaller areas appear differently between the two maps.

Geochemical Characteristics of Brackish Groundwater

The chemical composition of BGW is spatially variable because it depends in part on local geologic, hydrologic, and climatic conditions. Chemical variations in BGW are important because different water types can impose different limitations on potential BGW use and treatment options (McMahon and others, 2015). This section illustrates how geochemical information compiled for this assessment might be used to guide national-scale resource evaluations to improve understanding of BGW resources and their limitations. Results included in this report, however, are by no means comprehensive, and further analysis could be done with geochemical data to better understand factors that affect specific BGW uses.

This section includes a discussion of (1) the spatial distribution of four major geochemical groups, determined using cluster analysis, and (2) the geochemical characteristics affecting water use and treatment. Geochemical analyses were completed with a subset of the major-ions dataset, consisting of about 15,000 saline groundwater samples (dissolved-solids concentration of ≥1,000 mg/L). Water samples with dissolved-solids concentrations greater than the brackish salinity range were included for these analyses because they can provide insight about processes responsible for creating BGW in the subsurface. In addition, BGW produced by dilution of more saline waters may preserve some of the characteristics of the higher saline waters, such as solute ratios. Dilution can happen in the subsurface or when highly saline water is blended with freshwater after extraction to lower the salinity before use. Characteristics affecting water use and treatment are presented within the context of the geochemical groups. Although geochemical analyses included samples with dissolved-solids concentrations greater than the brackish range, analytical results typically were used to make conclusions about BGW, which composes about 97 percent of the samples used for the analyses.

Geochemical Groups

Cluster analysis was used to classify saline groundwater into four geochemical groups on the basis of major cations, major anions, silica, dissolved-solids concentration, pH, and temperature. The geochemical characteristics of each group are discussed here to help assess factors that might affect water use or treatment. Geochemical characteristics distinguishing each group are summarized as follows (fig. 13):

1. *Group 1.*—The water in group 1 is a sodium-bicarbonate-dominant water type (sodium is the dominant cation and bicarbonate is the dominant anion) in which sulfate contributes about one-third of the total anion equivalents and has a mean pH of 8.1, which is higher than that of other geochemical groups. The mean dissolved-solids concentration is 1,810 mg/L. In total, 3,597 wells (24 percent) are included in this geochemical group.

2. *Group 2.*—The water in group 2 is a calcium-sulfate-dominant water type in which sodium and magnesium each contribute about one-quarter of the total cation equivalents. The mean dissolved-solids concentration is 2,460 mg/L. In total, 5,257 wells (35 percent) are included in this geochemical group.

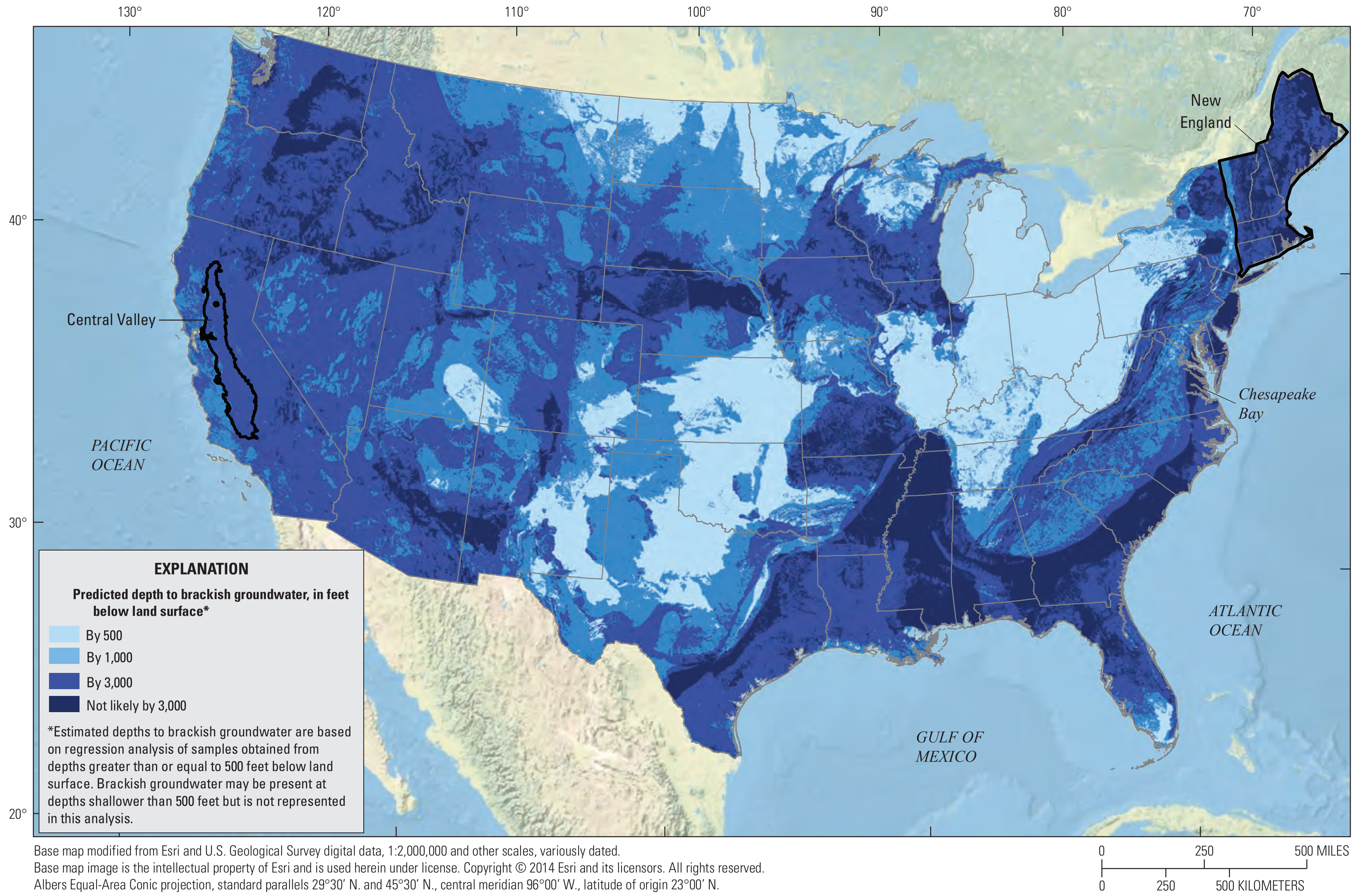

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Figure 12. Predicted depth to brackish groundwater in the conterminous United States. Depths range from 500 to 3,000 feet below land surface.

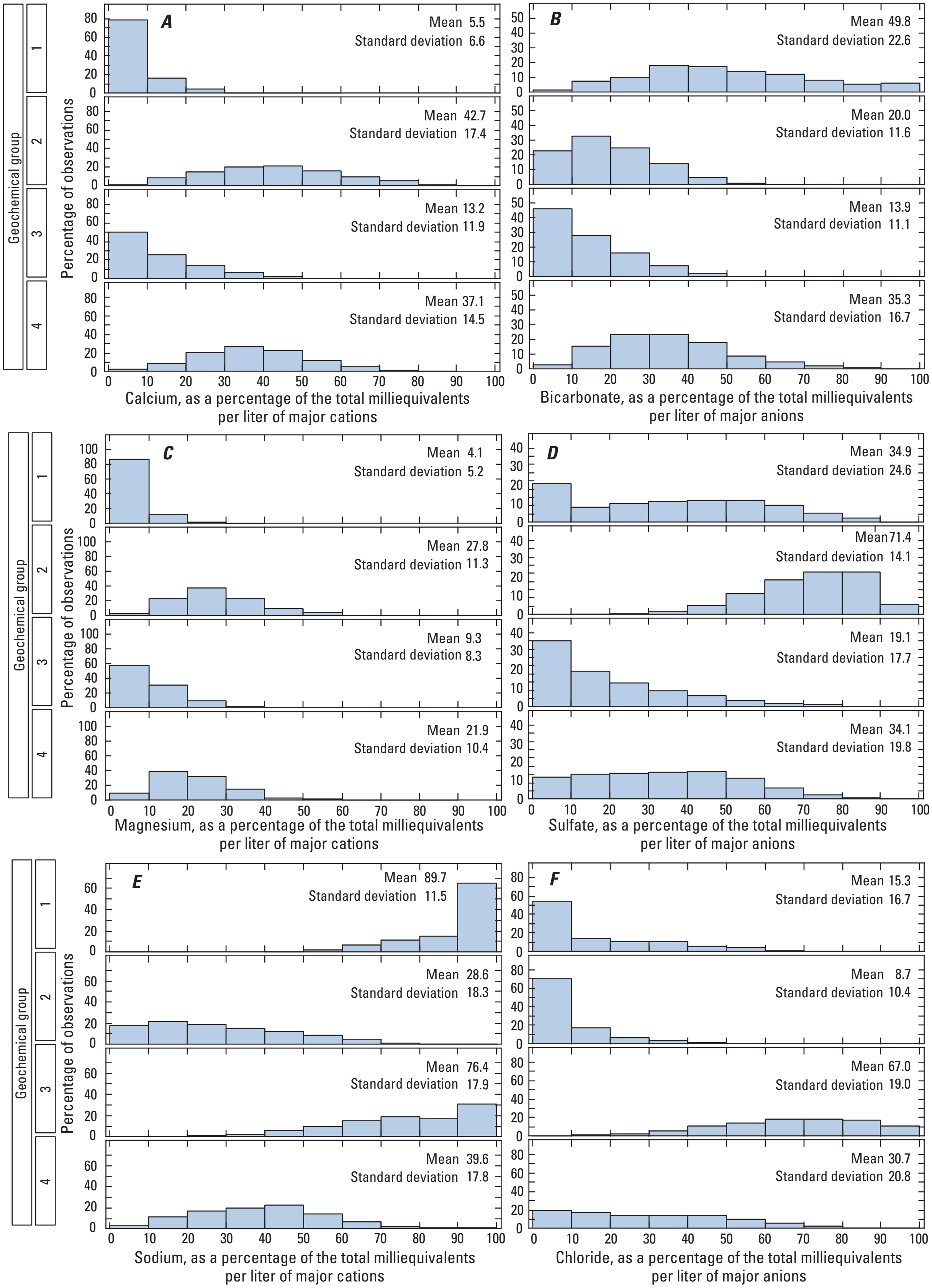
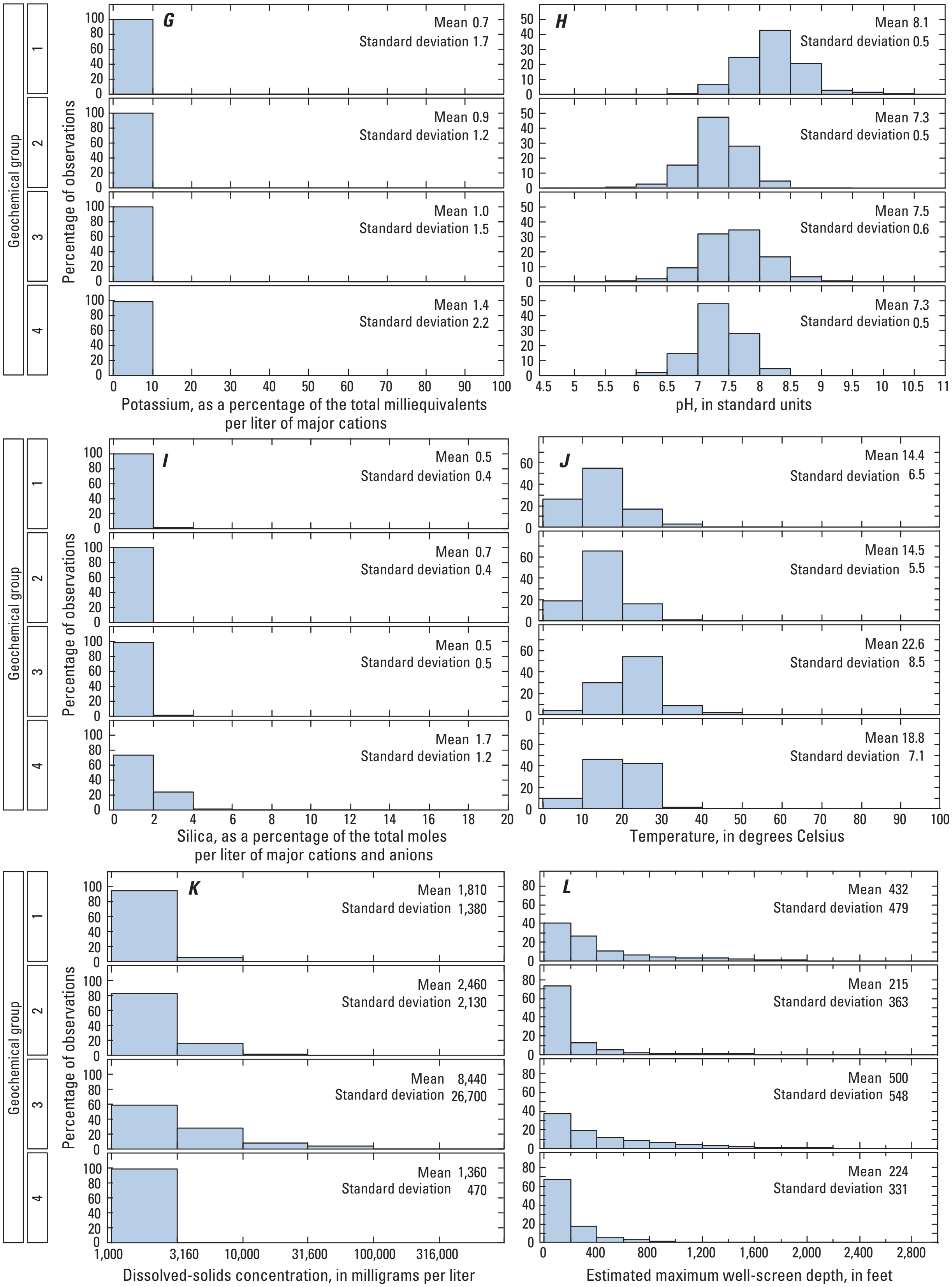


Figure 13. Statistical distributions for characteristics of the four geochemical groups determined using cluster analysis. *A*, calcium; *B*, bicarbonate; *C*, magnesium; *D*, sulfate; *E*, sodium; *F*, chloride; *G*, potassium; *H*, pH; *I*, silica; *J*, temperature; *K*, dissolved-solids concentration; *L*, estimated maximum well-screen depth.



Note: Dissolved-solids concentrations were log-transformed (base 10) in the cluster analysis

Note: Estimated maximum well-screen depth was not used in the cluster analysis

Figure 13. Statistical distributions for characteristics of the four geochemical groups determined using cluster analysis. *A*, calcium; *B*, bicarbonate; *C*, magnesium; *D*, sulfate; *E*, sodium; *F*, chloride; *G*, potassium; *H*, pH; *I*, silica; *J*, temperature; *K*, dissolved-solids concentration; *L*, estimated maximum well-screen depth.—Continued

3. *Group 3.*—The water in group 3 is a sodium-chloride-dominant water type that has a high mean dissolved-solids concentration (8,440 mg/L) relative to other geochemical groups. In total, 3,484 wells (23 percent) are included in this geochemical group.

4. *Group 4.*—The water in group 4 is a mixture of dominant cations and anions that has a low mean dissolved-solids concentration (1,360 mg/L) and a high percentage of silica (1.7 percent of the total moles of cations and anions) relative to other geochemical groups. In total, 2,641 wells (18 percent) are included in this geochemical group.

Although the groups were considered in the cluster analysis on the basis of sodium and potassium combined, the histograms in figure 13 indicate that potassium individually constitutes only about 1 percent of the cation equivalents. Well construction data were not used to develop the groups in the cluster analysis; however, the histograms in figure 13 show that samples in group 3 are more often from wells screened deeper than wells producing samples in other groups; consequently, group 3 samples have warmer temperatures and higher dissolved-solids concentrations.

Though each of the four geochemical groups is present across the United States, there are some notable patterns in their distribution (fig. 14). Extensive areas with group 1 waters are in North Dakota, South Dakota, eastern Montana, Wyoming, and farther south in Texas. Widespread areas with group 2 waters exist in most of the central United States. Large areas with group 3 waters exist in the southern parts of Texas, Louisiana, and Florida; in southwestern Arizona and western Utah; along the North Dakota-Minnesota border; and in central Michigan; group 3 waters tend to exist in aquifers that contain halite or connate marine water or that are affected by seawater intrusion. Extensive areas with group 4 waters exist in southern Idaho, eastern Washington, western parts of California, central Arizona, western Utah, southwestern New Mexico, the central United States, and southern Texas. Although dissolved-solids concentrations typically are vertically stratified, available data indicate that geochemical characteristics of water in some areas are similar in adjacent depth layers; however, lack of data makes it difficult to assess variability with depth in large parts of the Nation. The distribution of groups in the shallowest observed saline groundwater, which is of interest because this part of the resource is often more economical to develop than deeper parts, is shown in figure 15.

Maps of the spatial distribution of the four geochemical groups show that across many parts of the Nation, at the scale of this analysis, saline groundwater chemistry tends to be similar over distances of many tens of miles, and in some areas hundreds of miles (fig. 14). This similarity indicates that the predominant hydrologic and geologic factors controlling saline groundwater chemistry also vary at similar spatial scales. As noted by McMahon and others (2015), major-ion concentrations can vary by orders of magnitude for BGW, but patterns become evident when geochemical characteristics are evaluated within the context of specific geologic settings and hydrologic and geochemical processes; for example, high concentrations of dissolved sulfate in BGW are caused by pyrite oxidation in some geologic settings and by gypsum or anhydrite dissolution in others. Further examination of regional patterns of geochemistry with consideration for hydrogeologic settings and processes may be useful for distinguishing various causes of saline groundwater occurrences and could provide a basis for extrapolating results to areas with no data.

In addition to offering insights about origins and chemical characteristics that can affect use and treatment of water, geochemical type can affect the relation between dissolved-solids concentrations and specific conductance. In many investigations, such as this one, dissolved-solids concentrations are estimated from specific conductance values for samples lacking direct dissolved-solids measurements; however, it is important to recognize that there are shortcomings in using specific conductance to estimate dissolved-solids concentrations, including measurement or conversion error and varying specific conductance with specific ions or ion association (appendix 3). Sodium and chloride are the dominant ions in highly saline waters because dissolution of chloride salts generally is required to generate dissolved-solids concentrations much greater than that of seawater (McMahon and others, 2015); consequently, the sodium-chloride-dominant group 3 waters have less variety in major ions and greater linearity between dissolved-solids concentrations and specific conductance than the other water types (fig. 3–1). Compared with group 3, the other groups tend to have less linearity in the relation between dissolved-solids concentrations and specific conductance because mixtures of other solutes cause variability in the relation (appendix 3).

Geochemical Characteristics Affecting Water Use and Treatment

The chemical composition of BGW can differ depending on the geologic setting and associated hydrologic and geochemical processes interacting with it. This diversity can greatly affect the feasibility and cost of using BGW in different parts of the United States, depending on local or regional water use needs. Specific chemical constituents in BGW can exceed standards for a particular use (table 5), and it is essential to identify their occurrence and related processes to determine if BGW must undergo specialized treatment beyond what is required to reduce overall salt content. Other chemical characteristics can limit BGW use as well; for example, a high salinity or sodium-adsorption ratio can limit untreated BGW use for irrigation, and mineral precipitation (scaling) can impede BGW conveyance, storage, and treatment. Understanding the distributions of such geochemical characteristics could help predict constituents of concern that limit certain water uses or help determine water uses that are favorable in areas where water chemistry data are not available.

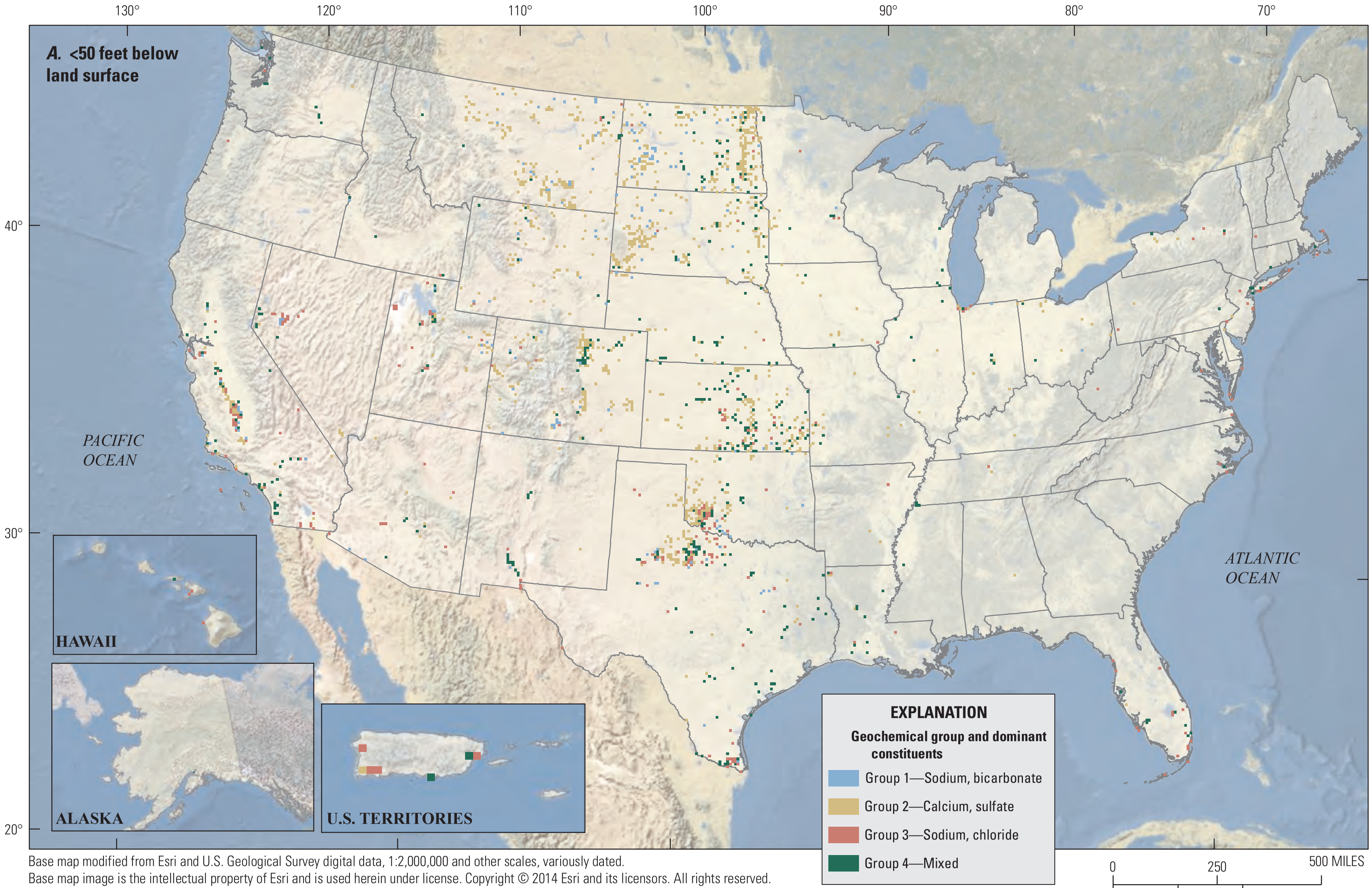


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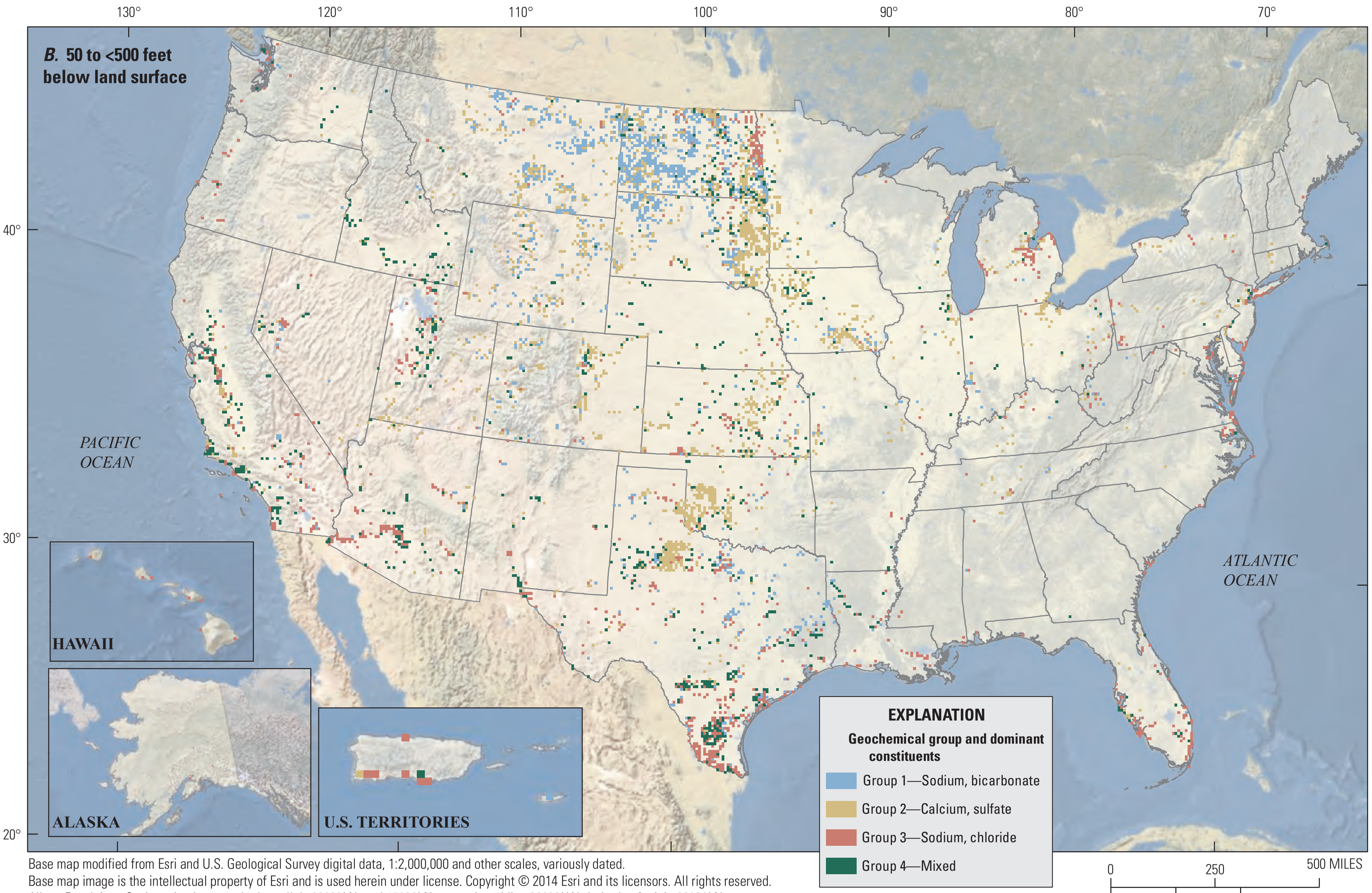
Figure 14. Distribution of geochemical groups at depths, in feet below land surface, in the United States and selected U.S. territories. *A*, less than (<) 50 feet; *B*, 50 to <500 feet; *C*, 500 to <1,500 feet; *D*, 1,500 to 3,000 feet. Large versions of these maps are available at https://doi.org/10.3133/pp1833.



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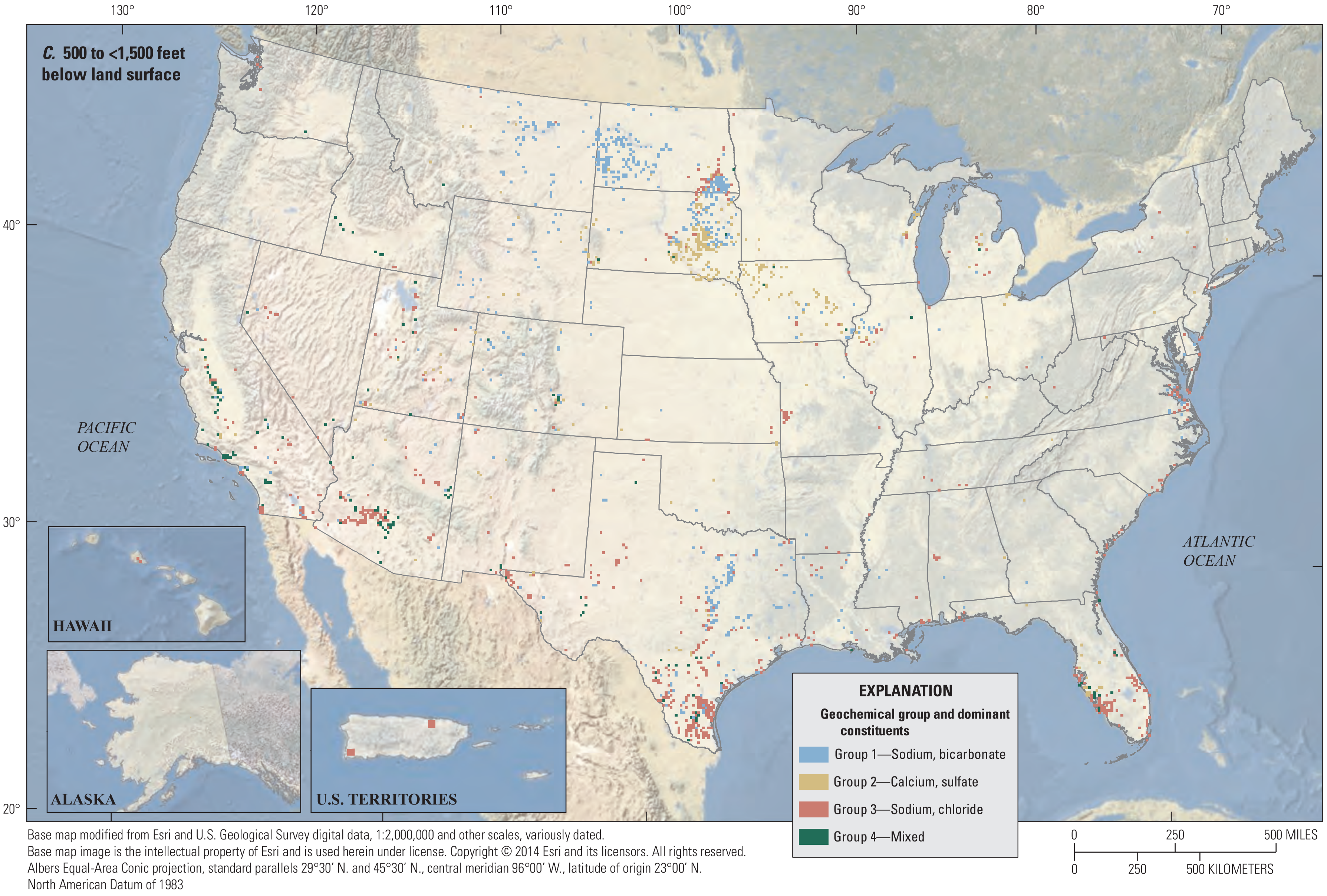

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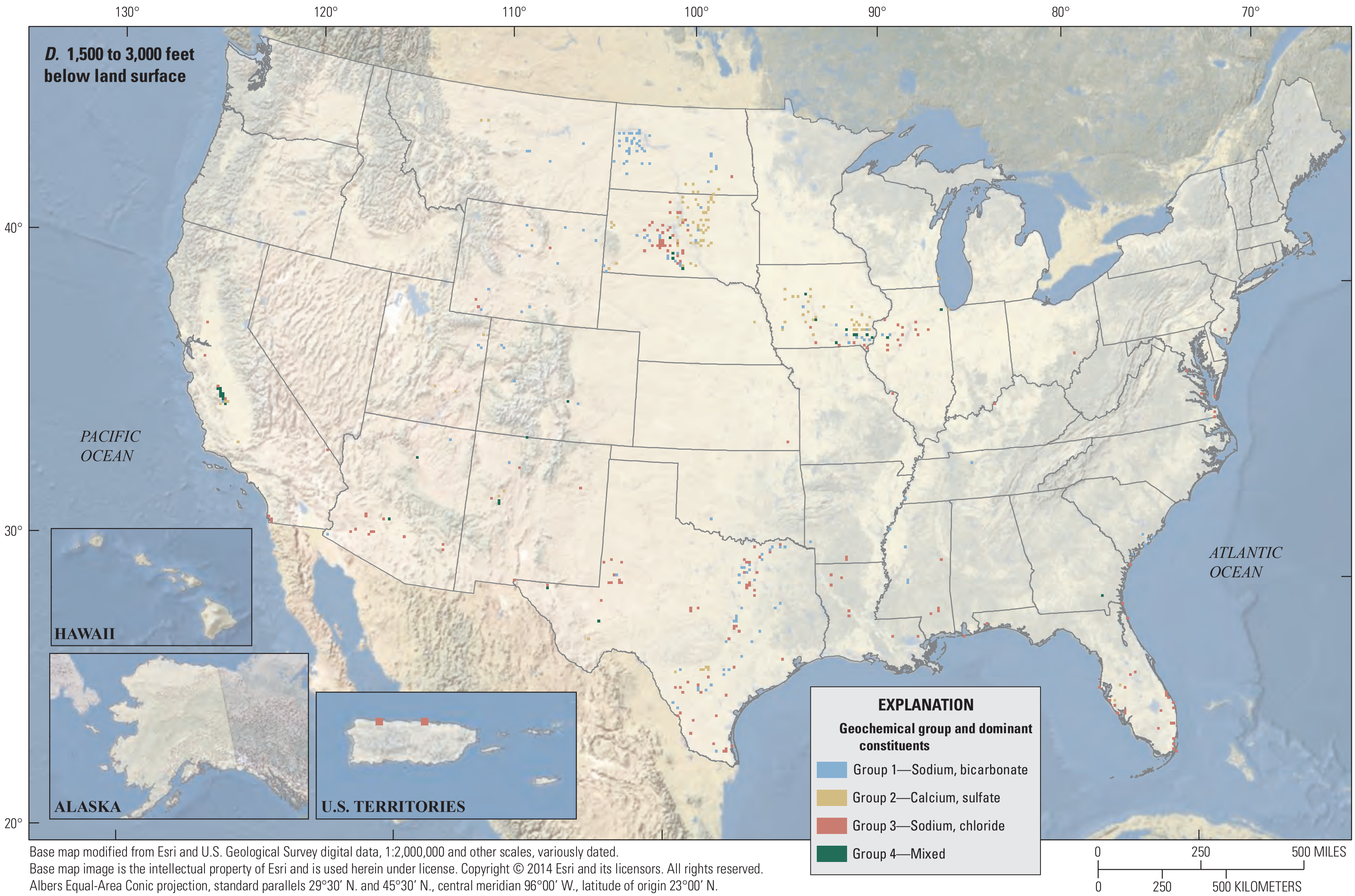

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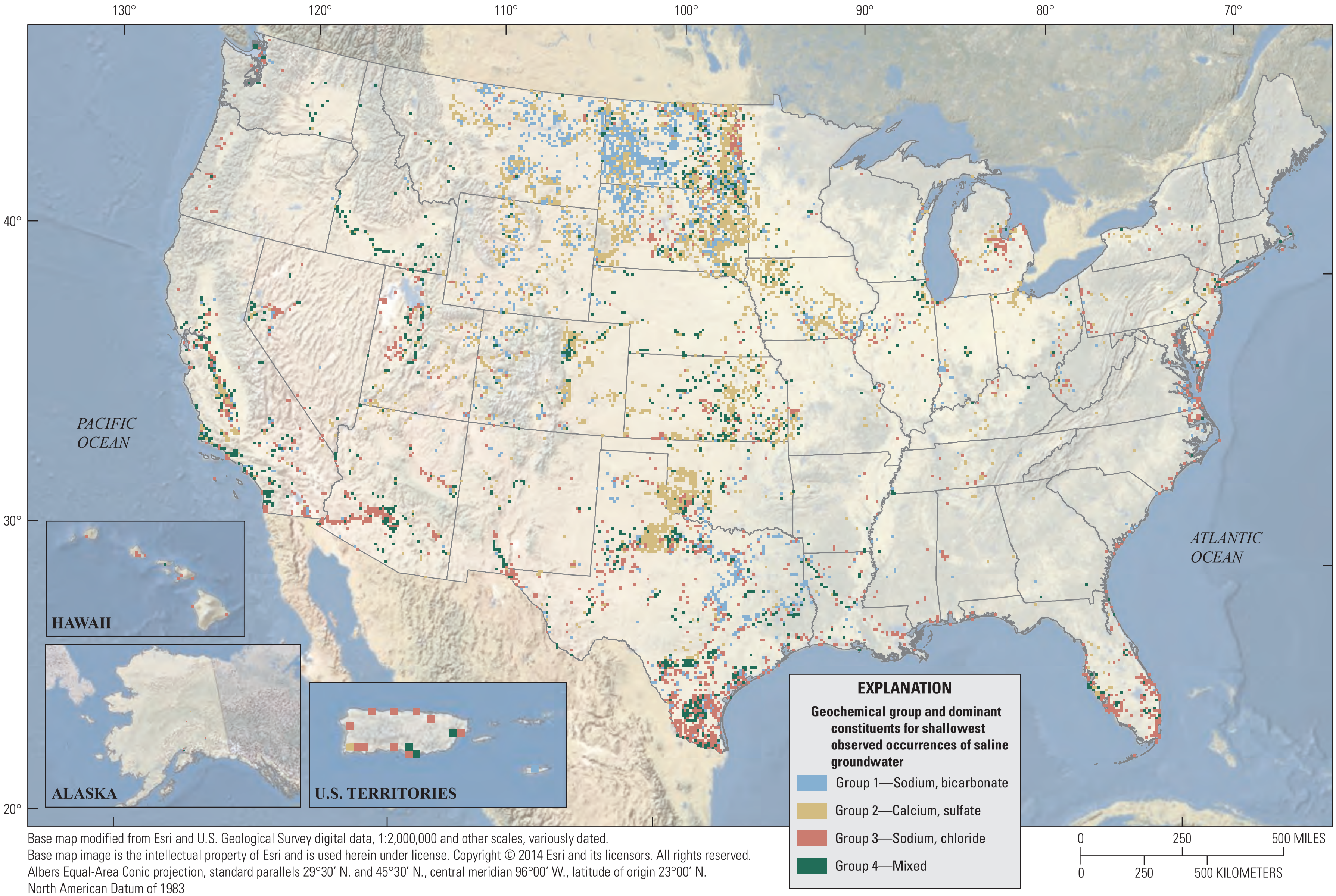

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Figure 15. Distribution of geochemical groups for the shallowest observed occurrences of saline groundwater in the United States and selected U.S. territories. A large version of this map is available at https://doi.org/10.3133/pp1833.

Table 5. Percentage of brackish groundwater samples that exceed selected water-quality standards for drinking water, livestock, and irrigation uses, by geochemical group.

[µg/L, microgram per liter; mg/L, milligram per liter]

Geochemical group	Chemical constituent and water-quality standard for drinking water[1]									
	Arsenic 10 µg/L		Fluoride 4 mg/L		Nitrate 10 mg/L		Selenium 50 µg/L		Uranium 30 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Group 1	1,054	11	3,206	14	2,223	2	1,041	3	508	8
Group 2	2,758	4	3,655	1	2,321	13	2,742	5	1,932	18
Group 3	1,711	19	2,935	6	1,724	7	1,359	3	801	14
Group 4	1,402	14	2,000	2	1,216	17	1,175	1	857	8
Total	6,925	11	11,796	6	7,484	9	6,317	3	4,098	14

Geochemical group	Chemical constituent and water-quality standard for livestock[2]											
	Arsenic 50 µg/L		Barium 10 mg/L		Boron 5 mg/L		Fluoride 2 mg/L		Iron 2 mg/L		Selenium 50 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Group 1	1,054	5	963	0	2,588	4	3,206	35	3,303	7	1,041	2
Group 2	2,758	1	2,511	0	3,872	2	3,655	10	4,977	18	2,742	5
Group 3	1,711	6	1,555	0	2,366	14	2,935	22	2,969	14	1,359	3
Group 4	1,402	2	1,256	0	1,991	1	2,000	7	2,343	14	1,175	1
Total	6,925	3	6,285	0	10,817	5	11,796	19	13,592	14	6,317	3

Table 5. Percentage of brackish groundwater samples that exceed selected water-quality standards for drinking water, livestock, and irrigation uses, by geochemical group.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter]

Geochemical group	Chemical constituent and water-quality standard for irrigation[3]									
	Arsenic 10 µg/L		Boron 750 µg/L		Fluoride 1 mg/L		Iron 5 mg/L		Selenium 20 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Group 1	1,054	11	2,588	57	3,206	58	3,303	6	1,041	3
Group 2	2,758	4	3,872	27	3,655	25	4,977	9	2,742	8
Group 3	1,711	19	2,366	70	2,935	43	2,969	9	1,359	7
Group 4	1,402	13	1,991	24	2,000	18	2,343	7	1,175	4
Total	6,925	11	10,817	44	11,796	37	13,592	7	6,317	6

[1]Primary drinking-water standards from U.S. Environmental Protection Agency (2016).

[2]Livestock water-quality standards are for cattle (Schroeder, 2015); however, tolerance may vary by animal species.

[3]Irrigation water-quality standards from Fipps (2003).

Human and Livestock Drinking Water

In addition to limitations imposed by a high dissolved-solids concentration, specific chemical constituents can directly affect the use of untreated BGW for human and livestock consumption; concentrations of these constituents can vary among the geochemical groups. Constituents such as arsenic, uranium, nitrate, boron, barium, fluoride, strontium, and manganese can be toxic to humans or animals; several benchmarks for human or livestock drinking water were exceeded for such constituents (table 5). Arsenic is one of these constituents that is particularly difficult to remove during reverse osmosis treatment (Vinson and others, 2011), and posttreatment could be required for BGW that contains this constituent. Arsenic most commonly exceeded standards for human and livestock drinking water in group 3 waters (table 5), which are sodium-chloride-dominant waters associated with higher dissolved-solids concentrations, deeper wells, and warmer temperatures than the waters of the other groups (fig. 13). Group 2 water, a calcium-sulfate-dominated water that is associated with shallower wells than the waters of the other groups (fig. 13), is present across most of the central United States (fig. 14) and had the lowest percentage of benchmark exceedances for arsenic.

Nitrate is another constituent that can limit the usability of BGW. The median concentration of nitrate for samples in all four geochemical groups generally was low (0.23 mg/L as nitrogen) relative to the drinking-water maximum contaminant level of 10 mg/L as nitrogen. Group 4 samples had the highest median concentration of nitrate (1 mg/L as nitrogen), and as much as 17 percent of group 4 samples exceeded the 10 mg/L drinking-water benchmark (table 5). Group 4 waters also are associated with the lowest dissolved-solids concentrations, indicating that mixing with recently recharged groundwater containing anthropogenic sources of nitrate may be a process that affects the chemical composition of that geochemical group.

These are just two examples of constituents that affect the use of BGW for human and livestock consumption, but BGW samples exceeded human or livestock drinking-water standards for other selected constituents of concern (table 5). Further analysis of the data could explore occurrences of various toxic constituents relative to BGW origins, geologic settings, reduction-oxidation conditions, and other factors.

Irrigation

Another potential use of BGW is for irrigation of agricultural crops. Untreated BGW use for irrigation may be limited by dissolved-solids concentration, specific constituents that are toxic to plants, or the relative proportions of solutes that affect properties of soils. High salinity in the root zone increases the osmotic pressure of the soil solution and causes a decrease in the rate of water absorption by plants and in the availability of soil water, which in turn can affect plant growth, plant yield, and seed germination (Phocaides, 2007). The PHREEQC program was used to calculate the osmotic pressure for individual saline water samples within each geochemical group. Calculated osmotic pressure was correlated with dissolved solids and specific conductance, but the relation differed slightly among the geochemical groups, particularly for water in the brackish salinity range (fig. 16). Differences in the ranges of osmotic pressure among the four water groups resulted from varying total ion concentrations and relative abundances (Cochrane and Cochrane, 2005), providing another example of how variability in the chemical composition of BGW can potentially affect the usefulness of the resource. Osmotic pressure also can affect the cost and efficiency of BGW treatment by reverse osmosis, as is discussed in the "Potential for Mineral Scale Formation" section. To offset limitations caused by high salinity, BGW is sometimes blended with freshwater. This blending approach is most feasible in areas where fresh surface water is readily available for irrigation.

One chemical constituent that can limit the use of water for irrigation is boron. Boron has an irrigation standard of 750 micrograms per liter (µg/L; table 5) but is toxic to plants at concentrations as low as 600 µg/L (Phocaides, 2007). Group 3 waters had the highest percentage of samples (70 percent) with a boron concentration that exceeded the standard for irrigation water (table 5). This group is predominantly sodium-chloride water type and can be associated with geologic formations that were once inundated by seawater. Boron is difficult to remove by using reverse osmosis (Glueckstern and Priel, 2007), particularly in the form of boric acid, which is the dominant boron species according to PHREEQC speciation calculations. Group 3 waters also had the highest percentage of samples that exceeded irrigation standards for arsenic. Exceedances for fluoride were most common in group 1 waters, and selenium was most problematic for group 2 waters (table 5).

Whereas high salinity water can be damaging to crops, low salinity water tends to leach soluble minerals and salts, such as calcium, from surface soils (Ayers and Westcot, 1994). This leaching can cause soil particles to disperse and fill in pore spaces, thereby decreasing soil infiltration rates. Excessive sodium in irrigation water also promotes soil dispersion and structural breakdown, typically under conditions where concentrations of sodium exceed those of calcium by a factor of about three (Ayers and Westcot, 1994); calcium is beneficial

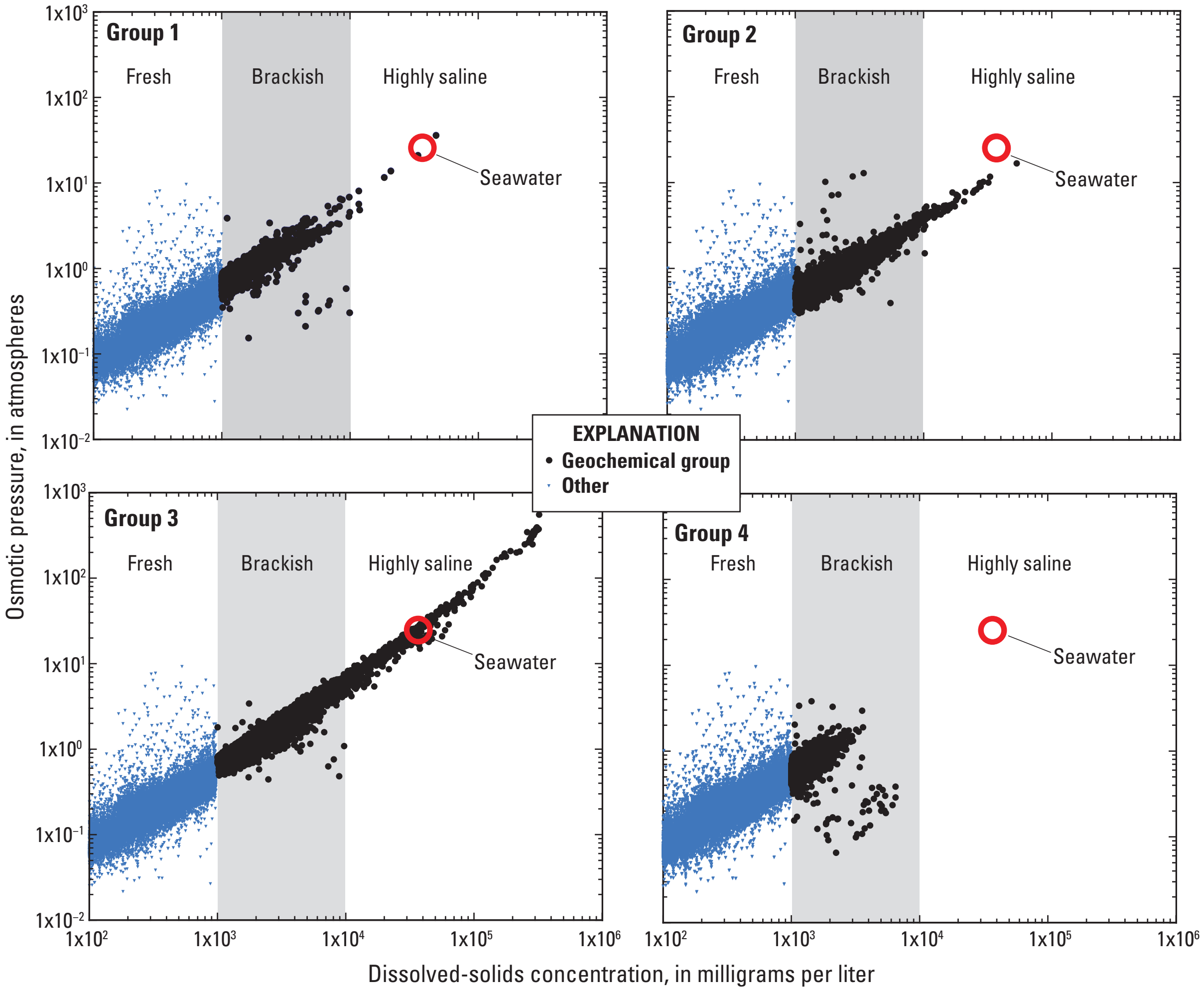


Figure 16. Osmotic pressure as a function of dissolved-solids concentration for the four geochemical groups and for other samples with dissolved-solids concentrations below 1,000 milligrams per liter.

because it counteracts the dispersing effects of sodium. Relatively high sodium content commonly results in greatly reduced infiltration rates because of soil dispersion and plugging and sealing of the surface soil pores, in much the same way as low-salinity water acts on soil. Problems associated with high-sodium water include soil crusting, poor seedling emergence, lack of aeration, and plant and root diseases (Wilcox, 1955).

The sodium-adsorption ratio, which was calculated by the PHREEQC program as described in appendix 2, is useful for assessing whether or not water infiltration rates through soil will be reduced or whether or not sodium will build up in the soil as a result of the composition of applied irrigation water. The sodium-adsorption ratio is typically not a problem in relatively saline water, but dilution through blending of BGW with freshwater would decrease specific conductance while potentially also decreasing the infiltration rate (fig. 17). The sodium-adsorption ratio-salinity diagram (fig. 17) is based on specific conductance (referred to along the *x*-axis as the “salinity hazard”) and the sodium-adsorption ratio (referred to along the *y*-axis as the “sodium hazard”) and commonly is used to determine the suitability of water for irrigation (Wilcox, 1955; Ayers and Westcot, 1994). The red lines indicate salinity hazard zones defined by Wilcox (1955) in which irrigation waters (1) can be used for irrigation on most crops (low), (2) can be used if waters are moderately leached (medium), (3) can be used if drainage is not restricted (high), or (4) cannot be used under ordinary conditions (very high).

As depicted by the black “reduction in infiltration rate” lines in figure 17, soil infiltration in waters with a low sodium-adsorption ratio will be slightly to moderately reduced for water with specific conductance values <500 µS/cm and severely reduced for water with specific conductance values <200 µS/cm; with increasing sodium-adsorption ratio, the plotted areas within the “reduction in infiltration rate” become larger (Ayers and Westcot, 1994). Although a greater salinity hazard is associated with higher specific conductance in this diagram, the sodium-adsorption ratio has less effect on reducing infiltration rates at higher specific conductance levels, and most of the groundwater samples studied would cause little or no reduction in rate of infiltration. Only group 1 and 3 water included a substantial part of samples that plot in the “slight to moderate reduction in infiltration rate” field, but the salinity hazard of these samples is high or very high; therefore, they are likely not suitable for irrigation without treatment or dilution. Even though different water types have widely varying sodium-adsorption ratios, the plots indicate that most BGW, if diluted, would not likely enter an area of the diagram where the sodium-adsorption ratio would be limiting.

Potential for Mineral Scale Formation

The geochemistry of BGW is important for understanding the limiting concentrations of constituents that could cause mineral precipitation (scaling), which could increase costs or exceed feasibility for conveyance, storage, use or treatment. Major ions are a fundamental control on mineral saturation states, a key geochemical characteristic for predicting scale formation during storage, conveyance, or treatment of BGW. Mineral scaling refers to the deposition or precipitation of minerals on a surface or membrane that stores, transmits, or filters water, which can impede flow. Corrosion can cause deterioration of metal surfaces but is less common with brackish water than with freshwater. Water treatment is commonly necessary to remove constituents that are related to scaling (Antony and others, 2011) or that exceed water use standards.

Reverse osmosis is the most common form of desalination treatment in the United States. The reverse osmosis systems include a thin, semipermeable barrier that transmits water under pressure while excluding solutes. For desalination through reverse osmosis, the applied pressure must exceed the osmotic pressure of the feedwater. The semipermeable membrane allows passage of water while retaining salts under the application of a driving force. The semipermeable membranes used for reverse osmosis have high salt-rejection properties. Higher dissolved-solids concentrations increase the pressure required for reverse osmosis (fig. 16). Water types with similar dissolved-solids concentrations may have slightly different osmotic pressures if they have different chemical compositions. Mineral scaling can increase substantially the pressure required for reverse osmosis, thus increasing energy and cost requirements for treatment. Without proper treatment of feedwater to reduce scaling potential, reverse osmosis systems can fail, so it is important to understand these problem constituents or oversaturated minerals and their relations to geochemical water types.

Mineral saturation indices were determined for calcite ($CaCO_3$), barite ($BaSO_4$), chalcedony (SiO_2), celestite ($SrSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$), and halite (NaCl) for saline groundwater samples (≥1,000 mg/L of dissolved solids). Mineral saturation indices indicate the thermodynamic potential for mineral precipitation on a scale in which 0 indicates equilibrium (no potential for precipitation), positive values indicate oversaturation (potential to precipitate), and negative values indicate undersaturation (potential to dissolve). Mineral saturation index values may not indicate actual amounts of phases that would precipitate; the extent of scaling will depend on a number of other factors including the optimal cross-flow rate and configuration of the membrane system (DeMichele and others, 2014).

Saline samples commonly were oversaturated with respect to calcite, barite, chalcedony, or all three constituents (table 6). Overall, calcite was oversaturated in the highest percentage of samples, followed by barite and then chalcedony. Most minerals show at least a slight increase in saturation index with increasing dissolved-solids concentration, but gypsum (fig. 18) and celestite showed marked increases. In addition, saturation index variation was much greater within the brackish salinity range than for higher dissolved-solids concentrations. A substantial fraction of samples from all four geochemical groups (48 to 74 percent) were oversaturated with respect to barite, particularly those from volcanic aquifers

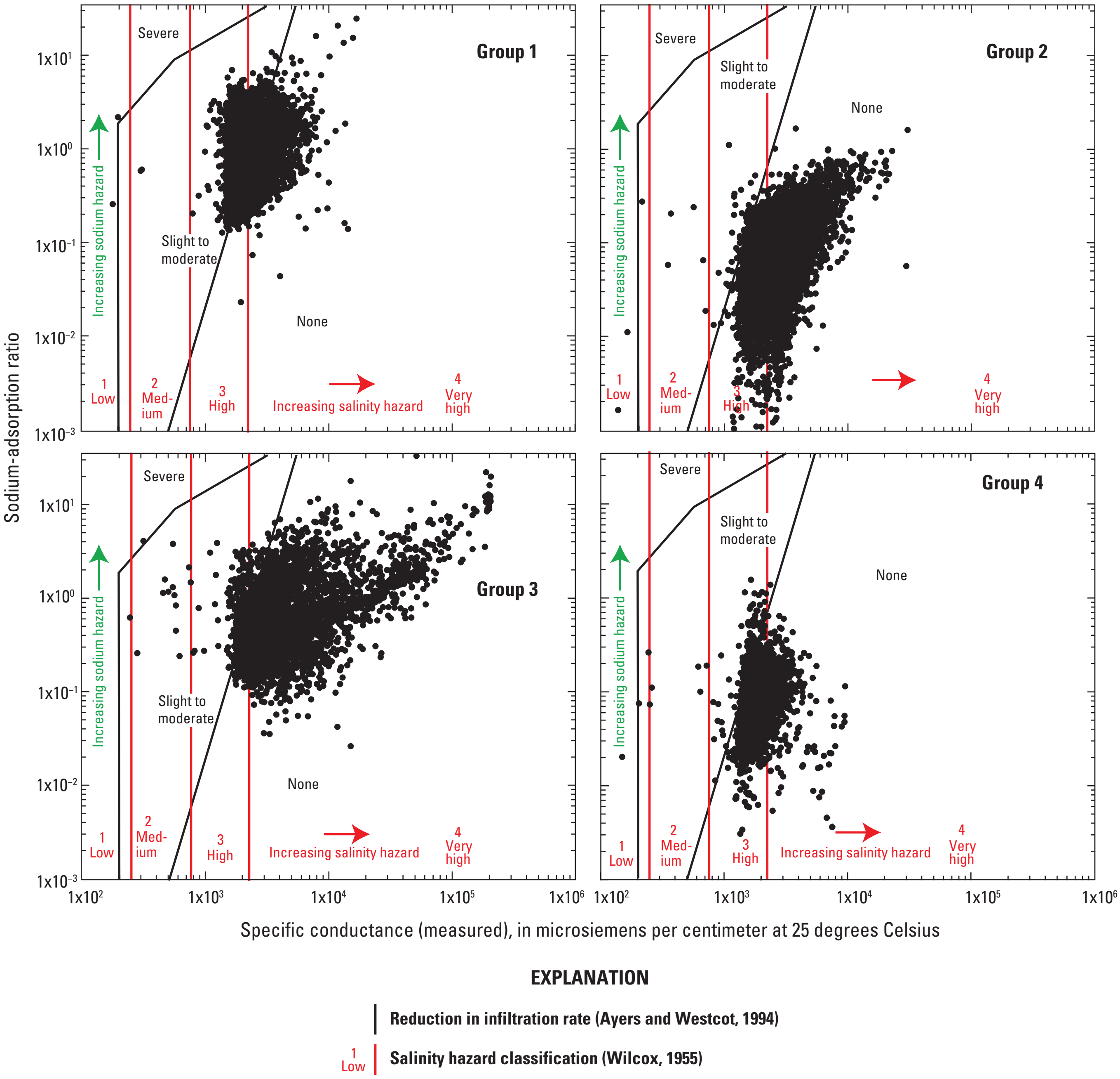


Figure 17. Measured specific conductance as a function of the sodium-adsorption ratio for the four geochemical groups plotted on a diagram showing the estimated reduction in infiltration rate of irrigation waters (from Ayers and Westcot, 1994) and zones of salinity hazard for crops (from Wilcox, 1955).

Table 6. Summary of mineral saturation indices for barite, calcite, celestite, chalcedony, gypsum, and halite and the Langelier saturation index for the four geochemical groups.

[Mineral saturation indices indicate the thermodynamic potential for mineral precipitation on a scale in which 0 indicates equilibrium (no potential for precipitation), positive values indicate oversaturation (potential to precipitate), and negative values indicate undersaturation (potential to dissolve). SI, saturation index; >, greater than; <, less than]

	Barite			Calcite			Celestite			Chalcedony		
Geochemical group	**Number of samples**	**Median SI**	**Samples with SI>0, in percent**	**Number of samples**	**Median SI**	**Samples with SI>0, in percent**	**Number of samples**	**Median SI**	**Samples with SI>0, in percent**	**Number of samples**	**Median SI**	**Samples with SI>0, in percent**
Group 1	956	–0.03	48	3,595	0.20	72	1,112	–1.9	<1	3,595	–0.11	33
Group 2	2,496	0.28	74	5,257	0.25	79	2,602	–0.63	4	5,257	0.02	52
Group 3	1,544	0.025	53	3,480	0.18	68	1,787	–1.2	3	3,480	0.02	52
Group 4	1,254	0.13	59	2,641	0.25	78	1,165	–1.5	1	2,641	0.29	81
Total	6,250	0.14	62	14,973	0.22	75	6,666	–1.1	3	14,973	0.03	53

	Gypsum			Halite			Langelier saturation index			
Geochemical group	**Number of samples**	**Median SI**	**Samples with SI>0, in percent**	**Number of samples**	**Median SI**	**Samples with SI>0, in percent**	**Number of samples**	**Median SI**	**Samples with SI<–1, in percent**	**Samples with SI>1, in percent**
Group 1	3,595	–2.0	0	3,595	–6.0	0	3,595	0.16	1	5
Group 2	5,257	–0.4	6	5,257	–6.7	0	5,257	0.28	2	5
Group 3	3,480	–1.4	2	3,480	–4.8	<1	3,480	0.14	4	4
Group 4	2,641	–1.0	0	2,641	–6.1	0	2,641	0.15	1	2
Total	14,973	–1.0	3	14,973	–6.0	<1	14,973	0.20	2	4

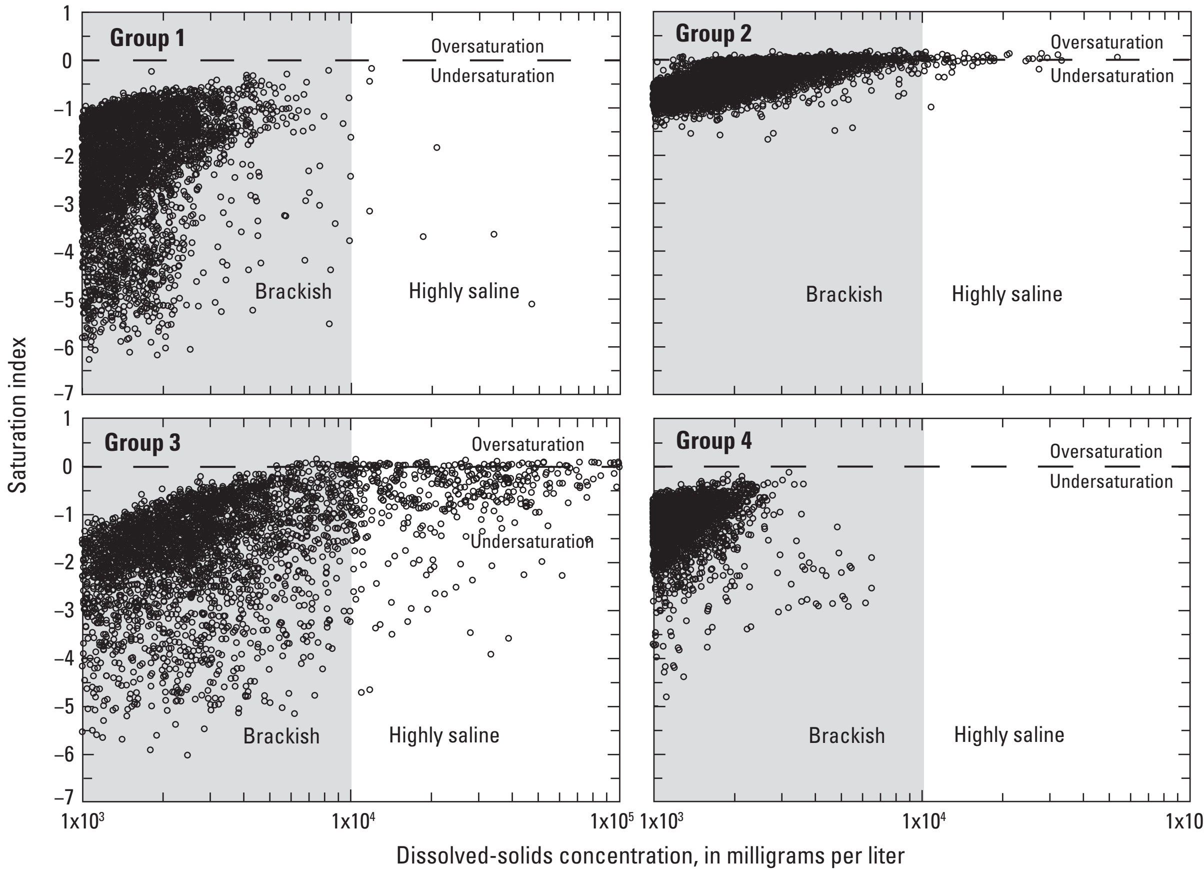


Figure 18. Saturation index as a function of dissolved solids for gypsum among the four geochemical groups.

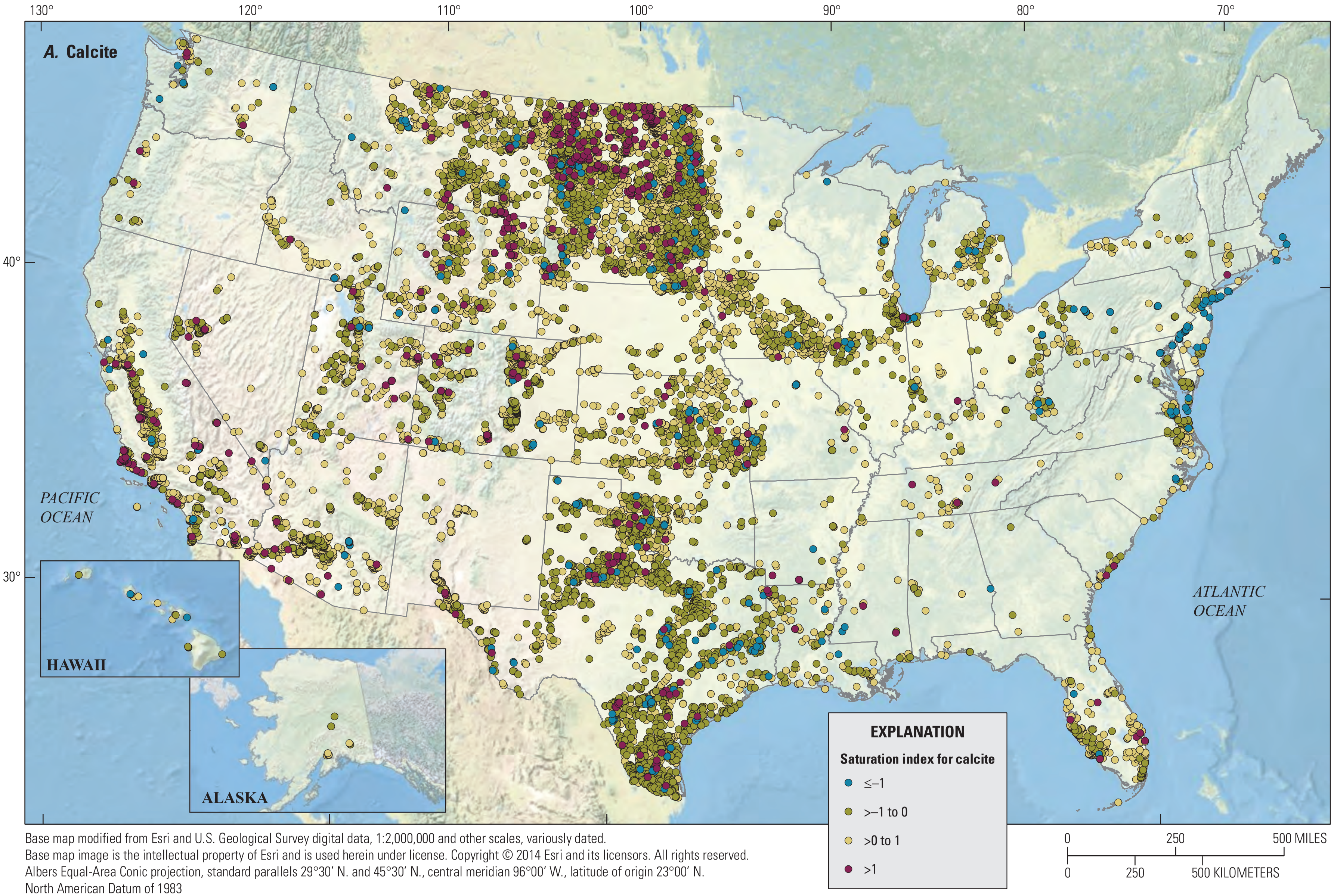
of the southwestern United States and unconsolidated aquifers in the northern Great Plains (McMahon and others, 2015).

Barite scaling is a costly problem for reverse osmosis treatment because flux decline and membrane damage are common in barite-saturated waters (Boerlage and others, 2002). The high percentage (81 percent) of samples in group 4 that were oversaturated with respect to chalcedony compared to other geochemical groups reflects the relatively high dissolved silica concentrations in these groundwaters (table 6). The removal of silica from water before reverse osmosis is difficult, and removal from the membrane after it forms a scale may not be possible (Koo and others, 2001). The saturation indices for calcite, chalcedony, and barite are depicted by colors on national-scale maps (fig. 19), indicating where these minerals could precipitate and result in problems for water treatment or other water uses.

The Langelier saturation index is another indicator of the degree of saturation of water with respect to calcite and is commonly used by the water-supply industry to determine potential for corrosion or scaling (Langelier, 1936). The Langelier saturation index represents the difference between the measured pH and the pH at saturation with respect to calcite and was calculated from measured values, as described in appendix 2. Calcite oversaturation and subsequent precipitation are a concern with respect to scaling but also are important to the prevention of corrosion of metal surfaces of water storage and transmission systems. A negative Langelier saturation index indicates the water could potentially dissolve calcite and, thus, could lead to corrosion, whereas a positive Langelier saturation index indicates the water is likely to deposit calcite in the distribution or treatment system.

The median Langelier saturation index of all groups was positive. Only 4 percent of saline samples exceeded a Langelier saturation index of 1, and only 2 percent of samples had a Langelier saturation index <–1 (table 6). As a result, deposition of calcite should be more prevalent than corrosion in infrastructure exposed to most saline groundwater. In contrast, the Langelier saturation index values of fresh groundwater in the United States were more often negative, and this fresh groundwater was more likely to be corrosive; <1 percent of fresh groundwater samples had a Langelier saturation index >1, and 21 percent had a Langelier saturation index <–1. The national distribution of the Langelier saturation index in saline groundwater was similar to that of the calcite saturation index, except that a different scale was used to show the propensity for either calcite precipitation or corrosion (fig. 19*A*, *D*).

Whereas other geochemical indices, including the osmotic potential and sodium-adsorption ratio, were calculated by using the PHREEQC program, which accounts for the chemical speciation of groundwater samples, the Langelier



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Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W., latitude of origin 23°00′ N.
North American Datum of 1983

Figure 19. Distribution of saturation indices in brackish groundwater in the United States. *A*, calcite; *B*, chalcedony; *C*, barite; *D*, the Langelier saturation index.

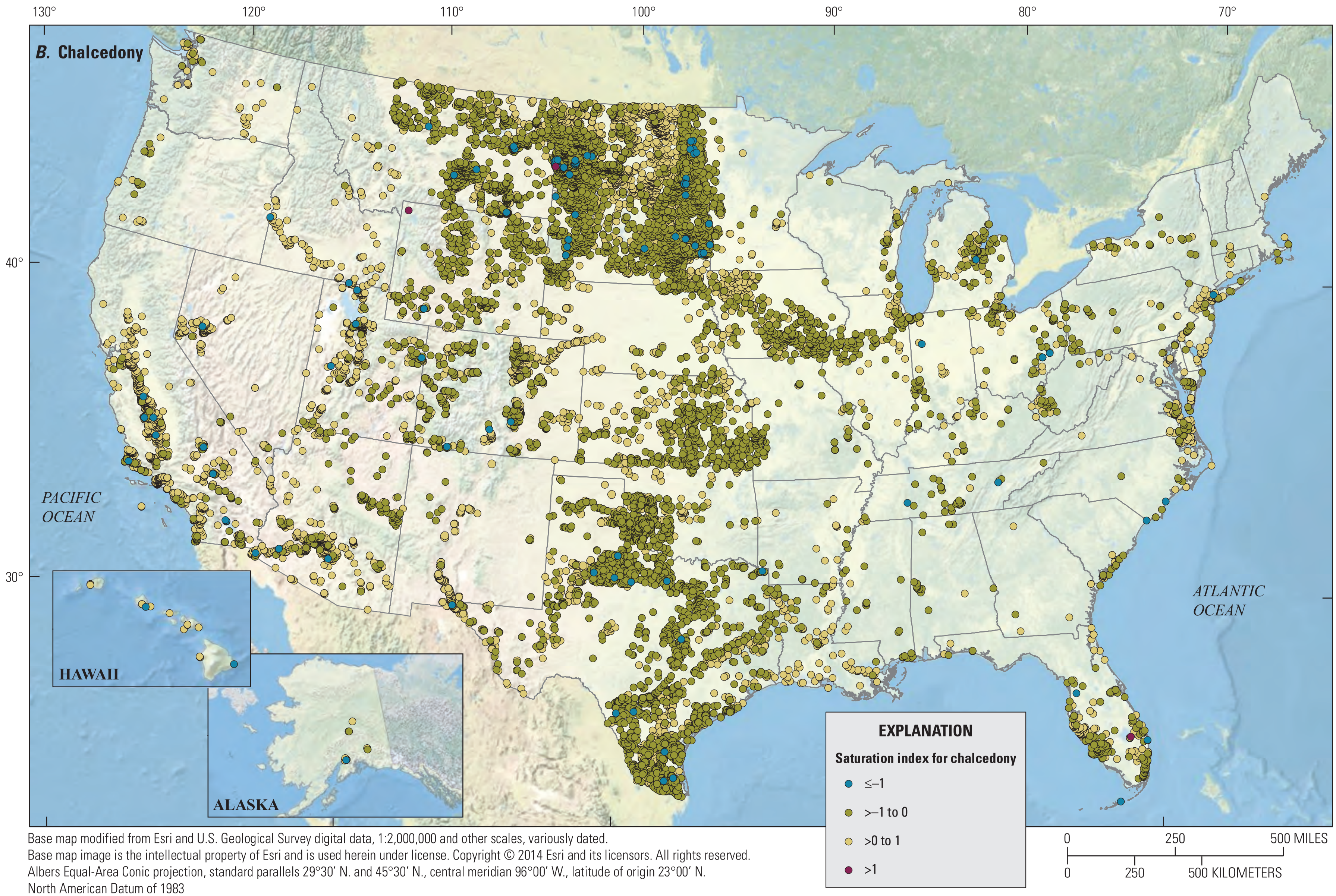

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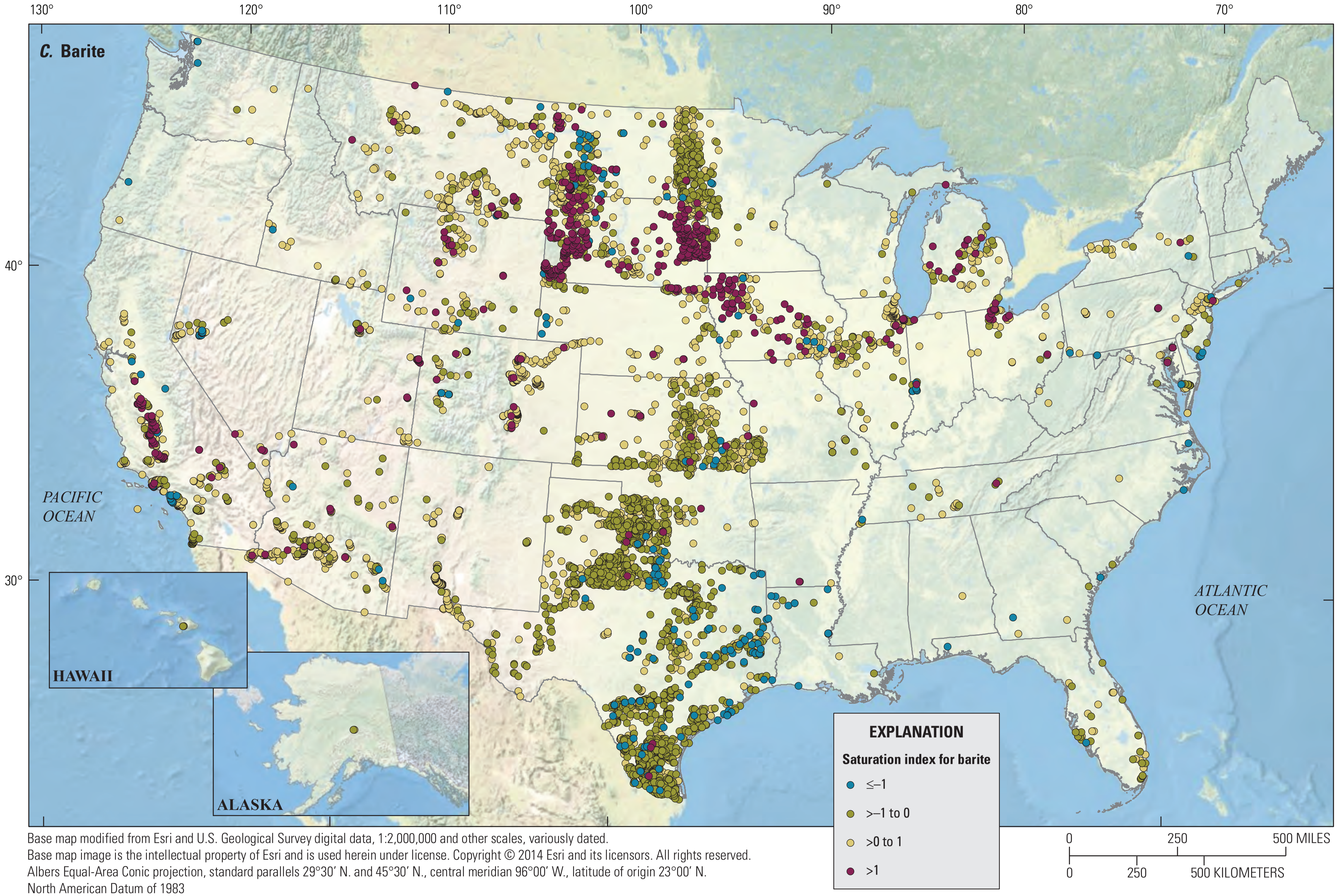
Figure 19. Distribution of saturation indices in brackish groundwater in the United States. *A*, calcite; *B*, chalcedony; *C*, barite; *D*, the Langelier saturation index.—Continued



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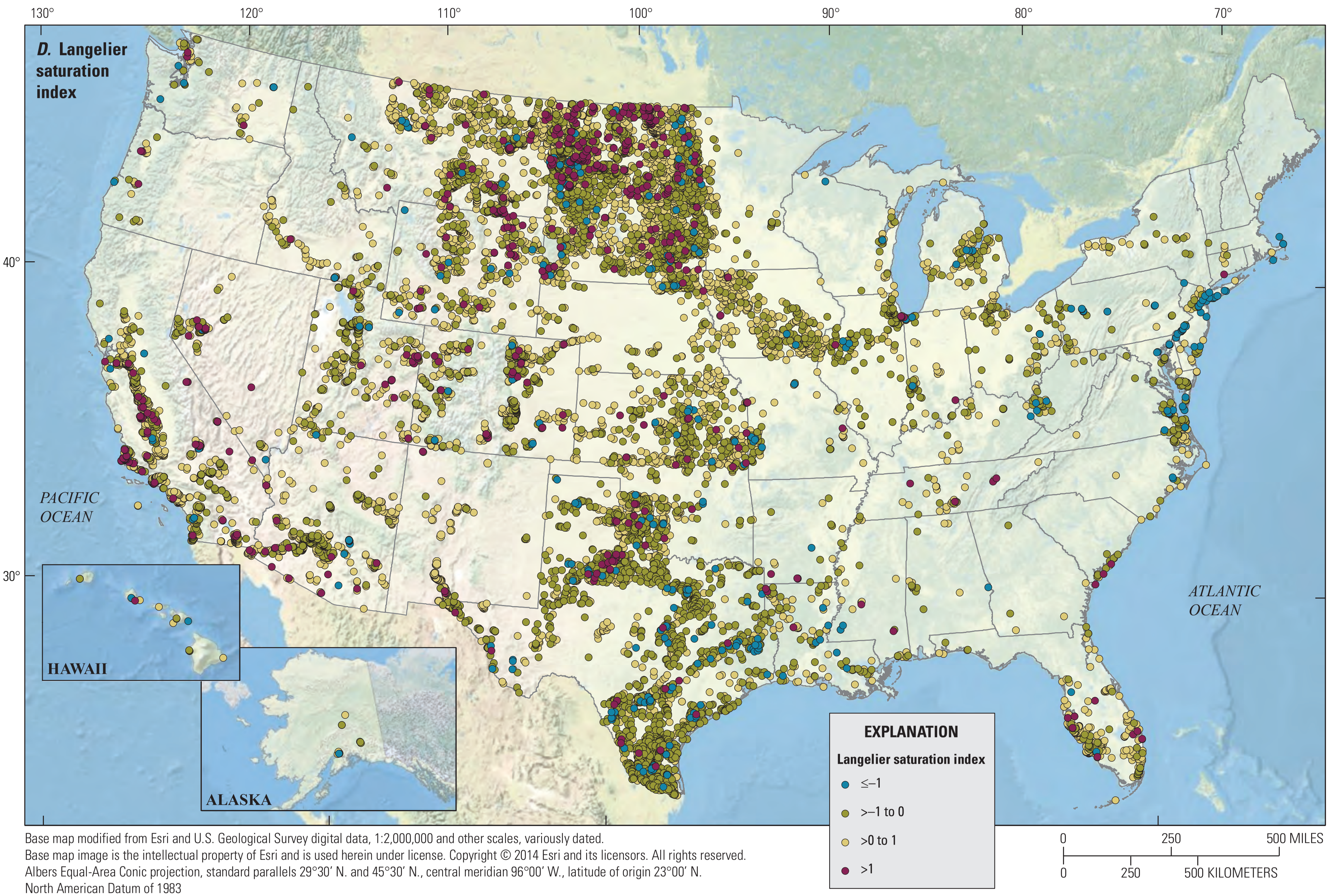

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North American Datum of 1983

Figure 19. Distribution of saturation indices in brackish groundwater in the United States. *A*, calcite; *B*, chalcedony; *C*, barite; *D*, the Langelier saturation index.—Continued

saturation index was calculated by the simpler classic method of using measured concentration values and not by the PHREEQC program. Langelier saturation index calculations using a geochemical model, such as the PHREEQC program, would provide values that are reflective of dissolved species interactions and, therefore, different from total concentration results; furthermore, PHREEQC modeling could indicate other factors that affect the corrosion of metal surfaces. For example, although PHREEQC calculations of mineral saturation indices indicated no oversaturation of calcite in samples in the potentially corrosive Langelier saturation index range (<-1), a substantial percentage (37 percent) of samples in this range were oversaturated with respect to chalcedony, which could feasibly limit corrosion of metal surfaces.

The PHREEQC program was used to simulate a treatment process resembling reverse osmosis in several steps (table 7), similar to process modeling done by McMahon and others (2015). Closed conditions were simulated to assess water chemistry in sealed tanks or distribution lines with no exchange of carbon dioxide with the atmosphere. In the initial solution (concentration factor = 0), groundwater was equilibrated in a system closed to atmospheric $P(CO_2)$ (simulating storage in a closed reservoir before treatment) at 15 °C and 1 atm, approximating groundwater conditions, and the reverse osmosis simulation steps (concentration factors of 1 to 6) were done at typical reverse osmosis conditions of 25 °C and 20 atm. For concentration factors >0, water was removed from the closed system incrementally (for example, estimating the effects of reverse osmosis). A concentration factor of 10 represents 90-percent product freshwater (which has been removed from the system and any further simulations) and 10-percent residual saline water.

The PHREEQC simulations of a hypothetical water-removal process such as reverse osmosis indicate that the mineral precipitation potential increases differ among the four geochemical groups during treatment as dissolved ions on the influent side of the membrane become concentrated (table 7). The median osmotic pressure of the remaining water after 90-percent removal increased most for group 3 samples. Calcite precipitated in the greatest amount (fig. 20*A*) relative to other considered minerals in each simulation, followed by chalcedony (fig. 20*B*; table 7). Calcite precipitation increased the most between concentration factors 1 and 2, ranging from 29 percent of the total mineral precipitated in group 3 samples to 43 percent of the total mineral precipitated in group 1 samples (fig. 20*A*; table 7). Silica, which is a major scalant for reverse osmosis (Koo and others, 2001) and modeled as chalcedony, precipitated in the greatest amounts (median of 0.00043 mole per liter [mol/L]) in samples from group 4. The simulated precipitation of chalcedony generally decreased during the first step, which was caused by the increase in the solubility of silica at higher temperatures (15 °C at a concentration factor of 0 to 25 °C at a concentration factor of 1; fig. 20*B*; table 7).

Gypsum precipitated only in groups 2 and 4 (fig. 20*C*); the highest median was 0.0039 mol/L for group 2 (table 7). Barite and celestite did not precipitate according to median precipitation values from the simulations for each group, although individual samples in groups 2 and 4 precipitated the most barite (47 percent of samples had barite precipitation) and individual samples in group 2 precipitated the most celestite (47 percent of samples had celestite precipitation) in the reverse osmosis simulations. Barite and celestite are particularly troublesome in water treatment because their needle-shaped crystals can readily pierce the reverse osmosis membrane (Chesters, 2009). The Pitzer database used with the PHREEQC program has no definitions for ferric iron species or ferrihydrite, so all the dissolved iron in a sample was assumed to precipitate as ferrihydrite. Median amounts of ferrihydrite precipitate ranged from 3.6×10^{-7} mol/L in group 4 to 1.4×10^{-6} mol/L in group 1 (table 7). High concentrations of iron or manganese could be a problem for treatment or for extraction from wells because of the potential for biofouling or well-screen encrustation.

Results of geochemical characterization summarized in this section are intended primarily to illustrate various potential approaches for adding value to the BGW database compilation that could be improved by further work. For example, geochemical groups derived from cluster analyses could be subdivided further to reflect more of the diversity in natural processes that create BGW (for example, McMahon and others, 2015). More sophisticated geochemical modeling could be used to predict more realistic mineral scaling processes (for example, involving open systems, and metastable phases), to explore complex soil processes associated with BGW irrigation, and for many other practical purposes aimed at optimizing use and treatment options.

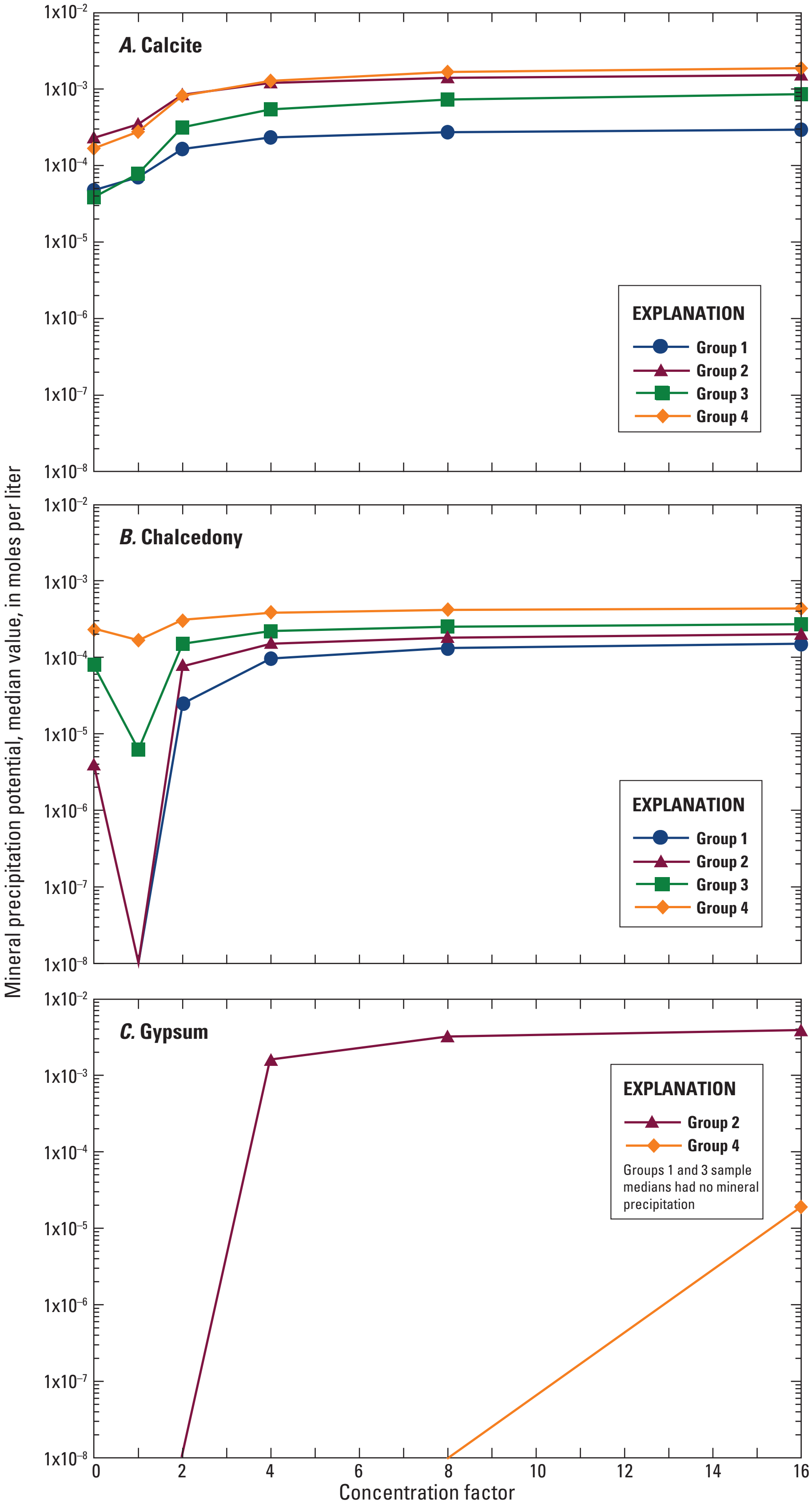
Regional- and Aquifer-Scale Brackish Groundwater

The natural occurrence of BGW and the ability of aquifers to store and transmit brackish water depend on hydrogeologic characteristics, including the type and age of aquifer material, groundwater residence time and flow velocities, recharge rates, and groundwater flow patterns. To describe BGW resources in the context of hydrogeologic characteristics, the United States was divided into 10 BGW regions (fig. 7)—Coastal Plains, Eastern Midcontinent, Southwestern Basins, Western Midcontinent, Eastern Mountains and Uplands, Northwestern Volcanics, Western Mountain Ranges, Alaska, Hawaii, and U.S. Territories (Puerto Rico and U.S. Virgin Islands). Although there is local variation, each region generally has similar composition, structure, and arrangement of geologic units. Groundwater conditions, such as the presence of primary or secondary porosity, hydraulic properties of aquifers, and the distribution of recharge and discharge areas, also are commonly similar within each region (Heath, 1984). Most BGW that is observed nationally exists within the Western Midcontinent region (table 4).

Table 7. Mineral-precipitation potentials for closed conditions during simulated water removal among the four geochemical groups.

[Ferrihydrite is not defined in the Pitzer database (Plummer and others, 1988) used by PHREEQC, but was allowed to precipitate from dissolved iron; atm, atmosphere; ºC, degree Celsius]

Geochemical group	Concentration factor	Model conditions	Median osmotic pressure, in atm	Median precipitated barite, in moles per liter	Median precipitated calcite, in moles per liter	Median precipitated celestite, in moles per liter	Median precipitated chalcedony, in moles per liter	Median precipitated gypsum, in moles per liter	Median precipitated ferrihydrite, in moles per liter
1	0	Initial solution—15 ºC and 1 atm	0.99	0	4.8×10^{-5}	0	0	0	1.4×10^{-6}
	1	Initial solution—25 ºC and 20 atm	1.0	0	7.1×10^{-5}	0	0	0	1.4×10^{-6}
	2	50 percent water removed—25 ºC and 20 atm	2.0	0	1.7×10^{-4}	0	2.5×10^{-5}	0	1.4×10^{-6}
	4	75 percent water removed—25 ºC and 20 atm	3.8	0	2.4×10^{-4}	0	9.6×10^{-5}	0	1.4×10^{-6}
	8	87.5 percent water removed—25 ºC and 20 atm	7.3	0	2.8×10^{-4}	0	1.3×10^{-4}	0	1.4×10^{-6}
	16	93.75 percent water removed—25 ºC and 20 atm	14	0	3.0×10^{-4}	0	1.5×10^{-4}	0	1.4×10^{-6}
2	0	Initial solution—15 ºC and 1 atm	0.77	0	2.3×10^{-4}	0	3.8×10^{-6}	0	7.2×10^{-7}
	1	Initial solution—25 ºC and 20 atm	0.79	0	3.5×10^{-4}	0	0	0	7.2×10^{-7}
	2	50 percent water removed—25 ºC and 20 atm	1.4	0	8.6×10^{-4}	0	7.6×10^{-5}	0	7.2×10^{-7}
	4	75 percent water removed—25 ºC and 20 atm	2.5	0	1.2×10^{-3}	0	1.5×10^{-4}	1.6×10^{-3}	7.2×10^{-7}
	8	87.5 percent water removed—25 ºC and 20 atm	4.5	0	1.4×10^{-3}	0	1.8×10^{-4}	3.2×10^{-3}	7.2×10^{-7}
	16	93.75 percent water removed—25 ºC and 20 atm	8.4	0	1.5×10^{-3}	0	2.0×10^{-4}	3.9×10^{-3}	7.2×10^{-7}
3	0	Initial solution—15 ºC and 1 atm	1.6	0	3.9×10^{-5}	0	7.6×10^{-5}	0	7.2×10^{-7}
	1	Initial solution—25 ºC and 20 atm	1.7	0	7.9×10^{-5}	0	6.2×10^{-6}	0	7.2×10^{-7}
	2	50 percent water removed—25 ºC and 20 atm	3.3	0	3.2×10^{-4}	0	1.5×10^{-4}	0	7.2×10^{-7}
	4	75 percent water removed—25 ºC and 20 atm	6.4	0	5.5×10^{-4}	0	2.2×10^{-4}	0	7.2×10^{-7}
	8	87.5 percent water removed—25 ºC and 20 atm	12	0	7.4×10^{-4}	0	2.5×10^{-4}	0	7.2×10^{-7}
	16	93.75 percent water removed—25 ºC and 20 atm	25	0	8.7×10^{-4}	0	2.7×10^{-4}	0	7.2×10^{-7}
4	0	Initial solution—15 ºC and 1 atm	0.64	0	1.7×10^{-4}	0	2.4×10^{-4}	0	3.6×10^{-7}
	1	Initial solution—25 ºC and 20 atm	0.66	0	2.8×10^{-4}	0	1.7×10^{-4}	0	3.6×10^{-7}
	2	50 percent water removed—25 ºC and 20 atm	1.2	0	8.3×10^{-4}	0	3.1×10^{-4}	0	3.6×10^{-7}
	4	75 percent water removed—25 ºC and 20 atm	2.3	0	1.3×10^{-3}	0	3.8×10^{-4}	0	3.6×10^{-7}
	8	87.5 percent water removed—25 ºC and 20 atm	4.4	0	1.7×10^{-3}	0	4.2×10^{-4}	0	3.6×10^{-7}
	16	93.75 percent water removed—25 ºC and 20 atm	8.4	0	1.9×10^{-3}	0	4.3×10^{-4}	1.9×10^{-5}	3.6×10^{-7}



Note: Curves indicate the median cumulative amount of mineral that precipitated in PHREEQC (Parkhurst and Appelo, 2013) computer program simulations.

Figure 20. Simulated mineral precipitation potential in brackish groundwater undergoing a treatment process resembling reverse osmosis to remove dissolved solids. *A*, calcite; *B*, chalcedony; *C*, gypsum.

The remaining areas underlain by substantial amounts of BGW are largely in the Coastal Plains, Eastern Midcontinent, and Southwestern Basins regions. BGW characteristics, considerations for BGW use, and saline groundwater use in each of these four regions are discussed in further detail within this section of the report. The Eastern Mountains and Uplands, Northwestern Volcanics, Western Mountain Ranges, Alaska, Hawaii, and the U.S. Territories regions have far less observed BGW than the Coastal Plains, Eastern Midcontinent, Southwestern Basins, and Western Midcontinent regions and are discussed only briefly.

Although the hydrogeologic conditions within each of the BGW regions are similar, variability exists among the principal aquifers within each of these regions; therefore, BGW characteristics are evaluated at the principal aquifer-scale where possible. This evaluation is primarily focused on the principal aquifers that had substantial amounts of BGW based on the data compiled for this assessment (table 8).

As part of the regional- and aquifer-scale assessments, the amount of subsurface volume (including air, water, and rock) that contains some BGW was estimated by using a coarse-resolution three-dimensional grid for areas where observations were available (tables 4 and 8); however, in order to determine the amount of groundwater that could be extracted from that volume, storage properties of the aquifers (specific yield for unconfined aquifers and specific storage or storage coefficient for confined aquifers) are needed. These values can vary widely throughout each aquifer, making it difficult to accurately estimate the actual amount of stored groundwater. Aquifer storage properties compiled as part of this report were not provided in a spatially distributed format and are likely representative of the freshwater part of aquifers; therefore, those values were not used to estimate the amount of BGW available in storage. To provide a plausible and consistent estimate for purposes of comparing BGW volumes, total grid cell volumes containing BGW were multiplied by 1 percent for a conservative estimate. However, this kind of estimate is highly uncertain, and associated results should be used with caution. Nonetheless, the results do provide a basis for comparison and planning. In addition, aquifer boundaries were considered in the volume calculations in only a simple way (see the “Data Gaps and Limitations” section).

Coastal Plains Region

The Coastal Plains region is along the gulf coast and Atlantic Ocean, extending from Long Island, New York, to the Rio Grande in Texas (figs. 7 and 21). Groundwater salinity in the aquifers of this region is primarily influenced by proximity to recharge areas, depth, aquifer permeability, dissolution of evaporites or carbonate rocks, seawater intrusion, and the presence of connate seawater (Miller, 1990; Reese, 1994; Trapp and Horn, 1997; Lester Williams, U.S. Geological Survey, written commun., 2013). Brackish zones are typically present as a transition between the zones of freshwater and brine (table 9). A total of 10 principal aquifers are mostly within this region (fig. 21); all aquifers but one have substantial amounts of BGW because at least 10 percent of their observed grid cell volume contained BGW (table 8).

Hydrogeologic Characteristics

This region consists primarily of dipping formations of sediments (table 9) originally deposited in flood plains, deltas, or shallow seas (Heath, 1984). Depositional environments are distinctly different in various areas of the region, and these differences were taken into consideration in the delineation of principal aquifers (fig. 21). The formations of the Southeastern Coastal Plain, Texas coastal uplands or Mississippi embayment, and Coastal lowlands aquifer systems are composed of a series of sand deposits separated by fine-grained layers that, in many areas, act as confining units that impede the vertical movement of groundwater and dip toward either the gulf coast or the axis of the Mississippi embayment (not shown on figure 21), depending on location. The layers generally thicken downdip and can reach thicknesses >39,000 ft within the gulf coast (Heath, 1984).

The Mississippi River Valley alluvial aquifer is a thin aquifer composed of predominantly coarse sands and gravels deposited within the valley by the braided ancestral meandering of the current Mississippi River and predominantly contains freshwater (Renken, 1998). The coastal plain sediments on the northern Atlantic coast and southeastern coastal plain of Georgia and South Carolina dip and thicken toward the Atlantic Ocean and are predominantly composed of layered clastic sediments with a few carbonate layers that overlie crystalline bedrock. Generally these sediments reach a maximum thickness of about 10,000 ft beneath the Atlantic Ocean near the coast. These Atlantic Coastal Plain sediments become less permeable as depth increases. The Floridan aquifer system extends throughout Florida and parts of Alabama, Georgia, and South Carolina; it reaches a thickness of 3,300 ft in south Florida. Much of the terrain in peninsular Florida and southwestern Georgia is karst. This aquifer system is composed of thick carbonate rocks of marine origin that dip and thicken to the southeast, where they underlie the surficial aquifer system, the Intermediate aquifer system, and the Biscayne aquifer.

Inundations of seawater during several geologic periods have affected the geologic and chemical characteristics of this region, leaving complex interbedded sediments caused by waves and currents, carbonate deposits created in shallow seas that can dissolve, and remnant seawater that still resides within some sediments (Heath, 1984; Trapp and Horn, 1997; Ryder and Ardis, 2002). Groundwater salinity generally increases downdip in the layered deposits, grading from freshwater to brine, as deposits become less permeable and groundwater flow becomes sluggish (Heath, 1984; Trapp and Horn, 1997). The Floridan aquifer system contains freshwater throughout updip areas of Alabama, Georgia, South Carolina, and northern Florida and within the center of peninsular Florida (Williams and Kuniansky, 2016). Brackish to highly

Table 8. Summary of observed brackish and highly saline groundwater in principal aquifers of the United States.

[Grid cells are categorized as “fresh,” “brackish,” or “highly saline” based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization “fresh” cells also could contain unobserved brackish or highly saline groundwater, “brackish” cells also could contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and “highly saline” cells also could contain observed or unobserved fresh and/or brackish groundwater. NA, brackish or highly saline groundwater not observed in listed principal aquifer; <, less than]

Principal aquifer[1]	Number of sampled wells	Statistics for samples[2]					Estimated grid cell volume represented by samples[2,4]				
								Brackish groundwater		Highly saline groundwater	
		Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median depth of sampled wells with brackish groundwater[3]	Median depth of sampled wells with highly saline groundwater[3]	Median sample dissolved-solids concentration, in milligrams per liter	Fresh, brackish, and highly saline groundwater, in cubic miles	Volume, in cubic miles	Percent of total	Volume, in cubic miles	Percent of total
Coastal Plains											
Biscayne aquifer	1,272	12	8	83	93	357	200	51	25	55	28
Coastal Lowlands aquifer system	18,185	23	1	285	1,479	462	16,571	5,475	33	769	5
Floridan aquifer system	5,604	11	2	605	850	190	7,829	1,611	21	473	6
Intermediate aquifer system	526	29	NA	210	NA	598	313	164	53	NA	NA
Mississippi River Valley alluvial aquifer	3,336	4	NA	87	NA	314	2,053	140	7	NA	NA
Northern Atlantic Coastal Plain or Castle Hayne aquifer system	12,655	4	1	176	181	150	6,923	876	13	244	4
Sand and gravel aquifers of alluvial or glacial origin	712	14	2	55	63	310	191	60	31	18	10
Southeastern Coastal Plain aquifer system	6,439	4	<1	760	2,530	150	7,980	866	11	167	2
Surficial aquifer system (Florida)	2,578	8	2	45	58	237	892	176	20	63	7
Texas coastal uplands or Mississippi embayment aquifer system	15,247	13	1	276	2,200	309	17,674	4,196	24	678	4
Principal aquifer not present or not determined	5,283	17	2	197	2,405	207	5,448	1,320	24	611	11
Eastern Midcontinent											
Cambrian-Ordovician aquifer system	4,514	9	1	1,565	1,857	328	9,001	1,975	22	295	3
Jacobsville aquifer	18	NA	NA	NA	NA	163	13	NA	NA	NA	NA
Marshall aquifer	167	17	10	245	1,048	428	348	91	26	98	28

Table 8. Summary of observed brackish and highly saline groundwater in principal aquifers of the United States.—Continued

[Grid cells are categorized as “fresh,” “brackish,” or “highly saline” based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization “fresh” cells also could contain unobserved brackish or highly saline groundwater, “brackish” cells also could contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and “highly saline” cells also could contain observed or unobserved fresh and/or brackish groundwater. NA, brackish or highly saline groundwater not observed in listed principal aquifer; <, less than]

Principal aquifer[1]	Number of sampled wells	Statistics for samples[2]					Estimated grid cell volume represented by samples[2,4]				
								Brackish groundwater		Highly saline groundwater	
		Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median depth of sampled wells with brackish groundwater[3]	Median depth of sampled wells with highly saline groundwater[3]	Median sample dissolved-solids concentration, in milligrams per liter	Fresh, brackish, and highly saline groundwater, in cubic miles	Volume, in cubic miles	Percent of total	Volume, in cubic miles	Percent of total
Eastern Midcontinent—Continued											
Mississippian aquifers	3,105	13	21	300	1,931	461	4,818	1,054	22	2,447	51
New York and New England carbonate-rock aquifers	906	13	1	72	205	288	732	143	20	10	1
New York sandstone aquifers	280	2	<1	113	72	190	257	20	8	3	1
Ordovician aquifers	229	11	4	126	912	362	434	85	20	50	12
Ozark Plateaus aquifer system	5,662	5	<1	337	1,718	250	7,543	831	11	101	1
Pennsylvanian aquifers	4,043	10	4	200	1,002	307	2,877	761	26	635	22
Sand and gravel aquifers of alluvial or glacial origin	9,089	5	<1	66	120	393	4,581	618	14	7	<1
Silurian-Devonian aquifers	2,826	15	7	334	1,800	496	4,552	1,133	25	1,230	27
Upper carbonate aquifer (Paleozoic)	22	NA	NA	NA	NA	321	58	NA	NA	NA	NA
Valley and Ridge aquifers	6,233	1	0	250	1,653	150	4,883	158	3	58	1
Principal aquifer not present or not determined	27,367	7	4	90	1,702	245	23,236	3,683	16	4,939	21
Southwestern Basins											
Basin and Range basin-fill aquifers	13,874	24	2	211	18	493	11,134	3,508	32	302	3
Basin and Range carbonate-rock aquifers	335	25	2	363	650	630	587	196	33	35	6
California Coastal Basin aquifers	3,403	26	1	186	103	590	1,960	599	31	85	4
Central Valley aquifer system	6,276	20	2	429	24	401	4,223	1,552	37	144	3
Rio Grande aquifer system	2,813	33	1	198	75	656	1,869	717	38	59	3

Table 8. Summary of observed brackish and highly saline groundwater in principal aquifers of the United States.—Continued

[Grid cells are categorized as “fresh,” “brackish,” or “highly saline” based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization “fresh” cells also could contain unobserved brackish or highly saline groundwater, “brackish” cells also could contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and “highly saline” cells also could contain observed or unobserved fresh and/or brackish groundwater. NA, brackish or highly saline groundwater not observed in listed principal aquifer; <, less than]

Principal aquifer[1]	Number of sampled wells	Statistics for samples[2]					Estimated grid cell volume represented by samples[2,4]				
		Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median depth of sampled wells with brackish groundwater[3]	Median depth of sampled wells with highly saline groundwater[3]	Median sample dissolved-solids concentration, in milligrams per liter	Fresh, brackish, and highly saline groundwater, in cubic miles	Brackish groundwater		Highly saline groundwater	
								Volume, in cubic miles	Percent of total	Volume, in cubic miles	Percent of total
Southwestern Basins—Continued											
Sand and gravel aquifers of alluvial or glacial origin	25	24	NA	29	NA	285	18	7	39	NA	NA
Southern Nevada volcanic-rock aquifers	6	NA	NA	NA	NA	223	44	NA	NA	NA	NA
Principal aquifer not present or not determined	7,485	20	1	175	95	439	10,466	2,672	26	128	1
Western Midcontinent											
Ada-Vamoosa aquifer	513	11	1	140	262	451	224	96	43	3	2
Arbuckle-Simpson aquifer	216	6	2	338	1,394	362	166	25	15	26	15
Blaine aquifer	513	80	2	106	266	2,753	158	125	79	32	20
Central Oklahoma aquifer	1,524	13	1	90	2,000	434	525	235	45	44	8
Colorado Plateaus aquifers	4,289	35	10	440	1,925	807	9,775	3,962	41	1,947	20
Denver Basin aquifer system	1,715	27	<1	57	45	545	1,356	334	25	10	1
Edwards-Trinity aquifer system	14,162	20	<1	350	525	498	11,713	5,081	43	218	2
High Plains aquifer	17,740	9	<1	100	120	351	11,239	1,441	13	83	1
Lower Cretaceous aquifers	6,431	57	4	900	835	1,492	12,110	8,616	71	956	8
Lower Tertiary aquifers	6,127	68	<1	150	32	1,340	6,132	4,739	77	39	1
Paleozoic aquifers	1,141	39	9	1,890	2,300	783	2,798	1,628	58	500	18
Pecos River Basin alluvial aquifer	1,400	58	4	180	200	1,820	720	527	73	132	18
Roswell Basin aquifer system	18	44	6	373	510	921	57	13	23	7	13
Rush Springs aquifer	440	30	<1	136	104	448	234	169	72	3	1

Table 8. Summary of observed brackish and highly saline groundwater in principal aquifers of the United States.—Continued

[Grid cells are categorized as “fresh,” “brackish,” or “highly saline” based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization “fresh” cells also could contain unobserved brackish or highly saline groundwater, “brackish” cells also could contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and “highly saline” cells also could contain observed or unobserved fresh and/or brackish groundwater. NA, brackish or highly saline groundwater not observed in listed principal aquifer; <, less than]

Principal aquifer[1]	Number of sampled wells	Statistics for samples[2]					Estimated grid cell volume represented by samples[2,4]				
		Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median depth of sampled wells with brackish groundwater[3]	Median depth of sampled wells with highly saline groundwater[3]	Median sample dissolved-solids concentration, in milligrams per liter	Fresh, brackish, and highly saline groundwater, in cubic miles	Brackish groundwater		Highly saline groundwater	
								Volume, in cubic miles	Percent of total	Volume, in cubic miles	Percent of total
Western Midcontinent—Continued											
Sand and gravel aquifers of alluvial or glacial origin	15,793	44	<1	72	34	891	4,700	3,238	69	66	1
Seymour aquifer	669	54	1	46	38	1,075	66	58	87	4	7
Upper Cretaceous aquifers	5,120	72	1	200	97	1,381	7,101	5,440	77	89	1
Western Interior Plains aquifer system	707	10	84	997	2,611	103,000	2,540	302	12	2,178	86
Wyoming (Upper) Tertiary aquifers	52	17	<1	100	NA	360	90	11	12	NA	NA
Principal aquifer not present or not determined	37,397	42	6	100	2,122	935	36,153	15,893	44	8,292	23
Eastern Mountains and Uplands											
Early Mesozoic basin aquifers	2,139	2	NA	274	NA	208	1,238	157	13	NA	NA
New York and New England crystalline-rock aquifers	3,934	<1	<1	35	602	150	2,931	9	<1	15	1
Piedmont and Blue Ridge carbonate-rock aquifers	8,578	<1	NA	190	NA	150	7,596	73	1	NA	NA
Sand and gravel aquifers of alluvial or glacial origin	3,370	2	<1	71	77	150	833	60	7	14	2
Principal aquifer not present or not determined	5,732	3	<1	141	463	157	4,991	299	6	14	<1
Northwestern Volcanics											
Columbia Plateau basaltic-rock aquifers	2,288	1	<1	215	287	205	3,529	48	1	3	<1
Columbia Plateau basin-fill aquifers	1,197	1	NA	43	NA	217	358	19	5	NA	NA

Table 8. Summary of observed brackish and highly saline groundwater in principal aquifers of the United States.—Continued

[Grid cells are categorized as “fresh,” “brackish,” or “highly saline” based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization “fresh” cells also could contain unobserved brackish or highly saline groundwater, “brackish” cells also could contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and “highly saline” cells also could contain observed or unobserved fresh and/or brackish groundwater. NA, brackish or highly saline groundwater not observed in listed principal aquifer; <, less than]

Principal aquifer[1]	Number of sampled wells	Statistics for samples[2]					Estimated grid cell volume represented by samples[2,4]				
		Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median depth of sampled wells with brackish groundwater[3]	Median depth of sampled wells with highly saline groundwater[3]	Median sample dissolved-solids concentration, in milligrams per liter	Fresh, brackish, and highly saline groundwater, in cubic miles	Brackish groundwater		Highly saline groundwater	
								Volume, in cubic miles	Percent of total	Volume, in cubic miles	Percent of total
Northwestern Volcanics—Continued											
Pacific Northwestern volcanic rock or basin-fill aquifers	517	1	<1	208	1,177	252	419	14	3	7	2
Sand and gravel aquifers of alluvial or glacial origin	14	7	NA	5	NA	232	5	<1	8	NA	NA
Snake River Plain volcanic rock or basin-fill aquifers	1,322	1	NA	113	NA	317	648	38	6	NA	NA
Principal aquifer not present or not determined	6,789	2	<1	165	97	234	5,072	303	6	4	<1
Western Mountain Ranges											
Northern Rocky Mountains Intermontane Basins aquifer systems	1,785	2	NA	115	NA	213	1,031	64	6	NA	NA
Puget Sound aquifer system	161	NA	NA	NA	NA	111	55	NA	NA	NA	NA
Sand and gravel aquifers of alluvial or glacial origin	518	3	NA	34	NA	234	302	19	6	NA	NA
Willamette Lowland basin-fill aquifers	370	1	NA	127	NA	169	237	10	4	NA	NA
Principal aquifer not present or not determined	7,652	3	<1	144	238	150	4,606	533	12	77	2
Alaska											
All groundwater resources	1,706	4	<1	127	170	159	707	100	14	24	3
Hawaii											
All groundwater resources	337	14	3	179	96	272	614	106	17	18	3

Table 8. Summary of observed brackish and highly saline groundwater in principal aquifers of the United States.—Continued

[Grid cells are categorized as "fresh," "brackish," or "highly saline" based on the maximum observed dissolved-solids concentration from well samples being less than 1,000 milligrams per liter (mg/L), between 1,000 mg/L and 10,000 mg/L, or greater than 10,000 mg/L, respectively. In this categorization "fresh" cells also could contain unobserved brackish or highly saline groundwater, "brackish" cells also could contain observed or unobserved fresh groundwater and unobserved highly saline groundwater, and "highly saline" cells also could contain observed or unobserved fresh and/or brackish groundwater. NA, brackish or highly saline groundwater not observed in listed principal aquifer; <, less than]

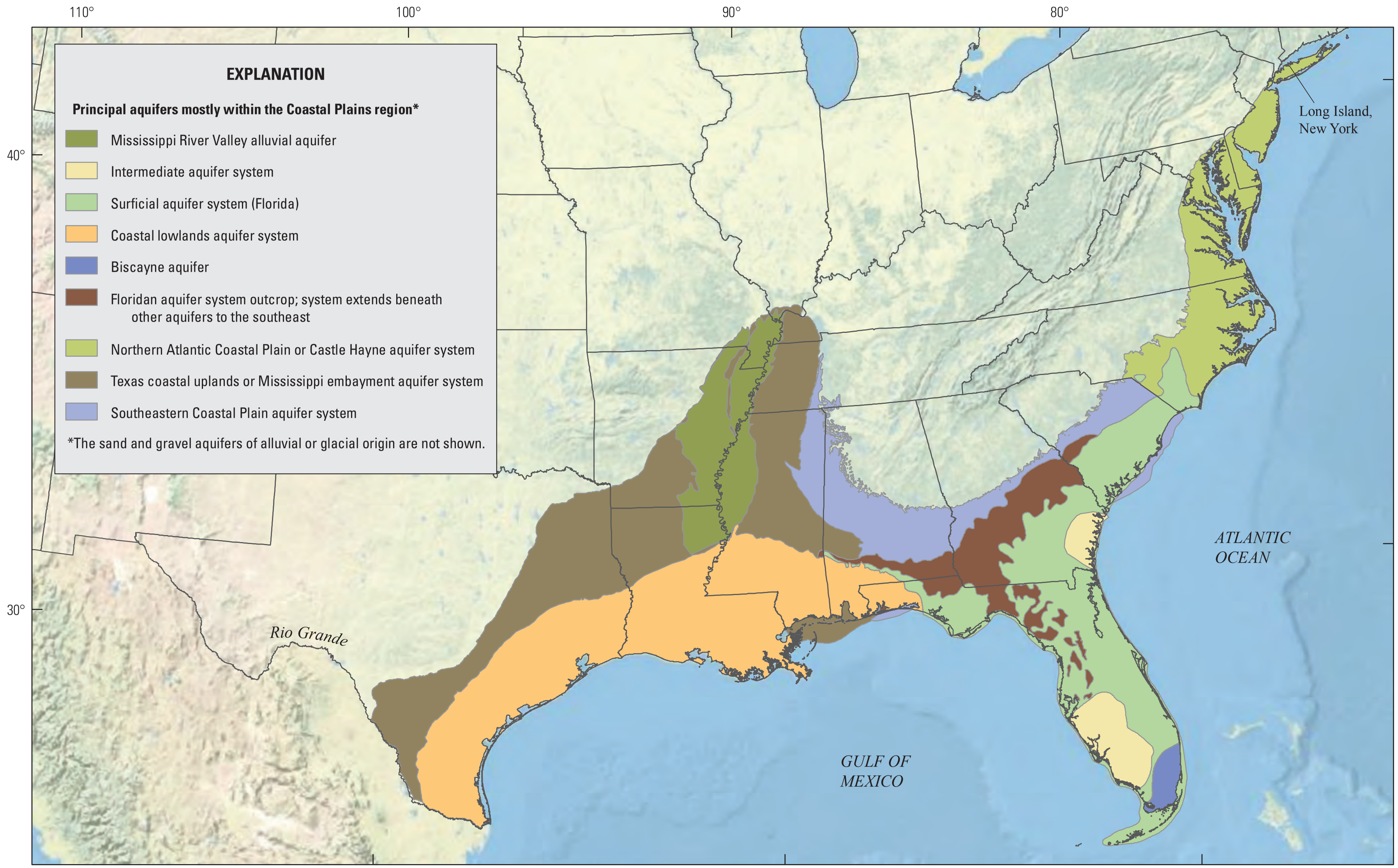
Principal aquifer[1]	Number of sampled wells	Statistics for samples[2]					Estimated grid cell volume represented by samples[2,4]				
		Sampled wells with brackish groundwater, in percent	Sampled wells with highly saline groundwater, in percent	Median depth of sampled wells with brackish groundwater[3]	Median depth of sampled wells with highly saline groundwater[3]	Median sample dissolved-solids concentration, in milligrams per liter	Fresh, brackish, and highly saline groundwater, in cubic miles	Brackish groundwater		Highly saline groundwater	
								Volume, in cubic miles	Percent of total	Volume, in cubic miles	Percent of total
U.S. Territories											
Groundwater resources in Puerto Rico	732	16	3	76	33	478	366	133	36	22	6
Groundwater resources in the U.S. Virgin Islands	181	81	6	95	47	1,450	56	41	73	8	14

[1] In some cases the principal aquifer may extend into other brackish groundwater regions; data reported here are for the entire principal aquifer.

[2] Values are shown with few significant figures to account for potential errors in the data, particularly with aquifer codes.

[3] Wells included in this analysis contain screening above 3,000 feet below land surface. Some wells, however, extend below this depth.

[4] Grid cell volumes include air, water, and rock occupied in the subsurface to 3,000 feet below land surface. Volumes are computed based on grid cell dimensions and on well construction and sample information associated with each grid cell. Estimates reported here reflect grid-cell volumes for areas where well observations are available. Entire principal aquifer subsurface volumes could be greater than those reported here because of the lack of observations in many grid cells.



Base map modified from Esri and U.S. Geological Survey digital data, 1:2,000,000 and other scales, variously dated.
Base map image is the intellectual property of Esri and is used herein under license. Copyright © 2014 Esri and its licensors. All rights reserved.
Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W., latitude of origin 23°00′ N.
North American Datum of 1983

Figure 21. Principal aquifers mostly within the Coastal Plains region. An interactive map for viewing the full extent of each principal aquifer is available at https://doi.org/10.3133/pp1833.

Table 9. Generalized hydrogeologic characteristics of principal aquifers with substantial amounts of brackish groundwater in the Coastal Plains region.

[Descriptions are generalized aquifer properties and not specific to the brackish zone. --, not applicable or not reported in publications reviewed for this study; gal/min, gallon per minute; ft, foot; <, less than]

Principal aquifer[1]	Geologic age[2]	General description of brackish zone(s)[2]	Principal depositional environment[2]	Principal composition[2]	Flow influenced by confining beds[2]	Specific yield, in percent (unconfined aquifers)[2]
Coastal Lowlands aquifer system	Miocene and younger	Downdip areas with low permeability and less freshwater circulation	Alluvial and marine	Beds of clay, silt, sand, and gravel with minor amounts of lignite and limestone	Yes	10 to 30
Texas coastal uplands or Mississippi embayment aquifer system	Cretaceous to Tertiary	Downdip areas with low permeability and less freshwater circulation	Alluvial and marine	Sand, silt, clay	Yes	10 to 30
Northern Atlantic Coastal Plain or Castle Hayne aquifer system	Cretaceous to present	Transition zone along coast; where flow paths are longer (deeper and toward coast), mixing with seawater	Alluvial and marine	Mostly semiconsolidated sand with clay layers; limestone	Yes	15
Surficial aquifer system (Florida)	Miocene and younger	Near coastline, areas where residual seawater has not been flushed; areas with upward leakage from underlying aquifers	Alluvial and marine	Unconsolidated sand, shelly sand, and some limestone	No	0.005 to 30
Biscayne aquifer	Pliocene and younger	Along coastline	Marine	Limestone, sandstone, and sand	No	15
Intermediate aquifer system	Miocene	Transition zone toward coastline and with depth because of interaquifer leakage or seawater intrusion	Marine	Limestone, sandstone, dolomite, and sand	Yes	--
Floridan aquifer system	Tertiary	Broad transition zones between freshwater near recharge zones and higher salinity water closer to the coastlines; transition zones where there is lateral seawater encroachment along the coastlines, upward leakage through faults and fractures, or the presence of ancient seawater or brine that has not been flushed out from the active freshwater flow system	Marine	Mostly carbonate rocks; limestone and dolomite grading into mixed carbonate-clastic and then entirely clastic facies in updip areas of the system	Yes	--
Southeastern Coastal Plain aquifer system	Paleocene to Tertiary	Transition zone toward downdip areas or where there is ancient seawater or brine that has not been fully flushed out of the freshwater flow system	Fluvial, deltaic, and marginal marine	Primarily sand beds with some gravel and limestone	Yes	15 to 20

[1] Sand and gravel aquifers of alluvial or glacial origin contain substantial amounts of brackish groundwater but typically are smaller in extent and not included in this table.

[2] Obtained from previously published work.

[3] Obtained from data compiled for this assessment.

[4] Well yield results should be used with caution if few values are available for an aquifer.

[5] Data are from reported pumping rates and not potential well yields; therefore, results probably represent minimum values.

Storage coefficient or specific storage where noted (confined aquifers)[2]	Presence of secondary porosity[2]	Presence of evaporites[2]	Number of brackish wells with a reported well yield[3,4]	Median well yield at brackish wells, in gal/min[3,5]	Interquartile range of well yield at brackish wells, in gal/min[3,5]	References
1×10^{-4} to 1.7×10^{-3}	No	Minimal in upper 4,000 ft	448	25	15 to 200	Heath (1984), Ryder (1995), Grubb (1998), Martin and Whiteman (1999), Ryder and Ardis (2002).
2.5×10^{-5} to 1.7×10^{-3}	No	Minimal in upper 4,000 ft	255	15	8 to 50	Heath (1984), Ryder (1995), Renken (1998), Arthur and Taylor (1998), Grubb (1998), Ryder and Ardis (2002).
1×10^{-4}	No	Yes	130	42	10 to 300	Heath (1984), Meisler (1989), Leahy and Martin (1993), Trapp and Horn (1997).
--	Yes (minor amounts)	--	18	4	1 to 10	Heath (1984), Miller (1990), Barr (1996), Schmerge (2001), Southwest Florida Water Management District (2006), Reese and Wacker (2009), Sepúlveda and others (2012).
--	Yes	--	3	<1	<1 to 2	Miller (1990), Bolster and others (2001).
6×10^{-6} to 6.2×10^{-4}	Yes	--	8	88	45 to 182	Miller (1990), Duerr and Enos (1991), Barr (1996), Schmerge (2001).
Median storage coefficient from 646 aquifer tests 4×10^{-4}	Yes	Within less permeable units between the Upper and Lower Floridan aquifers and in south Florida within the Lower Floridan aquifer and below system	44	265	95 to 610	Miller (1990), Reese (1994, 2004), Sepúlveda and others (2012), Kuniansky and Bellino (2012), Lester Williams (U.S. Geological Survey, written commun., 2013).
1×10^{-4} to 0.1 (average = 4×10^{-3})	Yes	--	22	53	16 to 100	Heath (1984), Miller (1990), Miller (1992), Lee (1993), Barker and Pernik (1994), Lester Williams (U.S. Geological Survey, written commun., 2013).

saline water is present at depth and along coastal areas. The shallower aquifers above the Floridan aquifer system tend to contain freshwater except near the coast. Salinity within the aquifer system is probably from remnant seawater and evaporite units along with typical lateral encroachment of seawater along the coast.

This region is primarily within humid climate zones, and rainfall is plentiful. Regional groundwater recharge is mostly from precipitation and generally happens in upland areas and where aquifers are unconfined. For the layered, dipping aquifers that are present across much of the region, recharge is primarily along the updip end of the geologic formations, where they outcrop in a series of bands that are about parallel to the modern coast or the embayment and to a lesser degree by downward seepage across the interbedded layers (Heath, 1984; Ryder, 1995; Trapp and Horn, 1997). Within the predominantly clastic aquifers, recharged water generally flows downgradient and discharges to the Atlantic Ocean, the Gulf of Mexico, primary rivers, or springs (Heath, 1984; Miller, 1990). The downgradient movement is slowed by the thickening of clay layers that cause longer residence times and less flushing of mineralized groundwater with freshwater. As a result, groundwater flow converges, discharging to major downdip streams (Heath, 1984).

For the Floridan aquifer system, composed of carbonate rocks, water mainly is recharged either in updip outcrop areas and over the central part of the peninsula directly into limestone where it outcrops or by seepage through soils that overlie the limestone (Heath, 1984; Williams and Kuniansky, 2016). Recharge moves fairly rapidly to major springs and rivers and downdip toward the coast. In southern Florida, this movement is slowed by the thickening of all units downdip, including the upper confining unit above the Floridan aquifer system (Williams and Kuniansky, 2016). Longer residence times of groundwater within deep parts of the Floridan aquifer system and in southern Florida allow more time for dissolution of rock and minimize flushing of mineralized groundwater by fresher groundwater.

Where the flow system has been unaltered, groundwater salinity generally increases with depth and away from recharge areas (Meisler, 1989; Ryder, 1995; Trapp and Horn, 1997; Grubb, 1998); however, high dissolved-solids concentrations can exist at shallow depths where groundwater from deep in the system moves upward and discharges to the shallow system (Meisler, 1989). In areas of substantial groundwater pumpage, the natural flow system and salinity patterns have changed (Ryder, 1995). In the Texas coastal uplands aquifer, for example, recharge rates in outcrop areas are estimated to have increased by about 1 to 3 inches per year because of pumpage (Ryder, 1995). This increased circulation of freshwater can affect the distribution of saline groundwater. In addition, seawater has migrated inland in some areas where well pumpage has reversed the natural flow direction of groundwater toward the coast (Miller, 1990; Trapp and Horn, 1997).

Aquifer hydraulic properties affect the ability of aquifers to yield and store groundwater and therefore affect the occurrence of BGW. Aquifer properties in this region are affected by depositional environment, secondary porosity, and postdepositional marine processes. Sediments typically are coarser near source areas, whereas clay and silt deposits associated with sluggish groundwater flow are more common downdip (Heath, 1984). Solution openings are common in carbonate formations, allowing large yields and rapid circulation of freshwater (Miller, 1990). Past inundations by the sea have reworked previously deposited sediments, resulting in complex interbedding that can potentially impede groundwater flow (Heath, 1984). Hydraulic properties (specific yield, storage coefficient, and specific storage) were compiled from previously published reports. This compilation indicated that specific yield was generally between 10 and 30 percent for most of the unconfined aquifers in this region and that storage coefficients for confined aquifers were highly variable, ranging over several orders of magnitude (table 9). The median storage coefficient from 646 aquifer tests of the Floridan aquifer system was 4×10^{-4}.

Distribution of Dissolved Solids

Dissolved-solids concentrations were available for about 67,000 wells in this region (fig. 22; table 4). Based on samples from those wells, most BGW is in Texas and southern Florida. More than one-half of the wells were sampled between 50 and 500 ft below land surface (table 4). The median dissolved-solids concentration increased slightly with depth. The percentage of sampled wells producing BGW was largest (19 percent) between 500 and 1,500 ft below land surface. At depths >1,500 ft below land surface, 18 percent of the wells had a dissolved-solids concentration within the brackish range, and another 18 percent had a dissolved-solids concentration greater than the brackish range. About 23 percent of the grid cell volume (including air, water, and rock) in the Coastal Plains region contained BGW for areas where dissolved-solids concentrations were available. The total grid cell volume within this region observed to contain BGW was nearly 15,000 mi^3, mostly existing between 50 and 1,500 ft below land surface (table 4); however, the actual volume of water that could be extracted for use probably is much smaller. Assuming that 1 percent of that volume can actually be extracted, the volume of available BGW is about 150 mi^3, or 507 million acre-feet.

The amount of observed BGW varied among principal aquifers of this region. More than 20 percent of the sampled wells from the Intermediate and Coastal lowlands aquifer systems produced BGW (table 8). For other principal aquifers, the percentage of sampled wells producing BGW ranged from 4 to 14 percent. The median depth of sampled wells that produced BGW ranged from 45 ft below land surface in the surficial aquifer system to 760 ft below land surface in the Southeastern Coastal Plain aquifer system (table 8). The percentage of

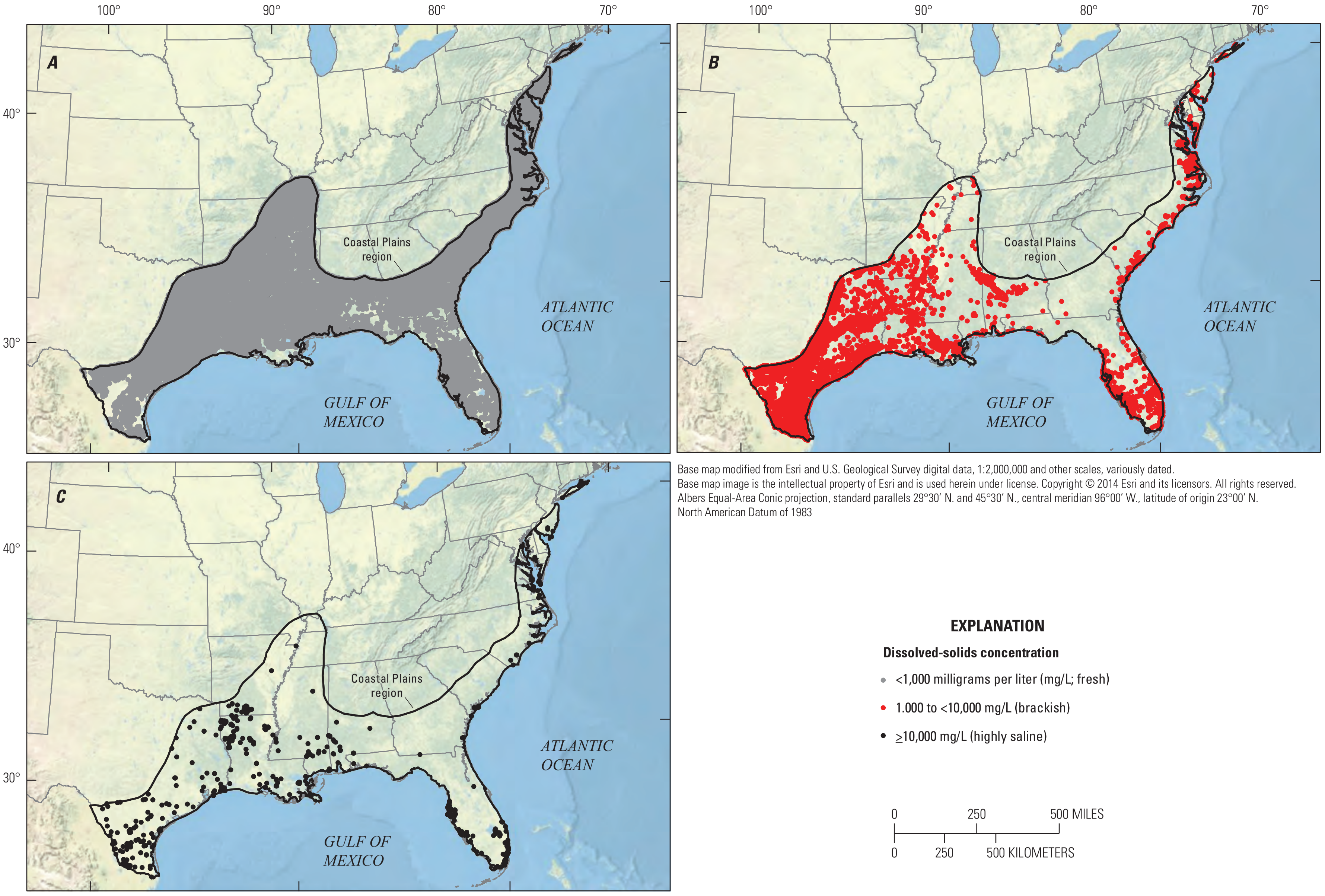


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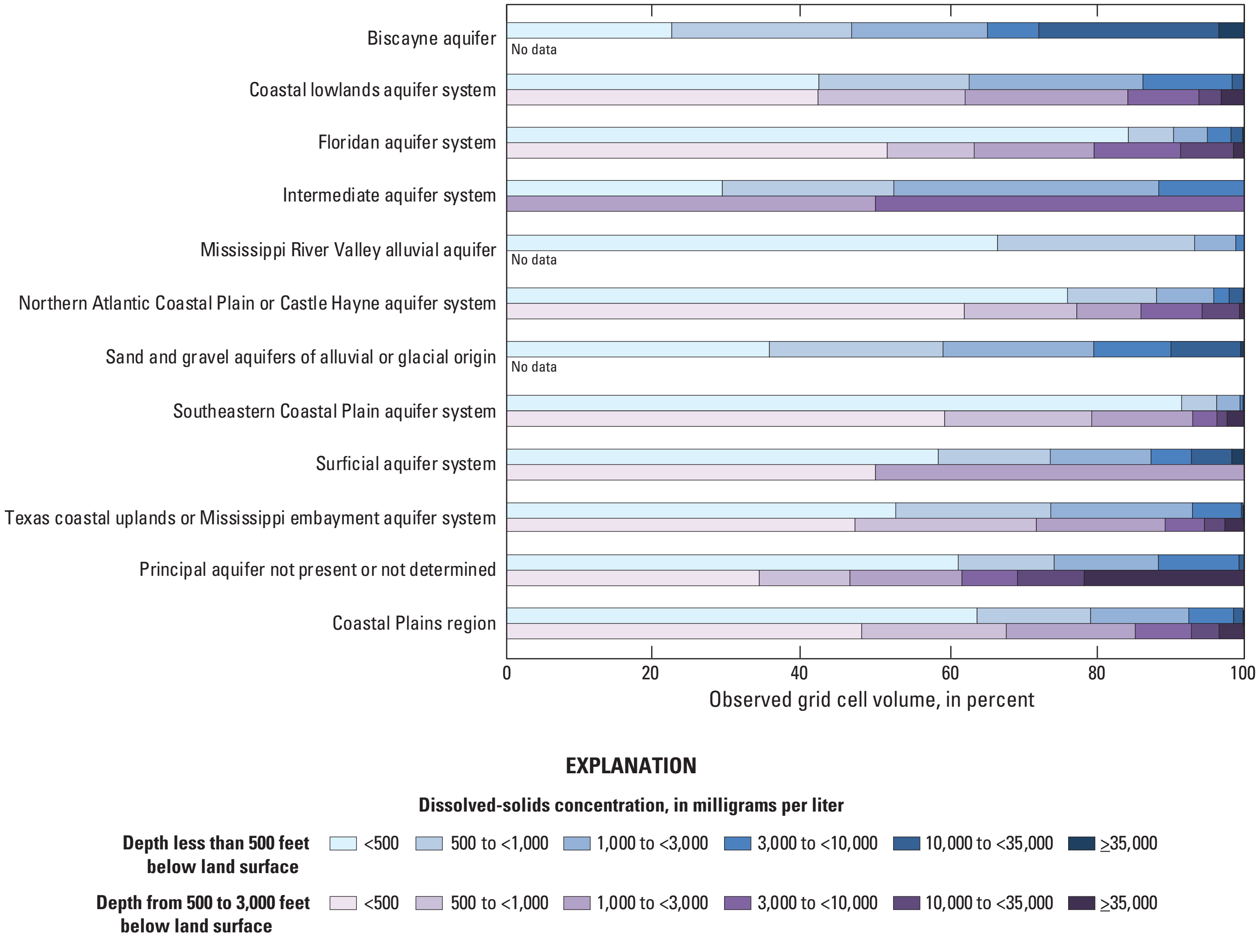
Figure 22. Locations of wells producing *A*, fresh; *B*, brackish; and *C*, highly saline groundwater from 0 to 3,000 feet below land surface in the Coastal Plains region.

grid cell volume containing BGW ranged from 7 to 53 percent among principal aquifers in this region (table 8); the Intermediate aquifer system contained the greatest percentage.

The distribution of categories of dissolved-solids concentrations across the region as a percentage of observed grid cell volume was determined for two depth intervals—<500 ft below land surface and between 500 and 3,000 ft below land surface. For depths as much as 500 ft below land surface in this region, about 80 percent of the observed grid cell volume was freshwater (<1,000 mg/L of dissolved solids), about 65 percent was less than the EPA secondary maximum contaminant level (500 mg/L of dissolved solids), about 15 percent was slightly saline (1,000 to 3,000 mg/L of dissolved solids), about 5 percent was moderately saline (3,000 to 10,000 mg/L of dissolved solids), and <5 percent was highly saline (>10,000 mg/L of dissolved solids; fig. 23). Below 500 feet, the percentages of grid cell volume for slightly saline and moderately saline groundwater were about the same, but the grid cell volume of freshwater decreased to about 70 percent, and the percentage of highly saline groundwater was slightly larger. For depths <500 ft below land surface, the Intermediate and Coastal lowlands aquifer systems had the largest percentages of brackish (slightly saline and moderately saline) groundwater volume. For depths between 500 and 3,000 ft below land surface, the principal aquifers with the largest percentages of grid cell volume for slightly saline groundwater were the Intermediate, surficial, and Coastal lowlands aquifer systems. The principal aquifer with the largest percentage of moderately saline groundwater was the Intermediate aquifer system.



Note: Volumes are based on grid cells that have been categorized by using the maximum dissolved-solids concentration in each cell.

Figure 23. Distribution of dissolved-solids concentrations as a percentage of observed grid cell volume, by principal aquifer and depth, in the Coastal Plains region.

Considerations for Developing Brackish Groundwater

In addition to limitations caused by high dissolved-solids concentrations, other chemical constituents can affect the usefulness of BGW. Primary processes that may affect the distribution of specific chemical constituents in the upper 3,000 ft of the subsurface in the Coastal Plains region include mixing with seawater (present day or prehistoric) or groundwater from underlying units, cation exchange, and dissolution of minerals in the unsaturated and saturated zones (Trapp and Horn, 1997; Grubb, 1998). The evolution of chemical water types is similar among the layered, dipping formations that compose most of this region's aquifers, shifting from a mostly calcium, magnesium, or sodium bicarbonate water type near the outcrop (recharge) areas to a sodium bicarbonate water type in middip areas and finally to a sodium chloride water type near the downdip end of the aquifers. This shift in the geochemical character of the groundwater is accompanied by an increase in dissolved-solids concentrations.

Data compiled for this assessment indicate that BGW contained specific constituents that can limit its use (fig. 24; tables 10, 11, and 12). Because BGW will usually be treated before use for drinking water, many of the chemical constituents that exceed water-quality standards for that use will be removed during desalination; however, the presence of large amounts of those constituents in the concentrated brine created as a byproduct of desalination can pose a challenge for disposal. In addition, some constituents, such as boron and arsenic, are not removed as easily as other constituents with common desalination methods. Constituents most likely to be present in untreated BGW in this region at concentrations that are greater than selected EPA primary drinking-water standards are arsenic (primarily in the surficial aquifer system and sand and gravel aquifers of alluvial or glacial origin) and nitrate (primarily in the sand and gravel aquifers of alluvial or glacial origin; table 10). Boron, fluoride, and iron concentrations in untreated BGW are the constituents more likely to be problematic for livestock consumption in some aquifers (table 11). Arsenic, boron, fluoride, and iron are of potential concern where untreated BGW from most of the principal aquifers is used for irrigation (table 12). Most of the BGW samples that exceeded selected water-quality standards are in southern Texas (fig. 24).

In addition to water quality considerations for developing BGW for use, it is also important to account for the ability of aquifers with BGW to yield usable amounts of water. Median well yields from data compiled for this assessment were larger for wells producing freshwater (75 gal/min) than for wells that produced brackish (20 gal/min) or highly saline (30 gal/min) groundwater in this region (table 13). About 24 percent of wells producing BGW had a yield >100 gal/min, and <1 percent of wells producing BGW had a yield >1,000 gal/min. The largest median yields of wells producing BGW were in the Floridan (265 gal/min), Intermediate (88 gal/min), Southeastern Coastal Plain (53 gal/min), and Northern Atlantic Coastal Plain or Castle Hayne (42 gal/min) aquifer systems (fig. 6; table 9). Although data were sparse below depths of about 1,000 ft below land surface, available data indicated that wells in the deeper intervals in this region were able to yield ≥10 gal/min and may be able to yield ≥1,000 gal/min in some areas (fig. 25).

Saline Groundwater Use

Amounts of saline groundwater use were estimated for each of the principal aquifers within this region by using a combination of data compiled as part of this assessment and data from the USGS Water-Use Program. According to these estimates, the Texas coastal uplands or Mississippi embayment aquifer system and the Coastal lowlands aquifer system provided the most saline groundwater for use in this region (fig. 26). Saline groundwater was most commonly used for mining and public supply, and smaller amounts were used for thermoelectric and industrial purposes. More than 60 percent of the 276 groundwater-sourced municipal desalination facilities in the United States reported by Mickley (2012) are within this region, mostly in Florida (fig. 2).

Eastern Midcontinent Region

The Eastern Midcontinent region extends westward from the Valley and Ridge Province of the Appalachian Mountains to about the eastern extent of the Cretaceous seas and southward from the Great Lakes region to (but not including) the Mississippi embayment of the Coastal Plains region (fig. 7). Groundwater salinity in the aquifers of this region primarily is affected by dissolution of evaporites or carbonate rocks; mixing with deeper, more highly saline water and brines in areas associated with evaporite deposits; and factors that affect residence time and potential for dissolution, such as proximity to recharge areas, depth of groundwater circulation, and permeability (Ells, 1979; Heath, 1984; Hem, 1989; Trapp and Horn, 1997; Sheets and Kozar, 2000). A total of 13 principal aquifers are mostly within this region (fig. 27). Nine of those aquifers contained substantial amounts of BGW because at least 10 percent of their observed grid cell volume contained BGW (table 8).

Hydrogeologic Characteristics

Most of the Eastern Midcontinent region is flat or gently sloping and is underlain by rock layers that are horizontal or gently dipping. Primary exceptions are the Valley and Ridge physiographic province of the Appalachian Mountains and the Ouachita Mountains in Oklahoma and Arkansas (fig. 28). The northern part of the region has been glaciated multiple times, leaving behind a layer of unconsolidated glacial-drift deposits of various thicknesses that overlie mainly consolidated sedimentary rocks. The underlying consolidated sedimentary rocks are primarily Paleozoic in age but range from Paleozoic to Tertiary (King and Beikman, 1974; Schruben and others, 1998). The rock lithology consists largely of sandstone,

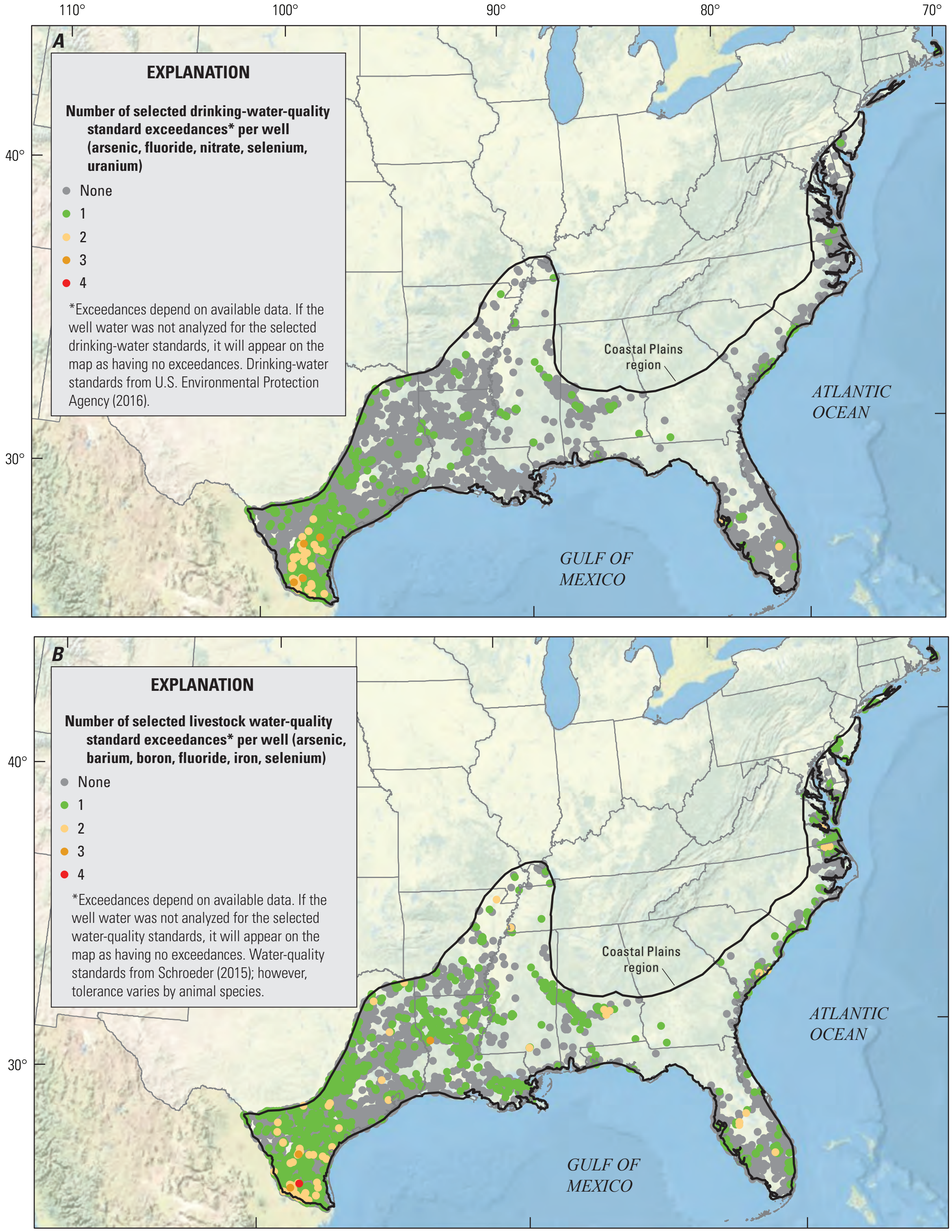


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Figure 24. Locations of wells producing brackish groundwater that exceeds selected water-quality standards in the Coastal Plains region. *A*, drinking water; *B*, livestock consumption; *C*, irrigation uses.

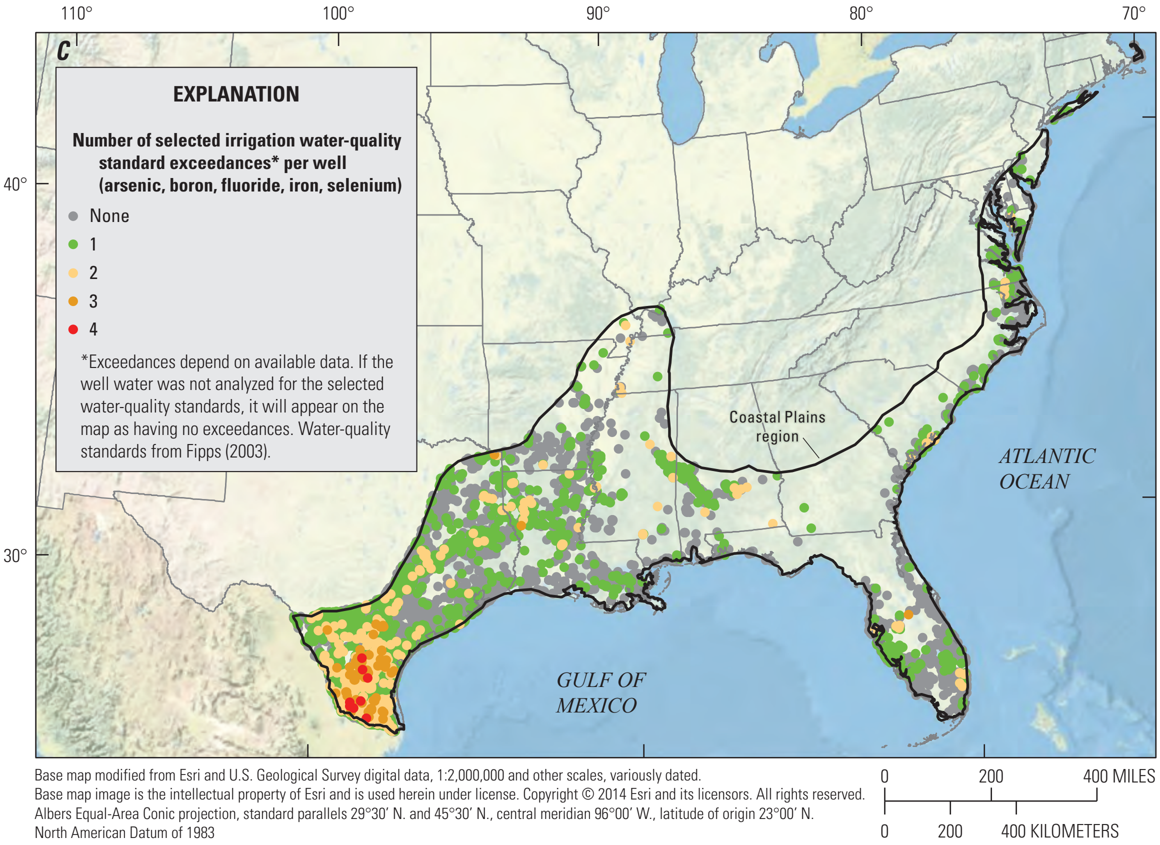

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Figure 24. Locations of wells producing brackish groundwater that exceeds selected water-quality standards in the Coastal Plains region. *A*, drinking water; *B*, livestock consumption; *C*, irrigation uses.—Continued

carbonate rocks (limestone and dolomite), shale, and conglomerate (Heath, 1984). Other rock units include evaporites and coal. Some units contain oil and natural gas.

The presence of large quantities of BGW in this region is related to inland embayments of the sea and evaporative basins where thick layers of sedimentary rock, including evaporite deposits (and related groundwater brines), were formed (table 14). Many of these consolidated Paleozoic sedimentary rocks were originally deposited within embayments of the sea. The sediments thicken toward the centers of several large structural basins that were once the deepest parts of the embayments. These large basins include the Appalachian, Michigan, and Illinois Basins (fig. 28; Swezey, 2002, 2008, 2009). These three basins are examples of intracratonic basins (well away from the plate margin). These basins may have been enhanced by subsidence of reactivated Midcontinent Rift during the Paleozoic Era (Catacosinos and others, 1996). Sediments more than 2.5 mi thick were deposited within the Michigan Basin (Olcott, 1992, fig. 14). Similarly, the depth to the bottom of the Appalachian Basin is >7 mi at its deepest point (Gold and others, 2005), and the Illinois Basin has consolidated sediments >2 mi thick (Swann, 1968).

Beneath the Paleozoic rocks are Precambrian metasedimentary and igneous basement rocks (Swezey, 2002, 2008, 2009). These basement rocks made up the continental plate or craton upon which the Paleozoic sedimentary rocks were deposited. Among the thick sequences of sedimentary rocks, a great variety of lithologies is represented; for example, carbon-rich layers, especially those deposited during the Carboniferous Period (late Paleozoic Era), resulted in layers known for coal, oil, and natural gas production. Layers such as shale, limestone, dolomite, and even cemented sandstone may act as confining units when secondary permeability is lacking. Fractured sandstone, on the other hand, composes the main water-transmitting layers of many of the aquifers (Olcott, 1992; Trapp and Horn, 1997).

Most of the region receives precipitation that is adequate to supply freshwater use and recharge aquifers. For this reason, there is typically an upper freshwater zone of groundwater above any BGW zone. Groundwater flow patterns vary throughout the region. In the western part of the region, groundwater can travel long distances eastward along extensive flow paths that originate outside of the region to the west. These flow paths eventually discharge to streams and rivers within the region, including the Missouri and Mississippi Rivers (fig. 28). Nearer these regional sinks, a component of groundwater flow is upwards, which brings the BGW to shallower depths.

Table 10. Percentage of brackish groundwater samples that exceed selected water-quality standards for drinking water, by brackish groundwater region.

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]									
	Arsenic 10 µg/L		Fluoride 4 mg/L		Nitrate 10 mg/L		Selenium 50 µg/L		Uranium 30 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Coastal Plains										
Biscayne aquifer	15	13	24	<1	26	0	6	0	3	0
Coastal Lowlands aquifer system	1,086	18	1,549	2	1,863	6	1,084	<1	858	5
Floridan aquifer system	23	4	225	5	113	0	13	0	10	0
Intermediate aquifer system	1	0	55	2	16	0	--	--	1	0
Mississippi River Valley alluvial aquifer	9	11	36	<1	42	2	3	0	--	--
Northern Atlantic Coastal Plain or Castle Hayne aquifer system	45	9	304	1	210	0	46	0	24	0
Sand and gravel aquifers of alluvial or glacial origin	14	21	49	0	67	28	14	0	1	0
Southeastern Coastal Plain aquifer system	7	14	151	17	82	1	7	0	1	0
Surficial aquifer system (Florida)	21	48	62	3	74	3	4	0	3	0
Texas coastal uplands or Mississippi embayment aquifer system	635	<1	884	3	1,027	4	630	<1	474	2
Principal aquifer not present or not determined	652	15	122	2	95	3	652	<1	636	3
Eastern Midcontinent										
Cambrian-Ordovician aquifer system	144	0	282	2	270	1	98	0	35	0
Jacobsville aquifer	--	--	--	--	--	--	--	--	--	--
Marshall aquifer	16	6	23	0	13	0	5	0	2	0
Mississippian aquifers	37	0	336	6	317	4	32	0	9	0
New York and New England carbonate-rock aquifers	7	0	59	0	54	0	8	0	6	0
New York sandstone aquifers	--	--	--	--	1	0	1	0	--	--
Ordovician aquifers	6	0	24	21	23	0	4	0	--	--
Ozark Plateaus aquifer system	58	36	178	8	182	5	39	0	21	5
Pennsylvanian aquifers	113	7	249	12	238	2	43	2	13	0

Table 10. Percentage of brackish groundwater samples that exceed selected water-quality standards for drinking water, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

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	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Eastern Midcontinent—Continued										
Sand and gravel aquifers of alluvial or glacial origin	92	16	259	0	322	19	80	0	18	6
Silurian-Devonian aquifers	124	2	314	1	310	<1	70	0	23	0
Upper carbonate aquifer (Paleozoic)	--	--	--	--	--	--	--	--	--	--
Valley and Ridge aquifers	9	11	21	0	26	8	5	0	4	0
Principal aquifer not present or not determined	423	3	801	6	645	14	358	0	299	2
Southwestern Basins										
Basin and Range basin-fill aquifers	654	41	1,884	17	1,602	23	307	<1	109	21
Basin and Range carbonate-rock aquifers	14	0	38	5	28	0	7	0	6	0
California Coastal Basin aquifers	166	11	556	<1	599	19	48	4	30	43
Central Valley aquifer system	277	18	498	1	668	22	292	16	93	51
Rio Grande aquifer system	140	19	751	5	438	5	115	0	63	14
Sand and gravel aquifers of alluvial or glacial origin	1	0	2	0	4	25	1	0	--	--
Southern Nevada volcanic-rock aquifers	--	--	--	--	--	--	--	--	--	--
Principal aquifer not present or not determined	290	14	799	14	563	14	160	1	171	5
Western Midcontinent										
Ada-Vamoosa aquifer	25	0	15	13	10	0	18	0	21	0
Arbuckle-Simpson aquifer	4	0	2	0	1	0	4	0	4	0
Blaine aquifer	88	0	206	<1	294	16	83	16	33	9
Central Oklahoma aquifer	82	2	61	2	87	24	55	4	78	19
Colorado Plateaus aquifers	234	15	719	9	660	4	264	7	92	7
Denver Basin aquifer system	103	5	225	1	329	37	112	12	105	32
Edwards-Trinity aquifer system	604	2	2,281	11	2,421	8	557	1	269	7

Table 10. Percentage of brackish groundwater samples that exceed selected water-quality standards for drinking water, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

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	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Western Midcontinent—Continued										
High Plains aquifer	412	49	929	32	1,080	28	397	16	241	26
Lower Cretaceous aquifers	550	1	1,340	13	1,328	4	561	2	519	4
Lower Tertiary aquifers	621	2	2,707	7	2,388	4	679	1	711	10
Paleozoic aquifers	23	0	74	3	68	0	21	0	17	6
Pecos River Basin alluvial aquifer	116	3	362	2	586	11	116	2	15	0
Roswell Basin aquifer system	--	--	2	0	1	0	--	--	5	0
Rush Springs aquifer	82	1	31	3	71	20	74	0	57	19
Sand and gravel aquifers of alluvial or glacial origin	829	3	3,251	1	3,742	18	872	3	535	15
Seymour aquifer	22	0	323	3	339	50	22	0	7	0
Upper Cretaceous aquifers	655	1	1,515	9	1,585	4	730	3	621	9
Western Interior Plains aquifer system	2	0	23	43	36	11	2	0	1	0
Wyoming (Upper) Tertiary aquifers	--	--	6	0	7	14	--	--	--	--
Principal aquifer not present or not determined	4,368	3	3,558	4	3,838	22	4,362	1	5,393	12
Eastern Mountains and Uplands										
Early Mesozoic basin aquifers	13	15	27	15	37	3	6	0	7	0
New York and New England crystalline-rock aquifers	3	33	7	0	8	13	2	0	--	--
Piedmont and Blue Ridge carbonate-rock aquifers	7	29	8	0	14	14	5	0	2	50
Sand and gravel aquifers of alluvial or glacial origin	10	0	42	0	46	13	9	0	1	0
Principal aquifer not present or not determined	114	6	36	0	39	13	114	0	114	5
Northwestern Volcanics										
Columbia Plateau basin-fill aquifers	2	0	9	0	13	69	2	0	--	--
Columbia Plateau basaltic-rock aquifers	2	50	9	0	11	64	2	0	2	0

Table 10. Percentage of brackish groundwater samples that exceed selected water-quality standards for drinking water, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]									
	Arsenic 10 µg/L		Fluoride 4 mg/L		Nitrate 10 mg/L		Selenium 50 µg/L		Uranium 30 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Northwestern Volcanics—Continued										
Pacific Northwestern volcanic rock or basin-fill aquifers	2	0	5	0	6	0	2	0	1	0
Sand and gravel aquifers of alluvial or glacial origin	1	100	1	100	1	0	1	0	--	--
Snake River Plain volcanic rock or basin-fill aquifers	9	78	10	0	17	35	6	33	--	--
Principal aquifer not present or not determined	38	47	87	2	65	45	31	7	11	82
Western Mountain Ranges										
Northern Rocky Mountains Intermontane Basins aquifer systems	15	27	27	4	25	8	8	0	2	50
Puget Sound aquifer system	--	--	--	--	--	--	--	--	--	--
Sand and gravel aquifers of alluvial or glacial origin	8	13	6	17	9	0	2	0	--	--
Willamette Lowland basin-fill aquifers	2	0	2	0	2	0	--	--	--	--
Principal aquifer not present or not determined	41	10	86	6	66	6	15	0	12	8
Alaska										
All groundwater resources	19	32	31	3	40	10	1	0	1	0
Hawaii										
All groundwater resources	7	0	17	0	13	0	7	0	7	0
U.S. Territories										
Groundwater resources in Puerto Rico	8	13	62	3	26	4	7	0	1	0
Groundwater resources in the U.S. Virgin Islands	13	8	21	0	13	8	13	0	--	--

[1] In some cases the principal aquifer may extend into other brackish groundwater regions; data reported here are for the entire principal aquifer.

[2] Primary drinking-water standards from U.S. Environmental Protection Agency (2016).

Table 11. Percentage of brackish groundwater samples that exceed selected water-quality standards for livestock consumption, by brackish groundwater region.

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]											
	Arsenic 50 µg/L		Barium 10 mg/L		Boron 5 mg/L		Fluoride 2 mg/L		Iron 2 mg/L		Selenium 50 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Coastal Plains												
Biscayne aquifer	15	0	14	0	6	0	6	0	29	48	6	0
Coastal Lowlands aquifer system	1,086	2	1,106	<1	1,482	8	1,482	8	1,655	6	1,084	<1
Floridan aquifer system	23	0	34	0	39	0	39	0	169	8	13	0
Intermediate aquifer system	1	0	3	0	14	0	14	0	19	0	--	--
Mississippi River Valley alluvial aquifer	9	11	8	0	12	0	12	0	60	48	3	0
Northern Atlantic Coastal Plain or Castle Hayne aquifer system	45	0	74	0	61	3	61	3	336	35	46	0
Sand and gravel aquifers of alluvial or glacial origin	14	0	14	0	11	9	11	9	38	39	14	0
Southeastern Coastal Plain aquifer system	7	0	7	0	7	29	7	29	122	16	7	0
Surficial aquifer system (Florida)	21	19	4	0	10	0	10	0	56	20	4	0
Texas coastal uplands or Mississippi embayment aquifer system	635	0	642	<1	736	4	736	4	1,120	13	630	<1
Principal aquifer not present or not determined	652	2	651	0	656	9	656	9	695	2	652	<1
Eastern Midcontinent												
Cambrian-Ordovician aquifer system	144	0	144	0	110	1	282	34	332	21	98	0
Jacobsville aquifer	--	--	--	--	--	--	--	--	--	--	--	--
Marshall aquifer	16	0	16	0	13	0	23	0	23	22	5	0
Mississippian aquifers	37	0	37	0	7	0	336	23	343	38	32	0
New York and New England carbonate-rock aquifers	7	0	7	0	6	0	59	3	50	8	8	0
New York sandstone aquifers	--	--	--	--	--	--	--	--	--	--	1	0
Ordovician aquifers	6	0	6	0	4	0	24	42	25	12	4	0
Ozark Plateaus aquifer system	58	21	58	21	77	0	178	24	215	18	39	0
Pennsylvanian aquifers	113	2	113	2	68	1	249	30	321	39	43	2
Sand and gravel aquifers of alluvial or glacial origin	92	3	92	3	49	2	259	1	332	42	80	0
Silurian-Devonian aquifers	124	0	124	0	99	0	314	15	340	34	70	0

Table 11. Percentage of brackish groundwater samples that exceed selected water-quality standards for livestock consumption, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]											
	Arsenic 50 µg/L		Barium 10 mg/L		Boron 5 mg/L		Fluoride 2 mg/L		Iron 2 mg/L		Selenium 50 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Eastern Midcontinent—Continued												
Upper carbonate aquifer (Paleozoic)	--	--	--	--	--	--	--	--	--	--	--	--
Valley and Ridge aquifers	9	0	9	0	8	0	21	14	26	38	5	0
Principal aquifer not present or not determined	423	<1	423	<1	381	1	801	17	1,102	16	358	0
Southwestern Basins												
Basin and Range basin-fill aquifers	654	18	444	0	1,079	13	1,884	35	1,063	4	307	<1
Basin and Range carbonate-rock aquifers	14	0	3	0	22	0	38	11	27	4	7	0
California Coastal Basin aquifers	166	1	270	0	584	4	556	4	484	8	48	4
Central Valley aquifer system	277	6	175	0	1,024	10	498	4	344	9	292	16
Rio Grande aquifer system	140	<1	166	0	197	0	751	15	211	4	115	0
Sand and gravel aquifers of alluvial or glacial origin	1	0	1	0	1	0	2	0	2	0	1	0
Southern Nevada volcanic-rock aquifers	--	--	--	--	--	--	--	--	--	--	--	--
Principal aquifer not present or not determined	290	7	287	0	537	4	799	31	536	7	160	1
Western Midcontinent												
Ada-Vamoosa aquifer	25	0	22	0	27	15	15	33	31	0	18	0
Arbuckle-Simpson aquifer	4	0	4	0	4	25	2	0	5	20	4	0
Blaine aquifer	88	0	94	0	125	3	206	2	103	6	83	16
Central Oklahoma aquifer	82	1	80	0	85	14	61	10	105	5	55	4
Colorado Plateaus aquifers	234	3	136	0	490	3	719	27	571	12	264	7
Denver Basin aquifer system	103	1	98	0	159	0	225	7	294	7	112	12
Edwards-Trinity aquifer system	604	0	598	0	613	5	2,281	53	1,008	7	557	1
High Plains aquifer	412	5	399	0	449	<1	929	63	550	3	397	16
Lower Cretaceous aquifers	550	<1	522	0	1,133	4	1,340	50	1,766	26	561	2
Lower Tertiary aquifers	621	<1	816	0	2,289	<1	2,707	19	3,295	13	679	1
Paleozoic aquifers	23	0	18	0	64	0	74	43	73	26	21	0
Pecos River Basin alluvial aquifer	116	0	117	0	148	0	362	28	140	3	116	2

Table 11. Percentage of brackish groundwater samples that exceed selected water-quality standards for livestock consumption, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]											
	Arsenic 50 µg/L		Barium 10 mg/L		Boron 5 mg/L		Fluoride 2 mg/L		Iron 2 mg/L		Selenium 50 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Western Midcontinent—Continued												
Roswell Basin aquifer system	--	--	6	0	6	0	2	0	6	17	--	--
Rush Springs aquifer	82	0	84	0	95	0	31	3	87	1	74	0
Sand and gravel aquifers of alluvial or glacial origin	829	0	729	0	2,710	<1	3,251	6	3,376	24	872	3
Seymour aquifer	22	0	25	0	43	0	323	16	46	2	22	0
Upper Cretaceous aquifers	655	<1	716	0	1,720	2	1,515	25	2,204	10	730	3
Western Interior Plains aquifer system	2	0	2	0	8	13	23	52	17	18	2	0
Wyoming (Upper) Tertiary aquifers	--	--	--	--	6	0	6	17	3	33	--	--
Principal aquifer not present or not determined	4,368	<1	4,997	<1	5,725	1	3,558	21	6,804	7	4,362	1
Eastern Mountains and Uplands												
Early Mesozoic basin aquifers	13	0	13	0	11	9	27	15	36	8	6	0
New York and New England crystalline-rock aquifers	3	33	2	0	3	0	7	0	7	14	2	0
Piedmont and Blue Ridge carbonate-rock aquifers	7	0	5	0	3	0	8	0	15	53	5	0
Sand and gravel aquifers of alluvial or glacial origin	10	0	11	0	29	0	42	2	47	30	9	0
Principal aquifer not present or not determined	114	0	116	0	145	0	36	3	153	10	114	0
Northwestern Volcanics												
Columbia Plateau basin-fill aquifers	2	0	1	0	4	0	9	0	8	13	2	0
Columbia Plateau basaltic-rock aquifers	2	0	2	0	4	0	9	0	7	0	2	0
Pacific Northwestern volcanic rock or basin-fill aquifers	2	0	2	0	1	0	5	0	4	25	2	0
Sand and gravel aquifers of alluvial or glacial origin	1	100	1	0	1	100	1	100	1	0	1	0
Snake River Plain volcanic rock or basin-fill aquifers	9	22	--	--	2	0	10	0	5	0	6	33
Principal aquifer not present or not determined	38	13	11	0	13	0	87	5	51	12	31	7

Table 11. Percentage of brackish groundwater samples that exceed selected water-quality standards for livestock consumption, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; <, less than; --, no brackish sample had a reported result for the chemical constituent]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]											
	Arsenic 50 µg/L		Barium 10 mg/L		Boron 5 mg/L		Fluoride 2 mg/L		Iron 2 mg/L		Selenium 50 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Western Mountain Ranges												
Northern Rocky Mountains Intermontane Basins aquifer systems	15	0	11	0	19	5	27	7	26	15	8	0
Puget Sound aquifer system	--	--	--	--	--	--	--	--	--	--	--	--
Sand and gravel aquifers of alluvial or glacial origin	8	13	7	0	3	0	6	17	11	0	2	0
Willamette Lowland basin-fill aquifers	2	0	--	--	2	0	2	0	2	0	--	--
Principal aquifer not present or not determined	41	2	19	0	60	2	86	15	90	32	15	0
Alaska												
All groundwater resources	19	5	3	0	4	0	31	6	43	51	1	0
Hawaii												
All groundwater resources	7	0	2	0	7	0	17	0	17	6	7	0
U.S. Territories												
Groundwater resources in Puerto Rico	8	0	10	0	15	0	62	3	29	10	7	0
Groundwater resources in the U.S. Virgin Islands	13	0	13	0	6	0	21	5	16	13	13	0

[1] In some cases the principal aquifer may extend into other brackish groundwater regions; data reported here are for the entire principal aquifer.

[2] Water-quality standards are for cattle (Schroeder, 2015); however, tolerance varies by animal species.

Table 12. Percentage of brackish groundwater samples that exceed selected water-quality standards for irrigation uses, by brackish groundwater region.

[µg/L, microgram per liter; mg/L, milligram per liter; --, no brackish sample had a reported result for the chemical constituent; <, less than]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]									
	Arsenic 10 µg/L		Boron 750 µg/L		Fluoride 1 mg/L		Iron 5 mg/L		Selenium 20 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Coastal Plains										
Biscayne aquifer	15	13	6	50	24	0	24	0	6	0
Coastal Lowlands aquifer system	1,086	18	1,482	67	1,549	38	1,549	38	1,084	2
Floridan aquifer system	23	4	39	18	225	59	225	59	13	0
Intermediate aquifer system	1	0	14	0	55	60	55	60	--	--
Mississippi River Valley alluvial aquifer	9	11	12	17	36	11	36	11	3	0
Northern Atlantic Coastal Plain or Castle Hayne aquifer system	45	9	61	34	304	30	304	30	46	0
Sand and gravel aquifers of alluvial or glacial origin	14	21	11	36	49	24	49	24	14	0
Southeastern Coastal Plain aquifer system	7	14	7	71	151	77	151	77	7	0
Surficial aquifer system (Florida)	21	48	10	10	62	18	62	18	4	0
Texas coastal uplands or Mississippi embayment aquifer system	635	<1	736	53	884	30	884	30	630	1
Principal aquifer not present or not determined	652	15	656	65	122	37	122	37	652	<1
Eastern Midcontinent										
Cambrian-Ordovician aquifer system	144	0	110	56	282	73	332	8	98	0
Jacobsville aquifer	--	--	--	--	--	--	--	--	--	--
Marshall aquifer	16	6	13	62	23	13	23	4	5	0
Mississippian aquifers	37	0	7	29	336	59	343	18	32	0
New York and New England carbonate-rock aquifers	7	0	6	17	59	39	50	6	8	0
New York sandstone aquifers	--	--	--	--	--	--	--	--	1	0
Ordovician aquifers	6	0	4	75	24	58	25	4	4	0
Ozark Plateaus aquifer system	58	36	77	16	178	44	215	10	39	0
Pennsylvanian aquifers	113	7	68	40	249	42	321	26	43	5
Sand and gravel aquifers of alluvial or glacial origin	92	16	49	22	259	7	332	26	80	1
Silurian-Devonian aquifers	124	2	99	20	314	52	340	15	70	0

Table 12. Percentage of brackish groundwater samples that exceed selected water-quality standards for irrigation uses, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; --, no brackish sample had a reported result for the chemical constituent; <, less than]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]									
	Arsenic 10 µg/L		Boron 750 µg/L		Fluoride 1 mg/L		Iron 5 mg/L		Selenium 20 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Eastern Midcontinent—Continued										
Upper carbonate aquifer (Paleozoic)	--	--	--	--	--	--	--	--	--	--
Valley and Ridge aquifers	9	11	8	38	21	38	26	35	5	0
Principal aquifer not present or not determined	423	3	381	28	801	36	1,102	8	358	0
Southwestern Basins										
Basin and Range basin-fill aquifers	654	41	1,079	61	1,884	56	1,063	3	307	6
Basin and Range carbonate-rock aquifers	14	0	22	5	38	24	27	0	7	0
California Coastal Basin aquifers	166	11	584	29	556	10	484	3	48	15
Central Valley aquifer system	277	18	1,024	81	498	13	344	7	292	25
Rio Grande aquifer system	140	19	197	18	751	34	211	2	115	2
Sand and gravel aquifers of alluvial or glacial origin	1	0	1	0	2	100	2	0	1	0
Southern Nevada volcanic-rock aquifers	--	--	--	--	--	--	--	--	--	--
Principal aquifer not present or not determined	290	14	537	23	799	54	536	5	160	6
Western Midcontinent										
Ada-Vamoosa aquifer	25	0	27	56	15	40	31	0	18	0
Arbuckle-Simpson aquifer	4	0	4	50	2	0	5	20	4	0
Blaine aquifer	88	0	125	44	206	13	103	2	83	39
Central Oklahoma aquifer	82	2	85	59	61	25	105	2	55	7
Colorado Plateaus aquifers	234	15	490	31	719	50	571	6	264	14
Denver Basin aquifer system	103	5	159	2	225	48	294	3	112	21
Edwards-Trinity aquifer system	604	2	613	53	2,281	79	1,008	3	557	4
High Plains aquifer	412	49	449	29	929	82	550	2	397	50
Lower Cretaceous aquifers	550	1	1,133	57	1,340	71	1,766	11	561	2
Lower Tertiary aquifers	621	2	2,289	26	2,707	36	3,295	6	679	2
Paleozoic aquifers	23	0	64	11	74	62	73	12	21	0
Pecos River Basin alluvial aquifer	116	3	148	13	362	73	140	<1	116	11

Table 12. Percentage of brackish groundwater samples that exceed selected water-quality standards for irrigation uses, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; --, no brackish sample had a reported result for the chemical constituent; <, less than]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]									
	Arsenic 10 µg/L		Boron 750 µg/L		Fluoride 1 mg/L		Iron 5 mg/L		Selenium 20 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Western Midcontinent—Continued										
Roswell Basin aquifer system	--	--	6	0	2	0	6	17	--	--
Rush Springs aquifer	82	1	95	13	31	3	87	0	74	0
Sand and gravel aquifers of alluvial or glacial origin	829	3	2,710	31	3,251	18	3,376	13	872	6
Seymour aquifer	22	0	43	30	323	48	46	2	22	14
Upper Cretaceous aquifers	655	1	1,720	62	1,515	41	2,204	5	730	4
Western Interior Plains aquifer system	2	0	8	50	23	78	17	12	2	0
Wyoming (Upper) Tertiary aquifers	--	--	6	17	6	17	3	0	--	--
Principal aquifer not present or not determined	4,368	3	5,725	40	3,558	44	6,804	4	4,362	3
Eastern Mountains and Uplands										
Early Mesozoic basin aquifers	13	15	11	55	27	22	36	3	6	0
New York and New England crystalline-rock aquifers	3	33	3	33	7	0	7	14	2	0
Piedmont and Blue Ridge carbonate-rock aquifers	7	29	3	0	8	25	15	33	5	0
Sand and gravel aquifers of alluvial or glacial origin	10	0	29	31	42	5	47	23	9	0
Principal aquifer not present or not determined	114	6	145	42	36	8	153	6	114	0
Northwestern Volcanics										
Columbia Plateau basin-fill aquifers	2	0	4	0	9	0	8	0	2	0
Columbia Plateau basaltic-rock aquifers	2	50	4	0	9	11	7	0	2	0
Pacific Northwestern volcanic rock or basin-fill aquifers	2	0	1	0	5	20	4	25	2	0
Sand and gravel aquifers of alluvial or glacial origin	1	100	1	100	1	100	1	0	1	0
Snake River Plain volcanic rock or basin-fill aquifers	9	78	2	50	10	40	5	0	6	50
Principal aquifer not present or not determined	38	47	13	15	87	21	51	8	31	10

Table 12. Percentage of brackish groundwater samples that exceed selected water-quality standards for irrigation uses, by brackish groundwater region.—Continued

[µg/L, microgram per liter; mg/L, milligram per liter; --, no brackish sample had a reported result for the chemical constituent; <, less than]

Principal aquifer[1]	Chemical constituent and water-quality standard[2]									
	Arsenic 10 µg/L		Boron 750 µg/L		Fluoride 1 mg/L		Iron 5 mg/L		Selenium 20 µg/L	
	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance	Number of brackish samples evaluated	Percent exceedance
Western Mountain Ranges										
Northern Rocky Mountains Intermontane Basins aquifer systems	15	27	19	5	27	30	26	8	8	13
Puget Sound aquifer system	--	--	--	--	--	--	--	--	--	--
Sand and gravel aquifers of alluvial or glacial origin	8	13	3	0	6	33	11	0	2	0
Willamette Lowland basin-fill aquifers	2	0	2	0	2	0	2	0	--	--
Principal aquifer not present or not determined	41	10	60	28	86	29	90	21	15	7
Alaska										
All groundwater resources	19	32	4	50	31	10	43	33	1	0
Hawaii										
All groundwater resources	7	0	7	29	17	0	17	0	7	0
U.S. Territories										
Groundwater resources in Puerto Rico	8	13	15	20	62	11	29	3	7	0
Groundwater resources in the U.S. Virgin Islands	13	8	6	67	21	19	16	13	13	0

[1] In some cases the principal aquifer may extend into other brackish groundwater regions; data reported here are for the entire principal aquifer.

[2] Water-quality standards from Fipps (2003).

Table 13. Well yields by dissolved-solids concentration category in the Coastal Plains region.

[gal/min, gallon per minute; mg/L, milligram per liter]

Dissolved-solids concentration (table 1)	Number of wells with a reported well yield	Median well yield, in gal/min	Wells with a well yield greater than 10 gal/min, in percent	Wells with a well yield greater than 100 gal/min, in percent	Wells with a well yield greater than 1,000 gal/min, in percent
Freshwater (<1,000 mg/L)	8,199	75	83	46	<1
Brackish (1,000 to <10,000 mg/L)	1,116	20	68	24	<1
Slightly saline (1,000 to <3,000 mg/L)	844	25	71	27	<1
Moderately saline (3,000 to <10,000 mg/L)	272	15	58	15	0
Highly saline (≥10,000 mg/L)	29	30	69	21	0

Groundwater flow in the Michigan Basin (fig. 28) has a unique pattern because it is surrounded on three sides by three of the Great Lakes—Lake Michigan, Lake Huron, and Lake Erie—which serve as a regional sink for groundwater flow. Groundwater flow starts as recharge from the surface of the peninsula between these lakes, and flow paths can extend to substantial depths and demonstrate a pattern of flow that is radially outward from the center of the peninsula. Again, BGW is carried upwards from deeper flow paths as groundwater discharges to the lakes (Ells, 1979).

Similarly, the Appalachian Basin has groundwater flow patterns that originate with recharge in the uplands and discharge to rivers in the valleys. Wells near discharge locations in the valleys intersect BGW at shallower depths than in the uplands because deeper groundwater circulation along the flow path has brought the water in contact with connate brines associated with the evaporite deposits (Sheets and Kozar, 2000). Groundwater flow paths in the Valley and Ridge physiographic province are complex (Swain and others, 2004). In general, ridges are recharge areas and streams and rivers in valleys are discharge areas; however, the permeability of the geologic units varies considerably; these units are folded and typically steeply dipping. This condition contributes to a wide variety of groundwater flow and groundwater quality conditions.

Aquifer properties in this region are affected by depositional environment, postdepositional lithification, and secondary porosity related to dissolution of minerals and by deformation and fracturing. Solution openings are common in carbonate formations of this region, allowing large yields and rapid circulation of freshwater (Heath, 1984). Hydraulic properties (specific yield, storage coefficient, and specific storage) were compiled from previously published reports. This compilation indicated that specific yield was generally between 2 and 21 percent for the unconfined aquifers in this region and that, similar to other regions, storage coefficients for confined aquifers were highly variable, ranging over several orders of magnitude (table 14).

Lithology and original depositional environment play an important role in determining the location, volume, and chemical characteristics of BGW. Of particular importance to the presence of BGW within this region is the isolation of embayments of seawater from the ocean within the basins multiple times during the Silurian, Devonian, and Mississippian Periods. Deposits of anhydrite, gypsum, and halite within the basins of the region were formed when the isolated seawater evaporated (Johnson, 2008). Brines associated with these evaporite deposits are either connate brines that persist within in these closed basins where groundwater circulation is impaired or brines that resulted from dissolution of the evaporite deposits (Hem, 1989; Sheets and Kozar, 2000). High dissolved-solids concentrations in groundwater can be the result of the dissolution of minerals such as carbonates and

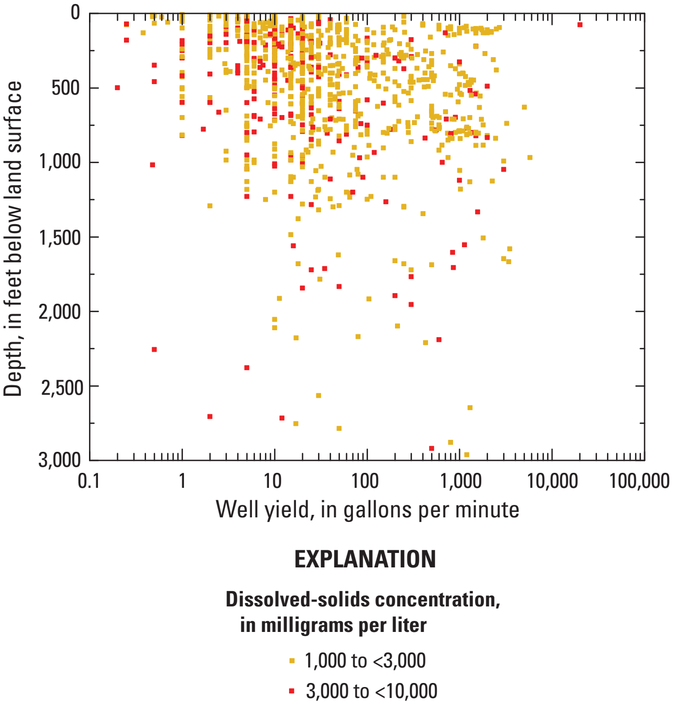

Figure 25. Distribution of well yields relative to depth below land surface at wells producing brackish groundwater in the Coastal Plains region.

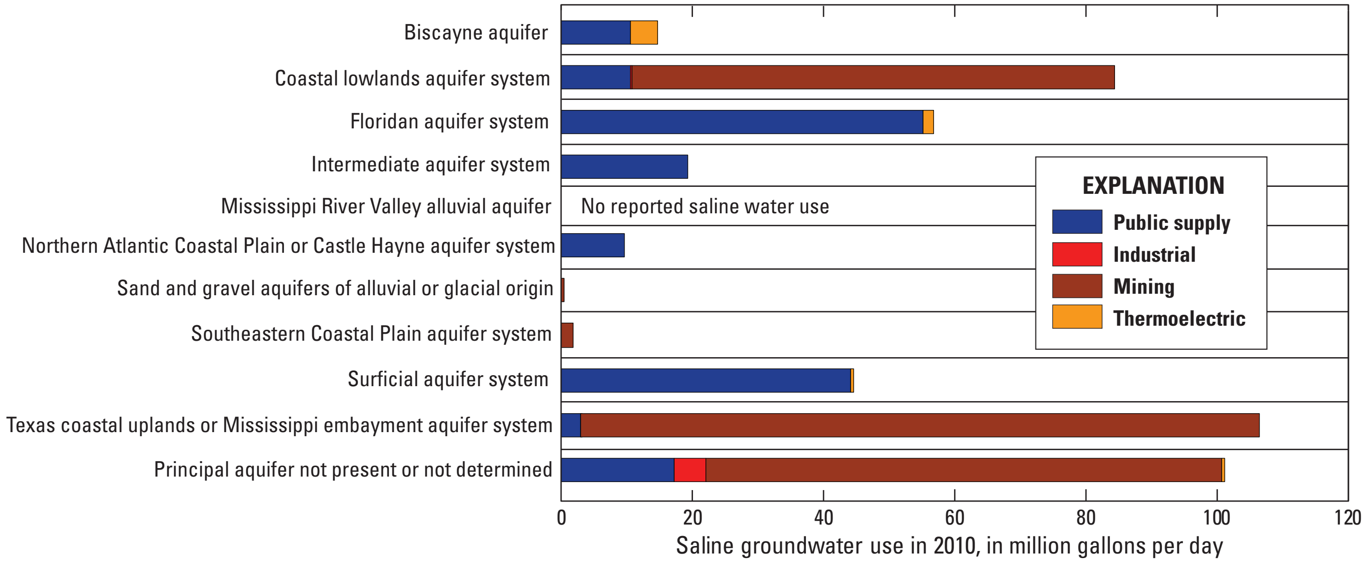

Figure 26. Estimated saline groundwater use from principal aquifers in the Coastal Plains region.

evaporite minerals. Anning and Flynn (2014, p. 34 and 76) demonstrated that the presence of buried evaporites also is a significant predictor of dissolved-solids concentrations in streams.

The spatial relation between basins and the distribution of samples with highly saline groundwater (dissolved-solids concentrations >10,000 mg/L) is shown in figure 29. Areas with numerous highly saline samples are associated with basins that have soluble evaporite deposits (halite, anhydrite, and gypsum), and BGW is typically present in transition zones between the fresh and highly saline groundwater. The pattern of highly saline samples suggests the potential for a connection between the Appalachian and Illinois Basins across the Cincinnati Arch in a band across south-central Kentucky. This pattern suggests the possibility of a continuation of the buried evaporites (not previously documented) and connection between the original inland saline waters from which the evaporites were deposited. Improved geologic maps of buried evaporite deposits have the potential to greatly improve the identification of areas of brackish and highly saline groundwater conditions.

Several of the principal aquifers in the region have evaporite deposits beneath them. These include the Pennsylvanian aquifers, the Marshall aquifer, the Mississippian aquifers, and parts of the New York and New England carbonate-rock aquifers (figs. 27 and 28). Known depths of evaporite deposits start at land surface outcrops along the edges of the basins and increase toward the center of the basins (bowl-shaped stratigraphy). Depths to solution-mined evaporite deposits range from 490 ft below land surface to as much as 6,600 ft below land surface in deep parts of the Appalachian and Michigan Basins (Dunrud and Nevins, 1981). Solution mining is a method for mining deeply buried salt and other evaporite deposits. Freshwater is injected into wells penetrating the buried evaporite deposits. The resultant brine is then pumped to the surface and the minerals extracted. Though these evaporite beds extend deeper than the lower limit of this assessment (3,000 ft), the presence of the evaporite deposits and associated brines relate to elevated dissolved-solids concentrations above 3,000 ft in depth because of groundwater circulation patterns that allow mixing with associated brines.

The four principal aquifers that overly evaporite deposits within the region have numerous groundwater samples with dissolved-solids concentrations that exceed 35,000 mg/L (in excess of seawater concentrations), indicating the likelihood of dissolution of evaporite deposits into the groundwater. The Ozark Plateaus aquifer system, the Ordovician aquifers, and the Jacobsville aquifer (fig. 27), on the other hand, lack the close proximity to evaporites and lack samples with dissolved-solids concentrations >35,000 mg/L. The Marshall aquifer (Mississippian in age), centered in the Michigan Basin, is unique for the region in that it has evaporite deposits in strata above it (Pennsylvanian in age) and beneath it (Silurian in age). Most of the Marshall aquifer is brackish, and freshwater is restricted to the areas where the aquifer outcrops along its periphery or is overlain directly by surficial glacial deposits.

Distribution of Dissolved Solids

Groundwater samples with dissolved-solids concentrations were available from about 69,000 wells in this region (fig. 30; table 4). Wells with BGW were most dense in the western part of the region. About 70 percent of the samples were from wells completed between 50 and 500 ft below land surface (table 4). Median dissolved-solids concentration increased slightly with depth to about 1,500 ft below land surface. Below that depth, the median dissolved-solids concentration increased by two orders of magnitude, and most observed

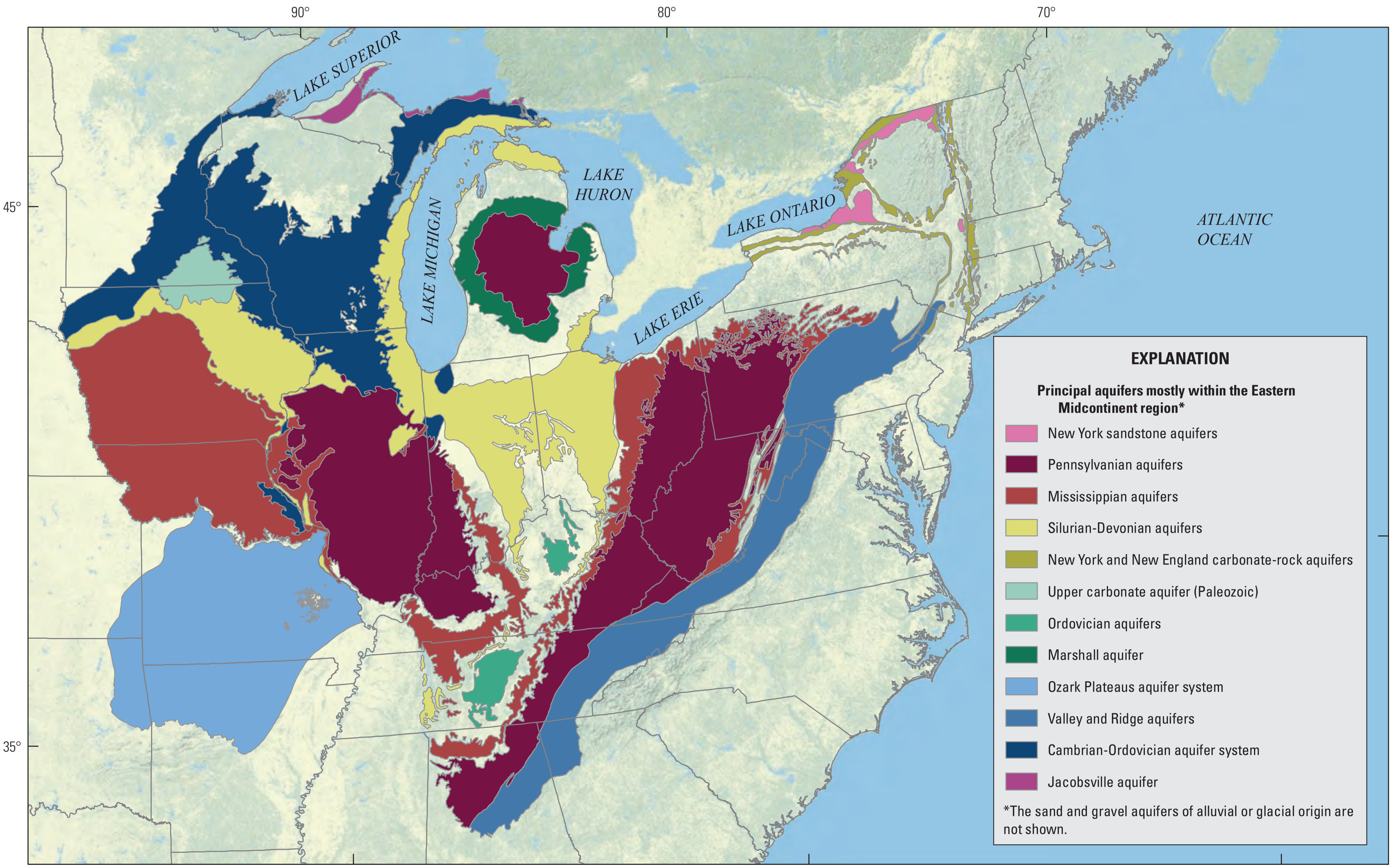

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Figure 27. Principal aquifers mostly within the Eastern Midcontinent region. An interactive map for viewing the full extent of each principal aquifer is available at https://doi.org/10.3133/pp1833.

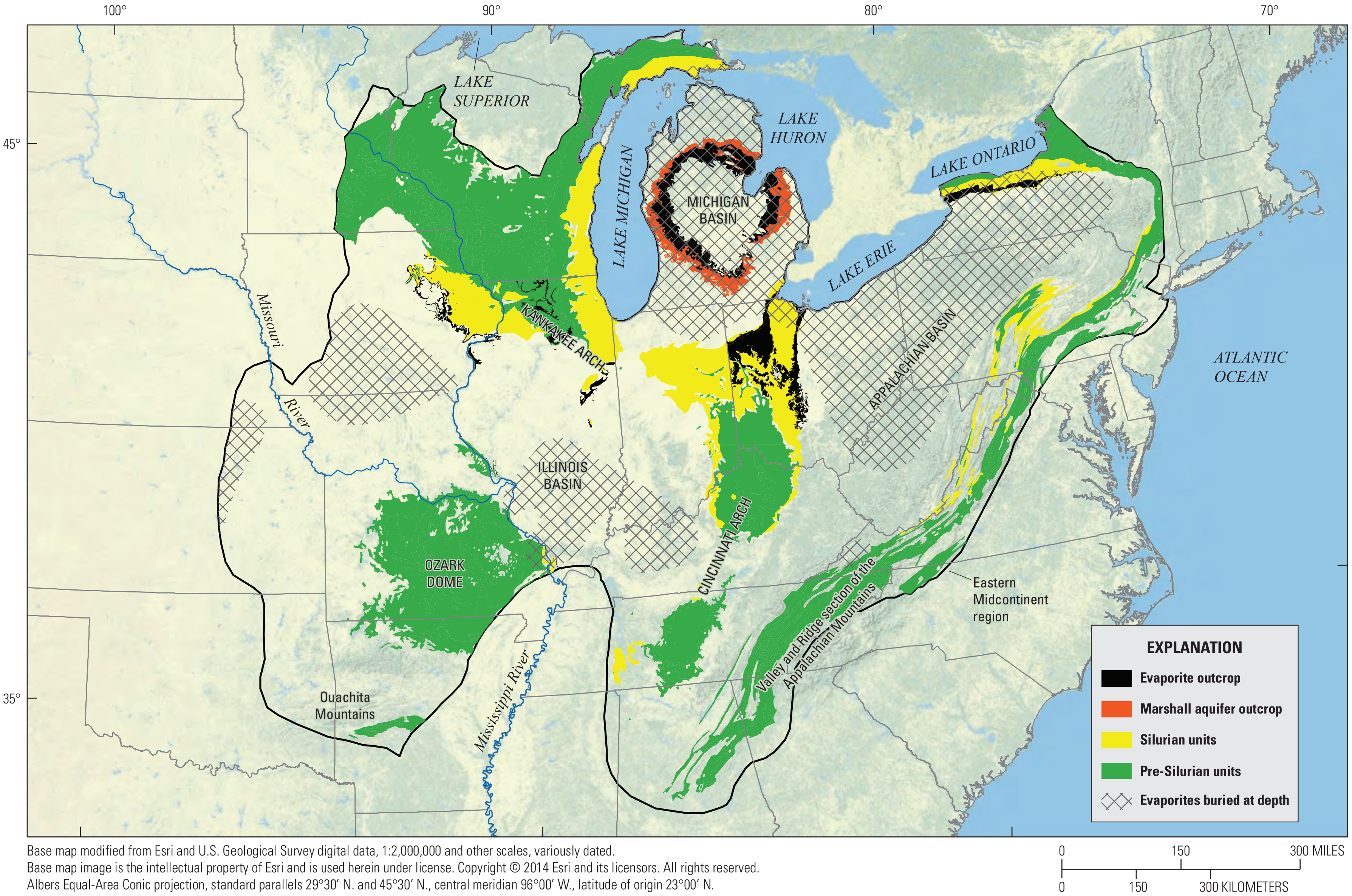

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Figure 28. Topographical and structural geologic features of the Eastern Midcontinent region.

Table 14. Generalized hydrogeologic characteristics of principal aquifers with substantial amounts of brackish groundwater in the Eastern Midcontinent region.

[Descriptions are generalized aquifer properties and not specific to the brackish zone unless noted. gal/min, gallon per minute; ft, foot; mi², square mile; --, not applicable or not reported in publications reviewed for this study]

Principal aquifer[1]	Geologic age[2]	General description of brackish zone(s)[2]	Principal depositional environment[2]	Principal composition[2]	Flow influenced by confining beds[2]
Cambrian-Ordovician aquifer system	Cambrian and Ordovician	The brackish zone is areally extensive in the southwestern half of the aquifer and in the east near Lake Michigan. Brackish groundwater exists beneath the freshwater. Locally it can be shallow to the top of the brackish zone, less than 500 ft especially near where it discharges to surface water. For example, in the eastern part of the aquifer brackish groundwater discharges to Lake Michigan.	Marine	Sandstone	Yes
Marshall aquifer	Mississippian	Brackish water exists beneath confining layers. The Marshall aquifer encompasses about 22,000 mi², of which about 12,000 mi² along its perimiter contains freshwater and about 10,000 mi² contains brackish to brine conditions. Brackish groundwater discharges to surface water including Saginaw Bay of Lake Huron.	Nearshore, marine, and restricted (evaporite) environment	Sandstone and siltstone	Yes, most sites are partly or fully confined
Mississippian aquifers	Mississippian	Brackish zone is areally extensive throughout this principal aquifer. In the Illinois and Appalachian Basins the brackish groundwater zone overlies highly saline groundwater and presumably represents a transition zone between freshwater above it and highly saline groundwater beneath.	Marine	Mainly limestone and dolomite in Iowa Basin; siltstone and sandstone in Michigan Basin; and limestone and sandstone in the Appalachian Basin.	Yes
New York and New England carbonate-rock aquifers	Paleozoic	The brackish groundwater is localized, not areally extensive. In western New York there are nearby salt evaporite deposits, however, dissolution of carbonate deposits are likely the main source.	Marine	Limestone and dolomite	Only locally
Ordovician aquifers (localized along Cincinnati Arch)	Ordovician	The brackish zone is localized, not areally extensive, and does not typically overlie more highly saline groundwater.	Marine	Limestone and dolomite	Only locally
Ozark Plateaus aquifer system	Mississippian through Ordovician	The brackish zone is areally exensive in the western part of the aquifer system (in eastern Oklahoma and Kansas), down gradient (east) of evaporite exposures.	Marine and Nonmarine	The water-yielding formations are mostly limestone and dolomite but locally include sandstone and chert.	Yes
Pennsylvanian aquifers	Pennsylvanian	The brackish zone is areally extensive throughout the Michigan, Illinois, and Appalachian basins. It is typically shallow to top of brackish zone.	Marine	Sandstone and limestone are parts of repeating sequences.	Yes
Silurian-Devonian aquifers	Silurian and Devonian	The brackish zone is areally extensive and typically represents a transition zone between freshwater and brine. The aquifer is typically overlain by a shale confining unit.	Shallow marine	Carbonates	Yes

---

[1] Sand and gravel aquifers of alluvial or glacial origin contain substantial amounts of brackish groundwater but typically are smaller in extent and not included in this table.

[2] Obtained from previously published work.

[3] Obtained from data compiled for this assessment.

[4] Well yield results should be used with caution if few values are available for an aquifer.

[5] Data are from reported pumping rates and not potential well yields; therefore, results probably represent minimum values.

Specific yield or porosity where noted, in percent (unconfined aquifers)[2]	Storage coefficient or specific storage where noted (confined aquifers)[2]	Presence of secondary porosity[2]	Presence of evaporites[2]	Number of brackish wells with a reported well yield[3,4]	Median well yield at brackish wells, in gal/min[3,5]	Interquartile range of well yield at brackish wells, in gal/min[3,5]	References
5	2.12×10^{-4}. The lower brackish/saline part ranges from 1×10^{-6} to 1×10^{-2}	Yes	Yes	97	200	50 to 490	Young (1992), Westjohn and Weaver (1996), Coon and Sheets (2006).
21 (porosity)	3×10^{-4}	Yes	Yes (primarily in units both below and above the Marshall)	5	250	222 to 451	Olcott (1992), Coon and Sheets (2006).
--	1×10^{-4} to 4×10^{-3}	Yes	Yes	39	10	4 to 15	Olcott (1992), Trapp and Horn (1997), Kozar and Mathes (2001).
--	--	Yes	Yes (western New York)	28	23	7 to 50	Olcott (1995).
--	--	--	--	2	14	13 to 15	Lloyd and Lyke (1995).
2.5 to 5 (in the brackish zone)	--	Yes	No or not identified	90	25	8 to 80	Imes and Emmett (1994), Miller and Appel (1997).
20 (porosity)	3×10^{-4}	Yes	Yes (below aquifer)	56	9	3 to 34	Olcott (1992), Lloyd and Lyke (1995), Coon and Sheets (2006).
Ranges from 1.7 to 3 in northeastern Illinois and from 1 to 5 in Ohio	9×10^{-5} to 4.8×10^{-3} (Wisconsin-Illinois), 1×10^{-5} to 5×10^{-2} (Indiana-Ohio-Michigan)	--	Yes	99	134	20 to 575	Prickett and others (1964), Bloyd (1974), Olcott (1992), Young (1992), Sasman and others (1981), Joseph and Eberts (1994), Bugliosi (1999), Coon and Sheets (2006).

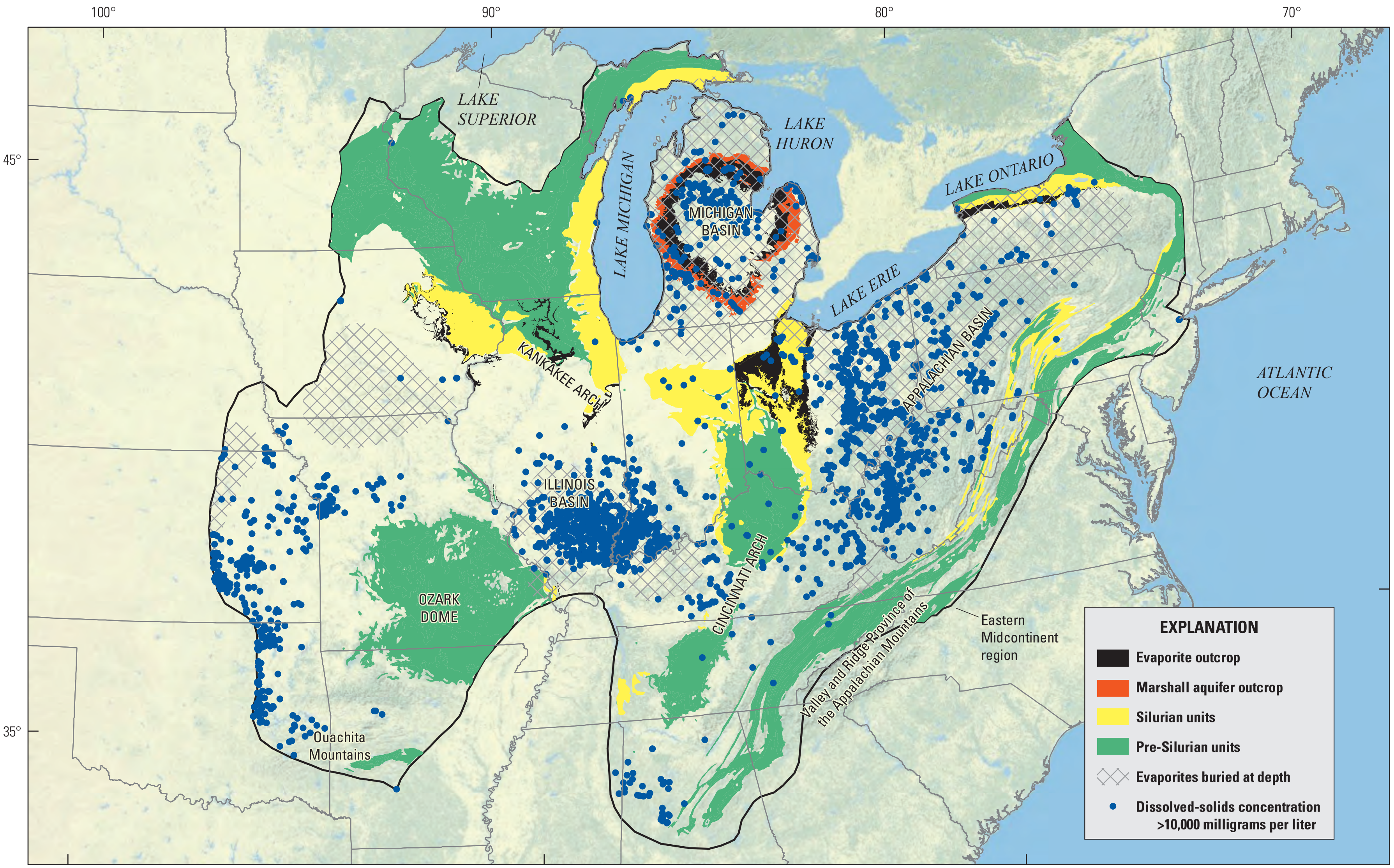

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Figure 29. Regional features of structural geology and the distribution of samples of highly saline groundwater (dissolved-solids concentrations greater than 10,000 milligrams per liter) in the Eastern Midcontinent region.

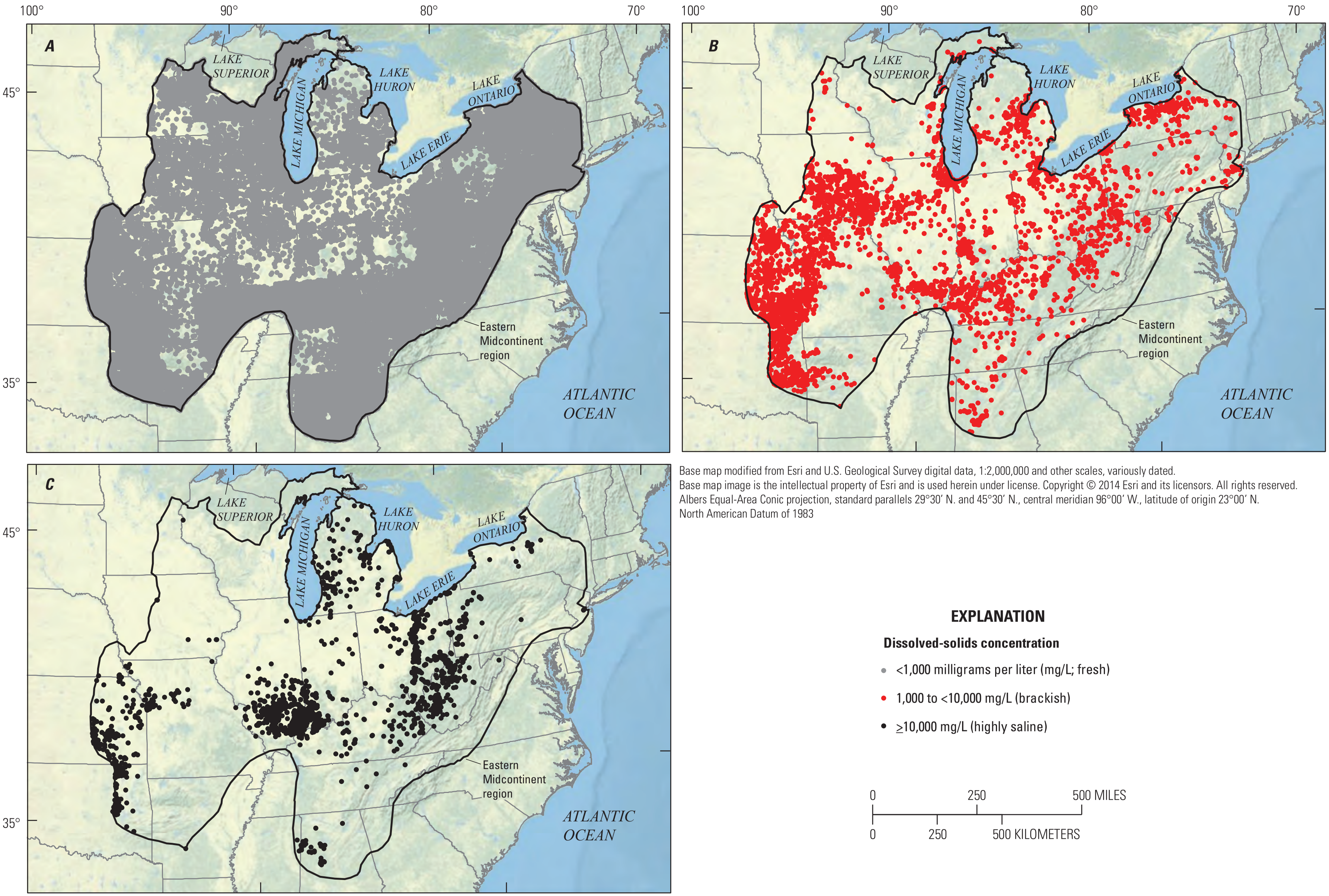

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Figure 30. Locations of wells producing *A*, fresh; *B*, brackish; and *C*, highly saline groundwater from 0 to 3,000 feet below land surface in the Eastern Midcontinent region.

groundwater had dissolved-solids concentrations greater than the BGW range. The percentage of sampled wells producing BGW was largest for the depth intervals between 500 and 3,000 ft below land surface. The amount of subsurface volume (including air, water, and rock) occupied by at least some BGW was between 16 percent of the observed grid cell volume for the depth intervals between 0 and 3,000 ft below land surface. The total grid cell volume of BGW observed within this region was about 10,400 mi^3. Assuming that 1 percent of that volume is water that can be extracted, the region could yield about 104 mi^3 (351 million acre-feet) of BGW.

The amount of observed BGW varied among principal aquifers of this region. Four of the principal aquifers within this region had dissolved-solids concentrations in the brackish range in ≥13 percent of the sampled wells (fig. 27; table 8)—the Marshall aquifer (17 percent), the Silurian-Devonian aquifers (15 percent), the Mississippian aquifers (13 percent), and the New York and New England carbonate-rock aquifers (13 percent). For the other principal aquifers, the percentage of sampled wells that produced BGW ranged from 0 to 11 percent. The percentage of observed grid cell volume containing BGW ranged from 0 to about 26 percent among principal aquifers in this region; the Pennsylvanian, Marshall, and Silurian-Devonian aquifers contained the largest percentages (table 8). Although the Western Interior Plains aquifer system is primarily in the Western Midcontinent region, it extends partially into the Eastern Midcontinent region. Dissolved-solids concentrations in that aquifer system have accumulated along the long flow paths necessary for brackish and highly saline groundwater to reach and extend into the Eastern Midcontinent region (Miller and Appel, 1997).

The distribution of categories of dissolved-solids concentrations across the region as a percentage of observed grid cell volume was determined for two depth intervals—<500 ft below land surface and between 500 and 3,000 ft below land surface (fig. 31). Of the observed volume <500 ft below land surface in this region, 85 percent was freshwater (500 to 1,000 mg/L of dissolved solids), about 15 percent was slightly saline (1,000 to 3,000 mg/L of dissolved solids), <5 percent was moderately saline (3,000 to 10,000 mg/L of dissolved solids), and <5 percent was highly saline (>10,000 mg/L of dissolved solids). Below 500 ft below land surface, the percentages of observed volume were 10 percent slightly saline and about 5 percent moderately saline groundwater, but the amount of freshwater decreased to about 35 percent and the amount of highly saline groundwater increased to about 30 percent. For depths <500 ft below land surface, the Marshall, Mississippian, and Pennsylvanian aquifers had the largest percentages of brackish (slightly saline and moderately saline) groundwater volume. For depths between 500 and 3,000 ft below land surface, the principal aquifers with the largest percentages of slightly saline groundwater were the Cambrian-Ordovician aquifer system and the New York and New England carbonate-rock aquifers. Principal aquifers with the largest percentages of moderately saline groundwater were the Marshall aquifer and the Ordovician and Silurian-Devonian aquifers. About 30 percent of the observed volume between 500 and 3,000 ft below land surface had dissolved-solids concentrations >35,000 mg/L (the approximate concentration of seawater).

Considerations for Developing Brackish Groundwater

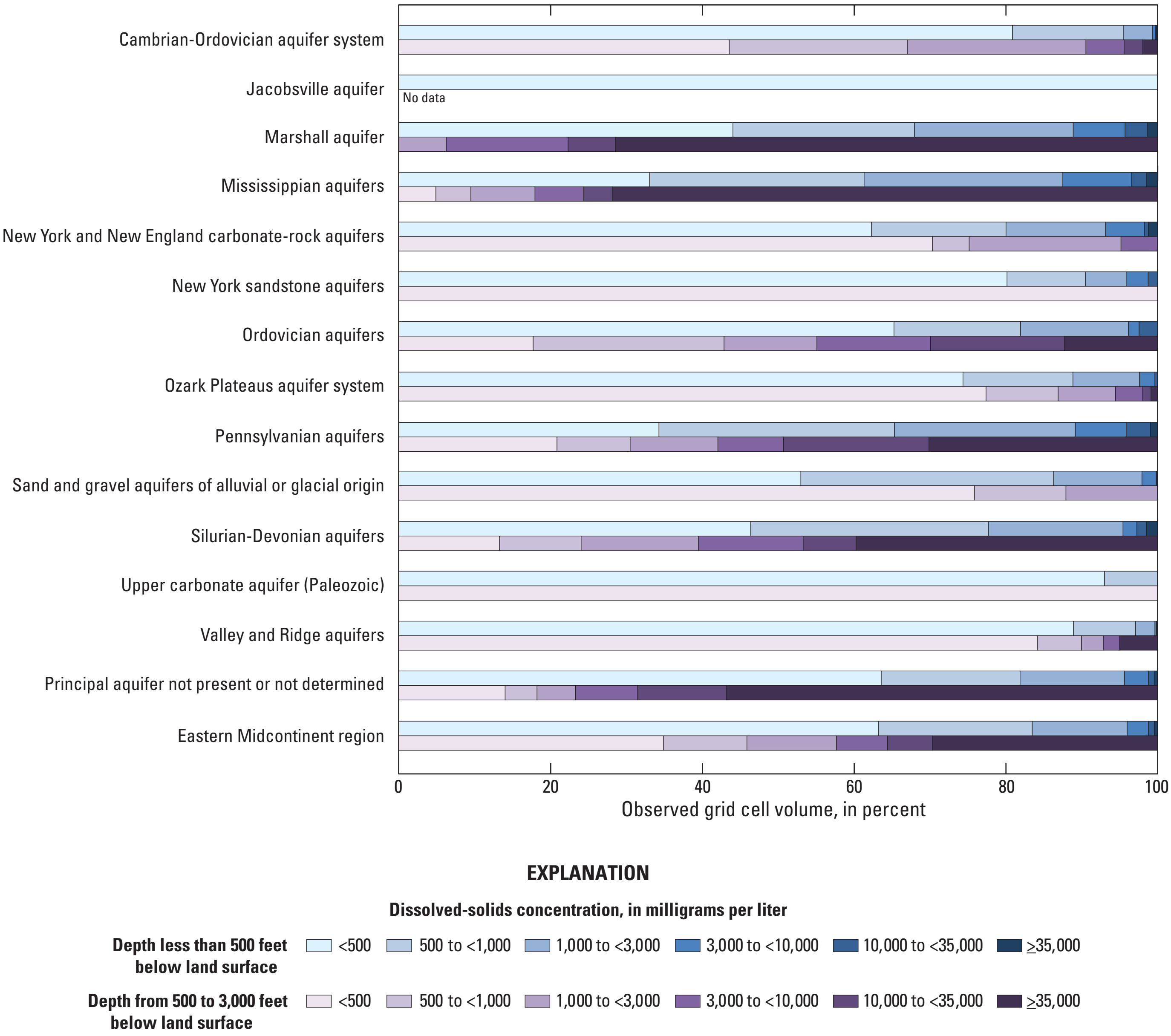
Constituents most likely to be present in BGW in this region at concentrations greater than selected drinking-water standards are arsenic (Ozark Plateaus aquifer system, sand and gravel aquifers of alluvial or glacial origin, and the Valley and Ridge aquifers), fluoride (Ordovician aquifers), and nitrate (sand and gravel aquifers of alluvial or glacial origin; table 10). Fluoride and iron concentrations in untreated BGW are the constituents most likely to be problematic for livestock consumption in some aquifers (table 11). Boron and fluoride are potential concerns for most of the principal aquifers where untreated BGW is used for irrigation (table 12). The BGW samples with exceedances for drinking-water standards are most common in the western part of the region (fig. 32).

Sampled wells producing BGW had the same median yield (25 gal/min) as freshwater wells (table 15). About 26 percent of wells producing BGW had a yield >100 gal/min, and about 3 percent of BGW wells had a yield >1,000 gal/min. The largest median yields of wells producing BGW were in the Marshall aquifer (250 gal/min), the Cambrian-Ordovician aquifer system (200 gal/min), and the Silurian-Devonian aquifers (134 gal/min; table 14). Although data were sparse for depths below about 1,000 ft below land surface, available information indicates that wells in the deepest intervals in this region are able to yield ≥10 gal/min and may be able to yield ≥1,000 gal/min in some areas, particularly wells producing slightly saline groundwater (1,000 to 3,000 mg/L of dissolved solids; fig. 33).

Saline Groundwater Use

In general, the potential for BGW use within the region is largely unrealized because of available potable groundwater; however, the brines from which brackish water can be generated through dilution are heavily used; for example, salt has been mined through solution mining for more than 100 years in Michigan, New York, and Ohio (Dunrud and Nevins, 1981). In this process, brines are pumped in order for the minerals to be extracted from them. Brines from the Michigan Basin, rich in magnesium, chloride, calcium, sodium, and bromide, provide the basis for an entire chemical industry. Companies such as The Dow Chemical Company have used these brines since the late 1800s to create hundreds of products such as potassium bromide and bleach (Ells, 1979; Schaetzl, n.d.).

Areas where a principal aquifer is not present or not determined and the Cambrian-Ordovician aquifer system provide the most saline groundwater for use in this region



Note: Volumes are based on grid cells that have been categorized by using the maximum dissolved-solids concentration in each cell.

Figure 31. Distribution of dissolved-solids concentrations as a percentage of observed grid cell volume, by principal aquifer and depth, in the Eastern Midcontinent region.

(fig. 34). It is possible that the simplistic methods used for assigning saline groundwater use to principal aquifers resulted in underestimated use for some of the aquifers, such as the Marshall aquifer, the Valley and Ridge aquifers, and the Silurian-Devonian aquifers. Saline groundwater most commonly was used for mining and less commonly for industrial applications (fig. 34). About 10 percent of the municipal desalination facilities across the Nation that use groundwater as their source are within this region (Mickley, 2012). Though scattered across the region, these facilities are primarily in Illinois, Iowa, and Ohio (fig. 2).

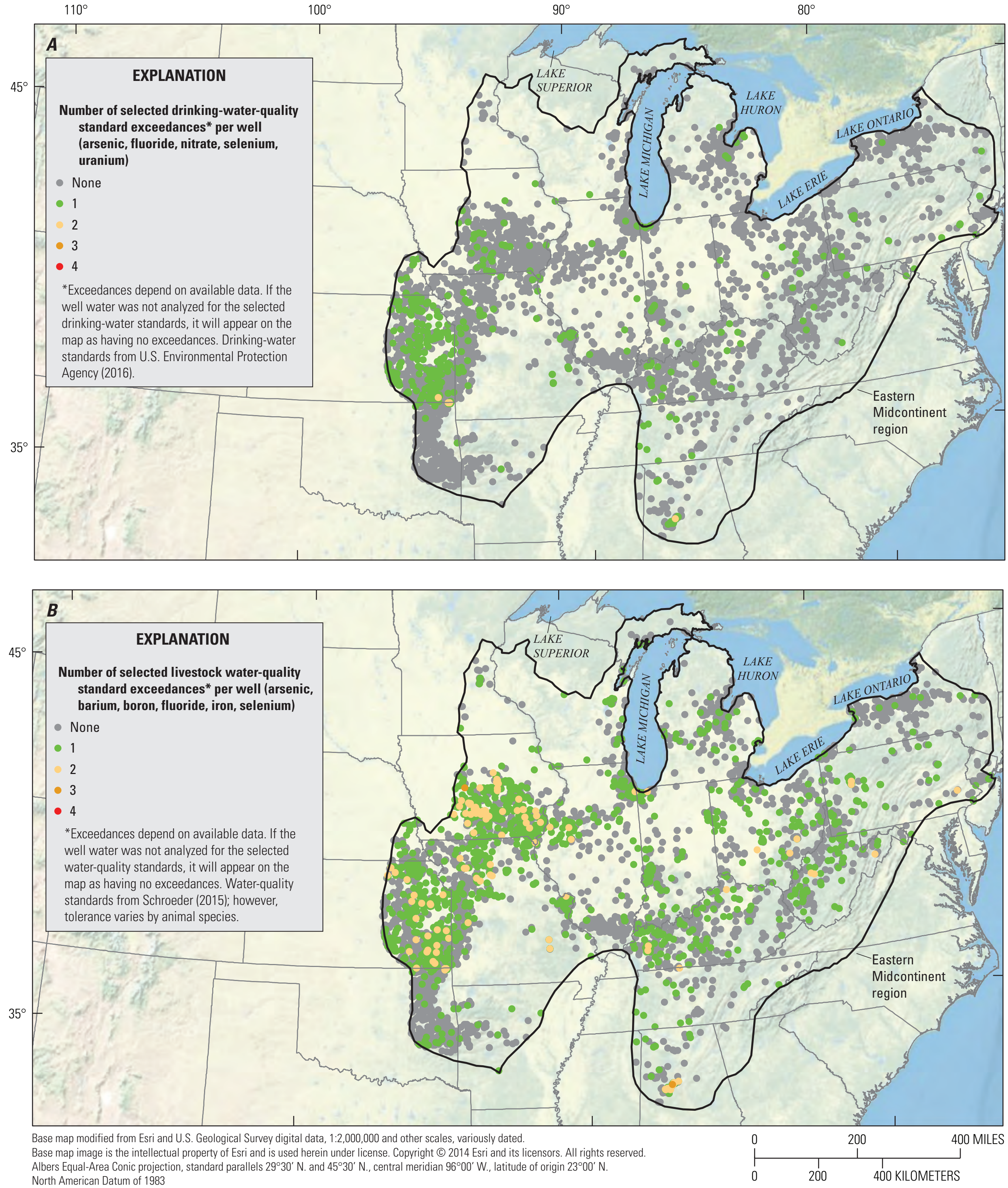


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Figure 32. Locations of brackish groundwater samples that exceed selected water-quality standards in the Eastern Midcontinent region. *A*, drinking water; *B*, livestock consumption, *C*, irrigation uses.

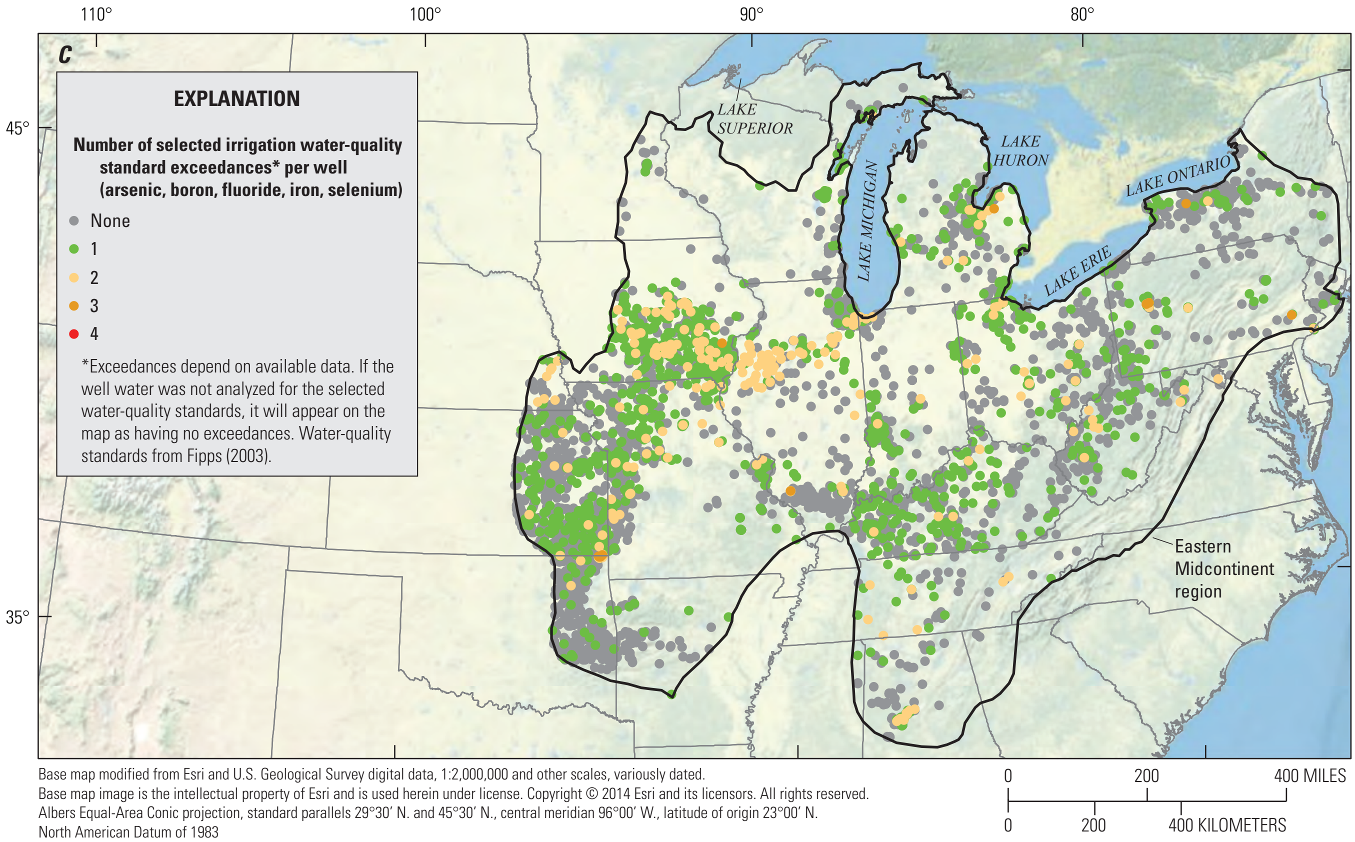

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Figure 32. Locations of brackish groundwater samples that exceed selected water-quality standards in the Eastern Midcontinent region. *A*, drinking water; *B*, livestock consumption, *C*, irrigation uses.—Continued

Table 15. Well yields by dissolved-solids concentration category in the Eastern Midcontinent region.

[gal/min, gallon per minute; mg/L, milligram per liter]

Dissolved-solids concentration (table 1)	Number of wells with a reported well yield	Median well yield, in gal/min	Wells with a well yield greater than 10 gal/min, in percent	Wells with a well yield greater than 100 gal/min, in percent	Wells with a well yield greater than 1,000 gal/min, in percent
Freshwater (<1,000 mg/L)	10,325	25	71	29	4
Brackish (1,000 to <10,000 mg/L)	792	25	71	26	3
Slightly saline (1,000 to <3,000 mg/L)	680	25	73	29	4
Moderately saline (3,000 to <10,000 mg/L)	112	15	54	12	2
Highly saline (≥10,000 mg/L)	20	7	40	25	0

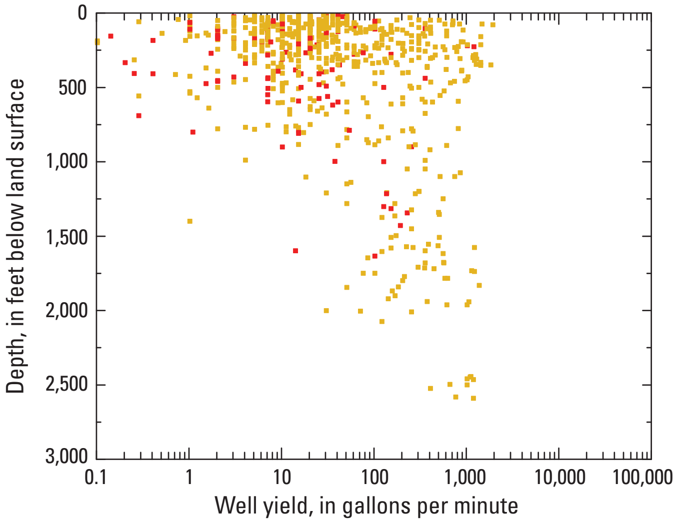

Figure 33. Distribution of well yields relative to depth below land surface at wells producing brackish groundwater in the Eastern Midcontinent region.

Southwestern Basins Region

The Southwestern Basins region consists of a series of sediment-filled basins that lie between mountain ranges in the southwestern United States (figs. 7 and 35). BGW is most commonly associated with concentration of minerals from evapotranspiration of shallow groundwater, dissolution of evaporates or of minerals over long flow paths, or dilution of connate seawater. Seven principal aquifers are mostly within this region (fig. 35), and at least some BGW is present in more than 30 percent of the observed grid cell volume (including air, water, and rock) for all principal aquifers except the southern Nevada volcanic-rock aquifers (fig. 35; table 8).

Hydrogeologic Characteristics

The geology of this region consists of four major lithology types—crystalline bedrock, marine carbonate rocks, volcanic rocks, and unconsolidated to consolidated alluvial sediments (table 16). These units are situated in a complex arrangement of mountains and sediment-filled valleys that were created from deformation and faulting. The relatively impermeable crystalline bedrock is exposed in the mountains and buried by other rocks and sediments of variable permeability (carbonate rock, volcanic rock, and alluvial sediments) in the valleys. Alluvial sediments interspersed with volcanic rocks fill the valleys and overlie either carbonate rocks, where

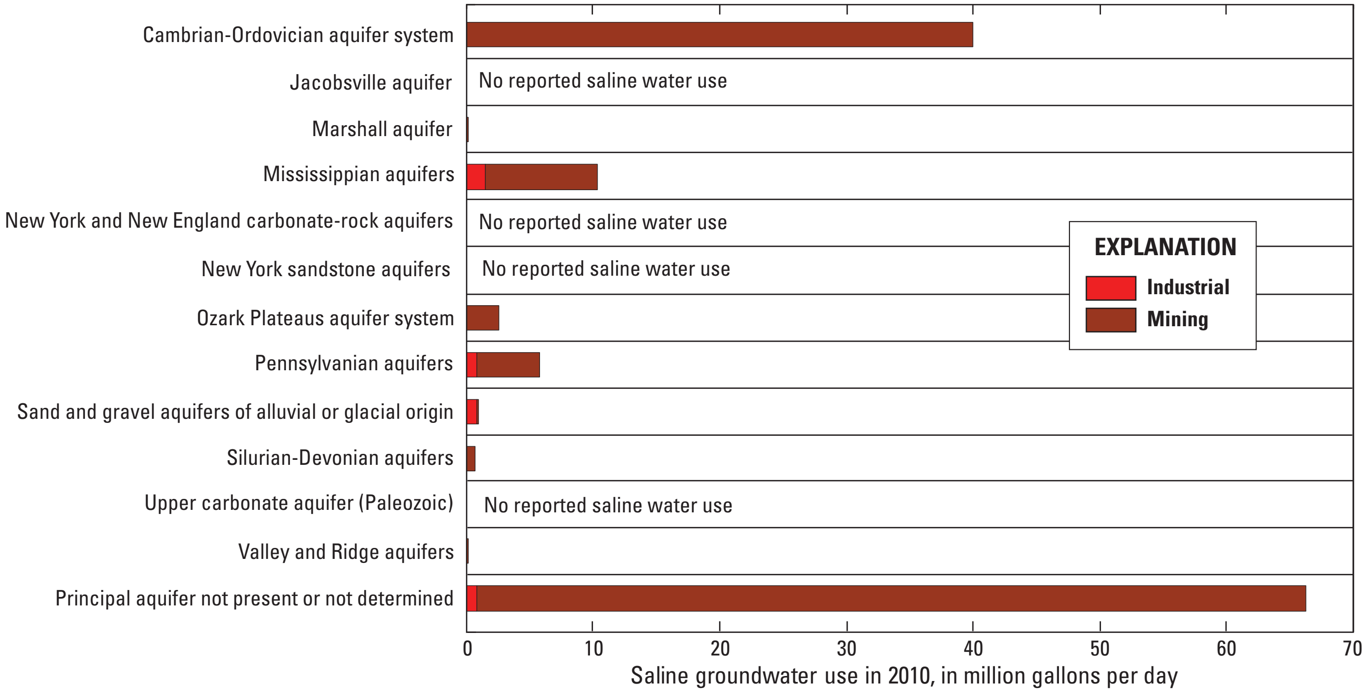

Figure 34. Estimated saline groundwater use of principal aquifers in the Eastern Midcontinent region.

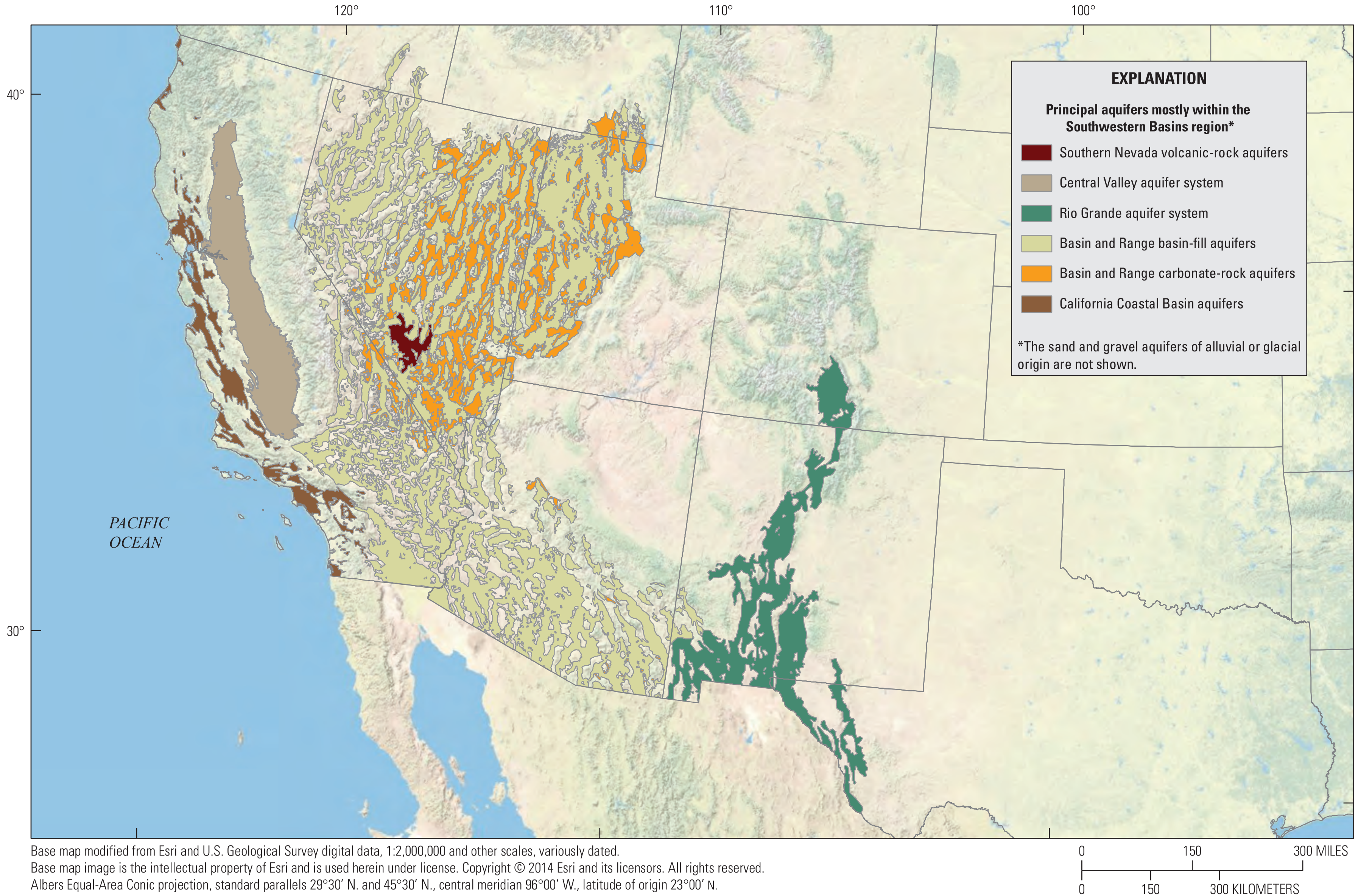

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Figure 35. Principal aquifers mostly within the Southwestern Basins region. An interactive map for viewing the full extent of each principal aquifer is available at https://doi.org/10.3133/pp1833.

Table 16. Generalized hydrogeologic characteristics of principal aquifers with substantial amounts of brackish groundwater in the Southwest Basins region.

[Descriptions are generalized aquifer properties and not specific to the brackish zone. gal/min, gallon per minute; ft, foot; --, not applicable or not reported in publications reviewed for this study]

Principal aquifer[1]	Geologic age[2]	Depth interval[2,3]	General description of brackish zone(s)[2]	Principal depositional environment[2]	Principal composition[2]	Flow influenced by confining beds[2]
Basin and Range basin-fill aquifers	Tertiary and Quaternary	Less than 500 ft	Shallow brackish groundwater in closed basins/playas, above confining units, or near streams (end of flow paths)	Alluvial	Unconsolidated sand, gravel, silt, and clay; interspersed volcanic rocks	Yes
		500 to 3,000 ft	Water at depths greater than a few thousand feet yield saline water that is confined and has poor hydraulic connection with shallower depths	Alluvial	Unconsolidated to consolidated sand, gravel, silt, and clay	Yes
Basin and Range carbonate-rock aquifers	Mesozoic and Paleozoic	0 to 3,000 ft	Geothermal and groundwater discharge areas	Marine	Interbedded limestone, dolomite, sandstone, shale, and volcanics; some beds of conglomerate and gypsum	Yes
Rio Grande aquifer system	Tertiary and Quaternary	Less than 500 ft	Shallow brackish groundwater occurs in closed basins and areas with upward-flowing deep-basin groundwater; seepage from older geologic units.	Alluvial	Unconsolidated gravel, sand, interbedded with clay and silt; interspersed with volcanic rocks	Yes
		500 to 3,000 ft	Deep circulation water and seepage from older geologic units	Alluvial		
California Coastal Basin aquifers	Tertiary and Quaternary	Less than 500 ft	Concentration by evapotranspiration, application of saline waters (oil-field brines and irrigation waters) at land surface, and seawater intrusion	Fluvial	Sand, gravel, silt, clay	Yes
		500 to 3,000 ft	Unconsolidated to semiconsolidated marine sediments containing saline connate water	Marine	Sandstone, siltstone, mudstone, diatomite, and siliceous shale; some volcanic rocks	
Central Valley aquifer system	Late Cretaceous to present	Less than 500 ft	Upper parts of unconfined system	Alluvial	Sand and gravel, mixed with fine grain; some volcanic rocks	Yes
		500 to 3,000 ft	Saline connate water in marine sediments	Marine	Sandstones, shales, sands, silts, siltstones	Yes

[1] Sand and gravel aquifers of alluvial or glacial origin have at least some brackish groundwater present in more than 30 percent of the observed grid cell volume but are limited in areal extent and not included in this table.

[2] Obtained from previously published work.

[3] 500 ft is an approximation of the boundary between shallow and deep brackish zones.

[4] Obtained from data compiled for this study.

[5] Well yield results should be used with caution if few values are available for an aquifer.

[6] Data are from reported pumping rates and not potential well yields; therefore, results probably represent minimum values.

Specific yield, in percent (unconfined aquifers)[2]	Storage coefficient or specific storage where noted (confined aquifers)[2]	Presence of secondary porosity[2]	Presence of evaporites[2]	Number of brackish wells with a reported well yield[4,5]	Median well yield at brackish wells, in gal/min[4,6]	Interquartile range of well yield at brackish wells, in gal/min[4,6]	References
3 to 25	--	No	Yes (near center of some basins)	803	1,570	449 to 2,780	Anderson (1995), Planert and Williams (1995), Robson and Banta (1995), Anning and others (2007).
--	1×10^{-5} to 1×10^{-1}		Yes	336	1,971	1,143 to 2,650	
--	6×10^{-5} to 1×10^{-2}	Yes	--	18	300	30 to 800	Anderson (1995), Planert and Williams (1995), Harrill and Prudic (1998), Heilweil and Brooks (2011).
5 to 30	--	--	--	42	10	3 to 150	Robson and Banta (1995), Ryder (1995), Wilkins (1998), Anning and others (2007).
		--	--	5	315	200 to 1,150	
12	--	--	--	26	425	40 to 800	Clark (1924), Poland and others (1959), Durham (1974), Planert and Williams (1995), Faunt (2009).
		Yes	--	10	900	800 to 2,000	
9 to 40	8.6×10^{-8} to 6.7×10^{-4} per ft (specific storage)	--	--	38	600	175 to 1,500	Bertoldi and others (1991), Planert and Williams (1995), Faunt (2009), Scheirer (2007), Schierer and Magoon (2007).
		--	--	46	1,507	1,130 to 2,185	

they have not been eroded, or crystalline bedrock (Anderson, 1995; Robson and Banta, 1995; Harrill and Prudic, 1998; Heilweil and Brooks, 2011). The relative thicknesses of the alluvial and carbonate sediments are not well documented except in the Great Basin area. Evaporite rocks, such as gypsum, halite, and anhydrite, are present near the central part of some basins in the region (Planert and Williams, 1995).

The climate in this region is the driest of the United States, and much of the precipitation that falls in the basins is lost to evapotranspiration before it reaches streams or groundwater; however, precipitation in the mountains contributes to streams and groundwater, which ultimately drain into the basins (Planert and Williams, 1995; Robson and Banta, 1995; Faunt, 2009; Heilweil and Brooks, 2011). As a result, groundwater recharge in this region is primarily seepage from streams as they enter basin valleys from the mountains. Other sources of recharge include irrigation-return flow, underflow from other basins, imported surface water, and treated wastewater.

Many of the basins are closed hydrologic systems, and the only outflow of water is by evapotranspiration (Anning and others, 2007). Other basins are either partially closed or open. In an open basin, groundwater discharges to a stream that leaves the basin. In partially closed basins, groundwater flow paths hydraulically connect basins below land surface. Recharged groundwater generally flows downgradient toward the center of the basin and eventually discharges to a stream, to a lake, or by evapotranspiration. In some cases, these flow paths are tens of miles. Sediment texture also becomes finer toward the center of basins (Bertoldi and others, 1991; Planert and Williams, 1995; Robson and Banta, 1995; Faunt, 2009), slowing the movement of groundwater and reducing the flushing action of the flow system. For these reasons, groundwater mineralization generally is greater near the center of the basins.

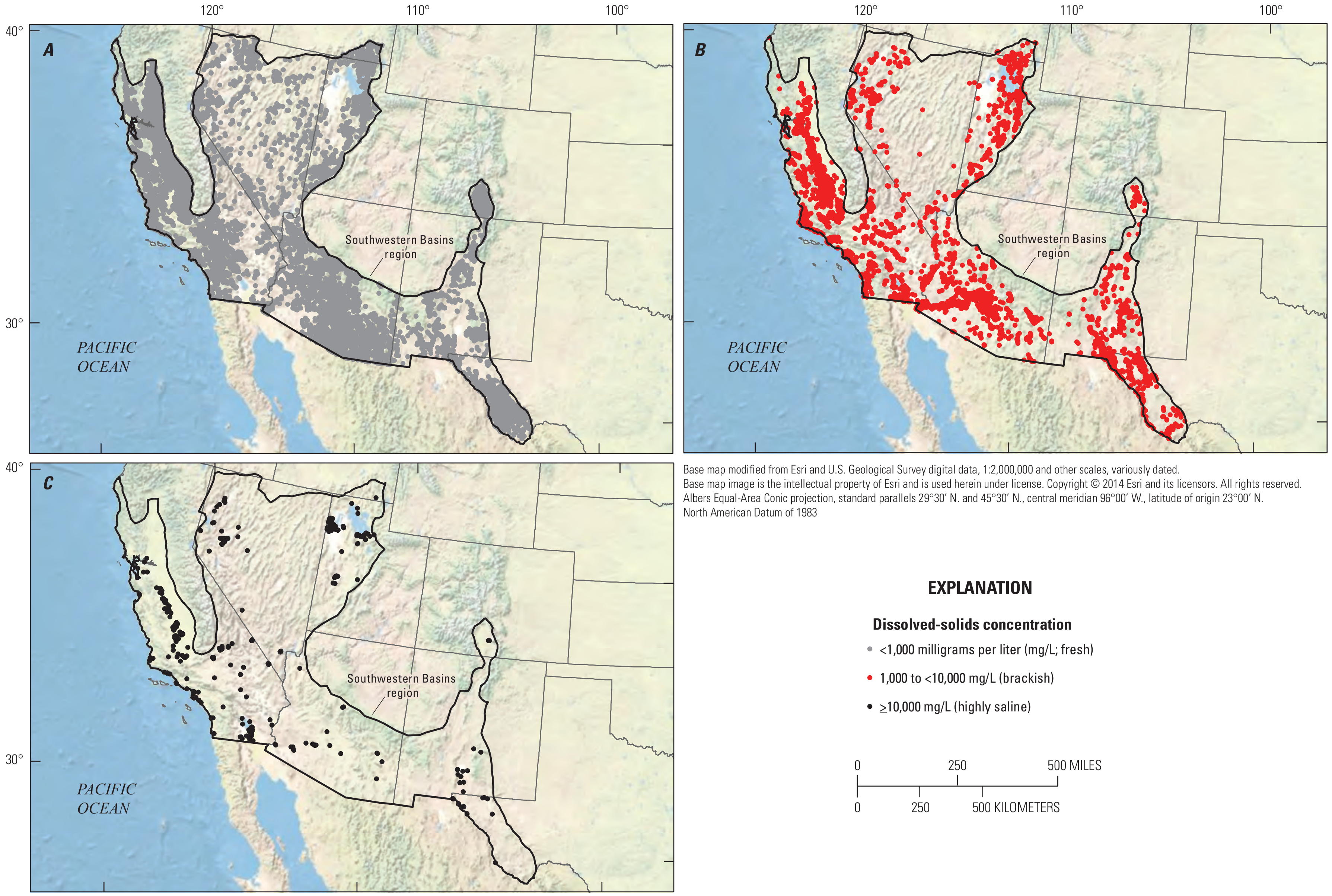
Distribution of Dissolved Solids

Groundwater quality for most of the region varies horizontally and vertically and is related to geology, mineralogy, structure, drainage patterns, and development (Anderson, 1995). Dissolved-solids concentrations are lower in recharge areas, such as along mountain fronts, and higher in discharge areas. In many parts of this region, BGW is in two zones—(1) a shallow zone affected by the concentration of minerals from evaporative processes, particularly in closed basins, and (2) a deep zone affected by long flow paths, the presence of soluble salts (such as gypsum, anhydrite, and halite), inflow from adjacent geologic units, or connate seawater. Other processes that are associated with elevated dissolved-solids concentrations in this region are stream leakage, thermal springs, oil-field brines, and seawater intrusion along the California coast (table 16).

A dissolved-solids concentration was available for samples from about 34,000 wells in this region, mostly representing depths between 50 and 500 ft below land surface (fig. 36; table 4). BGW is distributed throughout most of the region where data were available. Median dissolved-solids concentrations and the percentage of sampled wells producing BGW were greatest for the depth intervals of <50 ft and 1,500 to 3,000 ft below land surface (table 4). BGW was present in 31 percent of the observed grid cell volume (including air, water, and rock) for all depth intervals between 0 and 3,000 ft below land surface (table 4). The total observed grid cell volume containing BGW for those depth intervals within this region was about 9,300 mi^3, mostly between 50 and 1,500 ft below land surface (table 4). As a conservative estimate of the amount of BGW volume that could be used, 1 percent of that volume is 93 mi^3 (310 million acre-feet).

For most of the principal aquifers in this region, the percentage of sampled wells producing BGW ranged from 20 to 33 percent (table 8). The median depth of the sampled wells producing BGW ranged from 29 ft below land surface in the sand and gravel aquifers of alluvial or glacial origin to 429 ft below land surface in the Central Valley aquifer system (table 8). Except for the Southern Nevada volcanic-rock aquifers, the percentage of grid cell volume containing BGW between 0 and 3,000 ft below land surface ranged from about 30 to 40 percent among principal aquifers in this region (table 8); the sand and gravel aquifers of alluvial or glacial origin, Rio Grande aquifer system, and Central Valley aquifer system contained the largest percentages.

For depths <500 ft below land surface, about 40 percent of the observed volume in this region was less than the EPA secondary maximum contaminant level (500 mg/L of dissolved solids), about 65 percent was freshwater (< 1,000 mg/L of dissolved solids), about 20 percent was slightly saline (1,000 to 3,000 mg/L of dissolved solids), about 10 percent was moderately saline (3,000 to 10,000 mg/L of dissolved solids), and <5 percent was highly saline (>10,000 mg/L of dissolved solids; fig. 37). For depths >500 ft below land surface, this distribution does not change substantially across the region. For depths <500 ft below land surface, the California Coastal Basin aquifers and the Rio Grande aquifer system had the largest percentages of slightly saline groundwater. The Basin and Range carbonate-rock aquifers, the Rio Grande aquifer system, and the sand and gravel aquifers of alluvial or glacial origin had the largest percentages of moderately saline groundwater. For depth intervals between 500 and 3,000 ft below land surface, the principal aquifers with the largest percentages of slightly saline groundwater were the Central Valley aquifer system and the Rio Grande aquifer system. Between 5 and 10 percent of groundwater in the 500- to 3,000-ft-depth interval was moderately saline for all the principal aquifers in this region except for the Southern Nevada volcanic-rock aquifers.



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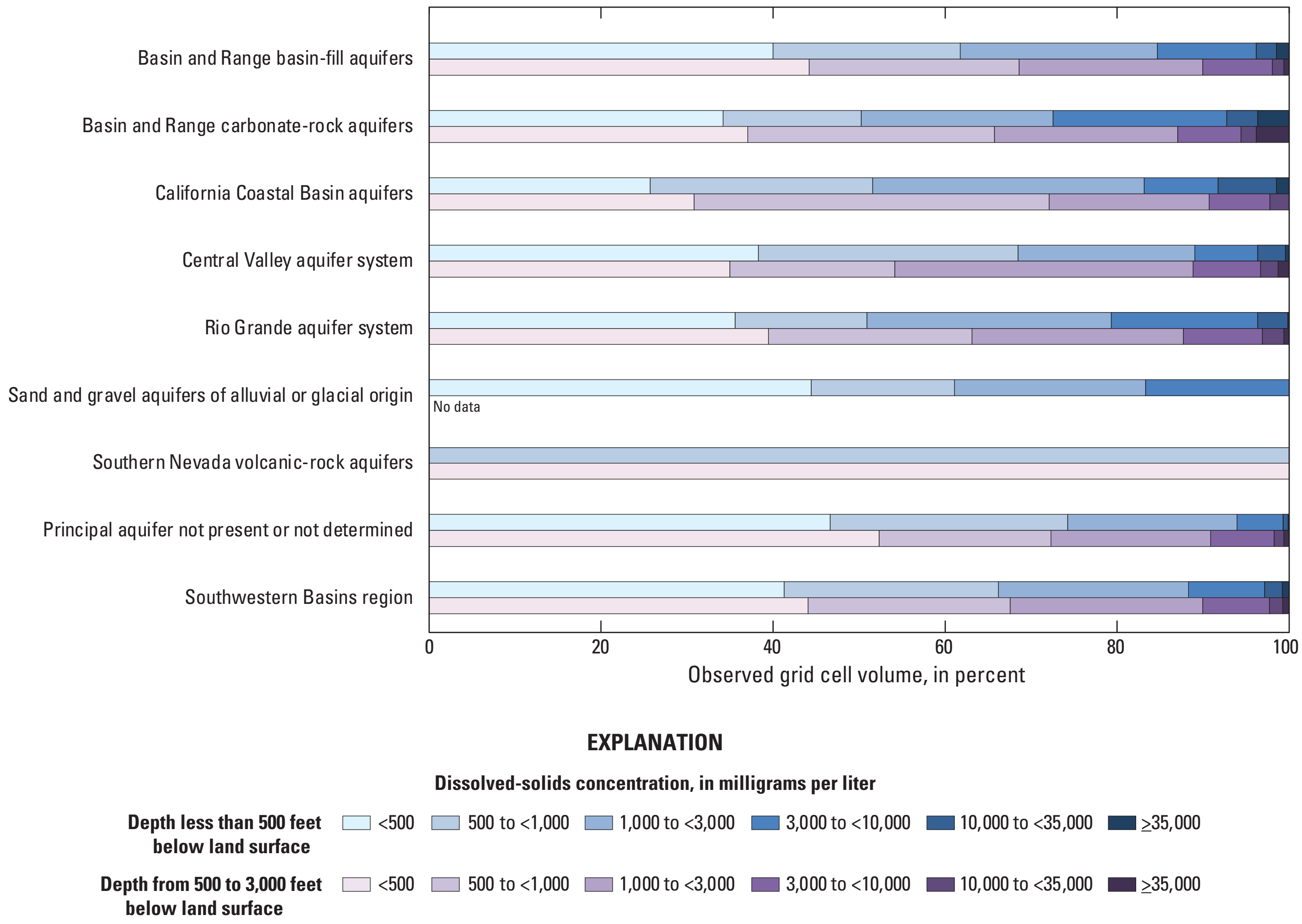
Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W., latitude of origin 23°00′ N.
North American Datum of 1983

Figure 36. Locations of wells producing *A*, fresh; *B*, brackish; and *C*, highly saline groundwater from 0 to 3,000 feet below land surface in the Southwestern Basins region.



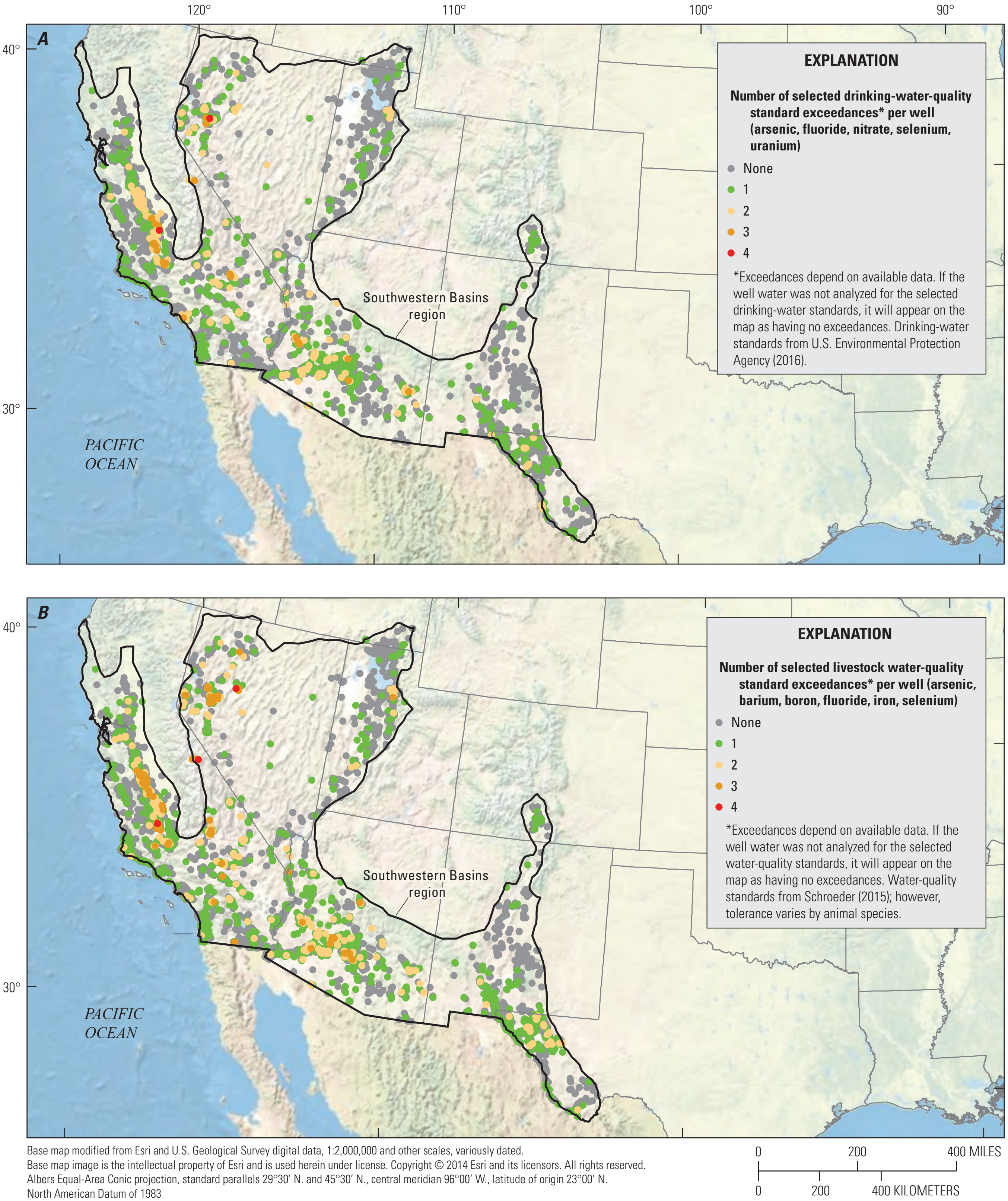
Note: Volumes are based on grid cells that have been categorized by using the maximum dissolved-solids concentration in each cell.

Figure 37. Distribution of dissolved-solids concentrations as a percentage of observed grid cell volume, by principal aquifer and depth, in the Southwestern Basins region.

Considerations for Developing Brackish Groundwater

Processes that affect the distribution of specific chemical constituents in this region include dissolution of calcite, dolomite, gypsum, and halite; precipitation of calcite and dolomite; exchange of calcium for sodium; weathering of feldspars and ferromagnesian minerals; formation of montmorillonite, iron oxyhydroxides, and probably silica; and mixing of local recharge, geothermal, or inflowing groundwater from other basins or along faults (Robertson, 1991; Harrill and Prudic, 1998; Wilkins, 1998). These processes can be different for closed hydrologic basins than for open basins (Robertson, 1991). Previous publications have identified specific constituents that can affect use, primarily for drinking-water purposes. In the Central Valley, nitrate and pesticides are present in groundwater beneath agricultural areas (Planert and Williams, 1995); hydrocarbons are present, especially in marine sediments (Scheirer, 2007; Scheirer and Magoon, 2007); and anoxic conditions in the center of the valley produce high iron, manganese, and arsenic (Bertoldi and others, 1991). In the Basin and Range basin-fill aquifers, fluoride, hexavalent chromium, arsenic, boron, barium, selenium, lead, and nitrate can potentially limit groundwater use (Robertson, 1991).

Data compiled for this assessment also indicate that BGW contains specific chemical constituents that can limit its use (fig. 38; tables 10, 11, 12). Arsenic, nitrate, and uranium were the selected constituents in this region that were most likely to be present in concentrations greater than drinking-water standards (table 10). The Basin and Range basin-fill aquifers contain the largest percentage of BGW samples that exceed selected standards for livestock consumption, but untreated BGW is generally safe for livestock in other principal aquifers (table 11). Arsenic, boron, or fluoride are potential concerns for most of the principal aquifers in this region where untreated BGW is used for irrigation (table 12). Drinking water, livestock, and irrigation water-quality exceedances are distributed throughout most of the region where BGW has been observed (fig. 38).



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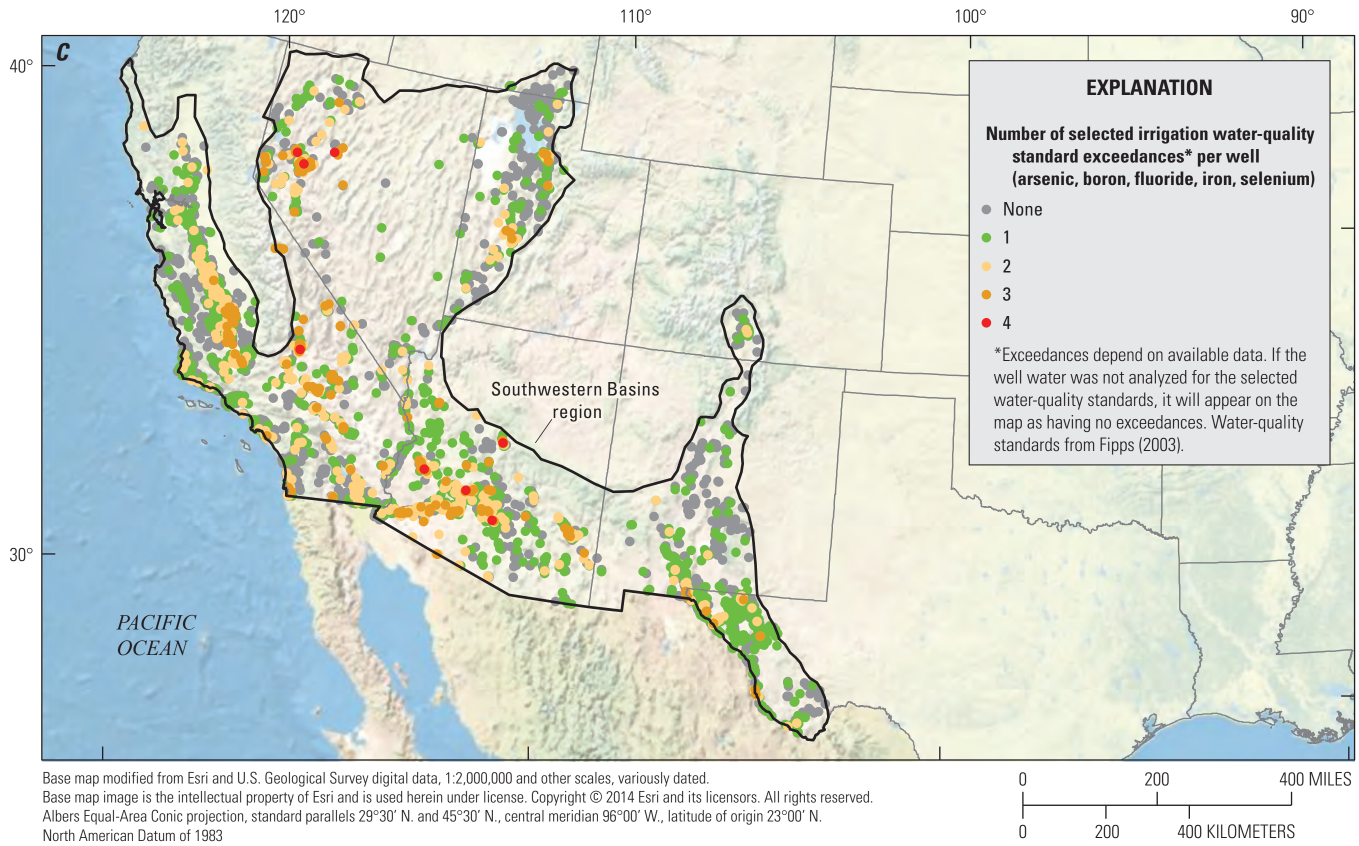
North American Datum of 1983

Figure 38. Locations of wells producing brackish groundwater that exceeds selected water-quality standards in the Southwestern Basins region. *A*, drinking water; *B*, livestock consumption; and *C*, irrigation uses.



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North American Datum of 1983

Figure 38. Locations of wells producing brackish groundwater that exceeds selected water-quality standards in the Southwestern Basins region. *A*, drinking water; *B*, livestock consumption; and *C*, irrigation uses.—Continued

Information describing aquifer hydraulic properties for this region was obtained from previously published reports, but in general, information was available only for depths up to about 2,000 ft below land surface (Anderson, 1995). In this region, hydraulic properties are affected primarily by depositional environment, proximity to volcanoes, and depth (Heilweil and Brooks, 2011). Values for specific yield varied widely for the region (between 3 to 40 percent) and within the individual principal aquifers in the region (table 16). Storage coefficients ranged from 0.00006 to 0.01 for the Basin and Range carbonate-rock aquifers and from 0.00001 to 0.1 in the deep, confined part of the Basin and Range basin-fill aquifers.

Well yields were reported for 19 percent of the sampled wells producing BGW in this region. About 80 percent of those wells had yields >100 gal/min, and most (almost 60 percent) of the brackish wells had reported yields >1,000 gal/min (table 17). The median reported yields for wells with water in the slightly saline and moderately saline ranges were about twice as large as the median yields for wells with freshwater. Although compaction and cementation of deep deposits could limit development of BGW resources in some areas (Anderson, 1995), reported yields indicated that shallow and deep wells that produce BGW yielded adequate amounts of water for many uses (fig. 39; table 17).

Saline Groundwater Use

Amounts of saline groundwater use were estimated for each of the principal aquifers containing BGW within this region by using a combination of data compiled as part of this assessment and data from the USGS Water-Use Program. According to these estimates, the Basin and Range basin-fill and California Coastal Basin were the principal aquifers that provided the most saline groundwater for use in this region (fig. 40). Saline groundwater was most commonly used for mining and public supply, followed by thermoelectric and industrial applications. Fourteen percent of municipal desalination facilities in the United States that use groundwater as their source are within this region (fig. 2; Mickley, 2012). Most of these facilities are near large population centers.

Western Midcontinent Region

The Western Midcontinent region is a broad area in the west-central part of the Nation; it extends from the southern border of Canada to the northern boundary of the coastal plain of Texas (fig. 7). Groundwater salinity in the shallower parts of the aquifers in this region may be affected by proximity to recharge areas and infiltration of highly mineralized surface

Table 17. Well yields by dissolved-solids concentration category in the Southwestern Basins region.

[gal/min, gallon per minute; mg/L, milligram per liter]

Dissolved-solids concentration (table 1)	Number of wells with a reported well yield	Median well yield, in gal/min	Wells with a well yield greater than 10 gal/min, in percent	Wells with a well yield greater than 100 gal/min, in percent	Wells with a well yield greater than 1,000 gal/min, in percent
Freshwater (<1,000 mg/L)	5,105	611	87	66	39
Brackish (1,000 to <10,000 mg/L)	1,537	1,350	91	79	58
Slightly saline (1,000 to <3,000 mg/L)	1,276	1,347	91	79	58
Moderately saline (3,000 to <10,000 mg/L)	261	1,400	91	83	59
Highly saline (≥10,000 mg/L)	19	25	63	42	16

water or irrigation-return flow; this mineralization is caused by evaporative concentration or leaching of minerals in the soil. Salinity in the deep parts of the aquifers may be affected by depth; aquifer permeability, which affects length of groundwater flow paths and groundwater residence time; connate seawater; and oil and gas production activities (disposal of saltwater, spills, leaks, and abandoned wells). Salinity may be affected by dissolution of evaporites or carbonate rocks; infiltration, which can be enhanced by pumping of mineralized water from underlying, overlying, or adjacent units; cation exchange; and sulfate reduction.

Brackish zones (table 18) are in localized areas (Denver Basin aquifer system), as a transition zone between freshwater and highly saline water or brine (Arbuckle-Simpson aquifer, Colorado Plateaus aquifers, Lower Cretaceous aquifers, Edwards-Trinity aquifer system, Paleozoic aquifers, and Western Interior Plains aquifer system), across much of the aquifer area (Pecos River Basin alluvial aquifer and Blaine aquifer), or either above or below freshwater (Seymour aquifer, Lower Tertiary aquifers, and Upper Cretaceous aquifers). A total of 19 principal aquifers are mostly within this region (fig. 41), and 17 of those contain substantial amounts of BGW as evidenced by the presence of brackish or highly saline groundwater in a large percentage of their observed grid cell volume (table 8).

Hydrogeologic Characteristics

The region is underlain by unconsolidated to consolidated and fractured sedimentary rocks of Paleozoic to Cenozoic age (table 18); sedimentary rocks were deposited in marine to continental environments and within sedimentary basins, where present (Heath, 1984; Coleman and Cahan, 2012). The lithology of the aquifer units in the region is dominated by young, unconsolidated alluvial and aeolian deposits and old, consolidated sandstone and carbonate (limestone and dolomite) deposits (table 18). The aquifer unit layers are generally separated from each other by fine-grained layers, many of which are composed of siltstone or shale that, in many areas, act as confining units with substantial thickness; the confining units can impede the vertical movement of groundwater (Heath, 1984; Jorgensen and others, 1993). In about 70 percent of the region's area, evaporite deposits (anhydrite, gypsum, or halite) exist within the sedimentary deposits (Johnson, 2008).

Periodic inundations of seawater during the Paleozoic and Mesozoic Periods, tectonic events that caused uplifts and basins, and erosion and deposition have greatly affected the geologic and chemical characteristics of this region (Downey and Dinwiddie, 1988; Taylor and Hood, 1988; Jorgensen and others, 1993). The result is many layers of sediments, which

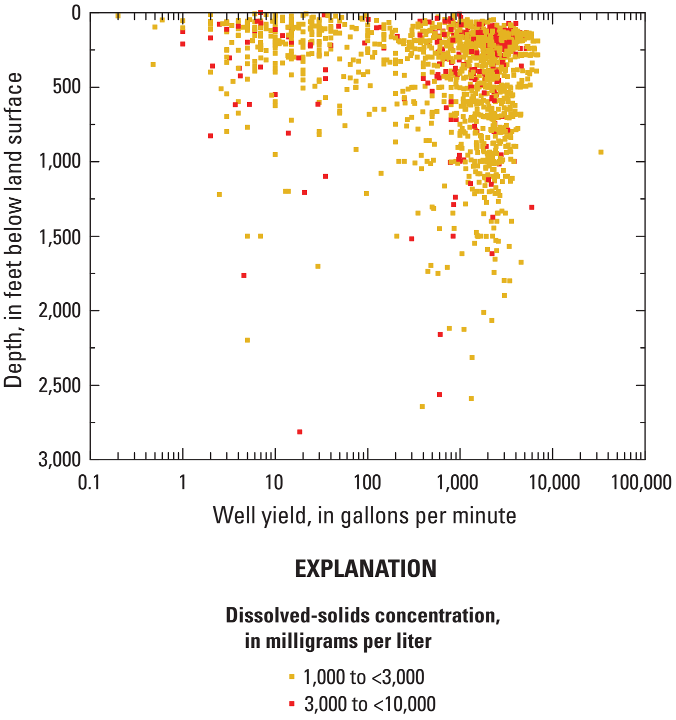

Figure 39. Distribution of well yields relative to depth below land surface at sampled wells producing brackish groundwater in the Southwestern Basins region.

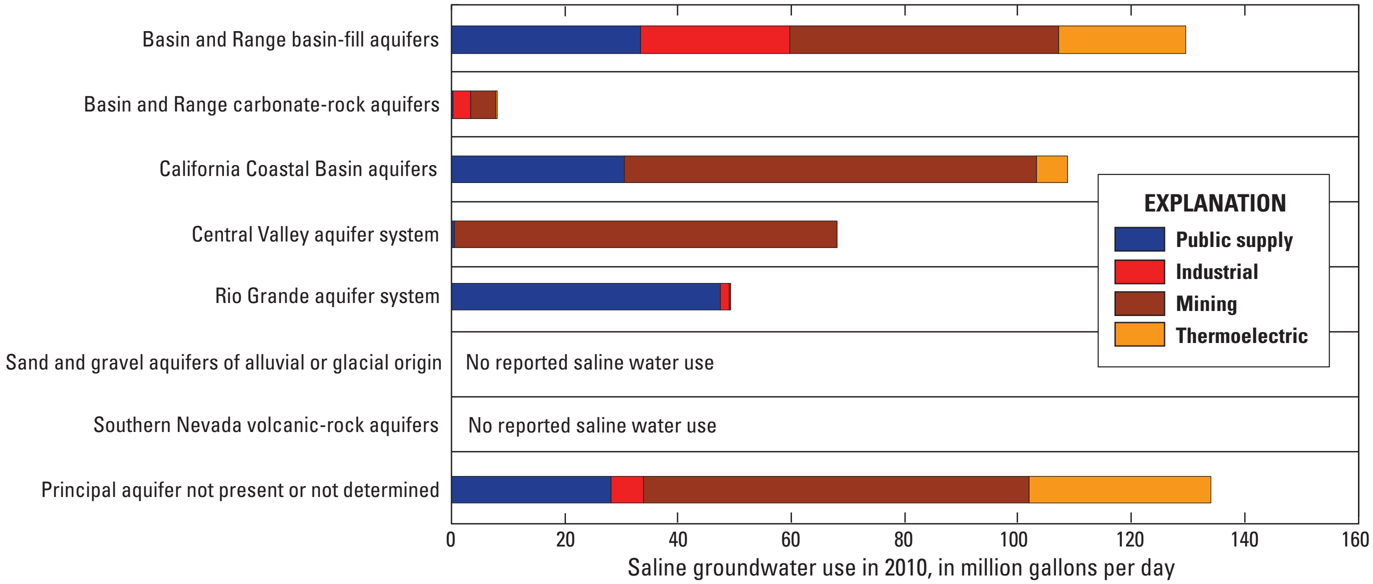

Figure 40. Estimated saline groundwater use from principal aquifers in the Southwestern Basins region.

were deposited in deltaic, alluvial, fluvial, aeolian, or various marine environments—deep, shallow, nearshore, shoreline, and tidal. The layers include carbonates, which were generally deposited in shallow seas; and evaporites, which were deposited as the seas became isolated. Connate seawater of historic origin still resides within some of the sedimentary layers. Groundwater salinity generally increases with depth, length of flow path, and residence time in the aquifers. Much of the water in the aquifers grades from freshwater to brine (table 18) as deposits become less permeable and groundwater flow becomes sluggish, increasing the contact time between the water and minerals and likely limiting flushing of connate seawater (Heath, 1984; Robson and Banta, 1995; Ryder, 1995; Whitehead, 1996; Miller and Appel, 1997).

The region is primarily within a continental climate zone, and average annual precipitation generally increases from west to east (Heath, 1984). Regional recharge to the unconfined aquifers is primarily from precipitation; and infiltration of water from streams, lakes, and canals, irrigation-return flow, and adjacent aquifer units. Regional recharge to the confined aquifers is primarily from precipitation, which happens mostly in the uplands (where the geologic units that compose the aquifer outcrop), and to a lesser degree, seepage from underlying and overlying layers (Heath, 1984; Robson and Banta, 1995; Ryder, 1995; Whitehead, 1996; Miller and Appel, 1997). In areas with deep sedimentary basins and evaporite deposits (Jorgensen and others, 1993; Busby and others, 1995; Johnson, 2008; Coleman and Cahan, 2012), groundwater residence times are longer, which provides more time for dissolution of evaporites and aquifer sediments and minimizes flushing of connate seawater (Busby and others, 1995).

Groundwater salinity generally increases with depth and away from recharge areas (Freethey and Gordy, 1991; Jorgensen and others, 1993; Busby and others, 1995; Kuniansky and Ardis, 1997; Craigg, 2001; Geldon, 2003); however, high concentrations of dissolved solids can exist at shallow depths where (1) water is infiltrating into the aquifer from surface water or from irrigation-return flow with increased dissolved solids because of evaporative concentration or leaching of minerals in the soil, such as in localized areas of the High Plains aquifer (Gutentag and others, 1984); (2) water is discharging at the surface from deep aquifers with dissolved-solids concentrations in the saline to brine range, such as in the Western Interior Plains aquifer system (Jorgensen and others, 1993); and (3) infiltration, which can be enhanced by pumping, of mineralized water from underlying, overlying, or adjacent units (for example in the Seymour aquifer; R.W. Harden and Associates, 1978; Ryder, 1995).

The Western Interior Plains aquifer system (Carboniferous in age) within this region (in Kansas, Nebraska, Oklahoma, and Colorado) is confined beneath sedimentary rock layers (Permian in age) that have evaporite deposits; however, it crops out and is unconfined to the east in the Eastern Midcontinent region. There are numerous groundwater samples within the region (from beneath the evaporites) and to the east downgradient (from beneath the evaporites) with dissolved-solids concentrations >35,000 mg/L. This suggests a major dissolved-solids source from dissolution of the evaporite minerals and subsequent groundwater transport. Some of the highest dissolved-solids concentrations within this region have been associated with the dissolution of halite and subsequent mixing and groundwater transport (Musgrove and Banner, 1993).

In the Western Midcontinent region, hydraulic properties are affected primarily by lithology, depositional environment, depth, and postdepositional processes (including tectonic activity and dissolution), which have resulted in faults, fractures, sinkholes, and caves (Olcott, 1992; Robson and Banta, 1995; Ryder, 1995; Whitehead, 1996; Miller and Appel, 1997).

Hydraulic properties (specific yield, storage coefficient, or specific storage) were compiled from previously published reports (table 18). Values for specific yield varied from 1 to 34 percent for the individual principal aquifers in this region (table 18). Storage coefficients ranged 0.000001 to 0.02 (table 18).

Distribution of Dissolved Solids

A dissolved-solids concentration was available for samples from about 115,600 wells in this region (fig. 42; table 4). BGW was observed throughout most of the area. About 85 percent of those wells were completed at depths <500 ft below land surface. Median dissolved-solids concentrations decreased slightly with depth from near surface (<50 ft below land surface) to 50 to 500 ft below land surface, and then increased with depth. The median dissolved-solids concentration for the 1,500- to 3,000-ft below land surface depth interval was more than an order of magnitude higher than for shallower depth intervals. The percentage of sampled wells with BGW was largest (49 percent) for wells completed between 500 and 1,500 ft below land surface. At depths >1,500 ft below land surface, about 85 percent of sampled wells produced either brackish or highly saline groundwater (table 4). BGW was present in about 50 percent of the observed grid cell volume (including air, water, and rock) for depths between 0 and 3,000 ft below land surface. BGW observed within this region mostly exists from 50 to 1,500 ft below land surface. At depths >1,500 ft below land surface, most groundwater is brackish or highly saline. The total observed subsurface grid cell volume that contained some BGW within this region was about 52,000 mi^3. Conservatively, if 1 percent of that water can be extracted, then 520 mi^3 (1,760 million acre-feet) of BGW potentially is available.

The percentage of samples with BGW varied among principal aquifers of this region from 6 to 80 percent (table 8). The aquifers with 50 percent or more of the sampled wells producing BGW were the Blaine aquifer, the Upper Cretaceous aquifers, the Lower Tertiary aquifers, the Pecos River Basin alluvial aquifer, the Lower Cretaceous aquifers, and the Seymour aquifer. For other principal aquifers, the percentage of sampled wells that produced BGW ranged from 6 to 44 percent. The median completion depth of sampled wells that produced BGW ranged from 46 ft below land surface in the Seymour aquifer to 1,890 ft below land surface in the Paleozoic aquifers (table 8). The estimated percentage of observed grid cell volume containing BGW ranged from 12 to 87 percent among the principal aquifers in this region; the Seymour aquifer contained the largest percentage (table 8).

Of the observed volume at depths <500 ft below land surface, 30 percent was less than the EPA secondary maximum contaminant level (500 mg/L of dissolved solids), about 50 percent was freshwater (<1,000 mg/L of dissolved solids), about 35 percent was slightly saline (1,000 to 3,000 mg/L of dissolved solids), about 15 percent was moderately saline (3,000 to 10,000 mg/L of dissolved solids), and <5 percent was highly saline (>10,000 mg/L of dissolved solids; fig. 43). Between 500 to 3,000 ft below land surface, about 15 percent of the observed grid cell volume was less than the EPA secondary maximum contaminant level (500 mg/L of dissolved solids), about 30 percent was freshwater, about 35 percent was slightly saline, about 15 percent was moderately saline, and 25 percent was highly saline.

For depths <500 ft below land surface, the aquifers with the largest grid cell volume percentages of slightly saline and moderately saline groundwater were the Roswell Basin aquifer system, the Blaine aquifer, the Seymour aquifer, the Lower Tertiary aquifers, the Rush Springs aquifer, the Upper Cretaceous aquifers, and the Pecos River Basin alluvial aquifer. For depth intervals between 500 and 3,000 ft below land surface, the principal aquifers with the largest percentages of slightly saline groundwater were the sand and gravel aquifers of alluvial or glacial origin, the Upper Cretaceous aquifers, and the Lower Tertiary aquifers. Principal aquifers with the largest percentages of moderately saline groundwater for those depth intervals were the Pecos River Basin alluvial aquifer and the Rush Springs aquifer.

Considerations for Developing Brackish Groundwater

In this region, factors that may affect the distribution of specific chemical constituents in the upper 3,000 ft include the presence of connate seawater; mixing, which can be enhanced by pumping, with highly mineralized groundwater from underlying, overlying, and adjacent units; dissolution of minerals, particularly evaporites and carbonates; cation exchange; sulfate reduction; and mixing with mineralized recharge caused by evaporative concentration and dissolution of minerals in the unsaturated zone (Jorgensen and others, 1993; Busby and others, 1995). The groundwater chemistry can also be affected by the groundwater residence time within the aquifer, which is directly related to flow-path length and aquifer permeability. In aquifers such as the Lower Cretaceous aquifers, the Paleozoic aquifers, and the Colorado Plateaus aquifers, which are aquifers where the brackish part of the aquifer is a transitional zone between freshwater in the recharge area and brine, dominant ion groups evolve from mostly calcium or magnesium bicarbonate near the recharge areas to calcium sulfate and sodium sulfate and finally to sodium chloride, particularly in areas with halite deposits. This shift in the geochemical characteristics of the groundwater is accompanied by an increase in dissolved-solids concentrations (table 18).

Data compiled for this assessment indicate that untreated BGW in this region contains specific constituents that can limit its use (fig. 44; tables 10, 11, and 12). In the 19 principal aquifers in this region, constituents at concentrations above selected drinking-water standards in at least 25 percent of the BGW samples are arsenic (High Plains aquifer), fluoride (High Plains aquifer and Western Interior Plains aquifer system), nitrate (Denver Basin aquifer system, High Plains aquifer, and

Table 18. Generalized hydrogeologic characteristics of principal aquifers with substantial amounts of brackish groundwater in the Western Midcontinent region.

[Descriptions are generalized aquifer properties and not specific to the brackish zone. gal/min, gallon per minute; mg/L, milligram per liter; --, not applicable or not reported in publications reviewed for this study; ft, foot]

Principal aquifer[1]	Geologic age[2]	General description of brackish zone(s)[2]	Principal depositional environment[2]	Principal composition[2]	Flow influenced by confining beds[2]	Specific yield, in percent (unconfined aquifers)[2]
Ada-Vamoosa aquifer	Pennsylvanian	Base of aquifer defined as the base of potable water, where dissolved solid concentration less than 1,500 mg/L. Excessive pumping may cause upward movement of connate seawater in deeper parts of the aquifer. Brines and wastes from oil-field activities may have caused local contamination in the aquifer	Alluvial, deltaic, and marine	Sandstone irregularly interbedded with shale and limestone	Yes	12
Arbuckle-Simpson aquifer	Cambrian and Ordovician	Dissolved solids generally less than 500 mg/L in aquifer where the aquifer units outcrop, defined as the zone of freshwater. Outside the outcrop area and below the freshwater zone, the water has higher dissolved solids because of dissolution of evaporites and presence of connate seawater	Marine	Limestone, dolomite, and sandstone	No	20
Blaine aquifer	Permian	Aquifer is generally brackish because of dissolution of evaporite minerals within the aquifer	Marine	Anhydrite, gypsum, shale, and dolomite	Yes	--
Central Oklahoma aquifer	Permian and Quaternary	Saline and brackish zone is generally below 500 ft. Pumping can cause upward movement of saline water; brines and wastes from oil-field activities may have caused local contamination of freshwater in the aquifer. Possible mechanisms for increasing salinity include dissolution of evaporites, presence of connate seawater, and long flow paths and residence time	Alluvial, fluvial, and deltaic	Alluvial and terrace deposits (clay, silt, sand, and gravel), sandstone, siltstone, mudstone, shale, limestone	Yes	1 to 21
Colorado Plateaus aquifers	Permian, Jurassic, Cretaceous, Paleocene, Eocene, Oligocene	A series of stacked aquifer systems generally within structural basins. Brackish in transition zones from recharge areas at basin margins to deeper parts of the aquifer, where longer flow path and longer residence times enables dissolution of evaporites, and in discharge areas	Continental and marine, geologic units deformed by repeated tectonic activity	Sandstone, limestone, conglomerate with siltstone, mudstone, coal beds, claystone, and shale	Yes	5 to 10 (Navajo-Nugget aquifer only)
Denver Basin aquifer system	Late Cretaceous to Quaternary	Near surface, where there is infiltration of surface water and irrigation return flow, dissolved-solid concentration was increased by evaporation and by dissolution of minerals in the subsurface and, with depth, as a result of ion-exchange and oxidation-reduction reactions	Alluvial, fluvial, eolian, and marine	Consolidated sandstone, shale, and siltstone, and unconsolidated sand and gravel	Yes	13 to 19

Storage coefficient or specific storage where noted (confined aquifers)[2]	Presence of secondary porosity[2]	Presence of evaporites[2]	Number of brackish wells with a reported well yield[3,4]	Median well yield at brackish wells, in gal/min[3,5]	Interquartile range of well yield at brackish wells, in gal/min[3,5]	References
2×10^{-4}	Yes	Yes	4	33	10 to 275	D'Lugosz and others (1986), Ryder (1995), Abbott (2000).
8×10^{-3}	Yes	Yes	1	2,500	--	Ryder (1995), Johnson (2008), Christenson and others (2009).
5×10^{-3} to 1×10^{-2}	Yes	Yes	17	650	150 to 940	Johnson (1985), Ryder (1995), Hopkins and Muller (2011).
1×10^{-4} to 4×10^{-4}, median 2×10^{-4}	--	Yes	19	115	18 to 275	Ryder (1995), Parkhurst and others (1996), Becker (2013), Mashburn and others (2014).
5×10^{-6} to 8×10^{-3}	Yes	Yes	376	12	6 to 30	Taylor and Hood (1988), Freethey and Gordy (1991), Robson and Banta (1995), Whitehead (1996), Fipps (2003), Geldon (2003).
less than 2×10^{-4} to more than 8×10^{-4}	No	Yes	22	51	15 to 1,100	Robson (1987), Robson and Banta (1995), Bruce and McMahon (1998), Paschke (2011), Musgrove and others (2014).

Table 18. Generalized hydrogeologic characteristics of principal aquifers with substantial amounts of brackish groundwater in the Western Midcontinent region.—Continued

[Descriptions are generalized aquifer properties and not specific to the brackish zone. gal/min, gallon per minute; mg/L, milligram per liter; --, not applicable or not reported in publications reviewed for this study; ft, foot]

Principal aquifer[1]	Geologic age[2]	General description of brackish zone(s)[2]	Principal depositional environment[2]	Principal composition[2]	Flow influenced by confining beds[2]	Specific yield, in percent (unconfined aquifers)[2]
Edwards-Trinity aquifer system	Early Cretaceous	Aquifer boundary is defined as the farthest updip extent of water that contains 10,000 mg/L dissolved solids. Water is brackish in the transition zone between fresh water and more saline water downdip, where flow is sluggish because of reduced permeability	Sediment deposited in terrestrial, supratidal, intertidal, and shallow marine environments on slowly subsiding carbonate platform in the following aquifer areas: Trans-Pecos, Edwards Plateau, Hill County, and Balcones Fault Zone	Limestone, dolomite, sandstone, sand, and shale	Yes	2 to 7.4
Lower Cretaceous aquifers	Early Cretaceous	Transitional zones between area of recharge or discharge and high salinity areas where long flow paths and slow groundwater velocity have resulted in incomplete flushing of connate seawater and cation-exchange reactions within the aquifer system	Deltaic, shoreline, or fluvial environments	Sandstone	Yes	15 (in Colorado, Kansas, Nebraska, and New Mexico)
Lower Tertiary aquifers	Early Tertiary	Aquifer is largely brackish; in Powder River Basin, dissolved solids decrease with depth. Probable mechanisms for salinity: cation exchange, sulfate reduction, and length of flow time or flow path from recharge to discharge	Fluvial, alluvial, deltaic, tidal, barrier-shoreface, and marine	Semiconsolidated to consolidated sandstone beds interbedded with siltstone, claystone, and coal beds	Yes	--
Paleozoic aquifers	Cambrian, Ordovician, and Mississippian	Transition zones in and downgradient from recharge areas; salinity increases in groundwater away from the recharge areas as it dissolves evaporites	Marine	Sandstone, shales, siltstone, carbonates, and evaporites	Yes	--
Pecos River Basin alluvial aquifer	Tertiary to Quaternary	Aquifer is generally brackish. Salinity is derived from dissolution of evaporites in underlying Permian-age units; infiltration of highly mineralized water from the Pecos River and irrigation return flow caused by evaporative concentration and leaching of minerals from the soil; oil and gas-related activities (disposal of salt water, spills, leaks, and abandoned wells); and pumping, which induces flow of highly mineralized water from the underlying aquifer	Alluvial, fluvial, eolian, lacustrine, valley-fill in solution-collapse features	Unconsolidated sand, gravel, silt, and clay with some caliche	Yes	12 to 20

Storage coefficient or specific storage where noted (confined aquifers)[2]	Presence of secondary porosity[2]	Presence of evaporites[2]	Number of brackish wells with a reported well yield[3,4]	Median well yield at brackish wells, in gal/min[3,5]	Interquartile range of well yield at brackish wells, in gal/min[3,5]	References
1×10^{-5} to 7.4×10^{-4}	Yes	Yes	96	10	5 to 20	Barker and others (1994), Bush and others (1994), Ryder (1995), Kuniansky and Ardis (1997).
1×10^{-6} to 8×10^{-4}	Yes (in Montana, North Dakota, South Dakota, and Wyoming); otherwise, generally no	Yes	1,371	11	4 to 30	Burkart (1984), Anna (1986), Downey (1986), Woodward and Anderson (1986), Downey and Dinwiddie (1988), Olcott (1992), Helgesen and others (1993), Whitehead (1996), Miller and Appel (1997).
--	Yes	--	1,318	8	4 to 15	Lowry and others (1986), Whitehead (1996), Flores and others (1999a, b).
1×10^{-6} to 1×10^{-4}	Yes	Yes	64	55	23 to 225	Williams (1970), Downey (1986), Busby and others (1995), Whitehead (1996).
2×10^{-4} per foot (specific storage)	--	Yes	10	790	250 to 1,000	Ryder (1995), Anaya and Jones (2009), Meyer and others (2011).

Table 18. Generalized hydrogeologic characteristics of principal aquifers with substantial amounts of brackish groundwater in the Western Midcontinent region.—Continued

[Descriptions are generalized aquifer properties and not specific to the brackish zone. gal/min, gallon per minute; mg/L, milligram per liter; --, not applicable or not reported in publications reviewed for this study; ft, foot]

Principal aquifer[1]	Geologic age[2]	General description of brackish zone(s)[2]	Principal depositional environment[2]	Principal composition[2]	Flow influenced by confining beds[2]	Specific yield, in percent (unconfined aquifers)[2]
Roswell Basin aquifer system	Permian and Quaternary	Aquifer is brackish in eastern part of aquifer in both basin fill and carbonate units; likely mechanisms are dissolution of evaporites within the aquifer units, leakage of mineralized water from underlying and adjacent geologic units, and irrigation return flow, with high dissolved solids	Alluvial and marine	Unconsolidated sand, silt, gravel, and clay and consolididated limestone, dolomite, sandstone, and gypsum	Yes	10 to 20
Rush Springs aquifer	Permian	Brackish in the western and eastern parts of the aquifer, increased salinity is likely caused by dissolution of evaporites within the aquifer units	Fluvial, eolian, and shallow marine	Sandstone	Yes	13 to 34, mean 25
Seymour aquifer	Quaternary	Dissolved solids increase downgradient from recharge areas because of infiltration of dissolved evaporite deposits from underlying and adjacent Permian-age units and possibly oil- and gas-related activities	Alluvial	Unconcolidated clay, silt, sand, gravel	Yes, in localized areas	10 to 20, mean 15
Upper Cretaceous aquifers	Late Cretaceous	Aquifer is largely brackish; in Powder River Basin, dissolved solids decrease with depth. Probable mechanisms for salinity: cation exchange, sulfate reduction, and length of flow time or flow path from recharge to discharge	Fluvial, deltaic, marine	Sandstone	Yes	--
Western Interior Plains aquifer system	Late Cambrian to Late Mississippian	Brackish in some upgradient areas; aquifer is generally saline to brine. Higher dissolved solids in basins, with long flow paths, sluggish movement, and long residence time.	Marine	Limestone, dolomite, and shale	Yes	--

[1] Sand and gravel aquifers of alluvial or glacial origin contain substantial amounts of brackish groundwater but typically are smaller in extent and not included in this table.

[2] Obtained from previously published work.

[3] Obtained from data compiled for this study.

[4] Well yield results should be used with caution if few values are available for an aquifer.

[5] Data are from reported pumping rates and not potential well yields. Therefore, results probably represent minimum values.

Storage coefficient or specific storage where noted (confined aquifers)[2]	Presence of secondary porosity[2]	Presence of evaporites[2]	Number of brackish wells with a reported well yield[3,4]	Median well yield at brackish wells, in gal/min[3,5]	Interquartile range of well yield at brackish wells, in gal/min[3,5]	References
5×10^{-4} in east and 5×10^{-2} in west	Yes	Yes	0	--	--	Fiedler and Nye (1933), Welder (1983), Daniel B. Stephens & Associates, Inc. (1995), Robson and Banta (1995), Huff (2004a).
3.5×10^{-3} to 2×10^{-2}	--	Yes	14	30	5 to 119	Fay and Hart (1978), Ryder (1995), Suneson and Johnson (1996), Becker and Runkle (1998).
--	No	Yes	0	--	--	R.W. Harden and Associates (1978), Ryder (1995).
--	Yes	--	692	8	4 to 15	Lowry and others (1986), Whitehead (1996).
--	Yes	Yes	6	56	20 to 70	Jorgensen and others (1993), Signor and others (1996), Renken (1998).

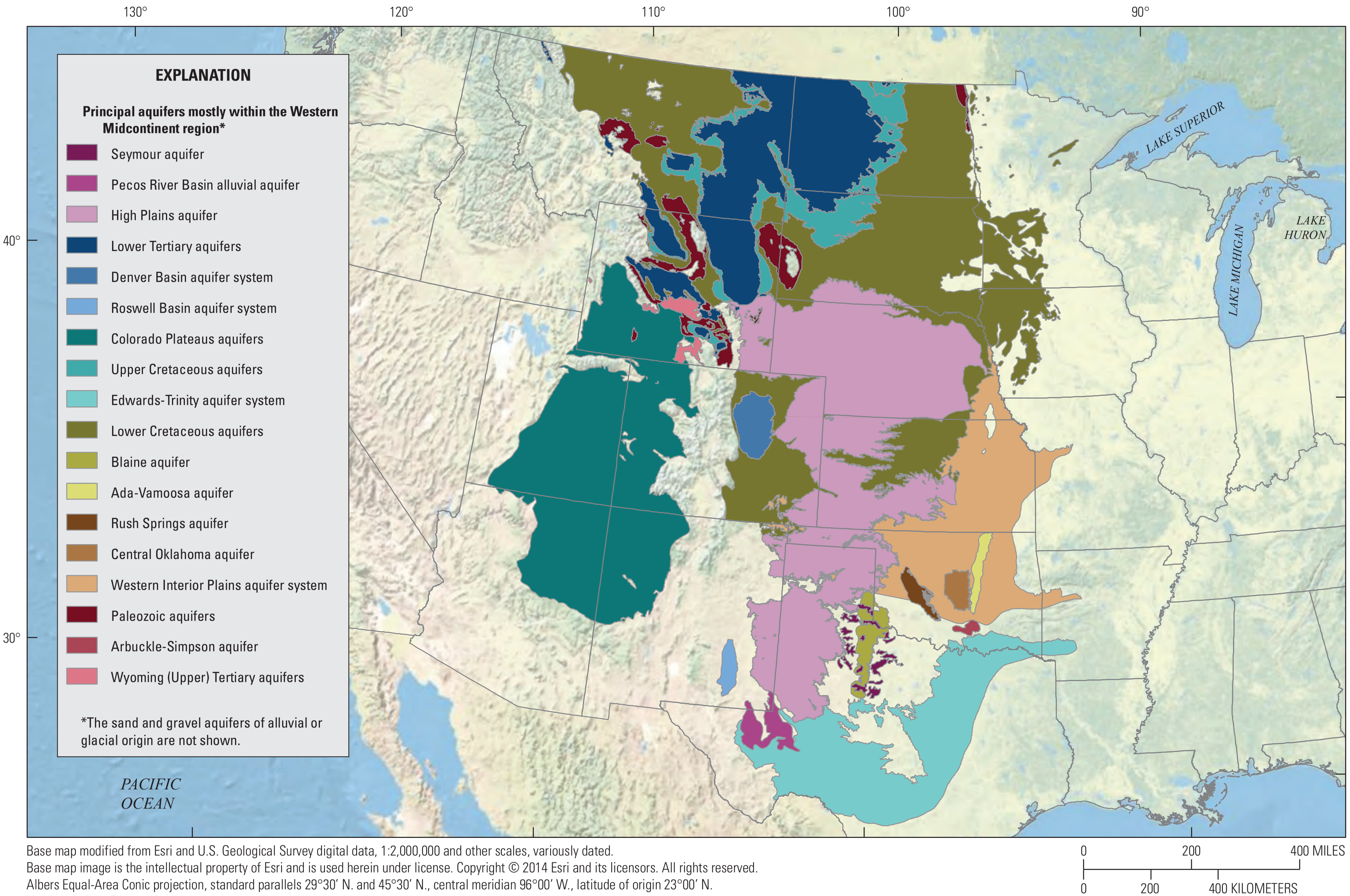

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Figure 41. Principal aquifers mostly within the Western Midcontinent region. An interactive map for viewing the full extent of each principal aquifer is available at https://doi.org/10.3133/pp1833.

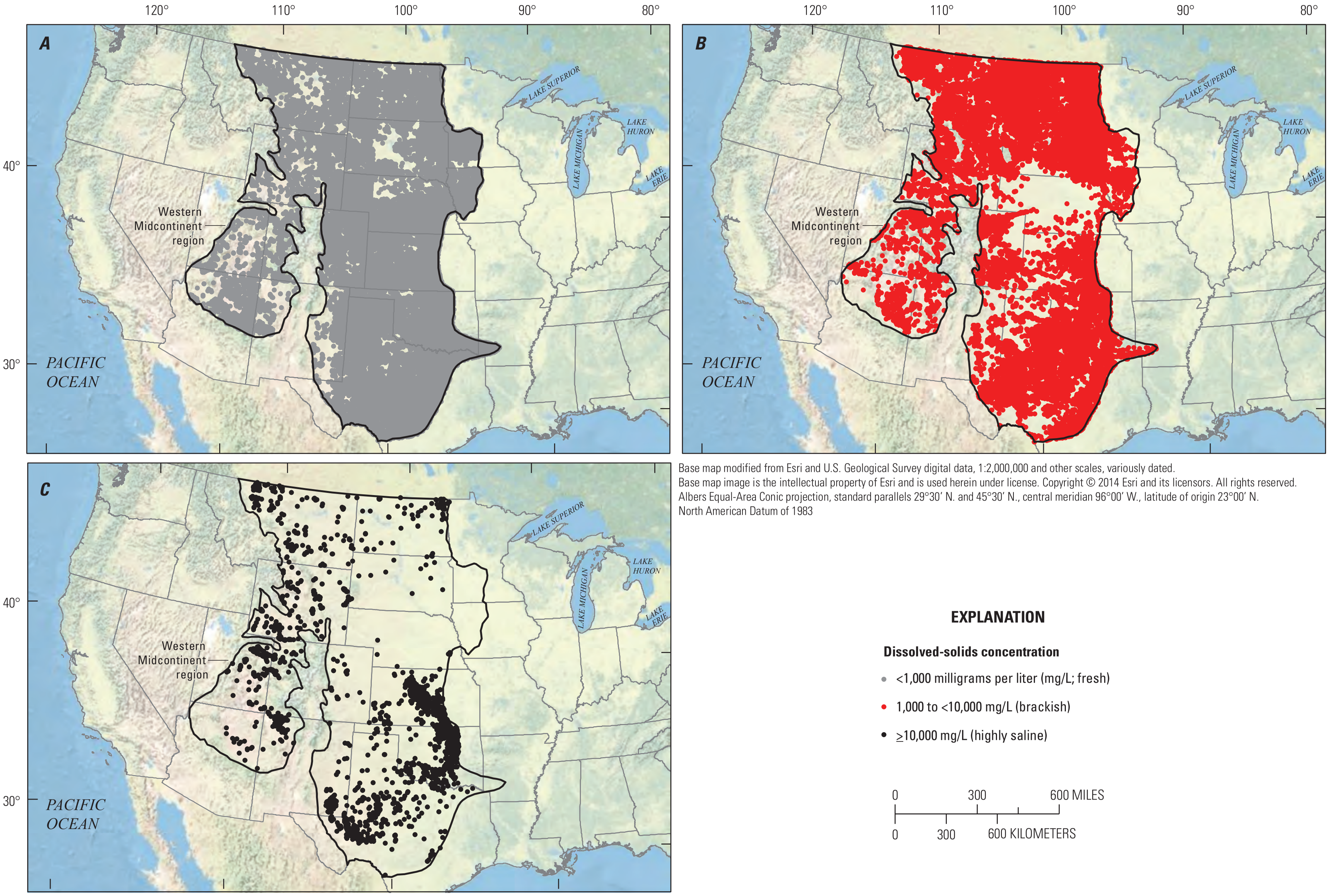

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Figure 42. Locations of wells producing *A*, fresh; *B*, brackish; and *C*, highly saline groundwater from 0 to 3,000 feet below land surface in the Western Midcontinent region.

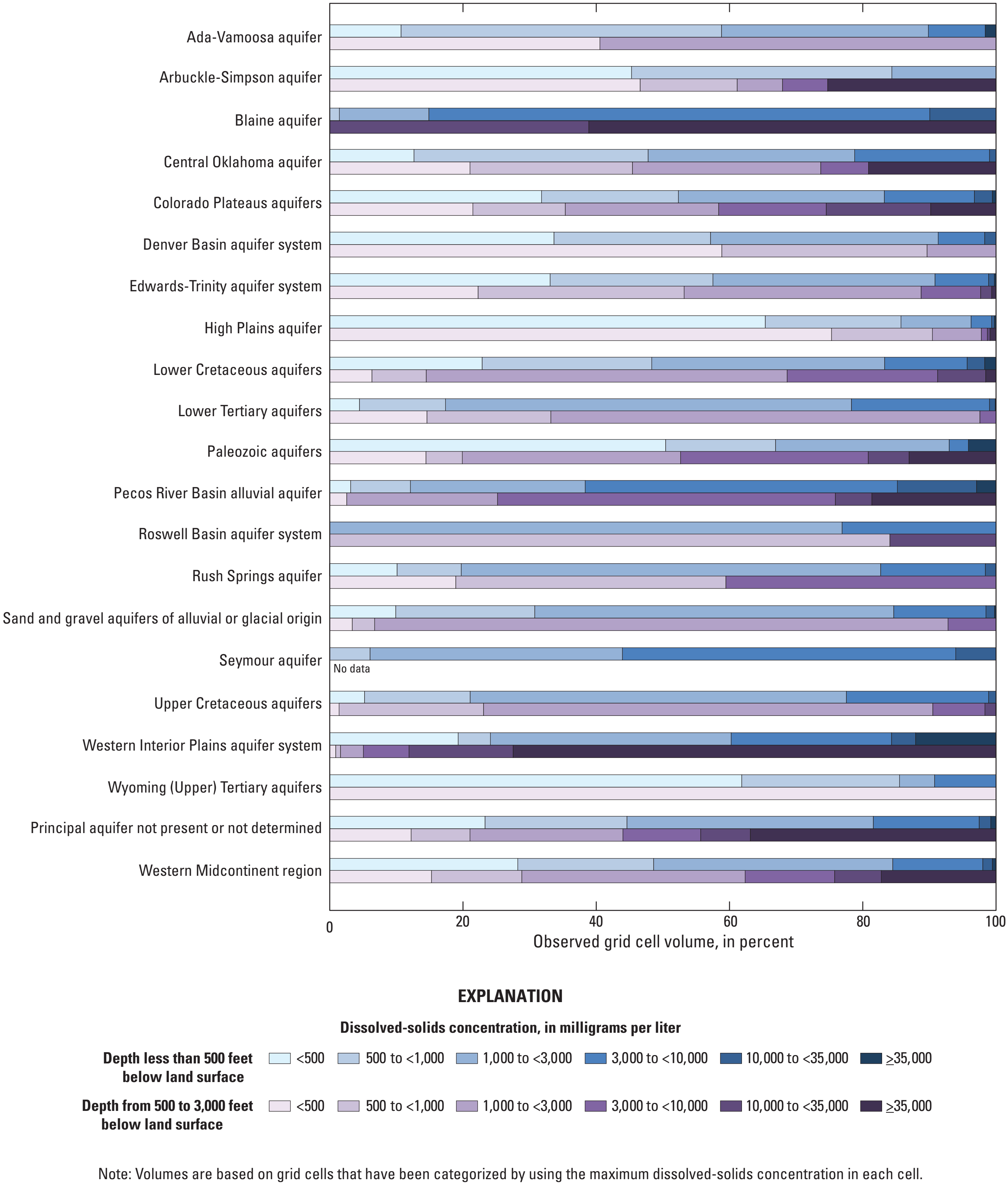
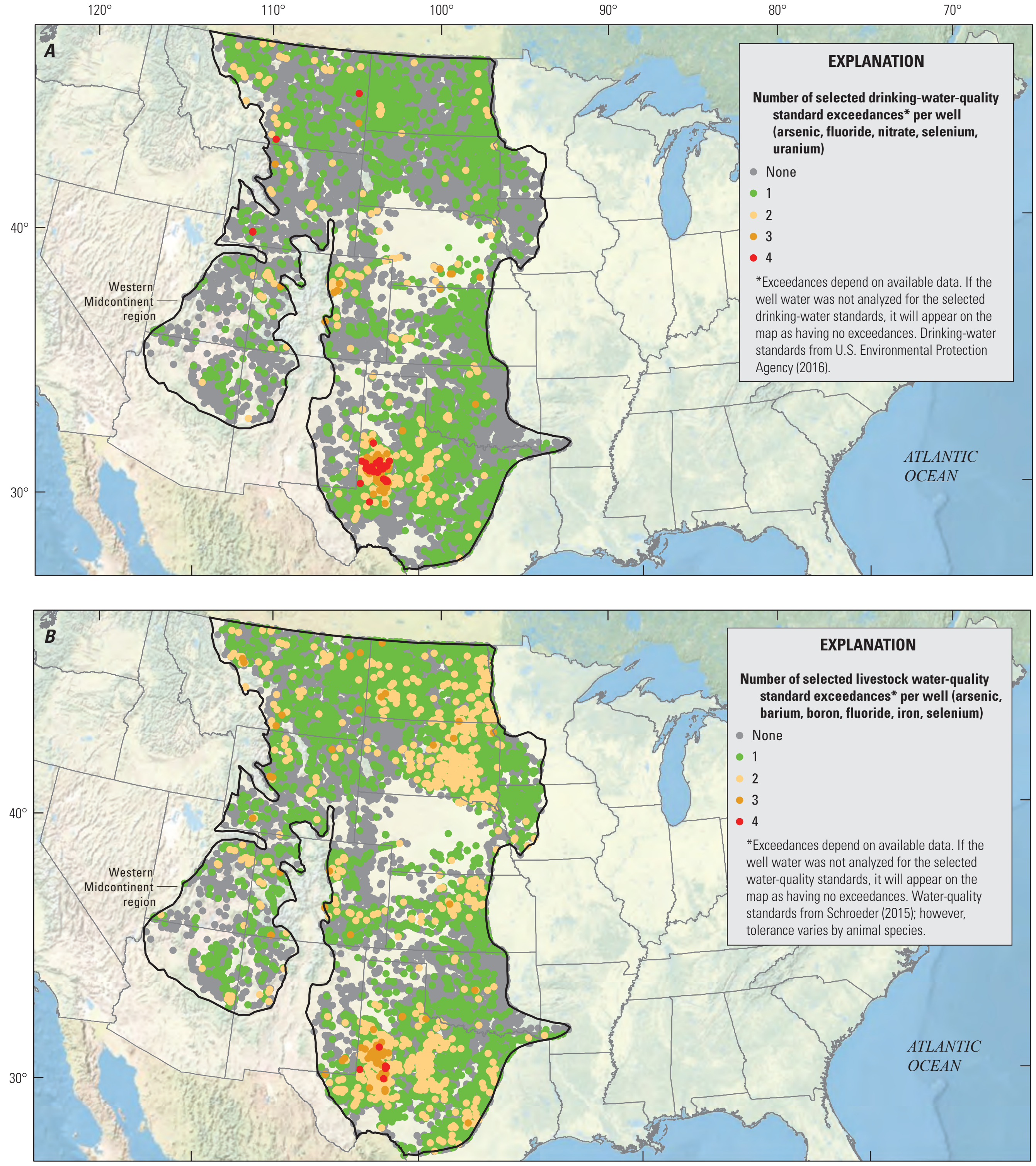


Figure 43. Distribution of dissolved-solids concentrations as a percentage of observed grid cell volume, by principal aquifer and depth, in the Western Midcontinent region.



*Exceedances depend on available data. If the well water was not analyzed for the selected drinking-water standards, it will appear on the map as having no exceedances. Drinking-water standards from U.S. Environmental Protection Agency (2016).

*Exceedances depend on available data. If the well water was not analyzed for the selected water-quality standards, it will appear on the map as having no exceedances. Water-quality standards from Schroeder (2015); however, tolerance varies by animal species.

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Figure 44. Locations of brackish groundwater samples that exceed selected water-quality standards in the Western Midcontinent region. *A*, drinking water; *B*, livestock consumption; and *C*, irrigation uses.

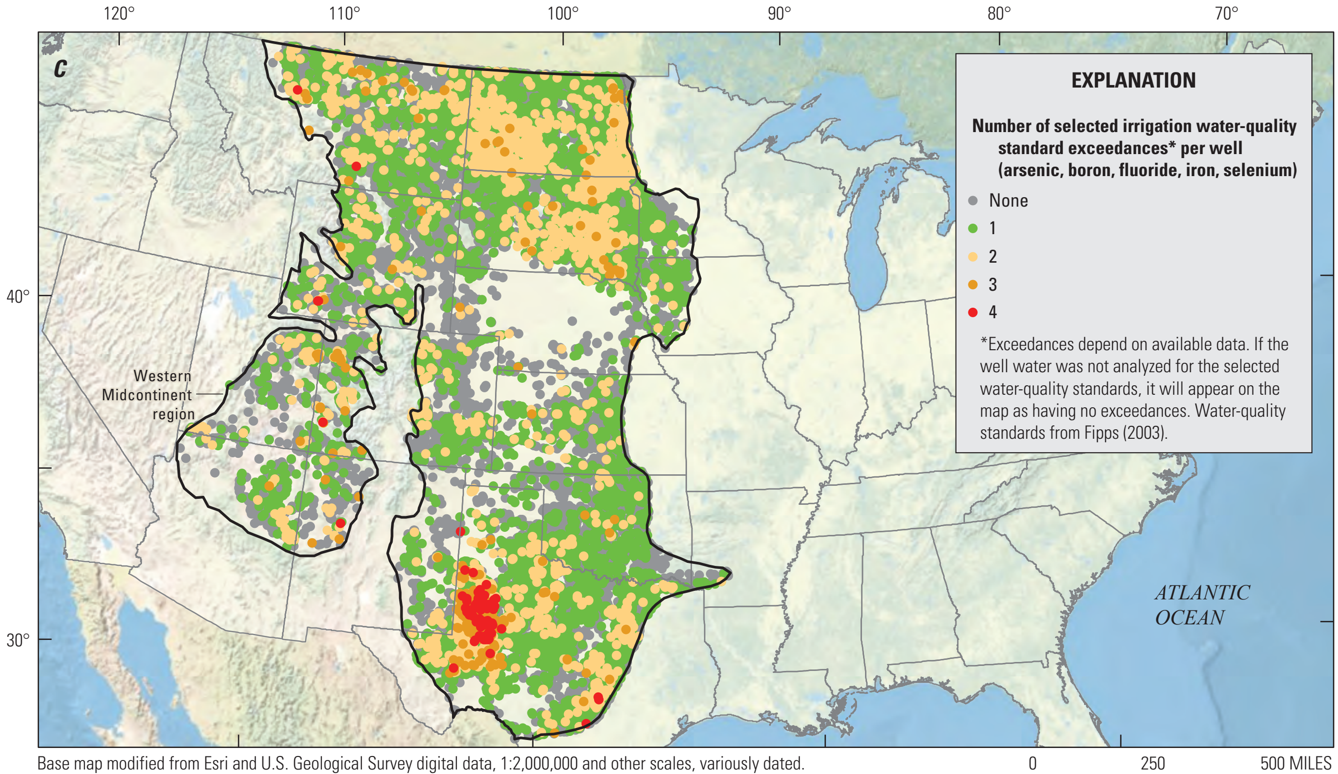

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Figure 44. Locations of brackish groundwater samples that exceed selected water-quality standards in the Western Midcontinent region. *A*, drinking water; *B*, livestock consumption; and *C*, irrigation uses.—Continued

Seymour aquifer), and uranium (Denver Basin aquifer system and High Plains aquifer; table 10). Constituents at concentrations that are greater than the selected livestock standards in at least 10 percent of the BGW samples are boron (4 principal aquifers), fluoride (13 principal aquifers), iron (10 principal aquifers), and selenium (3 principal aquifers; table 11). For untreated BGW used for irrigation, constituents of concern in at least 10 percent of the BGW samples are arsenic (2 principal aquifers), boron (17 principal aquifers), fluoride (16 principal aquifers), iron (6 principal aquifers), and selenium (6 principal aquifers; table 12). BGW samples that exceed selected standards are distributed throughout the region (fig. 44).

Well yields were compiled for this assessment for sampled wells producing fresh, brackish, and highly saline groundwater. In this region, median well yields were larger for wells producing freshwater (20 gal/min) than for wells producing BGW or highly saline groundwater (10 gal/min; table 19). Of the wells with BGW, about 44 percent had yields >10 gal/min, 7 percent had yields >100 gal/min, and 1 percent had yields >1,000 gal/min. The largest median yields of sampled wells producing BGW were in the Arbuckle-Simpson aquifer (2,500 gal/min), the Pecos River Basin alluvial aquifer (790 gal/min), the Blaine aquifer (650 gal/min), and the Central Oklahoma aquifer (115 gal/min; table 18). Available data indicate that well yields for the deeper intervals in this region are able to provide ≥10 gal/min and may be able to yield ≥100 gal/min in some areas (fig. 45).

Saline Groundwater Use

Amounts of saline groundwater use were estimated for each of the principal aquifers within this region by using a combination of data compiled for this assessment and from the USGS Water-Use Program. According to these estimates, the Western Interior Plains and Edwards-Trinity aquifer systems provided much of the saline groundwater for use in this region in 2010 (fig. 46). Results also indicate that the High Plains aquifer provides a large part of the saline groundwater that is used; however, results for an aquifer, such as the High Plains aquifer, that overlies another aquifer containing saline groundwater should be considered with caution because methods used for this assessment rely on the assumption that within each county, the amount of saline groundwater use from an aquifer is proportional to the percentage of wells producing saline groundwater within that aquifer from the data compiled for this assessment. This may not be a reasonable assumption if the data compiled for this assessment represent conditions for different aquifers than the data used by the Water-Use Program to determine

Table 19. Well yields by dissolved-solids concentration category in the Western Midcontinent region.

[gal/min, gallon per minute; mg/L, milligram per liter]

Dissolved-solids concentration (table 1)	Number of wells with a reported well yield	Median well yield, in gal/min	Wells with a well yield greater than 10 gal/min, in percent	Wells with a well yield greater than 100 gal/min, in percent	Wells with a well yield greater than 1,000 gal/min, in percent
Freshwater (<1,000 mg/L)	10,051	20	97	27	11
Brackish (1,000 to <10,000 mg/L)	8,333	10	44	7	1
Slightly saline (1,000 to <3,000 mg/L)	7,251	10	44	7	1
Moderately saline (3,000 to <10,000 mg/L)	1,082	10	43	8	1
Highly saline (≥10,000 mg/L)	49	10	45	16	4

saline groundwater use (see the "Data Gaps and Limitations" section). Saline groundwater was most commonly used for mining, which includes extraction of minerals that may be in the form of solids or liquids—minerals in solid form include coal, iron, sand, and gravel; and minerals in liquid form include crude oil and natural gas (Maupin and others, 2014). Twelve percent of the groundwater desalination facilities that treat water for municipal use are within this region (fig. 2; Mickley, 2012).

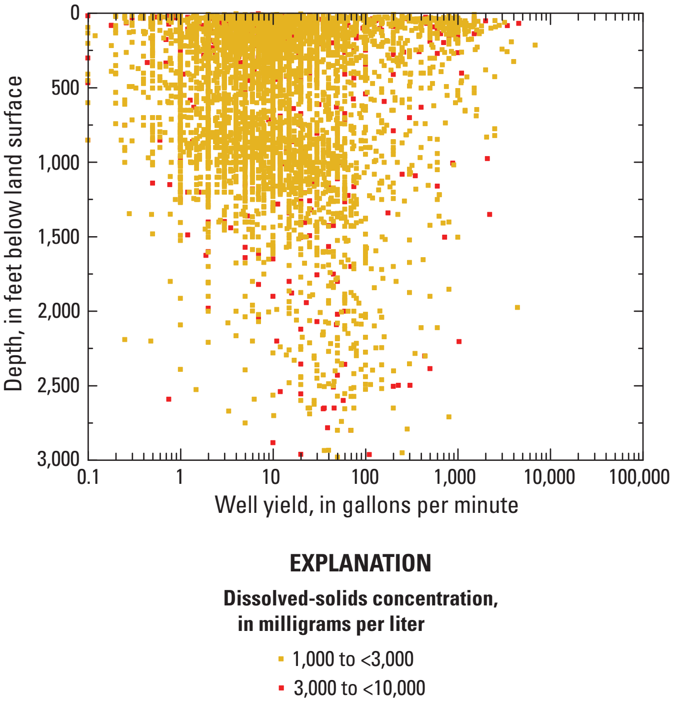


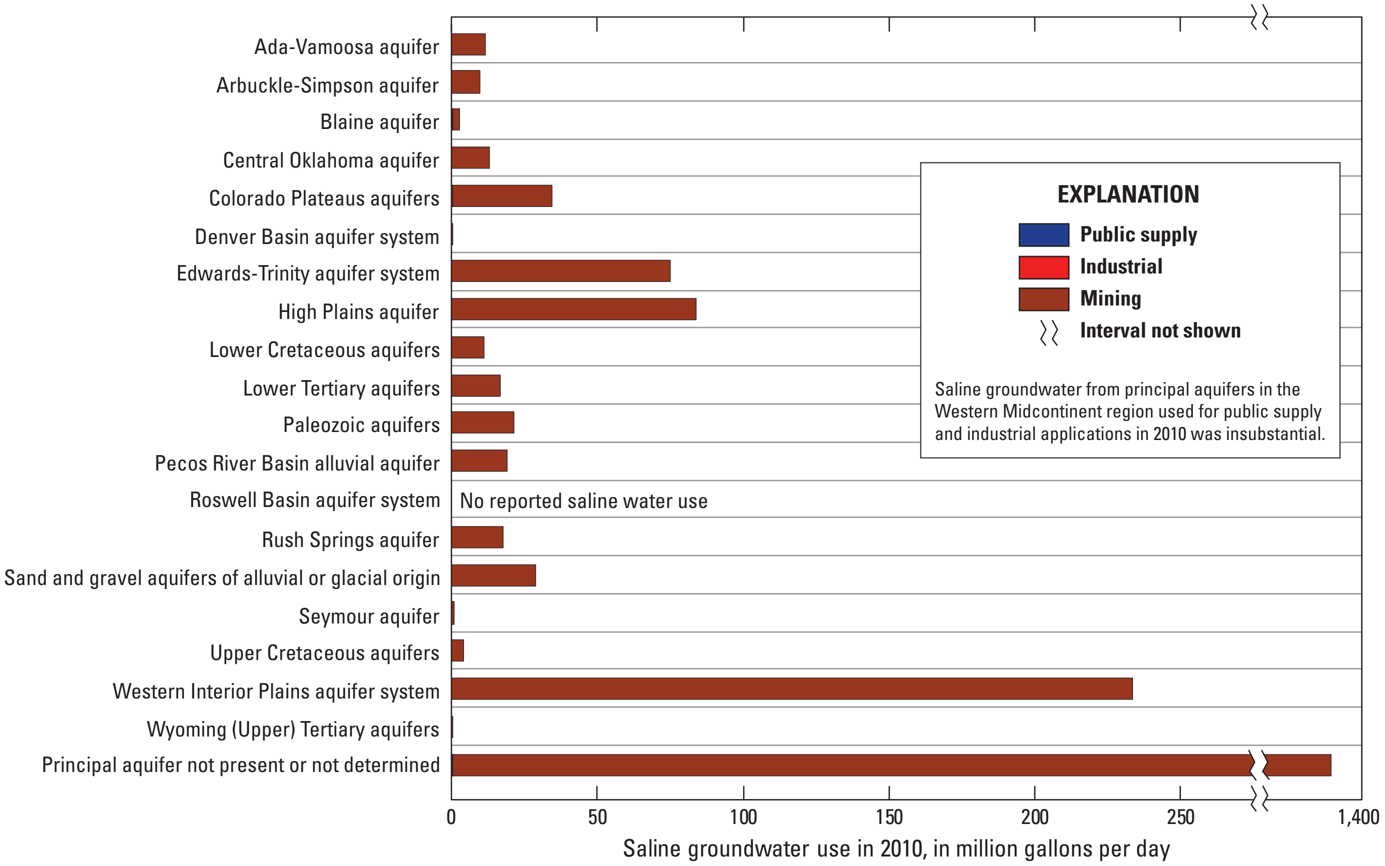
Figure 45. Distribution of well yields relative to depth below land surface at sampled wells producing brackish groundwater in the Western Midcontinent region.

Regions With Minimal Amounts of Observed Brackish Groundwater

Compiled groundwater chemistry data indicate that only a small percentage of the observed grid cell volume in the Eastern Mountains and Uplands, Northwestern Volcanics, and Western Mountain Ranges regions contains BGW <3,000 ft below land surface (table 4). These regions are primarily composed of geologic formations that are not associated with mineralized groundwater. In addition, much of the area within these regions receives plentiful precipitation and has minimal evapotranspiration. The Alaska, Hawaii, and U.S. Territories regions have large percentages of observed grid cell volume that contain BGW (table 4), but the total observed volume is relatively small because of their geographic size or minimal available data. Although these regions have less documented BGW than the four regions previously discussed in detail, BGW may still be an important resource locally. The regions that have minimal amounts of BGW are briefly described in the following sections.

Eastern Mountains and Uplands

The Eastern Mountains and Uplands region (fig. 47) includes three separated areas—(1) the upland areas of northern Minnesota and Wisconsin, (2) the New England States and eastern New York, and (3) the Piedmont and Blue Ridge Physiographic Provinces that extend from Alabama to Pennsylvania (Heath, 1984). The primary aquifer rock types in this region are consolidated crystalline bedrock and unconsolidated surficial deposits that include minor amounts of consolidated sedimentary rocks (sandstone, carbonate, or shale). The surficial aquifer, mostly of glacial origin, is the most widely used aquifer in the western part of the region because it is shallow, permeable, and widespread (Olcott, 1992). In the east, the surficial deposits are considered an aquifer primarily in valleys and generally have a smaller extent and thickness than in the northern Minnesota and Wisconsin area (Olcott, 1992, 1995). Although the consolidated-rock aquifers yield only modest



Saline groundwater from principal aquifers in the Western Midcontinent region used for public supply and industrial applications in 2010 was insubstantial.

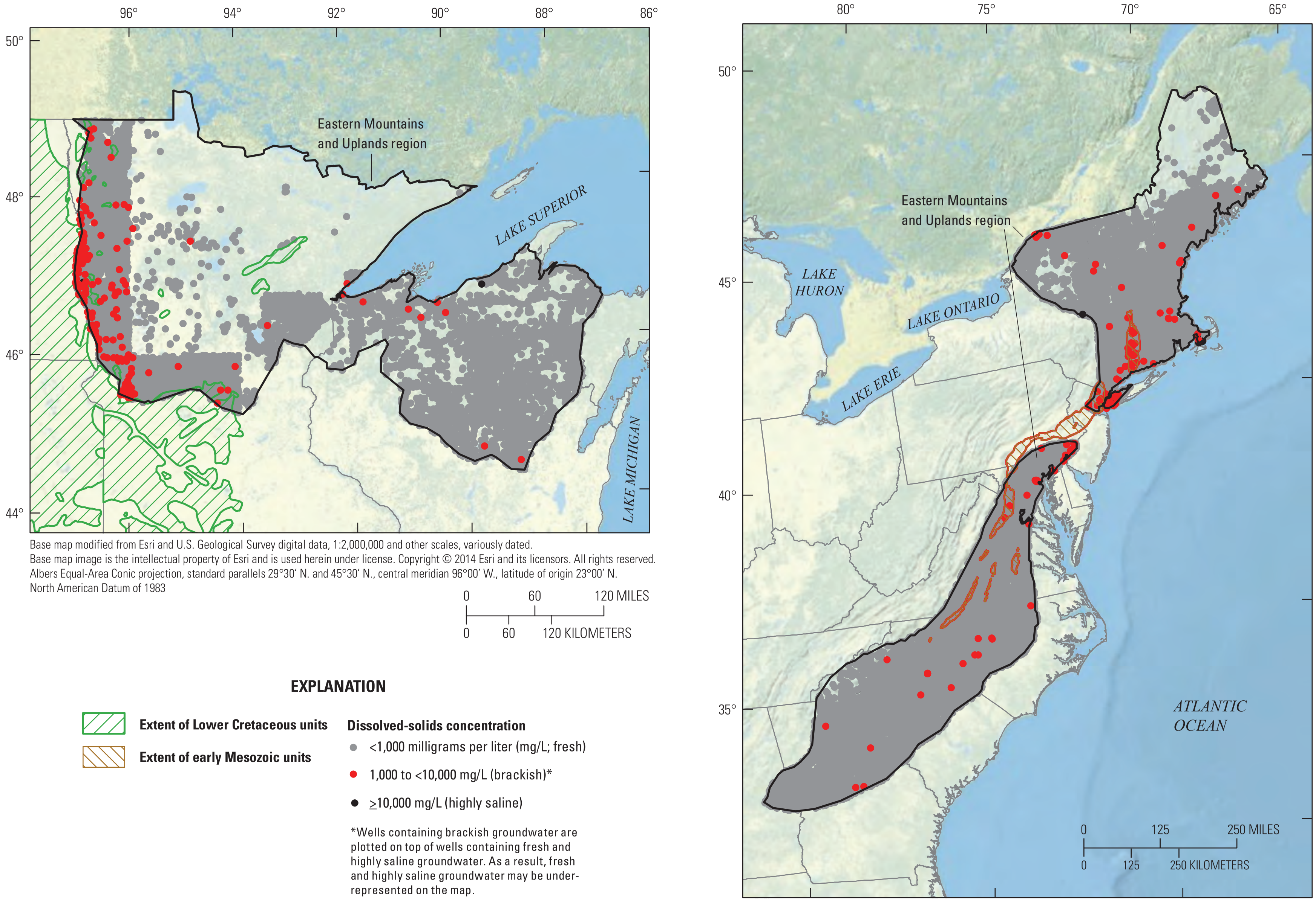
Figure 46. Estimated saline groundwater use from principal aquifers in the Western Midcontinent region.

amounts of water from joints and fractures, they are the only sources of water in many parts of the region and are therefore considered major aquifers.

The crystalline-bedrock and surficial aquifers that provide most of the water resources in this region generally are not associated with mineralized groundwater because they are composed of relatively insoluble materials and have rapid water movement through short groundwater flow paths (Olcott, 1995). Data compiled for this assessment indicate that dissolved-solids concentrations exceed 1,000 mg/L only in a small number of samples that are sparsely distributed across the region, and in a few samples that are clustered but still intermingled with freshwater in three areas—(1) along the western border of Minnesota, (2) in the early Mesozoic basins of central Connecticut and northern New Jersey, and (3) along the Atlantic coast (fig. 47). BGW in western Minnesota is <1,000 ft below land surface and coincides with the presence of long groundwater flow paths, Cretaceous rocks of marine origin (fig. 47), and thick glacial deposits (Olcott, 1992). The Cretaceous rocks in this region are primarily remnants of the thicker, more continuous Cretaceous formation to the west that is prevalent across most of the Western Midcontinent region. The early Mesozoic basins (fig. 47) are composed primarily of sandstone, siltstone, and shale with some limestone and conglomerate in a deep, downfaulted trough (Olcott, 1995). These rocks are slightly more soluble than the crystalline bedrock and surficial deposits and likely contain highly saline groundwater in the intervals that are deeper than those considered for this assessment (Olcott, 1995). Sampled wells producing BGW along the Atlantic coast often are within principal aquifers that are mostly within the Coastal Plains region, which indicates that the generalized BGW region boundary could be refined in those areas and that those brackish samples are not associated with geologic conditions common to the rest of the Eastern Mountains and Uplands region. In addition to the areas identified by compiled data as having wells that produce BGW, previous publications have indicated that several areas in southeast Pennsylvania coincide with a soluble carbonate-rock aquifer that may contain some mineralized groundwater at depth (Trapp and Horn, 1997).

BGW is present in about 3 percent of the observed grid cell volume (including air, water, and rock) between 0 and 3,000 ft below land surface in this region (table 4). The percentage of grid cell volume for the depth interval containing BGW ranged from <1 to about 13 percent among principal aquifers in this region (table 8); the Early Mesozoic basin aquifers had the largest percentage.

Descriptions of the mostly freshwater part of the major aquifers in this region indicate that aquifers in glacial deposits commonly yield 10 to 1,000 gal/min, crystalline-rock aquifers



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*Wells containing brackish groundwater are plotted on top of wells containing fresh and highly saline groundwater. As a result, fresh and highly saline groundwater may be underrepresented on the map.

Figure 47. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in the Eastern Mountains and Uplands region.

yield about 2 to 18 gal/min (Olcott, 1995; Trapp and Horn, 1997), and sandstone aquifers yield about 5 to 80 gal/min depending on the specific geologic composition (Trapp and Horn, 1997). Yields from the crystalline rock typically decrease as depth increases (Olcott, 1995), whereas yields per foot in at least some parts of the early Mesozoic basins increase with depth until about 600 ft below land surface (Trapp and Horn, 1997; Swain and others, 2004). Yields are greatest in the carbonate aquifers, especially where secondary openings have been enhanced by dissolution; however, these aquifers are of minimal extent in this region (Trapp and Horn, 1997). Compiled data indicate that in the few places where BGW is present, it is in low-yielding aquifers. Reported yields of brackish wells had a median of 30 gal/min. The interquartile range of the brackish well yields was 18 to 74 gal/min. The median depth of the sampled wells producing BGW ranged from 71 to 274 ft below land surface in the principal aquifers (table 8).

Compiled data indicate that other chemical constituents may limit the use of untreated BGW in this region (tables 10, 11, and 12). Constituents that had concentrations greater than the drinking-water standard in more than 20 percent of the BGW samples collected from a principal aquifer were arsenic (New York and New England crystalline-rock [not shown on any figure] and Piedmont and Blue Ridge carbonate-rock aquifers) and uranium (Piedmont and Blue Ridge carbonate-rock aquifers; table 10). Arsenic concentrations were greater than the standard for livestock for 33 percent of sampled wells producing BGW in the New York and New England crystalline-rock aquifers, and iron concentrations were greater than the livestock standard for at least 30 percent of sampled wells producing BGW in the Piedmont and Blue Ridge carbonate-rock aquifers and sand and gravel aquifers of alluvial or glacial origin (table 11). For multiple principal aquifers within this region, >20 percent of the BGW samples had concentrations of arsenic, boron, fluoride, and iron that were greater than the upper concentration limit that defines its suitability for use as irrigation water (table 12).

Northwestern Volcanics

The Northwestern Volcanics region is in the northwestern United States between the Cascade Range and Rocky Mountains (fig. 48). It consists of a thick sequence of lava rocks that are interbedded with unconsolidated deposits (Heath, 1984). Surficial deposits of coarse-grained materials also are present in large areas throughout this region along stream valleys and in basin lowlands (Whitehead, 1994). Though not prevalent, BGW has been associated primarily with geothermal systems, deep sedimentary rocks of marine origin, and the concentration of minerals in irrigated soils or shallow groundwater as a result of evapotranspiration (Whitehead, 1994).

The principal aquifers in the Northwestern Volcanics region consist of coarse-grained basin-fill sediments and volcanic rocks that range from fine-grained basalt to coarse-grained silicic deposits (Whitehead, 1994). In many areas, both types of deposits are present (Whitehead, 1994). BGW exists locally in these aquifers where underlying geothermal waters, primarily in silicic volcanic rocks in southwestern Idaho and southeastern Oregon, seep into the shallower aquifers along faults filled with coarse rock fragments and in shallow groundwater because of evapotranspiration in irrigated areas or closed basins (Whitehead, 1994). Hydrogeologic characteristics are unknown for much of the region because large parts of the aquifers are in areas with low water demand or are at deep intervals (Whitehead, 1992, 1994). Where it is known, permeability is extremely variable though hydraulic conductivity is thought to generally decrease with depth across the study area (Whitehead, 1994).

In geothermal water, concentrations of sodium, bicarbonate, sulfate, chloride, fluoride, silica, arsenic, boron, and lithium frequently are relatively large. Conversely, concentrations of calcium, magnesium, and hydrogen frequently are relatively small (Lindholm, 1996). Chemical characteristics of geothermal waters can present challenges for water use. Fluoride, arsenic, and iron are the minerals that most commonly cause water quality problems for drinking-water purposes at excessive concentrations (Whitehead, 1994). Geothermal water also can contain sodium at concentrations that, if applied to the land surface, will cause soil permeability to decrease and affect its usefulness for agricultural purposes.

Though generally not considered a principal aquifer, deep pre-Miocene marine deposits composed of limestone, dolomite, sandstone, and shale contain brackish and highly saline groundwater that has been considered a source of contamination for overlying freshwater aquifers (Whitehead, 1994). The marine sediments are mostly consolidated; however, they can yield enough water to be considered an aquifer in some shallow areas where secondary porosity in the form of weathered zones and fractures is present (Whitehead, 1992, 1994). Because the nature of these weathered zones allows water to circulate through the system quickly, these zones may be less likely than others to contain highly mineralized groundwater. Pre-Miocene marine deposits are likely present at depth throughout most of the region and could be as thick as 15,000 ft (Whitehead, 1994); however, descriptions of these deeper deposits are unavailable or poor in most areas (Erick Burns, U.S. Geological Survey, written commun., 2015).

Dissolved-solids concentrations from data compiled for this assessment suggest that BGW is most commonly present along the south and west boundaries of the Snake River Valley in Idaho, an area dominated by irrigated agriculture, at depths ranging from 18 to almost 10,000 ft below land surface (fig. 48; Lindholm, 1996). These areas also coincide with dense clusters of geothermal wells (Idaho Department of Water Resources, 2001). Most of the dissolved-solids concentrations in the brackish salinity range are <3,000 mg/L (slightly saline), making the BGW suitable for some purposes without treatment. Because a large number of the sampled wells yielding BGW are near the Snake River, it may be possible to blend BGW with fresher surface water for use if lower dissolved-solids concentrations are needed for irrigation or

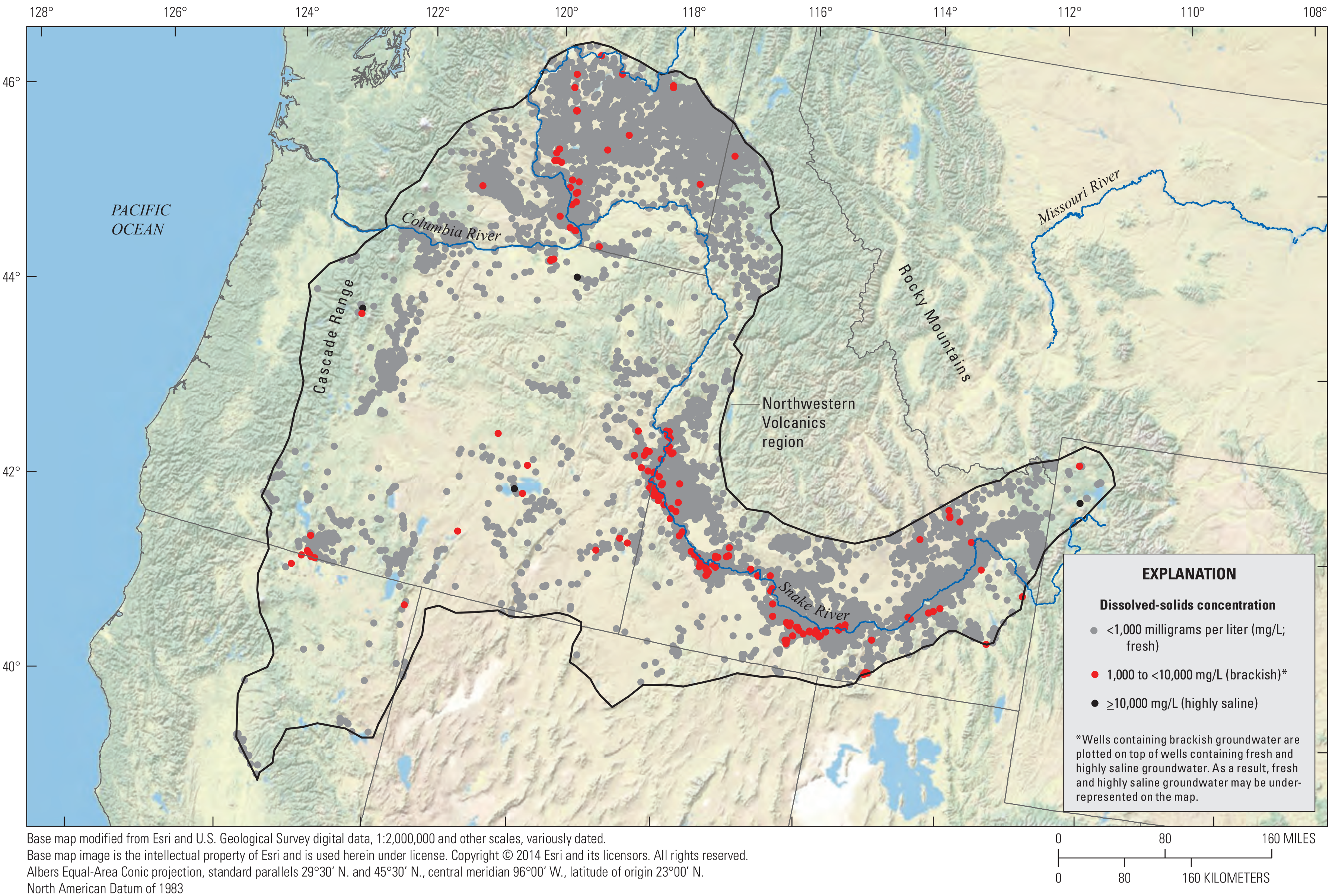

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Figure 48. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in the Northwestern Volcanics region.

other purposes. This approach could extend the usefulness of freshwater resources in the area. Few of the data compiled for this assessment included information about chemical constituents other than dissolved solids (tables 10, 11, and 12), and it was not feasible to draw any conclusions about which constituents might pose problems for drinking water, livestock, and irrigation uses.

BGW was present in about 4 percent of the observed grid cell volume between 0 and 3,000 ft below land surface (table 4). The percentage of volume containing BGW ranged from 1 to 8 percent among principal aquifers in this region (table 8); the sand and gravel aquifers of alluvial or glacial origin had the largest percentage. The median depth of the sampled wells producing BGW ranged from 5 to 215 ft below land surface (table 8). Reported yields of brackish wells had a median of 36 gal/min. The interquartile range of those well yields was 20 to 370 gal/min.

Western Mountain Ranges

The Western Mountain Ranges region includes the Sierra Nevada, Coast Ranges, Cascade Range, and Rocky Mountains of the western United States (fig. 49). Most of these ranges consist of narrow valleys filled with coarse alluvial sediments among tall mountains underlain by granitic and metamorphic rocks with sedimentary rocks along the edges. A few of the intermontane valleys are large enough to yield substantial amounts of water. Within the largest of these valleys are the Puget Sound aquifer system and Willamette Lowland basin-fill aquifers (fig. 6; Vaccaro and others, 1998; Conlon and others, 2005).

Unconsolidated basin-fill deposits provide most of the water in this region because they typically are productive and primarily contain freshwater (Whitehead, 1996). The thickness of these deposits is uncertain for many areas but is known to be as much as 900 ft below land surface in the eastern part of the region and as much as 3,000 ft below land surface in the Puget Sound and Willamette Lowland in the west (not shown; Whitehead, 1994, 1996). The characteristics of the deeply buried basin-fill deposits have been minimally documented, but the deposits generally become less permeable with depth because of compaction (Clark and Kendy, 1992; Whitehead, 1994, 1996). The basin-fill deposits of the Puget Sound aquifer system and Willamette Lowland aquifers are underlain by Miocene basaltic-rock aquifers that also yield substantial amounts of water. Pre-Miocene sedimentary rocks of marine origin also underlie most of the western part of the region and are a known source of BGW and highly saline groundwater (Whitehead, 1994); however, the low permeability of these rocks in many places is likely a limiting factor for extracting large amounts of water. Units underlying basin-fill deposits in the eastern part of the region are sedimentary, metamorphic, and igneous rocks that generally yield only enough water for domestic or livestock uses, primarily through fractures (Whitehead, 1996); however, younger basaltic rocks can be important aquifers in the western part of the region (Whitehead, 1994). Brackish and highly saline groundwater in this region is most commonly associated with marine sedimentary rocks, long or sluggish groundwater flow paths, saltwater intrusion along the coast, and geothermal waters from silicic volcanic rocks (Whitehead, 1994; Vaccaro and others, 1998; Conlon and others, 2005).

Geothermal wells and springs are common throughout many parts of this region (Whitehead, 1996). In the western part of the region, these springs commonly have high concentrations of silica or calcium carbonate, depending on the type of rocks the groundwater contacted (Whitehead, 1996). In the Puget Sound aquifer system, high dissolved-solids concentrations are associated with seawater intrusion and a sodium-chloride water type (Vaccaro and others, 1998).

Dissolved-solids concentrations from groundwater samples compiled for this assessment suggest that BGW is sparsely interspersed throughout much of the region within the intermontane lowlands (fig. 49). Dissolved-solids concentrations rarely exceeded 10,000 mg/L. BGW composed about 11 percent of the observed grid cell volume in this region (table 4). The percentage of volume containing BGW ranged from 0 to 6 percent among principal aquifers in this region (table 8); the Northern Rocky Mountains Intermontane Basins aquifer systems and the sand and gravel aquifers of alluvial or glacial origin had the largest percentages. The median depth of the sampled wells producing BGW ranged from 34 to 127 ft below land surface (table 8). Reported yields of brackish wells had a median of 10 gal/min. The interquartile range of those well yields was 5 to 25 gal/min.

Compiled data indicate that specific chemical constituents may limit the use of untreated BGW in this region, though results are based on only a few sampled wells and are thus considered incomplete (tables 10, 11, and 12). Selected constituents of most concern for drinking-water uses are arsenic and uranium, primarily in the Northern Rocky Mountains Intermontane Basins aquifer systems (table 10). For livestock, selected constituents with the largest percentages of samples that had concentrations greater than standards were arsenic, fluoride, and iron (table 11). Fluoride and arsenic are the constituents of most concern for using BGW for irrigation; however, the standards for boron and iron are frequently exceeded in samples that were not associated with a principal aquifer (table 12).

Alaska

The State of Alaska occupies a large area with diverse hydrogeologic settings, ranging from mountain ranges and intermontane plateaus to coastal plains (fig. 50). The principal geologic units also are diverse, consisting of glacial and alluvial deposits that overlie crystalline, metamorphic, and sedimentary rocks, including carbonates, sandstones, and shales. Because of its cold climate, large parts of Alaska are underlain by permafrost, which limits recharge and groundwater movement for most of the year (Heath, 1984). Saline groundwater has previously been associated with proximity

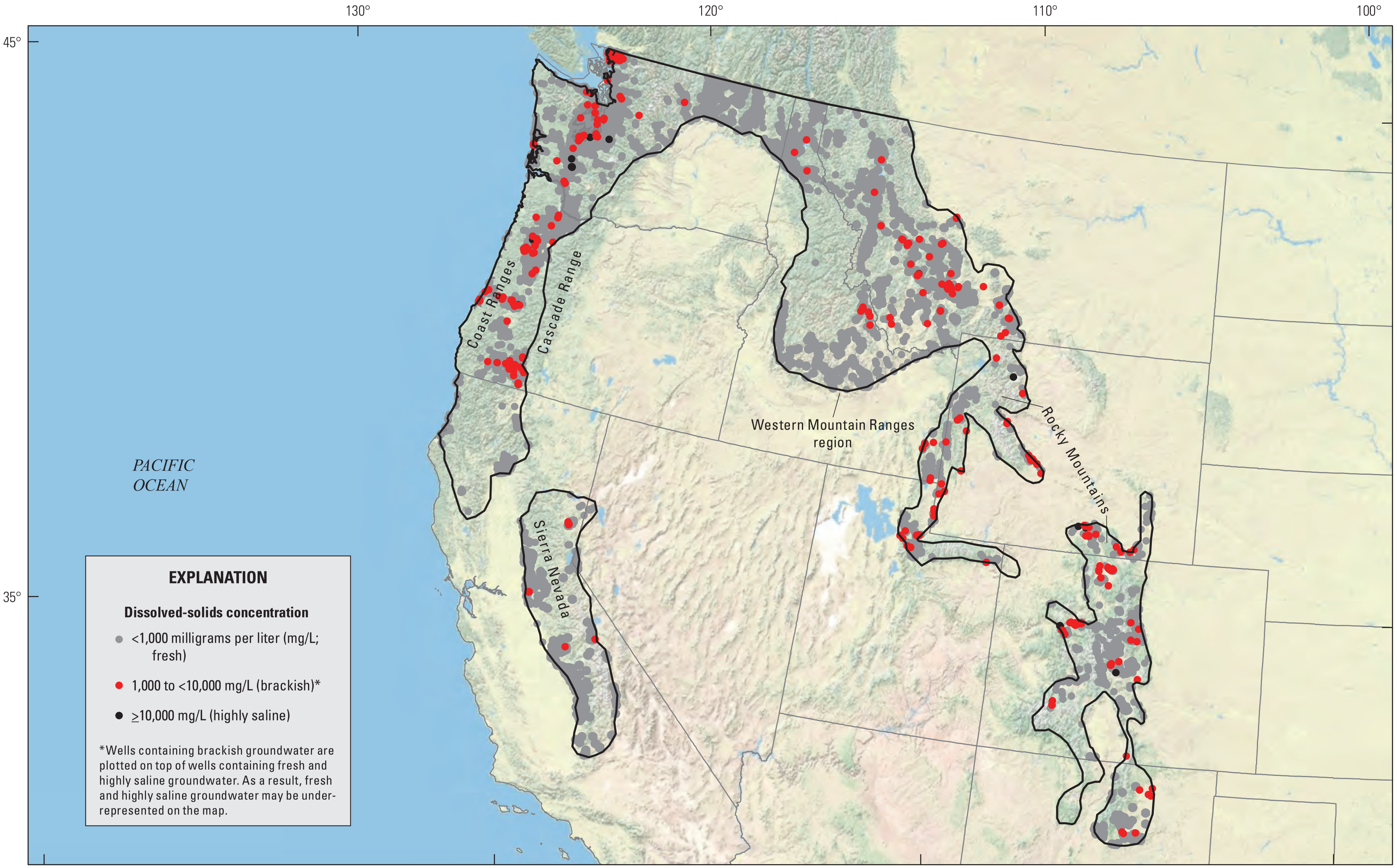

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Figure 49. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in the Western Mountain Ranges region.

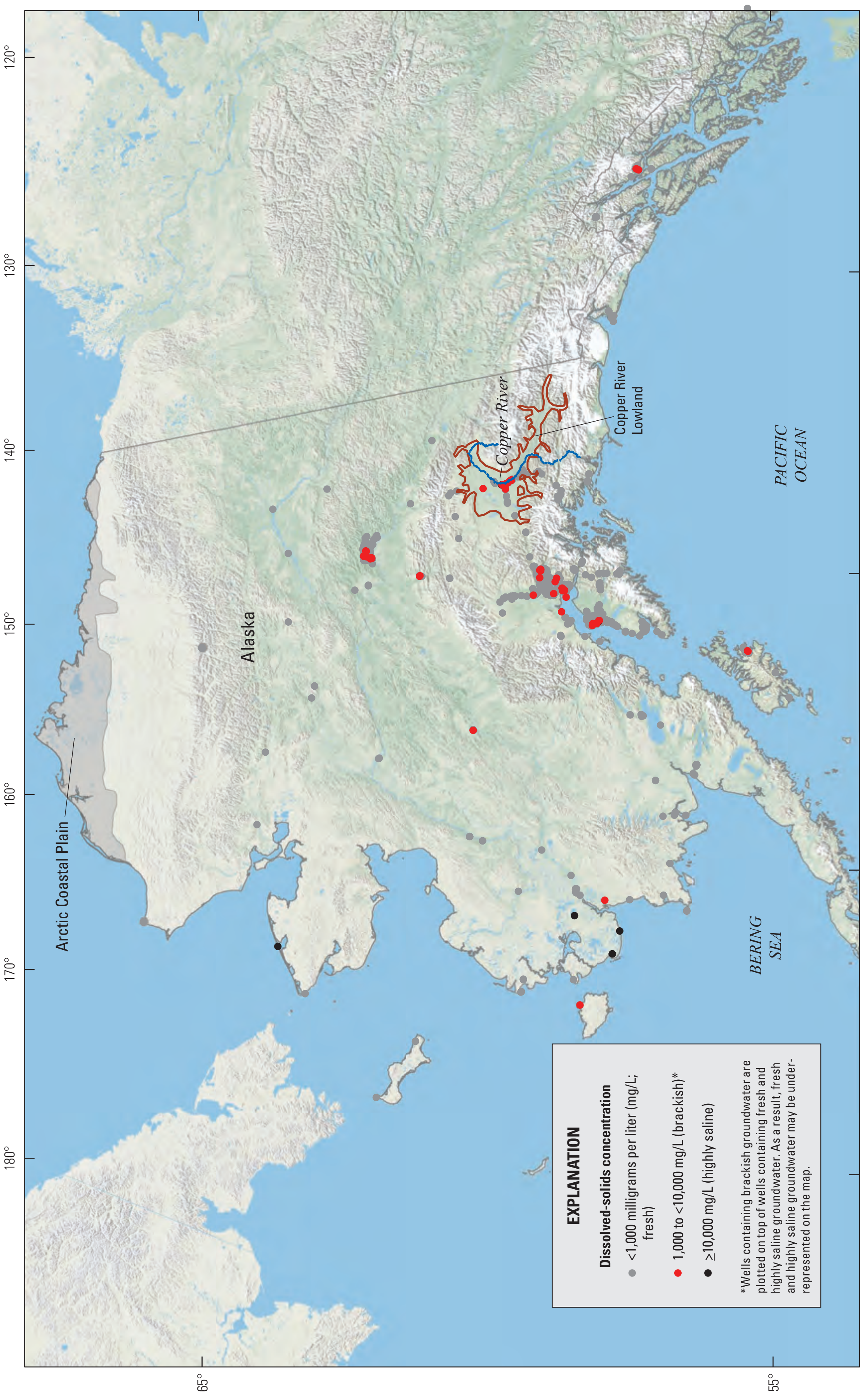

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Figure 50. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in Alaska.

to coastlines (Miller and others, 1999), the Copper River Lowland (Grantz and others, 1962), and areas underneath deep permafrost (Heath, 1984; Williams, 1970). It is likely that other areas have elevated dissolved-solids concentrations, such as where Mesozoic sediments or rocks of marine origin are present. These deposits are present in a large part of the State (Miller and others, 1999).

Groundwater chemistry data compiled for this assessment are minimal and are not representative of the diverse conditions across the State. Data compiled for this assessment generally support results from previous publications about the occurrence of BGW in Alaska, but data are not available for the Arctic Coastal Plain, an area where groundwater with elevated dissolved-solids concentrations has been reported (Miller and others, 1999; Williams, 1970) and 144.4 Mgal/d of saline groundwater is being used for mining purposes (fig. 5; Maupin and others, 2014). BGW is present in about 14 percent of the observed grid cell volume, mostly between 50 and 500 ft below land surface (table 4). The median depth of the sampled wells producing BGW is 127 ft below land surface (table 8). Data compiled for this assessment also indicate that arsenic concentrations could pose a problem for using untreated BGW for drinking-water purposes (table 10). Iron concentrations are of most concern for livestock; and arsenic, boron, and iron could be problematic for irrigation use (tables 11 and 12). Reported yields of brackish wells had a median of 10 gal/min; the interquartile range of well yields was 6 to 20 gal/min.

Hawaii

The State of Hawaii is composed of a series of eight main islands of volcanic origin (fig. 51) with a combined area of 6,426 mi^2 (Miller and others, 1999). The primary aquifers in Hawaii are within Miocene- to Holocene-age volcanic rocks that consist of layered sequences of permeable basalt. Minor aquifers exist within less extensive Quaternary-age sedimentary deposits of alluvium, coralline limestone, and consolidated beach or dune sand that overlie the volcanic rocks. Because of its hydrologic connections with the Pacific Ocean, BGW is present throughout Hawaii. Groundwater salinity generally increases with depth and along groundwater flow paths that originate inland and eventually terminate at the ocean or at nearshore springs. Within aquifers of the Hawaiian islands, freshwater floats on saltwater as a lens, and the BGW zone exists at the interface where they mix. This brackish zone can be thick if mixing is extensive. In some areas, such as where permeability of the aquifer material is high and recharge rates are low, freshwater is not available, and only brackish water overlies saltwater. BGW is used for cooling and industrial purposes. The BGW zone also serves as a repository for treated wastewater in limestone deposits.

Groundwater chemistry data compiled for this assessment indicate that most of the sampled wells producing BGW have shallow depths and are near the coastline (fig. 51; table 4). BGW is present in about 17 percent of the observed grid cell volume (0 to 3,000 ft below land surface), mostly between 0 and 500 ft below land surface (table 4). The median depth of the sampled wells producing BGW is 179 ft below land surface (table 8). The few data available for other selected chemical constituents (tables 10, 11, and 12) indicate that boron concentrations may be problematic for using untreated BGW for irrigation (table 12). A well yield was reported for only nine of the brackish wells. The median of those values was 510 gal/min, and the interquartile range was 350 to 700 gal/min.

U.S. Territories

Discussion of BGW in the U.S. territories is limited to Puerto Rico and the U.S. Virgin Islands (fig. 52). Puerto Rico and the U.S. Virgin Islands are part of a series of islands about 1,100 mi east-southeast of Miami, Florida, that consist of primarily volcanic and sedimentary rocks with locally intruded igneous rocks (Miller and others, 1999). The main aquifers in these islands are mostly within limestone, alluvium, or volcanic rocks. They are small in areal extent and typically yield small amounts of water. As is typical of island settings, BGW and highly saline groundwater are present throughout the aquifers of Puerto Rico and the U.S. Virgin Islands. Salinity generally increases between recharge areas in the island interiors and the coast. Saltwater intrusion from excessive pumping and during dry periods, along with contributions from dissolved salts from windborne sea spray, also affects the salinity of aquifers. In Puerto Rico, aquifers are occupied by fresh and saline groundwater; however, in the U.S. Virgin Islands, almost no fresh groundwater is available. As a result, desalination plants are used to provide usable water for urban areas where water demand is greatest.

Groundwater chemistry data compiled for this assessment indicate that most of the samples producing BGW are near the coastline in Puerto Rico, but BGW is present throughout the smaller land masses of the U.S. Virgin Islands (fig. 52). About 36 percent of the observed grid cell volume in Puerto Rico contains BGW, and about 73 percent of the grid cell volume in the U.S. Virgin Islands contains BGW (table 4). The median depth of the sampled wells producing BGW is <100 ft below land surface in Puerto Rico and the U.S. Virgin Islands (table 8).

Minimal data available for other selected chemical constituents indicate that a few wells have concentrations of arsenic, fluoride, and nitrate that would be problematic for using untreated BGW for human consumption (table 10). About 10 percent of the samples had an iron concentration that was greater than the upper limit for livestock consumption (table 11). In Puerto Rico, >10 percent of the wells had arsenic, boron, and fluoride concentrations greater than their respective standards for irrigation; in the U.S. Virgin Islands, >10 percent of the wells had boron, fluoride, and iron concentrations greater than standards for irrigation (table 12). The median yield for sampled wells producing BGW in Puerto Rico and the U.S. Virgin Islands was 20 gal/min, and the interquartile range was 8 to 90 gal/min.

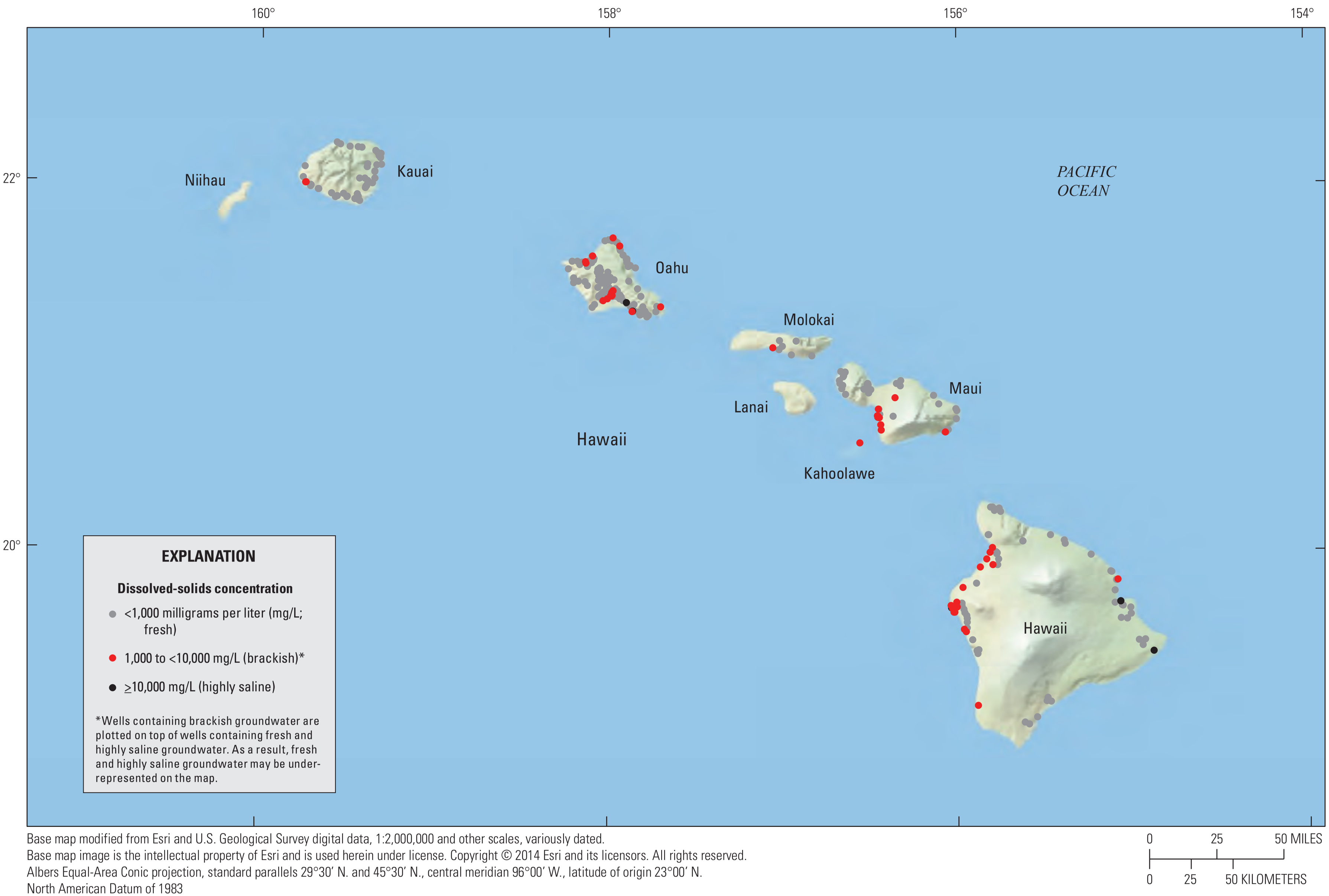

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Figure 51. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in Hawaii.

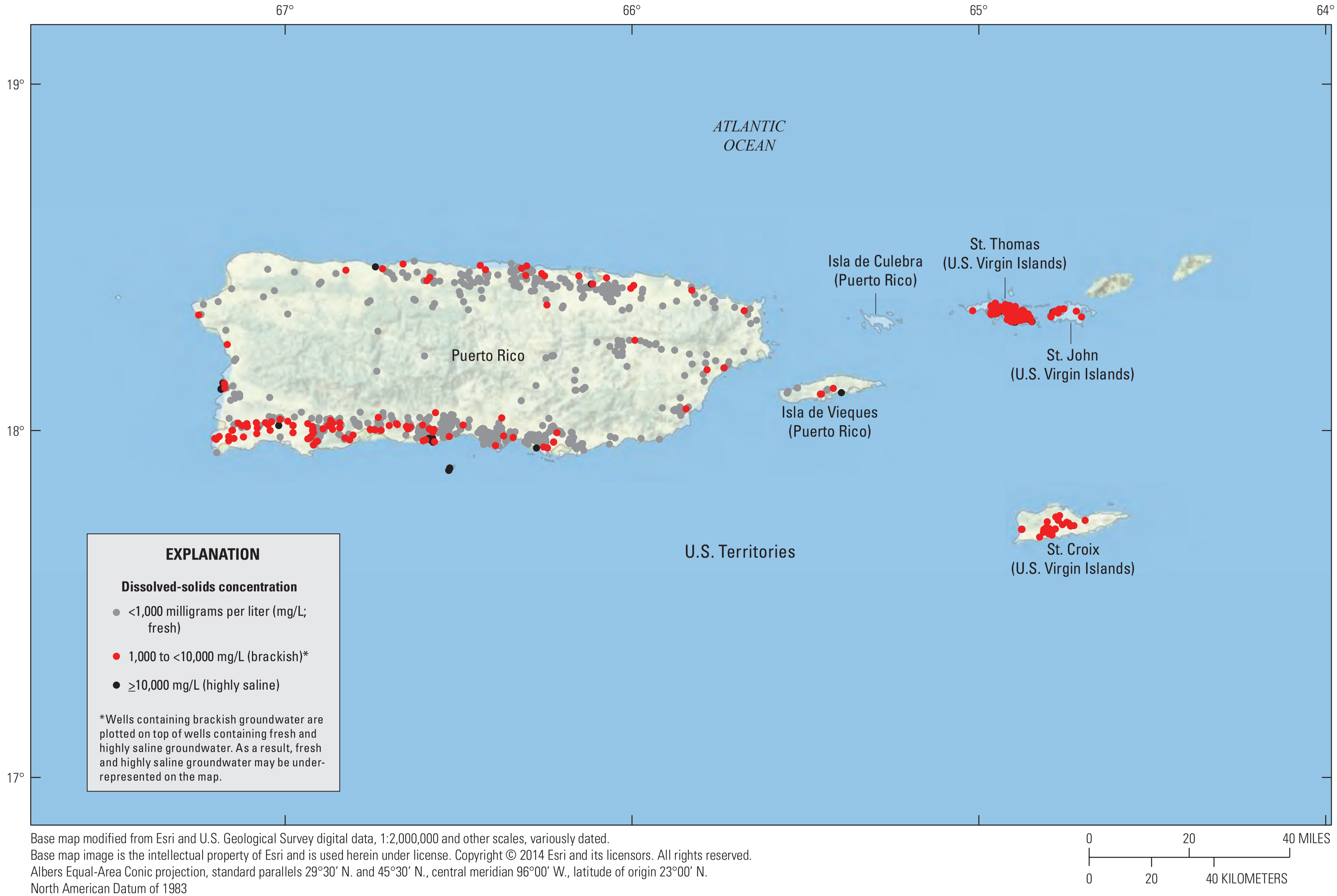

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Figure 52. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in selected U.S. territories.

Data Gaps and Limitations

Relative to previous national-scale studies, this assessment provides an updated national summary of the occurrence of BGW and a more complete characterization of BGW resources based on data from a wide variety of sources; however, as with other studies covering large areas, a lack of consistent and comprehensive data prevents a full characterization of the resource (Barthel, 2014). Because BGW has not been a focus of many studies in the past, there are few wells completed in these zones, and data were limited for describing the distribution of dissolved solids and other chemical characteristics, hydrogeologic characteristics, and use of BGW. In addition, this assessment was not designed to provide an evaluation of sustainable BGW development. Results from this assessment should be used with consideration of the data gaps and limitations detailed in the following sections.

Distribution of Dissolved Solids and Other Chemical Characteristics

Limitations to describing the distribution of dissolved solids and other chemical characteristics of BGW include (1) lack of a comprehensive and spatially unbiased dataset of dissolved-solids concentrations and related chemical data; (2) lack of detailed well-construction information for identifying the sample source hydrogeologic unit(s); (3) inconsistent or unknown sampling, preservation, analytical, and quality assurance techniques leading to uncertain data quality; and (4) data that span many periods.

Groundwater chemistry data, including dissolved-solids concentrations, were compiled from available data sources and, as such, do not represent a random sample of the distribution of values. Most of the water chemistry data that were compiled are biased to waters that are fresh, shallow, and located where water is being used; therefore, results presented throughout this report are similarly biased. Undocumented brackish zones are expected to be present between 500 and 3,000 ft below land surface. Although groundwater chemistry data were compiled from a variety of readily available sources, it was not possible to locate and include all data that have been collected. For practical purposes, data generally were constrained to sources that were in digital format, were easy to obtain, and contained a large number of records; therefore, brackish zones reported by others may not be represented in this assessment's results, especially for local-scale assessments. In some States, such as New Mexico, water chemistry information (including dissolved-solids concentrations) had been collected by private organizations and was not available (Sarah Falk, U.S. Geological Survey, oral commun., 2013).

This assessment did not compile chemistry data for potential offshore resources, which may be substantial (Post and others, 2013). Other constituents, such as organic compounds, dissolved gases, and suspended solids, that were not included in the datasets compiled for this assessment might be useful for characterizing BGW resources; for example, this assessment did not attempt to compile chemistry data for organic compounds, such as hydrocarbons. About 9 percent of the wells compiled for this assessment had groundwater samples that may have been produced along with oil and gas, and the presence of hydrocarbons associated with oil and gas would be problematic for many BGW uses.

For about one-half of the sites used for analyses, the dissolved-solids concentration was estimated from specific conductance by using statistical relations. The dissolved-solids concentration can be related to the conductivity of the water, but the relation is not a constant; rather, the relation is a function of the type and nature of the dissolved cations and anions in the water. The specific conductance correlates linearly with the dissolved-solids concentration for most concentration ranges and provides a useful and simple tool for estimating dissolved-solids content and salinity, but there are limitations in these estimates and in using specific conductance to calculate dissolved solids. Even in relatively simple chemical solutions, the relations that affect specific conductance may be complicated (McCleskey and others, 2012). Natural waters contain a variety of ionic and undissociated species, and a rigorous theoretical development of the meaning of specific conductance values for natural waters is generally not justifiable (Hem, 1989); however, an evaluation of the effects of specific major ions on specific conductance and in turn on estimated dissolved-solids concentrations can be useful for assessing BGW and is discussed in more detail in appendix 3.

Many groundwater chemistry records initially obtained as part of this assessment did not include location (latitude and longitude), well construction, or contributing aquifer information. Records that did not include a location and either a well depth or contributing aquifer value were excluded from analyses for this assessment. Well-screen intervals are needed to determine the vertical interval that is contributing groundwater to a well; however, well-screen intervals were available for only about one-third of the samples used for analyses. Total well depth, therefore, was used as a surrogate for well-screen intervals in most analyses but provided less certainty than well-screen intervals about the actual depth from which groundwater was collected.

Many sources of groundwater chemistry data did not provide documentation about sampling, preservation, analytical, and quality assurance techniques. Information about the techniques used is critical for fully understanding the quality of the data and potential differences among the data sources. Several checking routines were used to identify systematic errors in the data and remove those data before analyses (see the "Data and Methods Used for Analyses" section); however, errors are still likely to exist within the datasets. Data from some sources were originally provided as provisional, with the expectation that the data may include inaccurate information. None of the data have been independently verified as part of this assessment's methods. Despite these limitations, it is expected that data errors represent a small part of the thousands of records and that the generalized results provided within this report are reasonably accurate within the context of a national-scale assessment.

Chemistry data were collected during a long period (late 1800s to 2013), and the sample collection date was unknown for about 3 percent of the data records. It is reasonably assumed that the groundwater chemistry of most deep systems will not change substantially during the course of a century; however, this assumption is not reasonable for shallower systems that have been affected by human activities and changing weather patterns, and results presented herein might not represent current [2016] conditions.

Hydrogeologic Characteristics

Limitations in describing the hydrogeologic characteristics of sediments bearing BGW include (1) an inability to identify the aquifer contributing water to wells, (2) inadequate delineation of the physical boundaries of aquifers, (3) a lack of information about the aquifer hydraulic properties needed to estimate the amount of available BGW in storage and the aquifer's ability to transmit BGW, and (4) a deficiency of data for describing hydrogeologic variables that could be used to predict the occurrence of BGW.

Knowledge about the aquifer contributing water to a well is essential for understanding the hydrogeologic setting associated with BGW. A contributing aquifer or geologic unit was provided with the data for roughly 65 percent of the wells used for this assessment; however, naming conventions were not consistent among data sources, and consistent aquifer names had to be assigned for summarizing groundwater chemistry data at the aquifer scale. To do this, aquifer names and geologic units were converted to principal aquifer names as described by Reilly and others (2008) where possible. For records that did not include aquifer or geologic unit information, an attempt was made to estimate a contributing principal aquifer by comparing well location and depth with aquifer boundaries. In many cases, the aquifer boundaries were based on only a few data points, thus producing uncertain results. Methods used for determining which principal aquifer produced the groundwater sample did not include a thorough evaluation of the lithology at each well and may not have yielded accurate results for all records; therefore, dissolved-solids information that is summarized at the aquifer scale can be considered approximate, especially in areas with complex geology and where few data are available for a given aquifer.

The USGS has made progress toward digitizing and further defining the horizontal and vertical boundaries of principal aquifers; however, the definitions of some of those aquifer boundaries either have been partially based on the extent of freshwater or have relied on data that were primarily from freshwater zones. In some cases, the freshwater boundary coincides with the boundary of permeable sediments. In other cases, especially in deep geologic units, it is unknown whether permeable sediments that are not within a principal aquifer boundary contain BGW. Additionally, it was beyond the scope of this assessment to compile groundwater level data needed to improve understanding of the boundaries of unconfined aquifers.

In order to fully characterize BGW resources, information is needed about the ability of sediments bearing BGW to store and transmit water. Aquifer hydraulic properties, such as porosity, permeability, and storage coefficients, are needed to characterize the amount of BGW that potentially can be extracted. Many published reports provide ranges of some aquifer properties, but those ranges can span several orders of magnitude, making it difficult to apply the data to real-world problems. Site-specific information and databases are rarely provided with published reports. In addition, it was difficult to locate information about aquifer hydraulic properties that were specific to brackish zones; consequently, data presented in this report are generalized and likely represent freshwater zones. This is a problem for an understanding of the ability of brackish zones to store and transmit water because the presence of saline groundwater often is associated with changes in aquifer properties. Well-yield data were compiled and used to provide some measure of the ability of wells producing BGW to provide usable amounts of water; however, well-yield values were available for only about 16 percent of the wells compiled for this assessment.

Because of the limitations described in the preceding paragraphs, a coarse three-dimensional grid was used to estimate the subsurface volume that contained BGW. This method is simplistic and does not provide highly accurate results. If a grid cell contained a sampled well that was categorized as producing BGW on the basis of the maximum dissolved-solids concentration, the entire grid cell volume was assumed to contain BGW. Consequently, this method tended to overestimate BGW volumes within areas where observations were available. Calculations did not consider aquifer porosity or storage properties; therefore, volumes represent the total subsurface volume including air, water, and rock. This approach provides estimates that yield much larger volumes than the actual amount of groundwater that can be extracted. As an attempt to provide more realistic values for BGW volumes, total grid cell volumes containing BGW were conservatively multiplied by 1 percent; however, resulting estimates are highly uncertain. Finally, results only represent areas for which chemistry data were available, and only about 15 percent of the subsurface volume between 0 and 3,000 ft below land surface is represented by groundwater chemistry samples compiled as part of this assessment. This underestimates the true extent of BGW across the Nation but it may provide reasonable approximations of the percentages of regional and aquifer volumes that contain BGW in areas where groundwater is being used.

Aquifer boundaries were considered in the volume calculations in only a simple way. Because grid cells were not clipped to aquifer boundaries, the amount of volume assigned to aquifers was potentially overestimated. To test the potential uncertainty of brackish volumes related to aquifer boundaries and the potential uncertainty related to the lack of dissolved-solids concentration data in many areas, a more refined evaluation of subsurface volumes was completed for selected principal aquifers that had more complete information for describing aquifer boundaries and dissolved-solids concentrations (appendix 4). Comparison of results from the coarse and refined estimates would not be useful for total volumes but may be useful for comparing the percentages of aquifer volumes. Those comparisons showed that the estimated percentages of aquifer volumes containing BGW from the refined evaluation were sometimes higher and sometimes lower than the coarse estimates—within about 7 percentage points for the Coastal lowlands aquifer system, about 16 percentage points for the Central Valley and Denver Basin aquifer systems, and about 23 percentage points for the Marshall aquifer (tables 8 and 4–1). These results represent differences between the coarse and refined estimates that are a factor of 2 to 3.

For areas where dissolved-solids concentration or specific conductance data were not available, a regression model was developed to predict the occurrence of BGW on the basis of geospatial data, such as geology and other variables that are related to dissolved-solids concentrations; however, this approach also has limitations. Regression models are dependent upon the availability of data to inform the predictions. As discussed previously, available dissolved-solids concentration data were biased toward fresh and shallow conditions, and that bias can affect results; for example, the regression equation specifically includes an adjustment for depth, but there are far fewer data available at depth to inform predictions. In addition, information about the spatial distribution of hydrogeologic and geochemical characteristics related to groundwater salinity are not always available at an appropriate level of detail; for example, the presence of evaporite deposits is a strong predictor for the occurrence of saline groundwater, but data were generalized. Other variables such as the mineralogy of aquifer sediments, groundwater residence time, and position along groundwater flow paths could be used to predict groundwater chemistry but are generally not available across the Nation.

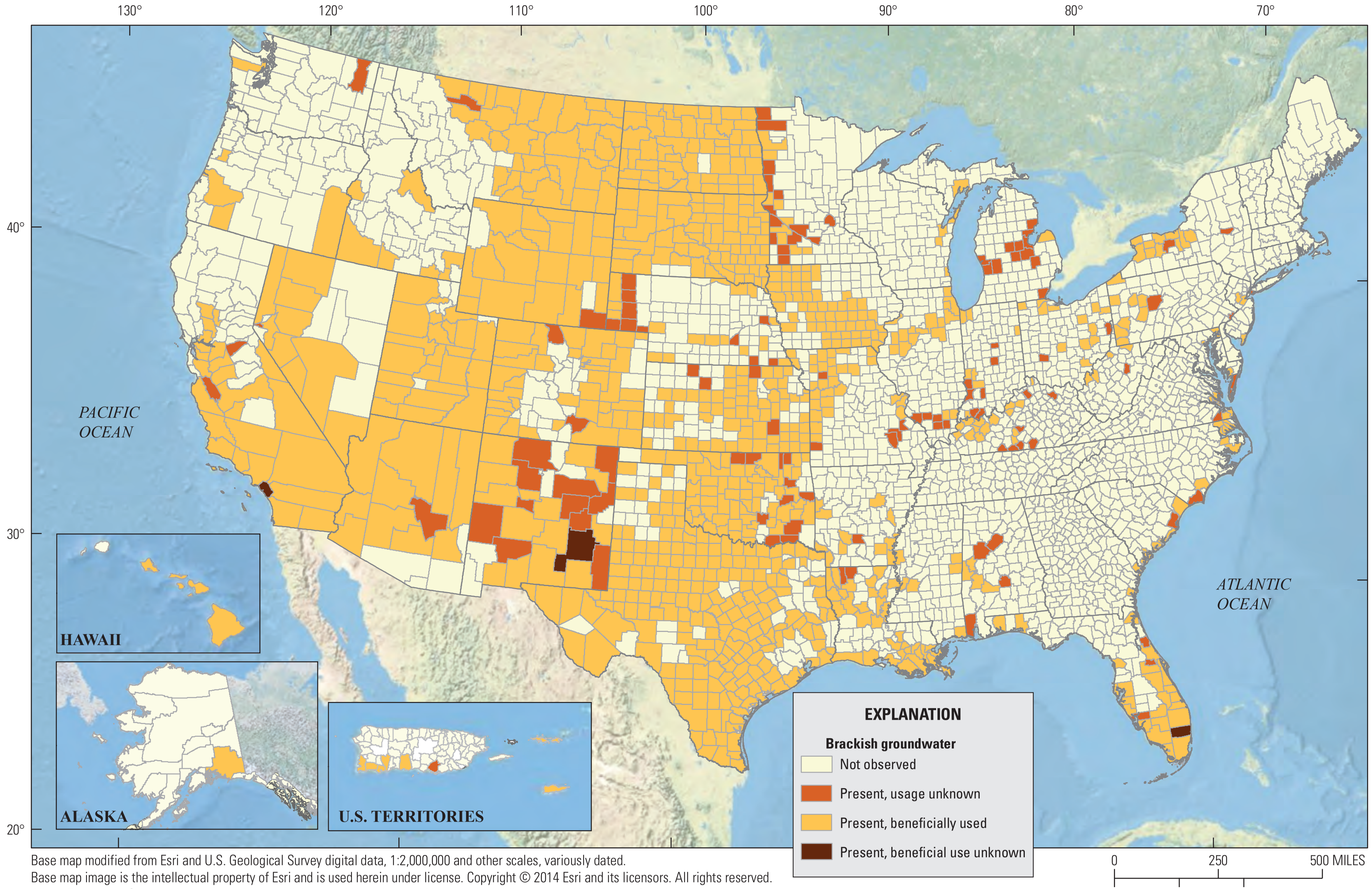
Saline Groundwater Use

Estimates of saline groundwater use presented in this report should be considered with their limitations in mind. The USGS Water-Use Program compiles water use data for the Nation on a 5-year cycle (Maupin and others, 2014). These data are routinely compiled by county for several freshwater and saline water use categories; saline water is defined as having a dissolved-solids concentration >1,000 mg/L. A more frequent (yearly) inventory of water use (fresh and saline) would better allow for recognizing temporal changes in saline water use. Compilation of fresh and saline water use by aquifer rather than by county would provide better data for hydrologic characterization. Water use by aquifer was last compiled in 2000 (Maupin and Barber, 2005) but only for freshwater; a similar inventory with specific saline classifications (for example, brackish salinity range [1,000 to 10,000 mg/L of dissolved solids]) would aid in characterization and development of BGW resources. For this assessment, it may be reasonable to assume that a large part of the saline groundwater use is within the brackish range because the cost to use or treat saline water for most purposes generally increases as the dissolved-solids concentration increases (Barlow, 1963; Bureau of Reclamation, 2003; Pearce, 2008). In addition, BGW in many locations is available at shallower depths than the depth that higher salinity groundwater is available, resulting in lower drilling and pumping costs. For the purposes of this report, results are presented as saline groundwater use to remain consistent with the original data from the Water-Use Program.

Although based on the best available information, results of saline groundwater use nonetheless are associated with notable uncertainties. Saline groundwater use is not reported for several States, some categories of saline uses are not reported for some years and some States, and the use categories that are compiled are not always consistent from year to year. Additionally, irrigation or domestic water-supply categories have never been reported for saline groundwater, and some use categories, such as mining, rely on minimal data. As part of this assessment, saline groundwater use was assigned to a principal aquifer where feasible, but methods were simplistic. Those assignments rely on the assumption that within each county, the amount of saline groundwater use from an aquifer is proportional to the percentage of wells producing saline groundwater within that aquifer from the geochemistry data compiled for this assessment. This would not be a reasonable assumption if the data compiled for this assessment represent uses for different aquifers than those represented by the Water-Use Program data for determining saline groundwater use. It is likely that this is the case for some aquifers; for example, most of the reported saline groundwater use for the High Plains principal aquifer from the Water-Use Program is for mining, but data compiled for this assessment indicate that saline groundwater from the High Plains aquifer is being used for other purposes, such as irrigation, domestic water supply (saline water use categories that are not included in the Water-Use Program), and public water supply. Saline groundwater used for mining is most likely pumped from deep aquifers that are underrepresented by the chemistry data compiled for this assessment. Evidence of BGW use based on geochemistry and information on well water use compiled for this assessment (fig. 53) indicates that the resource might be used in more counties across the Nation than was reported by the Water-Use Program (fig. 4).

Sustainability

This assessment does not evaluate the potential for BGW to be replenished if the resource is developed or examine the effects of extracting and treating BGW on the surrounding environment, and it does not take into account legal considerations for developing BGW; however, this information is essential for developing the resource (National Research



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Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W., latitude of origin 23°00′ N.
North American Datum of 1983

Figure 53. Evidence of brackish groundwater use from data compiled for this assessment, by county.

Council, 2008; Tidwell and others, 2014). BGW resources are likely to be dominated by old water that is not actively being recharged. Whereas many freshwater resources are renewable at some reasonable timescale, it is likely that BGW resources are not. The extraction of BGW resources has the potential to enhance movement of more mineralized (highly saline groundwater) water into freshwater zones (and vice versa) and cause substantial groundwater level decreases and land subsidence. If zones of fresh and brackish groundwater are hydraulically connected, then development of BGW may also affect the flow and availability of freshwater, cause cascading effects on streamflow and other surface-water bodies, or both as the hydrologic system adjusts to BGW withdrawals. Extraction of BGW could also affect aquifer hydraulic properties. BGW withdrawals from an aquifer could cause changes in water chemistry, potentially causing dissolution or precipitation of minerals and modifying the ability of aquifer sediments to transmit water. Additionally, treatment of BGW would require management of the desalination wastewater disposal stream without causing unwanted environmental effects. Finally, results from assessments of the potential for these effects would be needed in order to determine if institutional controls, such as interstate compacts, treaties, and water rights allocations, would be violated if BGW were developed.

Next Steps for Assessing Brackish Groundwater

Major investments in assessing the Nation’s natural resources, such as water, have been undertaken because of the importance of these resources to health of the population, economic development, and overall well-being of society. The information produced from these assessments allows society to make more informed decisions about using or conserving a resource. The national brackish groundwater assessment is based on that theme, and it provides basic information about the occurrence and characteristics of largely unexplored BGW resources and creates a foundation for directing future research. This assessment provides information about BGW at national, regional, and aquifer scales and is not a sufficient basis for understanding site-specific or local-scale conditions. An important next step for characterization and possible development of BGW resources is the collection and evaluation of more detailed information on these resources.

This assessment intends to make clear that BGW resources reside within aquifers or aquifer systems that also contain freshwater resources. This assessment illustrates that not only do the occurrence and quality of BGW vary horizontally and vertically within aquifers, but they also can vary within the same aquifer and even among wells quite close to one another. An additional complicating factor is that these waters are connected hydraulically; thus, the development of one resource will affect the quantity and quality of other groundwater resources. Withdrawals from any aquifer or groundwater system will affect the hydrologic budget, which directly translates to changes in water moving into, flowing out of, or remaining in storage within the system. Depending on the hydrogeology, these effects could take many years to become apparent. The potential effects of withdrawals from the BGW part of the aquifers on adjoining, overlying, or underlying water resources (fresh and saline) have mostly been unexplored.

A variety of factors affect the occurrence and characteristics of BGW. Climate, geology, hydrogeology, geochemistry, and different sources of salinity all require consideration in the evaluation of BGW resources. Statistical models may build on the understanding of these factors in some areas to predict probabilities of similar resources existing in areas without direct measurement. Such approaches could be useful for water resource managers interested in BGW as an additional or alternative resource in water-scarce areas.

An understanding of the occurrence and distribution of BGW, the hydrogeologic and chemical characteristics of aquifers that contain BGW, the use of BGW, and BGW sustainability would be improved through the compilation of additional existing data, collection of new data, and use of additional tools for assessing these potential resources.

Filling Data Gaps—Occurrence and Distribution of Brackish Groundwater

Most of the groundwater chemistry data compiled as part of this assessment were from water-supply wells that were completed at depths <500 ft below land surface. Additional dissolved-solids concentrations and hydrogeologic data for underrepresented areas and depths could be used to better define the amount of BGW potentially available for use. As demonstrated by the saline groundwater pilot studies, borehole geophysical logs can be used to estimate dissolved-solids concentrations and aquifer characteristics in many areas where data are lacking, particularly for deep intervals with few water-supply wells. The type of information that can be obtained depends on the types of geophysical logs collected—resistivity logs can be used to estimate dissolved-solids concentrations and the presence of oil and gas compounds; neutron and sonic logs can be used to estimate aquifer porosity; gamma ray logs indicate lithology, which can be used to determine aquifer boundaries; and spontaneous potential logs are used to estimate the permeability of aquifer materials. Information about any of these properties for brackish zones would provide a greater understanding of these zones as potential resources. Primary recommendations to provide a more complete picture of the occurrence and distribution of BGW resources are to do the following:

- Focus on additional data collection and compilation in local areas of potential BGW development. Compile detailed comprehensive datasets with pertinent information from a wide variety of sources. The expanded information gathered would include local data and maps, data from desalination facilities, proprietary databases where possible (such as IHS Markit oil and gas data), and geophysical logs.

- Compile and use existing geophysical data for estimating dissolved-solids concentrations to supplement chemical data.
- Acquire and extrapolate new and existing spatial data in three dimensions to produce maps in GIS formats.

Filling Data Gaps—Hydrogeologic Characterization

A more thorough methodology for identifying BGW in an aquifer would logically lead to more accurate assessments of the hydrogeologic characteristics associated with BGW resources. Assessments of hydrogeologic characteristics (such as aquifer material, depth, residence time, thickness, flow patterns, and recharge rates) can be partly improved through updating the horizontal and vertical extents of aquifers that contain BGW if those extents are not available, are based on limited data, or are limited to boundaries associated with the extent of freshwater or parts of the aquifer that are being used. It is likely that additional information from local- or site-scale studies is available to help define the boundaries and hydrologic characteristics of permeable sediments. Publication of these updated aquifer boundaries as digital spatial data would likely be of interest to the scientific community and end users, such as water resources managers and other stakeholders. Evaluation of BGW resources could also be improved with more detailed review of the lithology associated with wells, information about well-screen intervals, and characteristics of the geologic units associated with principal aquifers. Further refinement could be achieved by defining aquifer subunits associated with BGW. Hydrogeologic characteristics associated with brackish zones that are not part of a principal aquifer could be evaluated to determine if there are substantial permeable zones that have not previously been considered for development.

In order to fully characterize BGW resources, more information is needed about the ability of BGW-bearing sediments to store and transmit water. Aquifer tests could be completed for brackish zones to obtain information about hydraulic properties and to assess the ability of those aquifers to store and yield groundwater. Primary recommendations to provide a more comprehensive hydrogeologic characterization of BGW resources are to do the following:

- Compile additional data from multiple sources (local reports, databases, geophysical and lithologic logs, and numerical models) that provide estimates of needed parameters.
- Complete regional groundwater availability assessments of the Nation's priority principal aquifers using a consistent approach.
- Make available new and existing geologic maps and site-specific geophysical and geochemical data in GIS formats.

Filling Data Gaps—Geochemistry

Efforts to compile geochemistry data for this assessment were focused primarily on large digital datasets that were readily available. Compilation of additional existing geochemistry data, especially in areas where data are sparse, could improve future assessments and begin to fill data gaps. After existing data sources have been exhausted, collection and analysis of new groundwater samples from brackish zones could fill remaining data gaps. Analyses of these water samples would include dissolved cations and anions (inorganics), trace constituents (metals), selected organic compounds, suspended material, and radionuclides, all of which are related to the geologic setting. Information about these chemical constituents would help refine our understanding of the constraints that might inhibit or increase costs for desalination and use. Knowledge of the geochemistry other than dissolved-solids concentrations (for example, dissolved-gas concentrations) is incomplete at all depths. Primary recommendations to provide a better understanding of the geochemistry of BGW resources are to do the following:

- Complete a more thorough review and compilation of existing geochemistry data that are not readily accessible in digital format.
- Locate or drill additional wells to collect and analyze groundwater for depths >500 ft below land surface.
- As part of groundwater availability assessments (quantity), include analysis of baseline chemistry of entire aquifers (fresh, brackish, and highly saline water) where feasible.
- Explore links between geochemistry, required water treatment, and potential end users with the aid of geochemical modeling and simulations.

Filling Data Gaps—Brackish Groundwater Use

Estimates of the amount of BGW being used would be enhanced through the collection of more detailed salinity information with water use estimates to determine what part of saline groundwater use was specific to the brackish range. Saline groundwater use data could also be collected for additional categories, such as irrigation and domestic supply. New methods for collecting water use data for categories with known data limitations such as mining could be investigated and implemented if determined to be feasible. Mining is one of the largest uses of saline groundwater, and improving methods used to estimate water use for mining would be a benefit to understanding BGW use. Finally, all these data should be collected and categorized by principal aquifer. Primary recommendations to provide a more thorough inventory of BGW use are to do the following:

- Complete a more detailed and thorough assessment of BGW and highly saline groundwater use.
- Compile all uses by principal aquifer.
- Create a complete inventory of desalination facilities.

Filling Data Gaps—Sustainability

A full characterization of water resources would include site-specific determinations of the quantity and quality of BGW in addition to the other water resources in the immediate vicinity. As data gaps in the characterization of BGW resources are filled, additional analytical tools can be applied. Three-dimensional mapping software can be used to interpolate available dissolved-solids data across aquifers. Three-dimensional maps provide depictions of brackish zones, such as the depth to BGW and the subsurface volume that is occupied by BGW. As part of the current [2016] assessment, four principal aquifers with relatively complete data were selected for interpolated three-dimensional mapping. Additional aquifers containing BGW could be analyzed in this manner in future assessments.

Questions about the sustainability of developing BGW resources could be addressed through the development of groundwater flow models. These models provide a mechanism for tracking water movement in, through, and out of an aquifer system while assessing the implications of BGW withdrawals on all waters (fresh, brackish, and highly saline) that jointly reside within the aquifer system. Groundwater age in conjunction with aquifer permeability data could be used to enhance these models by providing additional information about how quickly groundwater moves through the system. In areas where detailed decision tools such as these do not exist, it is possible to aid stakeholders and decision makers in the development of tools to help communities assess the viability of their BGW supplies for various development scenarios. Primary recommendations to provide a better understanding of the sustainability of developing BGW resources are to do the following:

- Assess BGW sustainability with use of appropriate tools (models to simulate water movement and transport) to quantify the response (flow and chemistry) of a principal aquifer to extraction of BGW. Numerical models, groundwater age dating, and time-series water quality sampling would aid in understanding effects of development, such as the alteration of hydraulic properties because of changes in water chemistry; effects on geochemistry of the inflow of more mineralized or fresher water into the reservoir (for example, mobilization of other unwanted constituents); possibility for subsidence; and whether or not BGW resources are renewable at a timescale of human use.
- If appropriate tools are lacking, develop or adapt new tools to determine long-term viability of developing aquifers containing BGW. Build replicable numerical groundwater flow models to estimate aquifer productivity.
- Cooperate with local, State, and Federal agencies to aid in evaluation of the suitability and feasibility of resources for identified uses as newly acquired information becomes available.
- Compile information regarding legal or contractual issues related to using BGW.

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Appendixes 1–4

Appendix 1. Estimation Results for Dissolved-Solids Regression Model

Appendix 2. Equations Used in Geochemical Analysis

Appendix 3. Relation Between Dissolved-Solids Concentration and Specific Conductance

Appendix 4. Estimating Brackish Groundwater Volumes for Selected Principal Aquifers With Three-Dimensional Models

Appendix 1. Estimation Results for Dissolved-Solids Regression Model

Estimation results for the dissolved-solids regression model, including coefficient estimates, standard errors, *t* values, and probability levels of significance, are presented in table 1–1 available at https://doi.org/10.3133/pp1833. The model was constructed by using nonlinear least-squares multivariate regression with the dependent variable equal to the natural logarithm of the dissolved-solids concentration, in milligrams per liter.

Appendix 2. Equations Used in Geochemical Analysis

Equations used for geochemical analysis include equations for calculating the Langelier saturation index (Langelier, 1936), sodium-adsorption ratio, and osmotic pressure. Many different indices are used by the water treatment community to measure scaling potential or corrosivity, and the specific index depends on the intended water use, water type and temperature, and material in contact with water (Singley, 1981; Rossum and Merrill, 1983). The Langelier saturation index was assessed because it is widely used by the water treatment community and provides a means of determining the potential for calcite to form a scale that would hinder the corrosion of distribution lines or tanks. The Langelier saturation index (*LSI*) is defined by the equation

$$LSI = pH - pH_s, \qquad (2\text{–}1)$$

where

pH is the measured pH and
pH_s is the calculated pH at calcite saturation, derived from the following equation:

$$pH_s = (9.3 + A + B) - (C + D), \qquad (2\text{–}2)$$

where

A is [log(*dissolved solids*) − 1] / 10,
B is –13.12 × log(T + 273) + 34.55,
T is the temperature, in degrees Celsius,
C is log(*calcium as calcium carbonate [CaCO$_3$]*) − 0.4, and
D is log(*alkalinity as calcium carbonate [CaCO$_3$]*).

The *LSI* was calculated directly by using measured temperature, pH, alkalinity, and calcium concentrations, and dissolved-solids concentrations were measured or estimated from specific conductance as described in the "Data and Methods Used for Analyses" section. An *LSI* range of –1 to +1 has a relatively low potential for corrosion or scaling; however, waters at an *LSI* <–1 will likely dissolve calcite (and potentially corrode steel), and waters at an *LSI* >1 will likely precipitate calcite scale (Hem, 1989). Several other mineral scaling or corrosivity indices are available and consider other constituents in the water; for example, the Larson and Singley indices consider chloride and sulfate, which can increase the acidity of water and cause corrosion (Barringer and others, 1993).

The sodium-adsorption ratio commonly is used in evaluating the suitability of water for irrigation (Wilcox, 1955; Suarez and others, 2008). The sodium-adsorption ratio (*SAR*) of water is represented by the following equation:

$$SAR = \frac{Na}{\sqrt{Ca + Mg}}, \qquad (2\text{–}3)$$

where

Na is sodium concentration, in moles per liter,
Ca is calcium concentration, in moles per liter, and
Mg is magnesium concentration, in moles per liter.

The *SAR* value of each sample was calculated by using the PHREEQC computer program, which takes into account solute species interactions (Parkhurst and Appelo, 2013). Because the sodium-adsorption ratio is intended to indicate potential for irrigation water to affect soil properties through ion interactions, the total concentration of parameters in equation 2–3 were replaced with PHREEQC output for the respective ion concentrations. Use of water with a high *SAR* value and low to moderate specific conductance may be detrimental to crops and reduce the soil infiltration rate (Suarez and others, 2008). The forces that bind clay particles together are disrupted when too many large sodium ions come between them; when this separation occurs, the clay particles expand and cause swelling and soil dispersion; however, the adverse effects of a given elevated *SAR* value on soil physical properties are reduced with increasing specific conductance until specific conductance itself becomes detrimental to crop growth (Ayers and Westcot, 1994).

The osmotic pressure (Π; in atmospheres) was calculated for each sample by using the following equation (Wall, 1958):

$$\Pi = \frac{RT \ln\left(a_{H_2O}\right)}{V_{H_2O}}, \qquad (2\text{–}4)$$

where

R is the molar gas constant, 0.082, in liters by atmospheres per degree kelvin by mole,
T is absolute temperature, in kelvins,
$\ln\left(a_{H_2O}\right)$ is the natural logarithm of the activity of water (unitless) calculated by using the Pitzer aqueous model (pitzer.dat database in the PHREEQC program), and
V_{H_2O} is the molar volume of water, in liter per mole.

Osmosis is the natural process by which a pure solvent moves from an area of low-solute concentration, across a semipermeable membrane that blocks the salts, to an area of high-solute concentration (Voet and others, 2001); therefore, osmotic pressure is nearly proportional to the salt concentration of the water. Osmosis is important in the study and use of brackish water for (1) irrigation because plant cells are semipermeable and osmotic pressure affects plant growth, and (2) reverse osmosis desalination, which involves applying pressure to reverse the natural flow of pure solvent through a semipermeable membrane to remove salts. Osmotic potentials of brackish or highly saline water require more energy for the reverse osmosis process than do those of freshwater. The osmotic pressure of seawater is about 27 atmospheres, whereas the osmotic pressure of fresh and brackish water ranges from 2 to 17 atmospheres. The pressure required for reverse osmosis desalination of seawater is about 56 atmospheres, and this pressure consumes about 3 kilowatthours per cubic meter (Al-Karaghouli and Kazmerski, 2013).

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Appendix 3. Relation Between Dissolved-Solids Concentration and Specific Conductance

Measured dissolved-solids concentrations are positively correlated with measured specific conductance (fig. 3–1) because most major solutes are ions that facilitate electron transfer through aqueous solutions; however, the relation between dissolved-solids concentrations and specific conductance is not the same for different geochemical water types. Relations between dissolved-solids concentrations and specific conductance are important because (1) specific conductance commonly is measured as a proxy for dissolved solids; (2) physical and chemical properties of brackish groundwater (BGW) affecting its use or treatment may be more simply related to either dissolved-solids concentrations or specific conductance, which are useful for the classification and assessment of BGW; and (3) dissolved-solids concentrations and specific conductance can be used for quality control checks on laboratory determinations of major-ion constituents (Hem, 1989).

For samples with no measured dissolved-solids concentration, values were estimated on the basis of specific conductance and equations derived for varying concentration ranges, as discussed in the “Data and Methods Used for Analyses” section. For a given dissolved-solids concentration or specific conductance value, however, the composition of constituents that compose dissolved solids in BGW can vary greatly depending on associated geologic sources and processes. For example, group 3 samples, which are sodium-chloride dominant, have the most linear relation between dissolved solids and specific conductance, whereas the sulfate-dominant group 2 samples have low specific conductance relative to dissolved-solids concentrations compared to samples from other groups (fig. 3–1); thus, comparisons between measured and modeled dissolved-solids concentration and specific conductance values provide information about the quality of the data and insights about the meaning and implications of these two representations of bulk solution properties. Because of the importance of dissolved-solids concentration and specific conductance values for assessment of BGW, this section focuses on the quality of their relation, their dependence on different ion compositions, and the theoretical considerations of specific conductance measurements.

To conduct an electric current, solute ions must move through the solution to transfer electrical charges, and the effectiveness of a particular ion in this process depends on its charge, its size, the way it interacts with the solvent, and other factors. The property that encompasses these characteristics of an ion is called ionic mobility, and this mobility represents the velocity of an ion in a potential electrical gradient of 1 volt per centimeter (Hem, 1989). Ionic mobility decreases with increasing dissolved-solids concentrations because of interferences and interactions among the ions. In addition, temperature-compensation circuits on most specific conductance instruments are based on the conductivity versus temperature functions of 0.01-molar potassium-chloride or sodium-chloride solutions and therefore may not provide accurate compensation in more saline solutions, such as seawater, or at temperatures substantially higher or lower than 25 degrees Celsius (Miller and others, 1988) or for solutions not dominated by potassium or sodium chloride.

Comparison of measured dissolved-solids concentrations and measured specific conductance in the BGW database generally indicates an approximately linear relation between the measurements but also includes some minor scatter and several outliers that deviate from the regression line (fig. 3–1). The regression line is defined by equation 1 in the “Data and Methods Used for Analyses” section and is used in this report to derive dissolved-solids concentrations from measured specific conductance data for samples in the dissolved-solids dataset that do not have a dissolved-solids concentration measurement. The slight decrease in slope at greater concentrations is typical of all salts, and the break in slope varies for different salts (Hem, 1989). To assess the source of the outliers and other aspects of data quality, dissolved-solids concentration and specific conductance measurements were compared with output from the PHREEQC computer program (Parkhurst and Appelo, 2013) to evaluate their agreement with modeled values. The PHREEQC program calculates the dissolved-solids concentration from the sum of constituents analyzed, and it calculates the specific conductance of a solution from the concentrations, activity coefficients, and diffusion coefficients of all the charged species. The specific conductance values obtained through calculation with the PHREEQC Pitzer database are similar to measurements of a large variety of solutions that range from 10 to 100,000 microsiemens per centimeter at 25 degrees Celsius (Parkhurst and Appelo, 2013).

A plot of modeled specific conductance and modeled dissolved-solids concentration (fig. 3–2) shows the variability in the relation between modeled values of dissolved-solids concentration and specific conductance, which is caused by different salts, and how that variability can affect uncertainties when a calculated quantity is derived from a measured one. The modeled dissolved-solids concentrations and specific conductance values (fig. 3–2) show more agreement than measured values (fig. 3–1) because of the absence of measurement error; to avoid overprinting of data points, fresh groundwater samples were not plotted. Curves representing various simple salts, including magnesium chloride ($MgCl_2$), sodium chloride (NaCl), potassium chloride (KCl), sodium sulfate (Na_2SO_4), magnesium sulfate ($MgSO_4$), potassium sulfate (K_2SO_4), and sodium bicarbonate ($NaHCO_3$), were generated in the PHREEQC program for solutions of varying concentrations up to those in equilibrium with their most stable mineral phase (fig. 3–2). The sodium chloride curve is nearly linear throughout the range, whereas the curves for other salts are less linear. The sulfate salts in particular show a decrease in

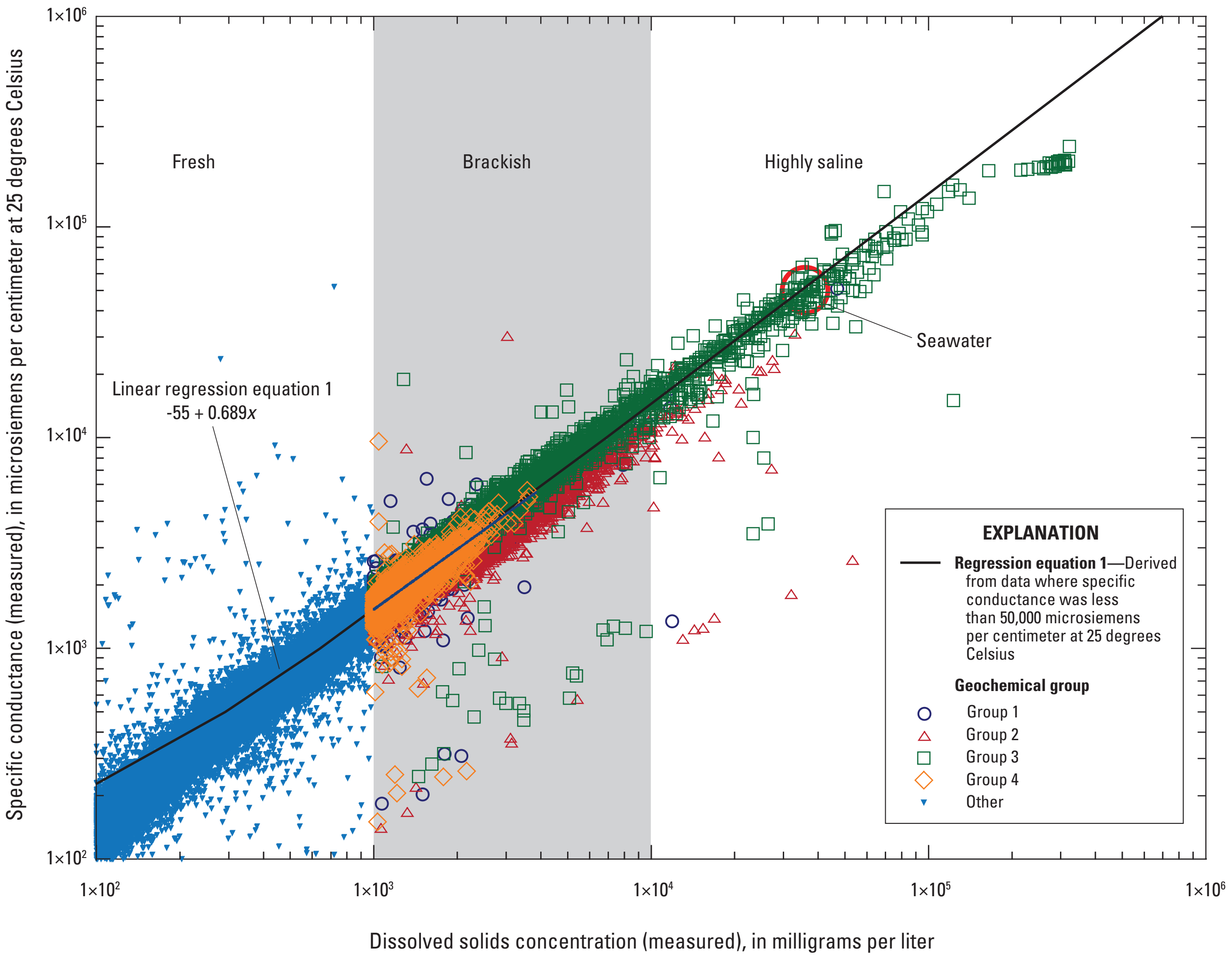

Figure 3–1. Dissolved solids as a function of specific conductance for measured data in the four geochemical groups and other fresh groundwater data not assigned to a group. Geochemical groups are discussed in the “Geochemical Characteristics of Brackish Groundwater” section of this report.

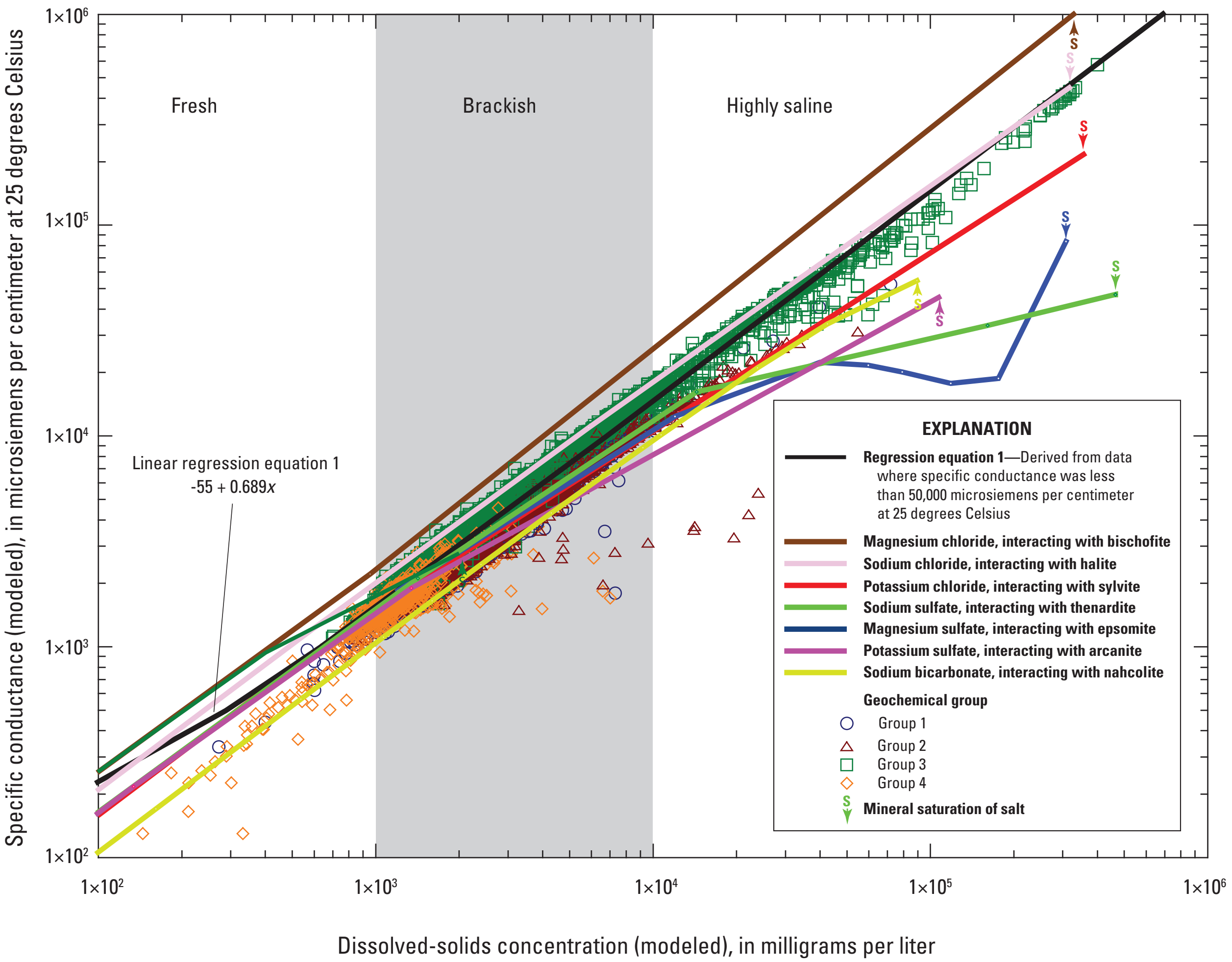

Figure 3–2. Modeled specific conductance as a function of modeled dissolved solids for the four geochemical groups defined by cluster analysis and other fresh groundwater data not in the groups. Modeling was done by using the computer program PHREEQC (Parkhurst and Appelo, 2013). Curves indicate simulated simple salt solutions (magnesium chloride, sodium chloride, potassium chloride, sodium sulfate, magnesium sulfate, potassium sulfate, and sodium bicarbonate), each with varying concentration up to the point of saturation with its most stable mineral phase. Geochemical groups are discussed in the “Geochemical Characteristics of Brackish Groundwater” section of this report.

specific conductance relative to dissolved-solids concentrations above about 30,000 milligrams per liter as a result of ion pairing of sulfate, which would decrease the concentration of free ions in solution and consequently decrease the specific conductance in comparison to a solution with the same salt concentration but no ion pairing. Ion associations or complexes form in natural waters, particularly between the alkaline Earth calcium, magnesium, and strontium cations and sulfate, carbonate, and bicarbonate anions (Stumm and Morgan, 1981). As a result, estimates of dissolved solids made by using specific conductance measurements are likely to be less accurate for high than for low concentrations of dissolved solids because of approximations that do not account for specific salt types in solution.

Comparisons of measured dissolved solids to modeled dissolved-solids concentrations and specific conductance values (not shown in figure 3–2) indicate that scatter in measured values is partly consistent with theoretical predictions but includes additional deviations or outliers. Comparisons of modeled values of dissolved-solids concentrations and specific conductance (fig. 3–2) indicate that theoretical ionic interactions can explain some of the scatter in the measured data (fig. 3–1). For example, samples assigned to geochemical group 2 (calcium-sulfate-dominant water type) tend to have lower osmotic pressure than group 3 samples (sodium-chloride-dominant water type) at any given dissolved-solids concentration because of differences in molar mass and ion interactions. Minor deviations from these theoretical correlations may reflect measurement uncertainties or possibly conversion errors (for example, dissolved-solids concentrations derived from specific conductance measurements by using approximate correlations or from specific conductance values that were not temperature corrected). Relatively few samples (<0.1 percent) indicated major deviations (greater than about 300 milligrams per liter of dissolved solids), which could result from transcription errors or other data inconsistencies; therefore, dissolved-solids-based brackish groundwater classifications that rely on values determined from measured or even calculated specific conductance values can be useful but may not be suitable for all purposes. Ideally, measured dissolved-solids concentrations together with concentrations of major ions of interest should be considered to best determine the suitability of brackish water for specific uses.

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Appendix 4. Estimating Brackish Groundwater Volumes for Selected Principal Aquifers With Three-Dimensional Models

Estimates of groundwater volumes are inherently uncertain, but uncertainty in the estimation method of using a coarse three-dimensional grid at a national scale (described in the "Three-Dimensional Mapping of Observed Dissolved-Solids Concentrations" section) can be reduced with additional data. Four principal aquifers with brackish groundwater (BGW) were selected for more refined volumetric assessments in a pilot feasibility test. These refined assessments also helped determine some of the uncertainty related to obtaining volume estimates by using observed dissolved-solids concentrations assigned to the coarse three-dimensional grid used for this assessment. Unlike that coarse volumetric assessment, the refined volumetric assessment was constrained to the physical boundaries of the selected aquifers. In addition, dissolved-solids concentrations were estimated between the available sample locations, providing a more complete representation across the aquifer than was provided in the coarse assessment.

For unconfined aquifers, the upper boundary is the water level, but it was beyond the scope of this assessment to compile groundwater level data needed to improve understanding of the boundaries of aquifers. The assessment also did not include information needed to estimate the amount of BGW in storage that would be available for extraction. Calculations did not consider aquifer porosity or storage properties; therefore, volumes represent the total subsurface volume, including air, water, and rock, and are considerably larger than the actual amount of groundwater that can be extracted. Results should be considered simplified estimates, especially for areas with complex geology and where few data are available for a given aquifer.

Methods

Principal aquifers containing BGW were selected for refined volumetric assessment through a ranking process based on their size, density of samples with a dissolved-solids concentration, average dissolved-solids concentration, and aquifer shape (single polygon or fragmented). Principal aquifers with smaller single polygon boundaries, higher sample densities, and higher average dissolved-solids concentration were chosen.

Dissolved-solids concentration data associated with depth intervals based on well-screen information for each principal aquifer were interpolated by using a three-dimensional kriging approach (Journel and Huijbregts, 1978) to create a three-dimensional volumetric pixel-grid model (voxel model) of dissolved-solids concentration (Geosoft, 2016). A voxel cell is a volume element representing a value, in this case dissolved-solids concentration, in a three-dimensional grid space. Voxel models were created with grid cells having dimensions of 328 feet (ft) by 328 ft to 1,641 ft by 1,641 ft on the horizontal plane and 32.8 ft on the vertical plane (table 4–1). The data are denser vertically than horizontally; therefore, a greater emphasis (x,y to z cell dimension ratio of 10 to 50) was applied to the vertical axis, and a 1 to 10 strike and dip weight was given to the horizontal plane to increase the importance of data along the plane during the gridding process by imparting a horizontal anisotropy. This horizontal anisotropy is coincident with subhorizontal stratification often exhibited in sedimentary basin aquifers with porous media (Woumeni and Vauclin, 2006).

Voxel models were clipped at the horizontal aquifer boundary and clipped at the bottom and top surfaces of the aquifer with a digital elevation model created from published contour maps of aquifer extents to remove any model cells outside of the mapped aquifer that were created from the gridding process. A digital elevation model representing the 3,000-ft depth (the limit of this assessment) was used to remove model data in parts of the aquifers that were deeper than 3,000 ft before calculations were completed (table 4–1).

Data limitations that caused uncertainty in the modeled results included heterogeneity within the aquifer (locations of confining units and high transmissivity zones), a lack of data for well-screen intervals, and a lack of samples with a dissolved-solids concentration in some areas. Aquifer boundaries were used to limit the voxel model extent, but it was beyond the scope of this assessment to further refine the volume of subsurface BGW and the extractable part by developing geologic and hydrogeologic models that include digitized interpretations of the geometry and hydraulic properties of confining units and permeable zones (Ahmed, 2009).

Dissolved-solids concentration data are entered into the voxel model at well locations over the full length of well screens. Well-screen intervals were not available for all wells but are needed for the model to provide vertical locations of the dissolved-solids values within the aquifers. Missing well-screen intervals were estimated from existing well depths and estimated well-screen lengths. The estimated well-screen lengths were determined either by using a regression equation developed from existing well depths and well-screen lengths for each aquifer or by using the median value of screen length for the aquifer if the coefficient of determination (R^2) from the regression equation was too low (less than [<] 0.5; high error). The well depth was then used as the bottom of the estimated screened interval, and well depth minus the estimated screen length was used for the top of the screened interval.

To help fill spatial data gaps in dissolved-solids concentrations near the edges of aquifers, additional wells within an 18.6-mile (30-kilometer) buffer of the aquifers were included in the model. Using data outside the model boundary to estimate results inside the model boundary likely would result in errors in some locations. Blanking distances used in the three-dimensional kriging process ranged from 20 to 200 grid cells, and a max search radius of 32 to 128 grid cells was used

Table 4–1. Estimated percentage of subsurface volumes containing brackish groundwater for selected principal aquifers.

Brackish groundwater region	Principal aquifer	Number of wells used for analysis	Wells with brackish groundwater, in percent	Total subsurface volume of aquifer, in cubic miles[1]	Estimated voxel volume containing brackish groundwater, in percent	Voxel model cell size, in feet	
						x,y	z
Coastal Plains	Coastal Lowlands aquifer system	22,391	20	44,484	35	1,641	32.8
Eastern Midcontinent	Marshall aquifer	151	17	749	48	656	32.8
Southwestern Basins	Central Valley aquifer system	6,885	24	8,035	18	1,641	32.8
Western Midcontinent	Denver Basin aquifer system	1,916	27	1,573	7	328	32.8

[1] Subsurface volumes include air, water, and rock occupied in the subsurface to 3,000 feet below land surface. Volumes are computed based on voxel-cell dimensions and on well construction and sample information associated with or near each voxel cell.

to extrapolate estimates beyond the wells and to fill in gaps. Wells were plotted on cross sections to provide a qualitative view of where results are most reliable. Interpolated dissolved-solids concentrations are more reliable closer to wells. Volume estimates for the four selected principal aquifers, one within each of the four regions, are detailed in the following sections.

Coastal Plains Region

The Coastal lowlands aquifer system, which is located along the Gulf of Mexico coastline spanning the States of Texas, Louisiana, Mississippi, and Alabama (fig. 21), consists of five distinct permeable zones (Osborn and others, 2013). Well depth did not correlate (high p values; greater than [>] 0.05) with screen length in four of the five aquifers of the aquifer system. In the other aquifer, the correlation between well depth and screen length was significant (p value=0.0059) but did not explain the variance (R^2=0.0048); therefore, for each of the five aquifer subunits, a median well-screen length (aquifer 1, 20 ft; aquifer 2, 78.7 ft; aquifer 3, 3.7 ft; aquifer 4, 15 ft; and aquifer 5, 9.8 ft) was used as an estimate for wells with missing data for the screened interval. The lack of correlation is likely the result of a large variety of well designs used to produce water from aquifers with complex geology characterized by beds with a variety of orientations, thicknesses, permeability, and subcrop and outcrop locations.

Wells that produce BGW have a shallower median depth than the whole population of sampled wells; the standard deviation for well depths from the BGW wells is about four times the median. Most of the BGW is along the coast, with some higher dissolved-solids concentration areas extending inland on the eastern end, near the mouth of the Mississippi River (fig. 4–1*A*; at the end of this appendix). Moderately brackish dissolved-solids concentrations are observed on the western end across the width of the aquifer. The voxel was cut off at 3,000 ft for estimating voxel volumes. The five aquifers within the system dip toward the center of the Gulf of Mexico. The deepest two aquifers are separated from each other and from the top three aquifers by confining units and therefore were modeled separately. A total of 35 percent of the voxel volume of the aquifer system is estimated to contain BGW (table 4–1).

Eastern Midcontinent Region

Volume estimates of BGW were made for the Marshall aquifer within the Eastern Midcontinent region by using a voxel model. Well depth did not correlate (high p values; >0.05) with screen length, so a median well-screen length (25.9 ft) was used as an estimate at wells where data were missing. The aquifer has a bowl shape, and the highest dissolved-solids concentrations in groundwater are in the deepest parts of the aquifer just north of the center (fig. 4–2; at the end of this appendix). An estimated 48 percent of the voxel volume contains BGW (table 4–1).

Southwestern Basins Region

Volume estimates were made for the Central Valley aquifer system in the Southwestern Basins region by using a voxel model. The aquifer is aligned north to south with mountain ranges to the east and west. Well depth was correlated (p value < 0.0001) with the length of the screened interval (screened lengths increase with depth in this group of wells), explaining much of the variance (R^2=0.639), and was used to estimate screen length at wells where screen data were missing by using the following equation:

$$\log(screen\_length) = 0.7752 + 1.0685 \times \log(depth). \quad (4\text{–}1)$$

Wells with BGW have a deeper median well depth; the standard deviation of well depth for BGW wells is more than twice the median. Most of the BGW is along the western edge and top of the aquifer; BGW increases in area to the south and also is present and at the bottom of the aquifer in the south (fig. 4–3; at the end of this appendix). A total of 18 percent of the voxel volume contains BGW (table 4–1).

Western Midcontinent Region

Volume estimates were made for the Denver Basin aquifer system in the Western Midcontinent region by using a voxel model. The aquifer system is at the eastern toe of the foothills of the Rocky Mountains. Well depth correlated (p value < 0.0001) with screen length ($R^2=0.763$) and was used to estimate well-screen locations at wells where data were missing by using the following equation:

$$\log(screen\_length) = 0.4544 + 0.9027 \times \log(depth). \qquad (4\text{–}2)$$

Most of the BGW is in the northeastern part of the aquifer and along the eastern edge (fig. 4–4; at the end of this appendix). An estimated 7 percent of the voxel volume contains BGW (table 4–1).

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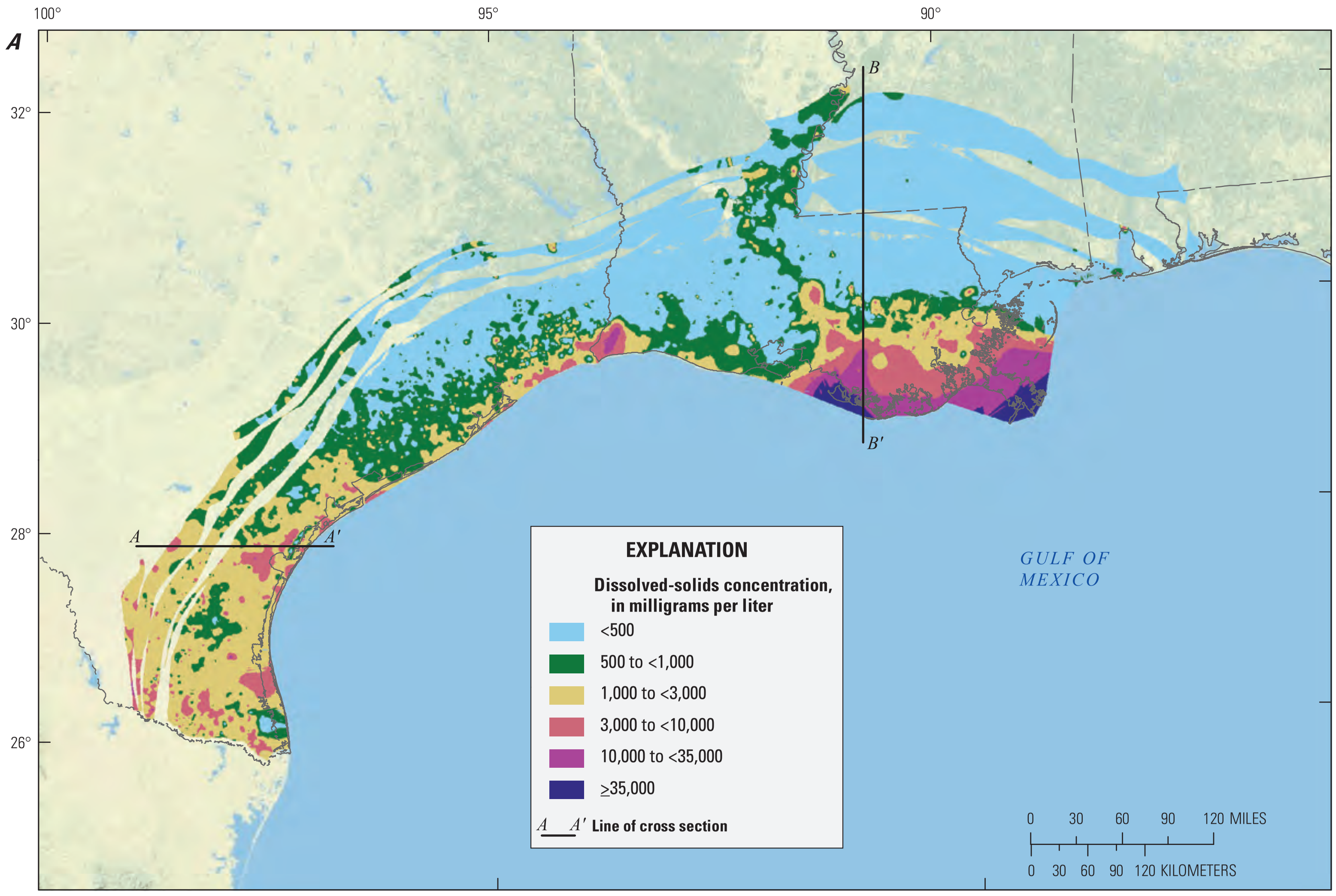

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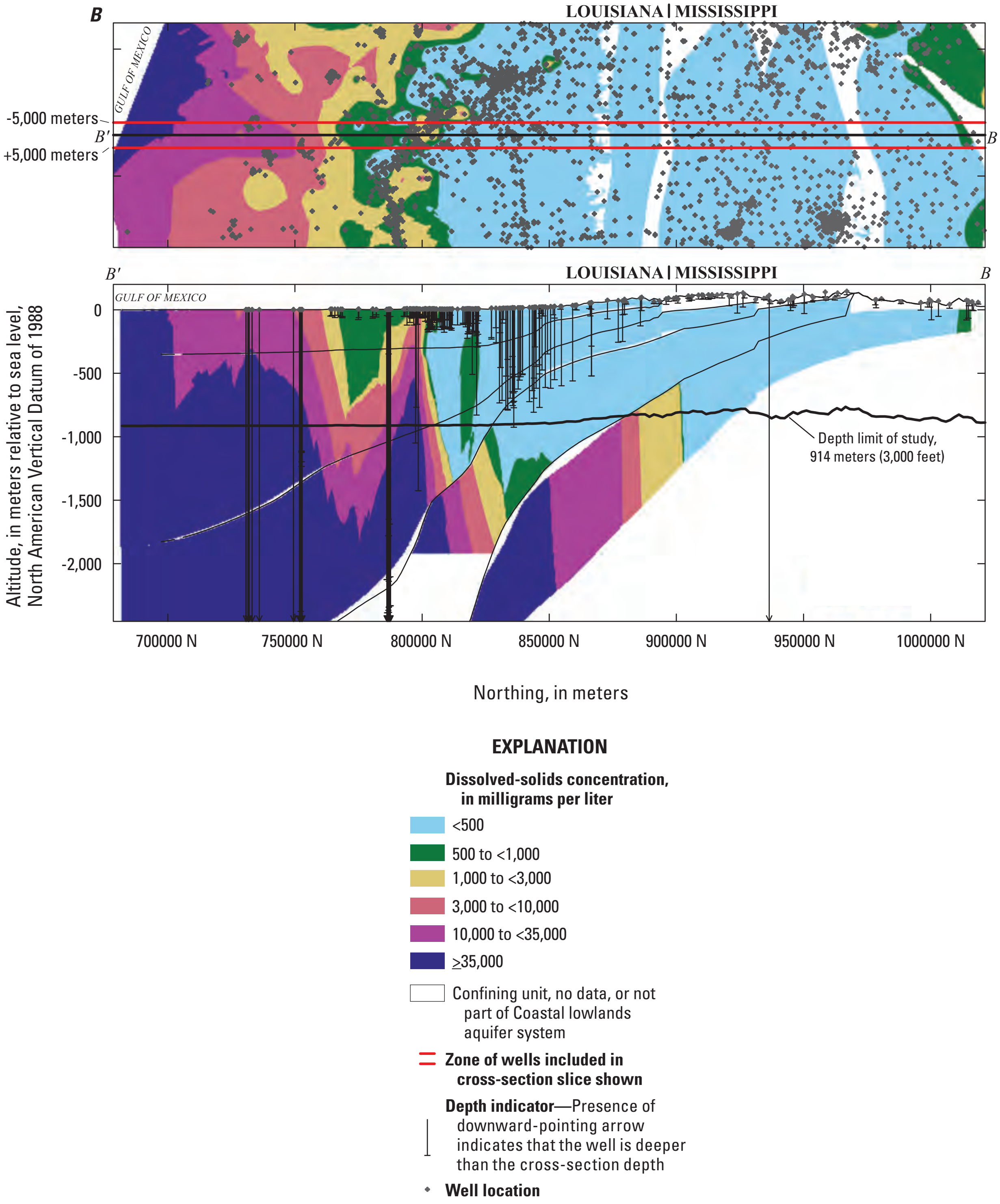
Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W., latitude of origin 23°00′
North American Datum of 1983

Figure 4–1. Three-dimensional dissolved-solids voxel model of the Coastal lowlands aquifer system (fig. 21). Confidence in the interpolated voxel decreases with distance from sampled wells. *A*, map of the top model layer; *B*, map and cross section of the top model layer with wells near *B–B′*; *C*, map and cross section of the top model layer with wells near *A–A′*; *D*, image of three-dimensional isosurfaces created from the voxel model. An interactive version of the three-dimensional image is available at https://doi.org/10.3133/pp1833.



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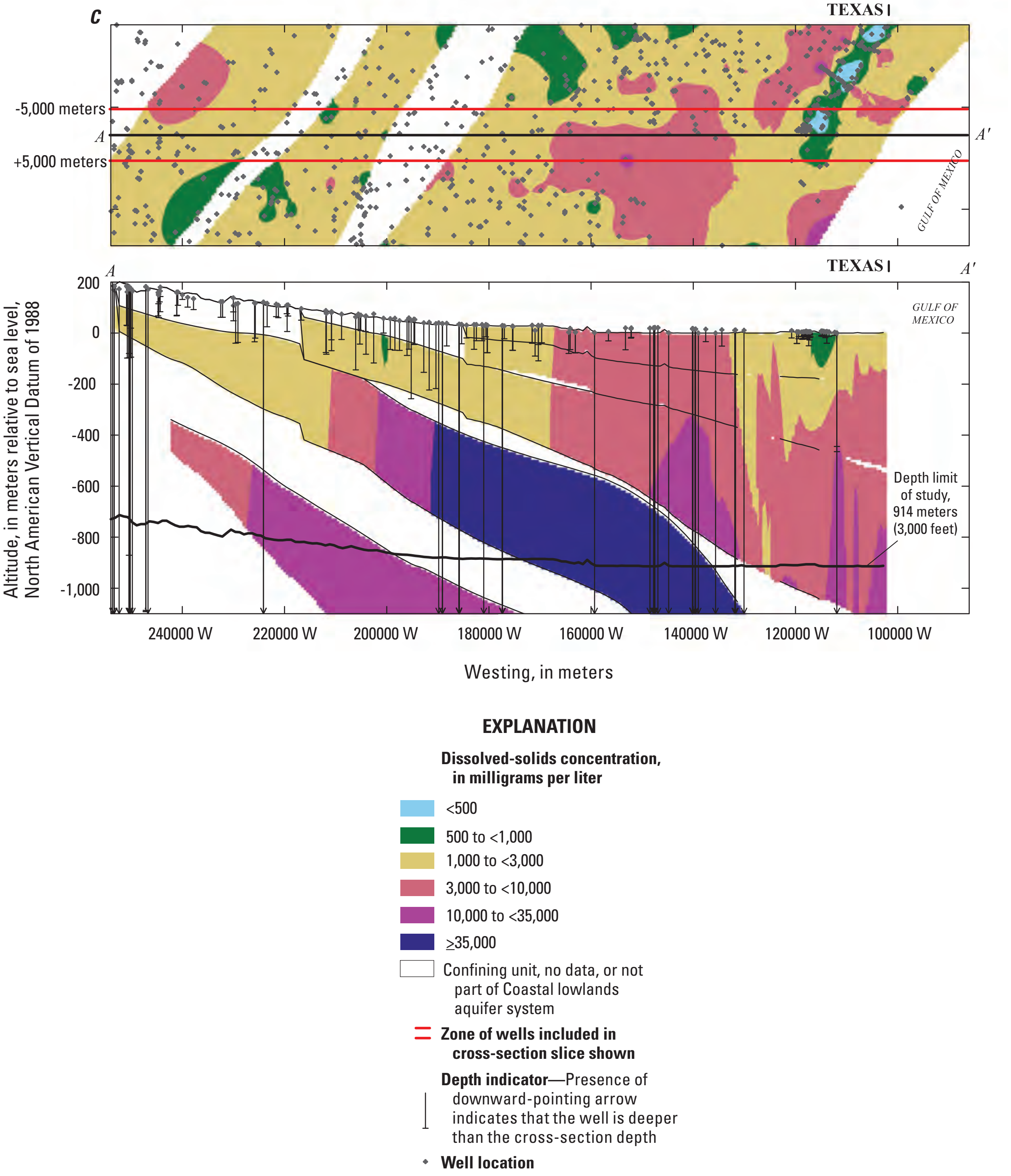

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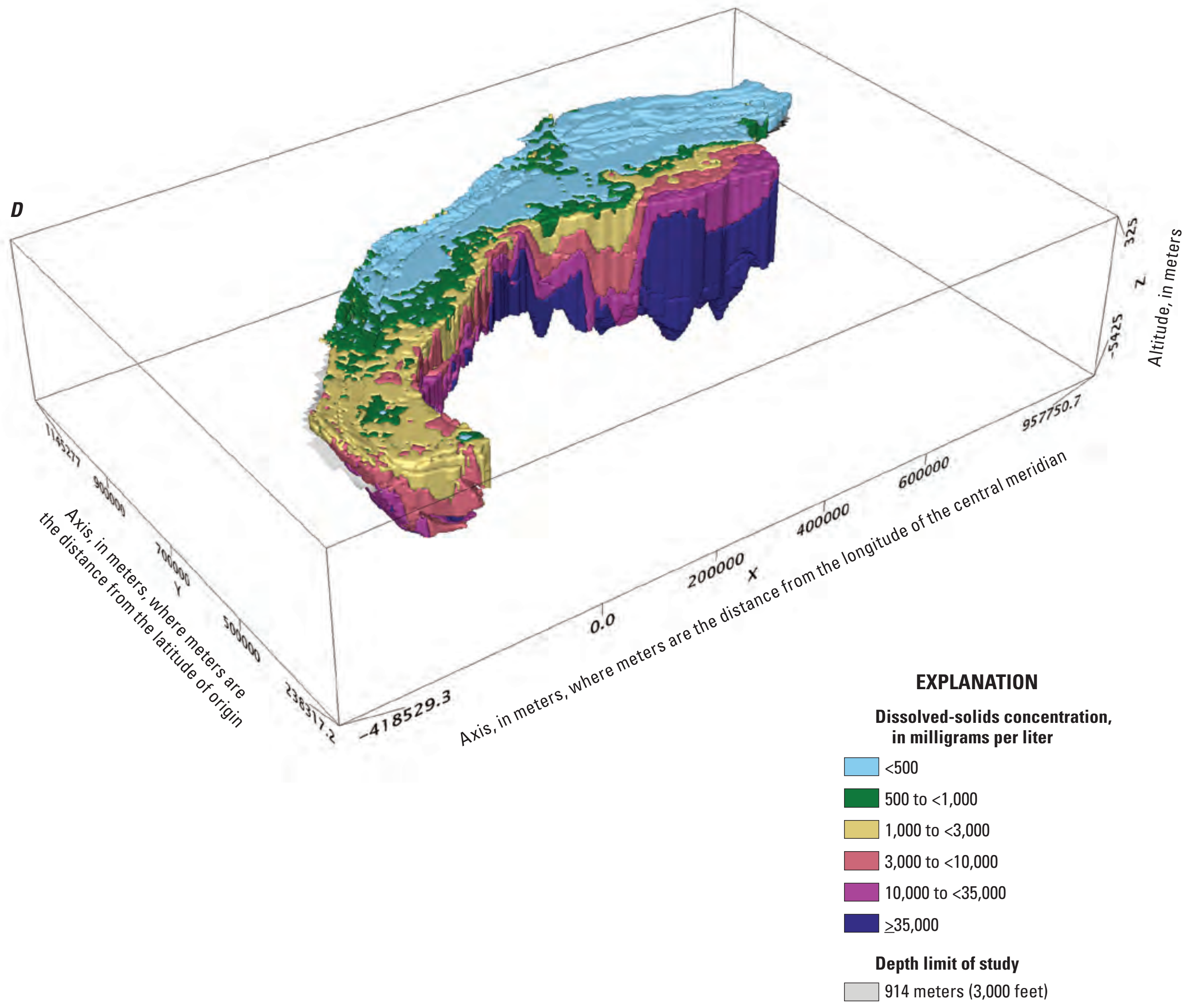

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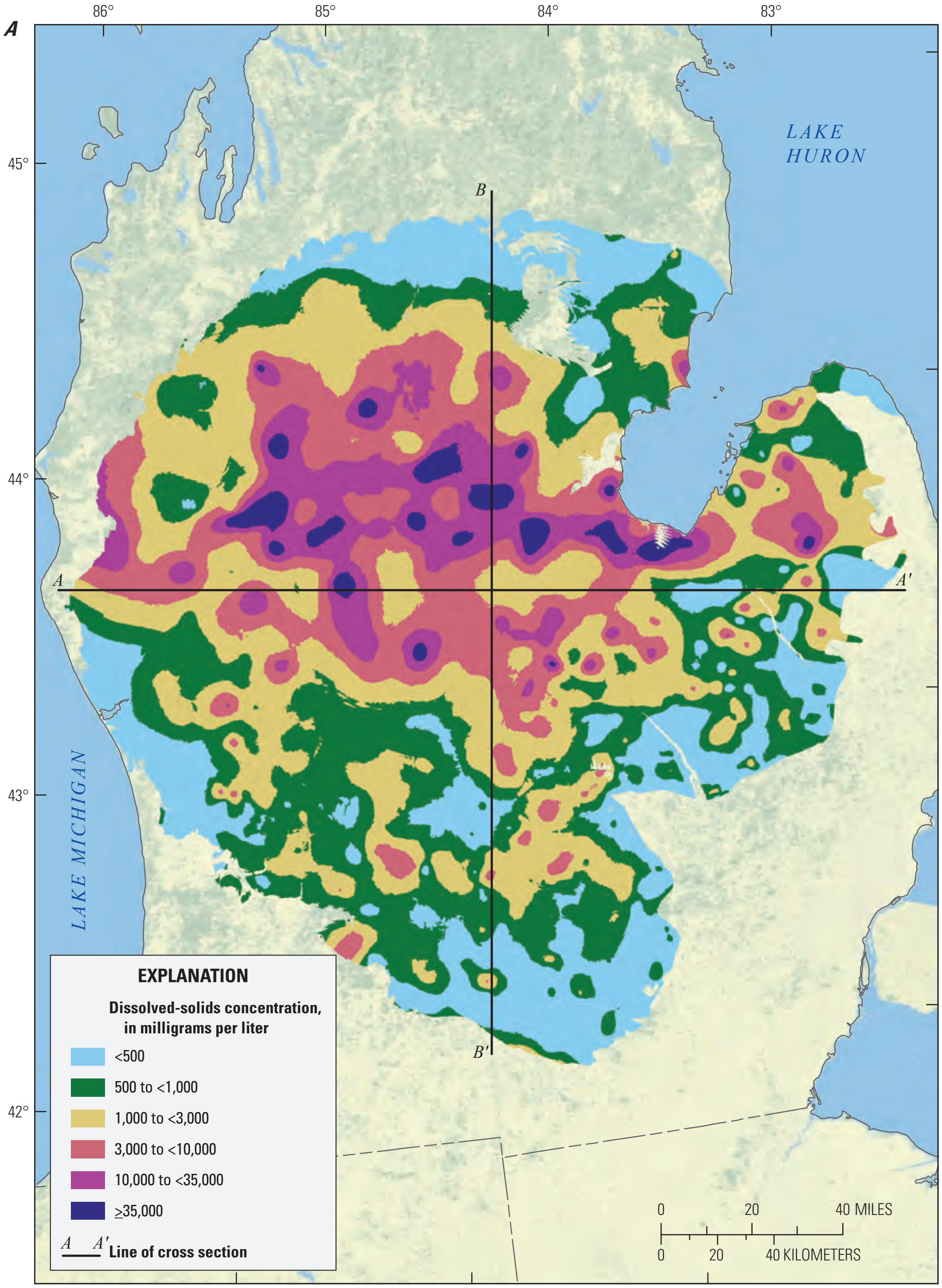

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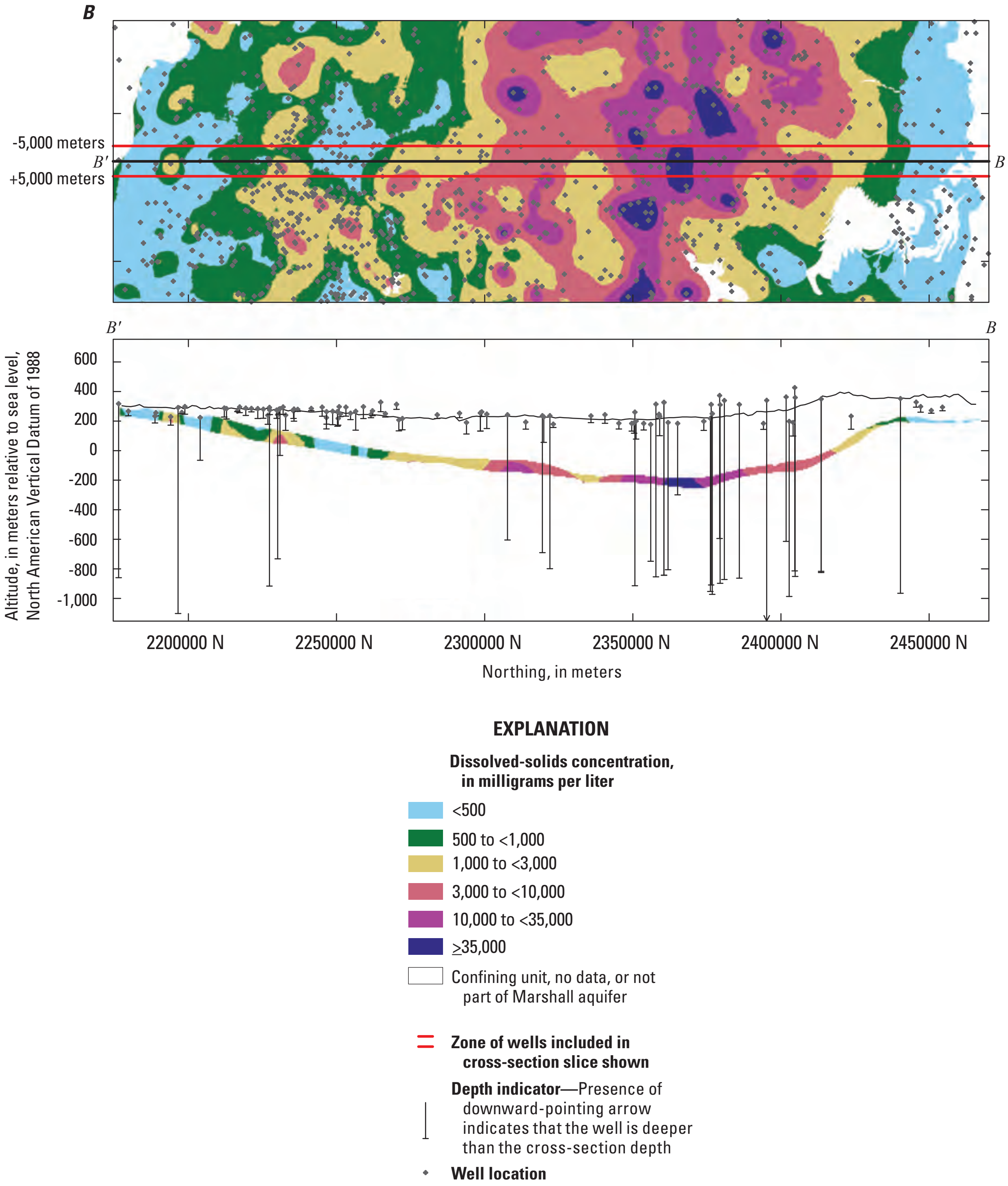
Figure 4–2. Three-dimensional dissolved-solids voxel model of the Marshall aquifer (fig. 27). Confidence in the interpolated voxel decreases with distance from sampled wells. *A*, map of the top model layer; *B*, map and cross section of the top model layer with wells near *B–B′*; *C*, map and cross section of the top model layer with wells near *A–A′*; *D*, image of three-dimensional isosurfaces (contours) created from the voxel model. An interactive version of the three-dimensional image is available at https://doi.org/10.3133/pp1833.



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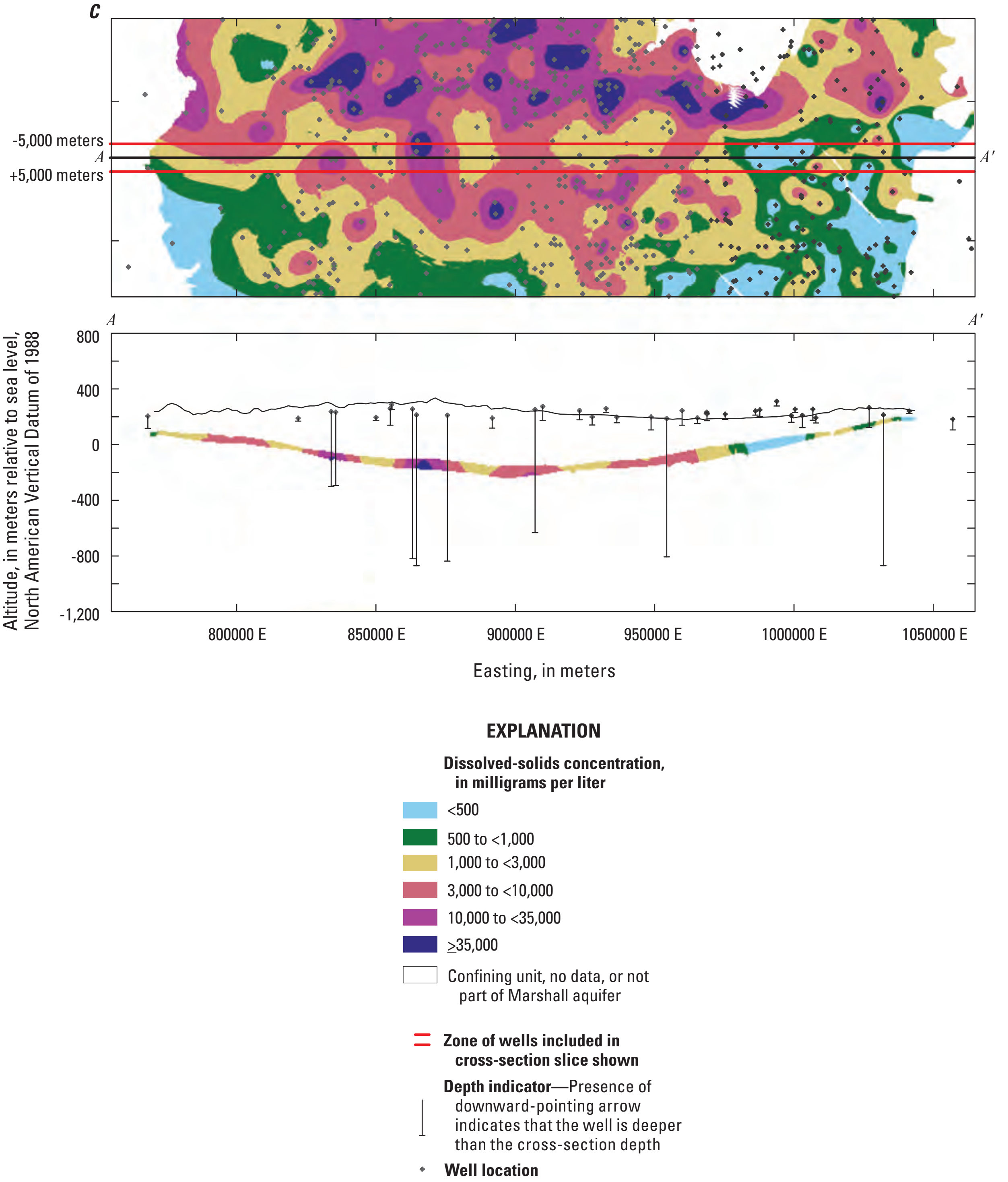

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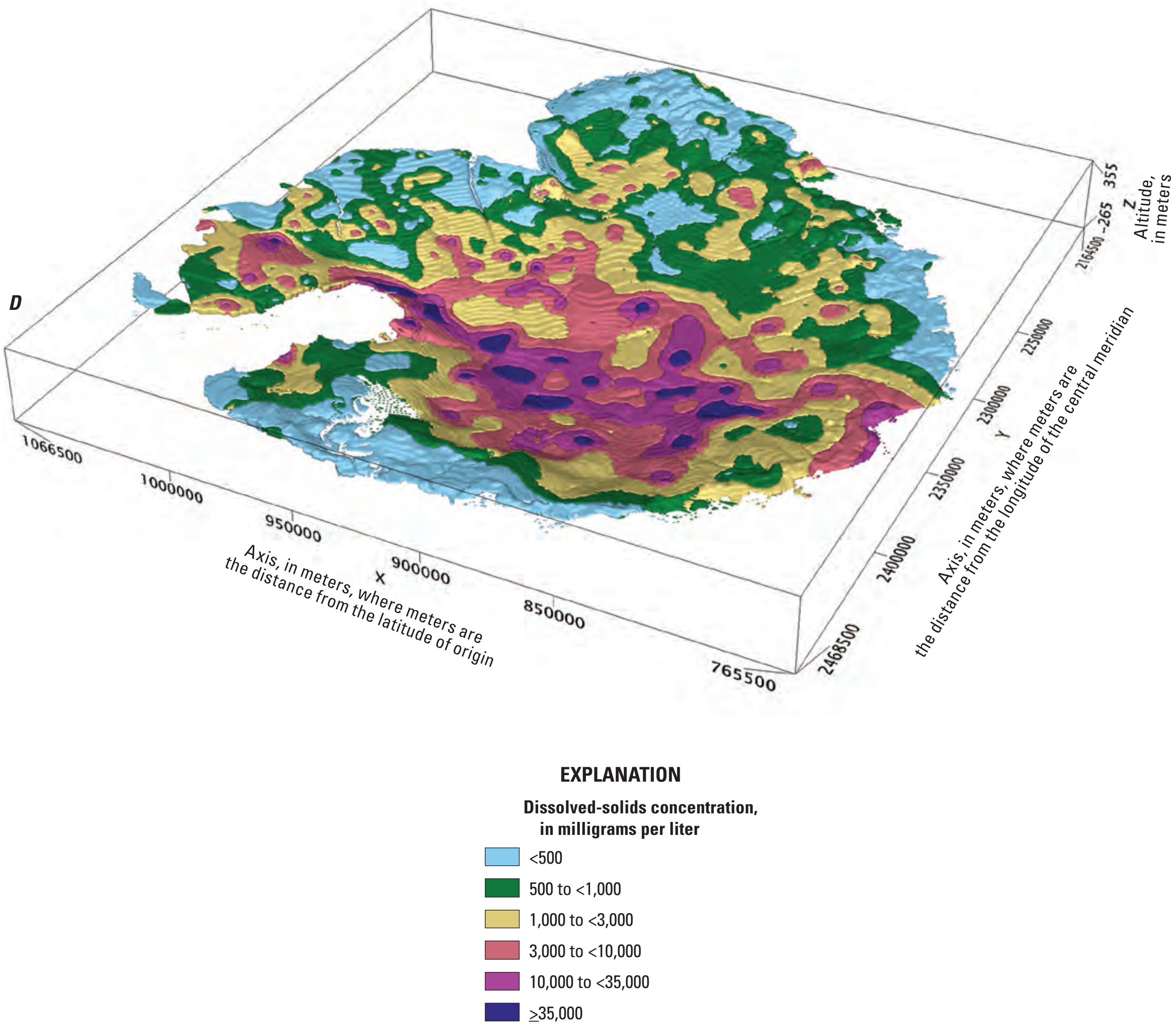

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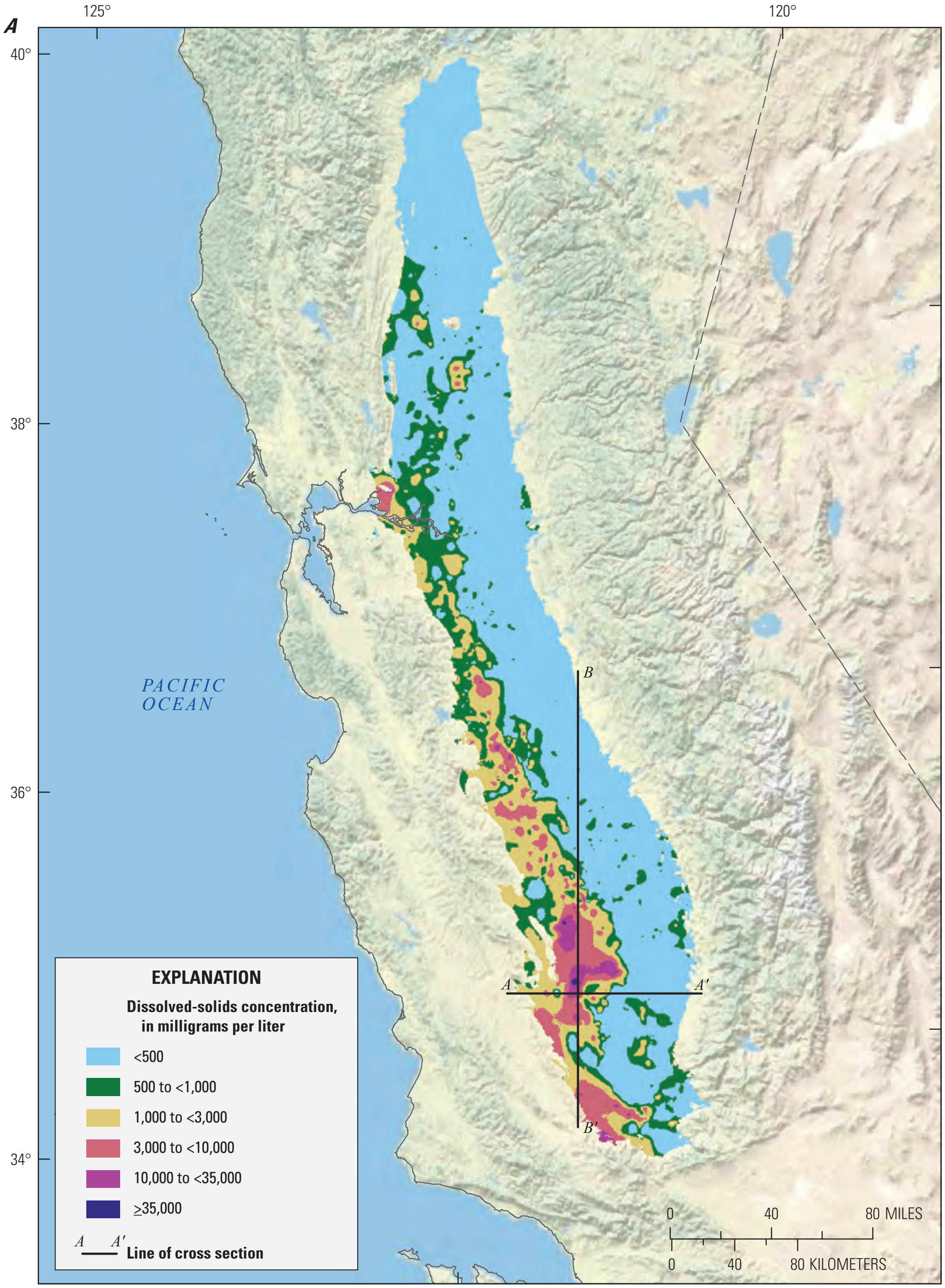

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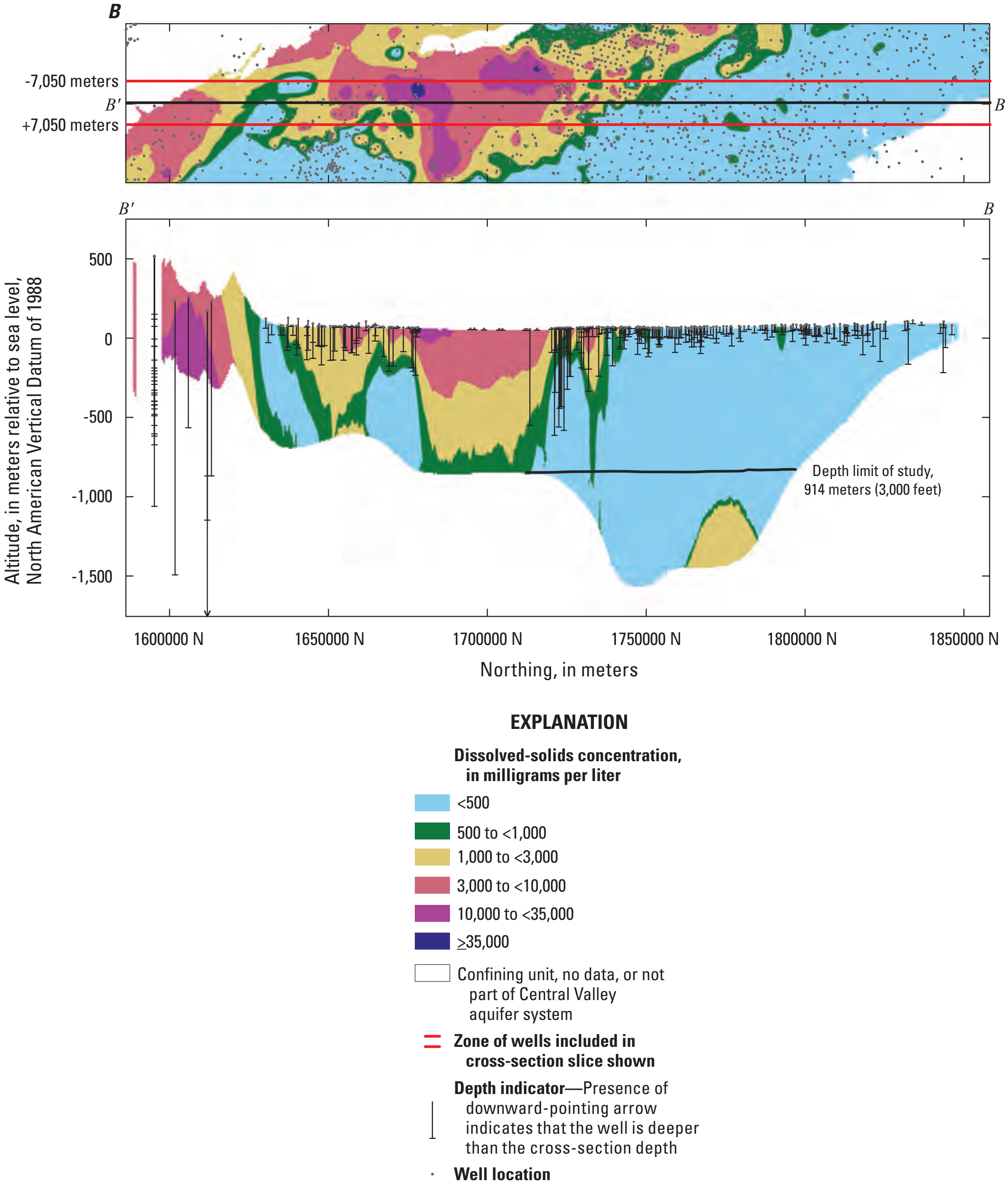
Figure 4–3. Three-dimensional dissolved-solids voxel model of the Central Valley aquifer system, California (fig. 35). Confidence in the interpolated voxel decreases with distance from sampled wells. *A*, map of the top model layer; *B*, map and cross section of the top model layer with wells near *B–B′*; *C*, map and cross section of the top model layer with wells near *A–A′*; *D*, image of three-dimensional isosurfaces (contours) created from the voxel model. An interactive version of the three-dimensional image is available at https://doi.org/10.3133/pp1833.



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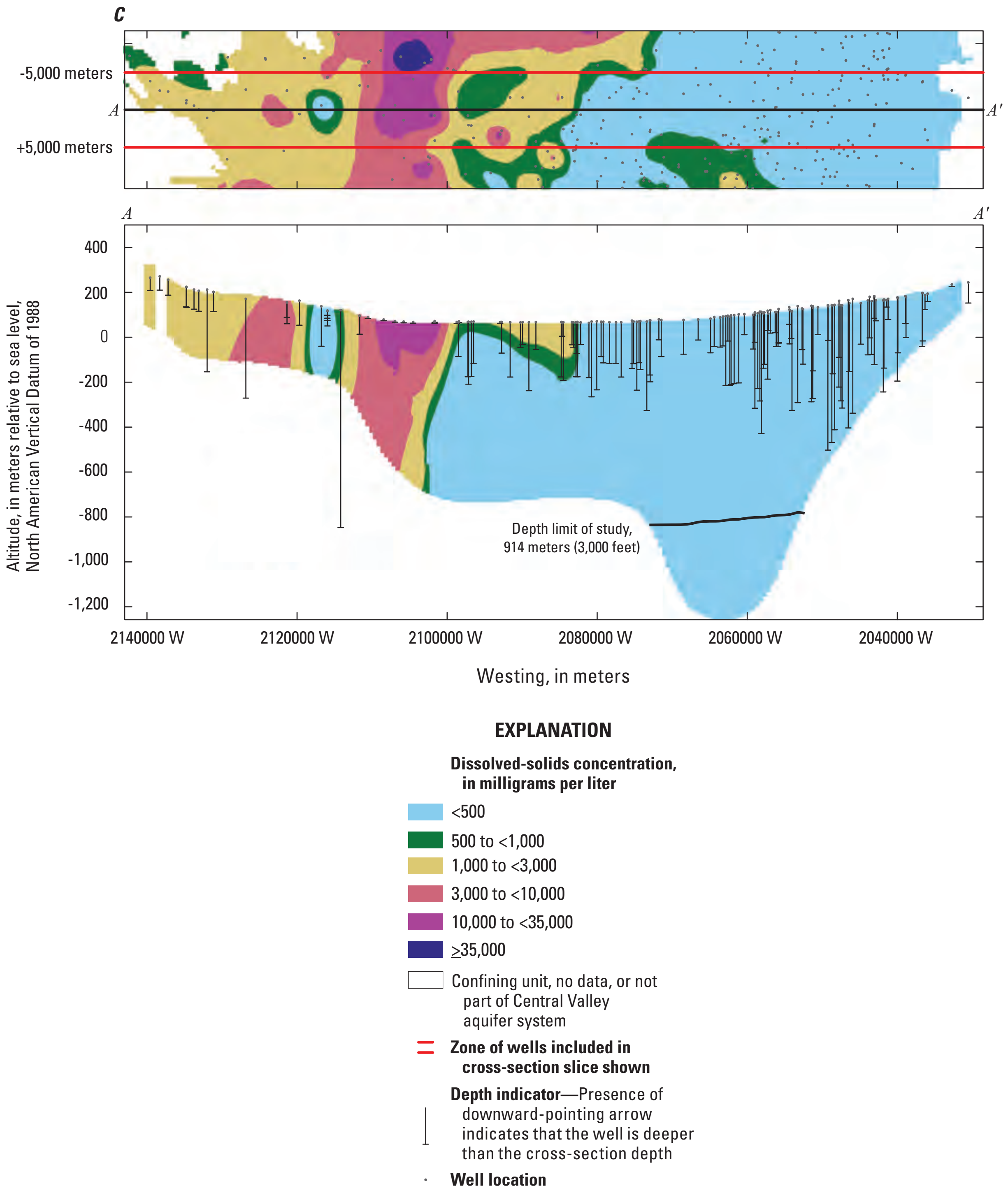

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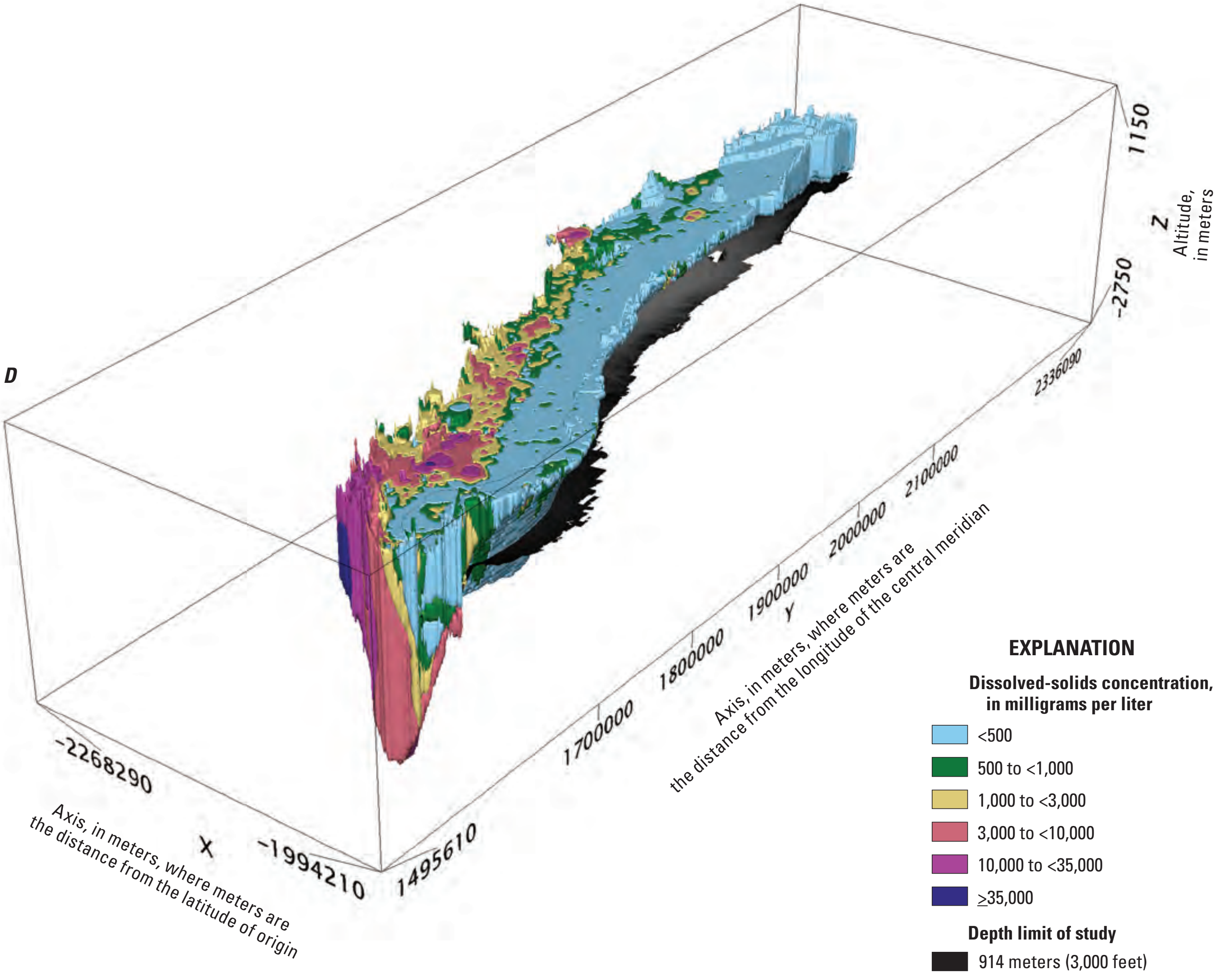

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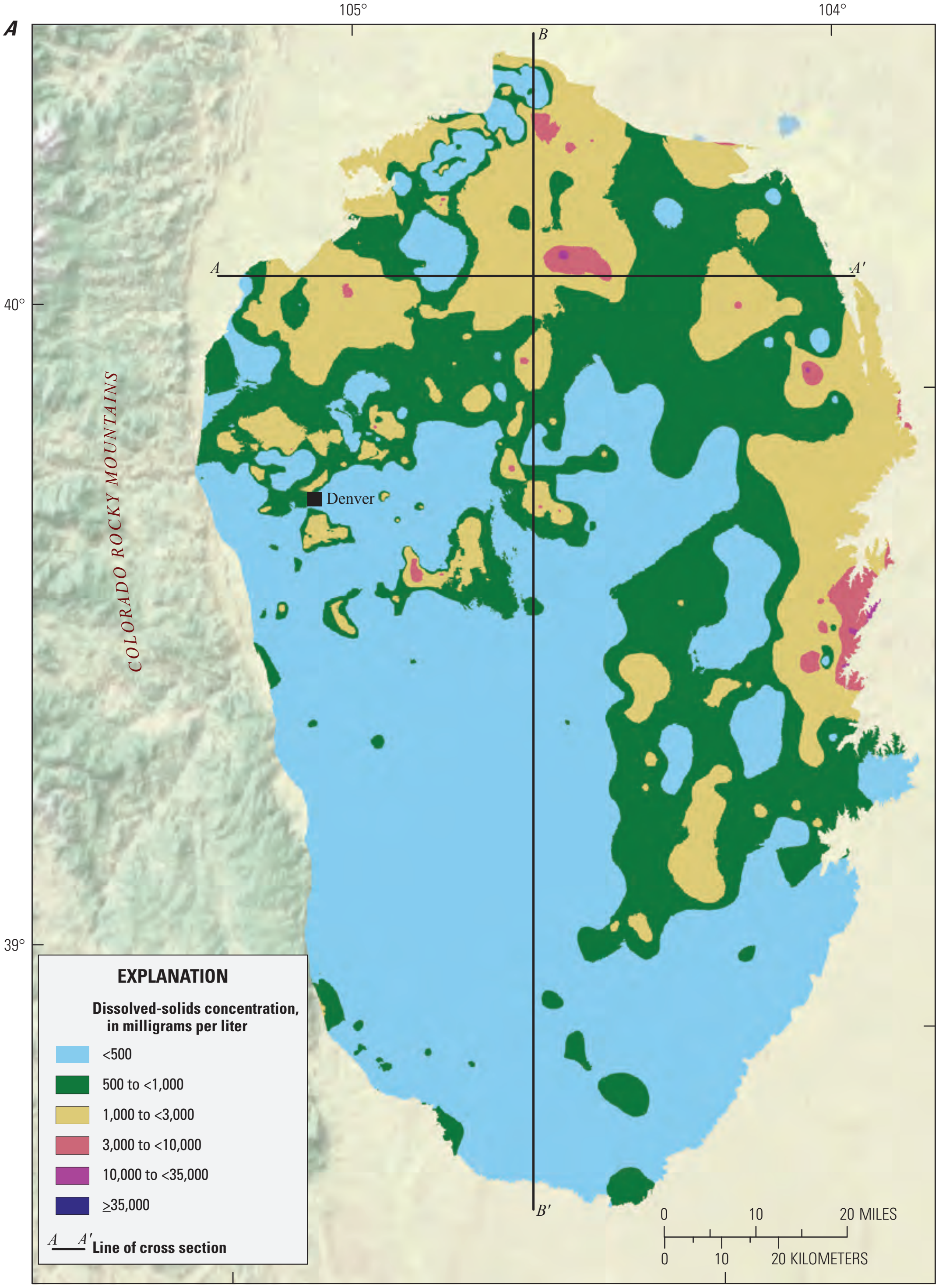

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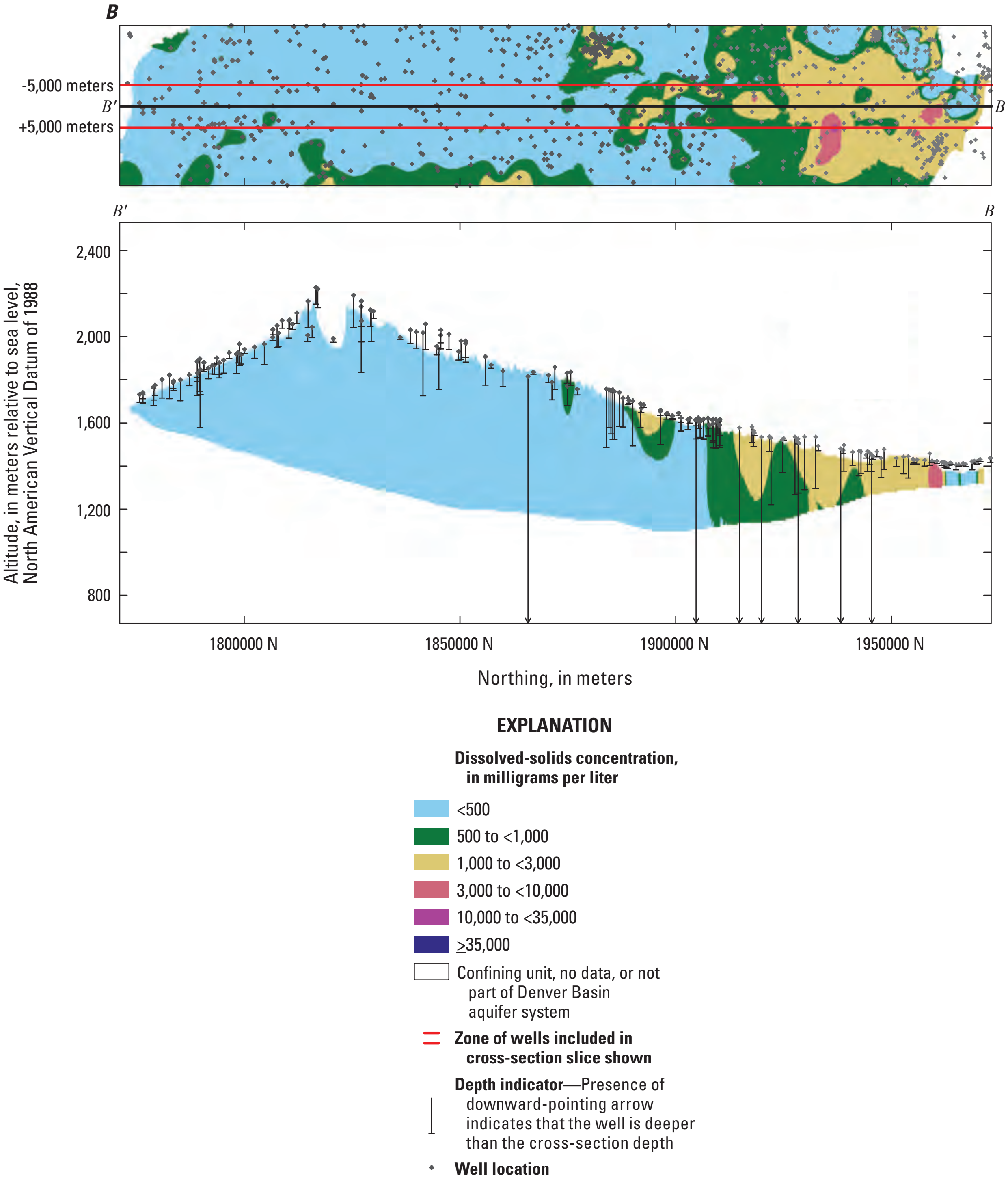
Figure 4–4. Three-dimensional dissolved-solids voxel model of the Denver Basin aquifer system, Colorado (fig. 41). Confidence in the interpolated voxel decreases with distance from sampled wells. *A*, map of the top model layer; *B*, map and cross section of the top model layer with wells near *B*–*B*′; *C*, map and cross section of the top model layer with wells near *A*–*A*′; *D*, image of three-dimensional isosurfaces (contours) created from the voxel model. An interactive version of the three-dimensional image is available at https://doi.org/10.3133/pp1833.



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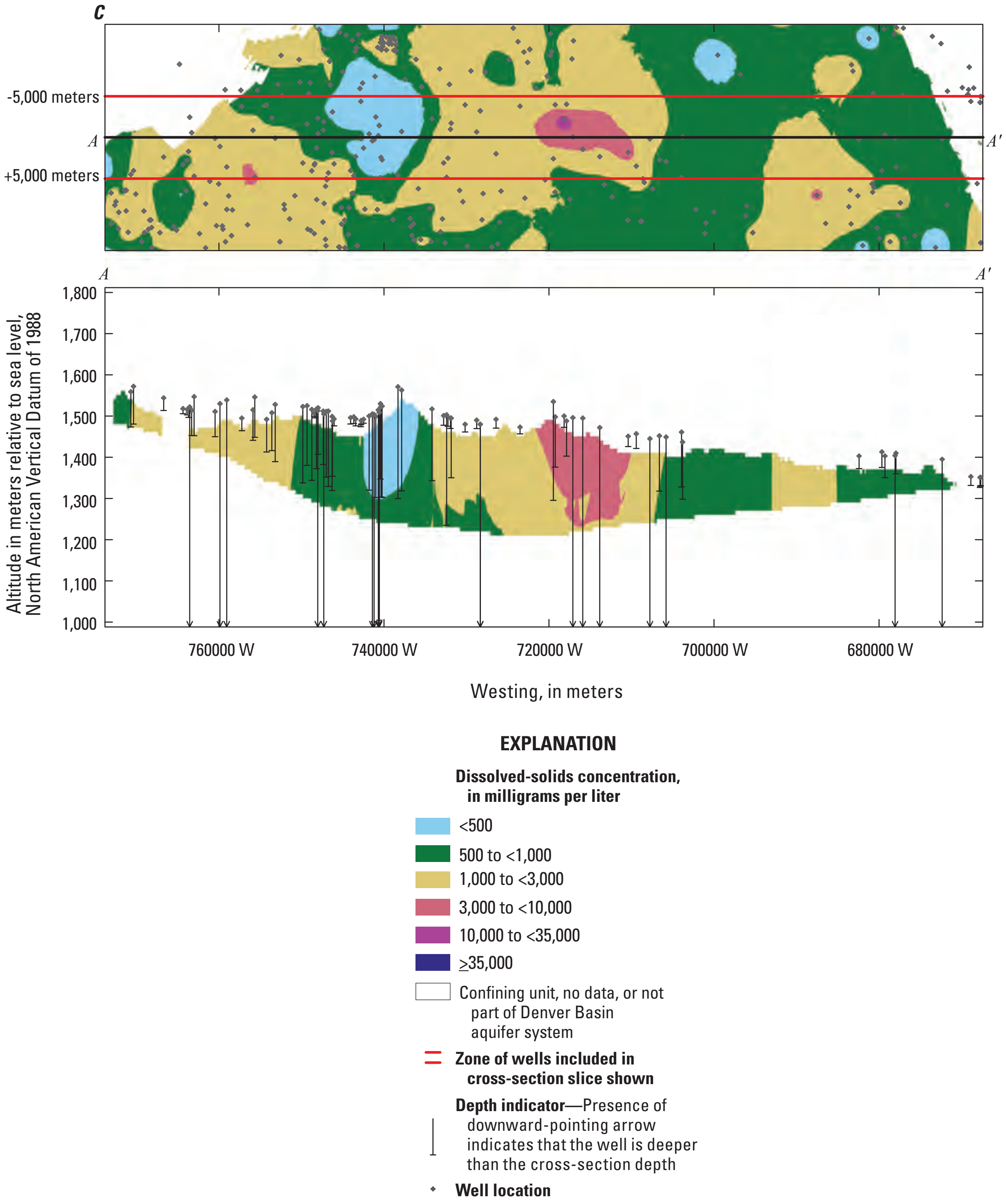

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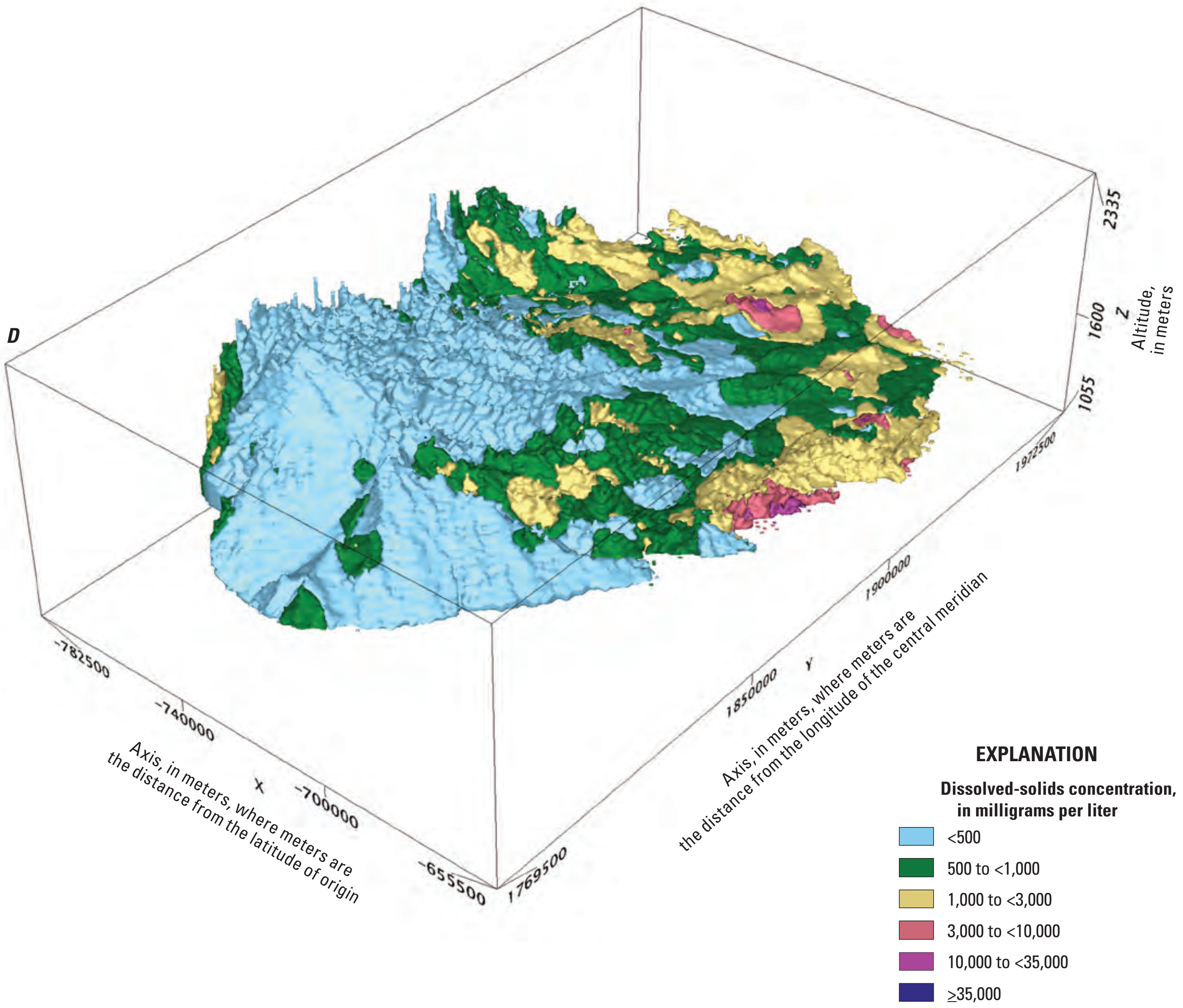

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