Introduction to Water-Quality Limitations on Beneficial Uses of Water

By Melinda L. Erickson, Anthony J. Tesoriero, Larry B. Barber, Christopher H. Conaway, Kenneth Belitz, and John K. Böhlke

Chapter A of

Knowledge Gaps and Opportunities for Understanding Water-Quality Processes Affecting Water Availability for Beneficial Uses

Edited by Anthony J. Tesoriero, Melinda L. Erickson, Christopher H. Conaway, Elizabeth J. Tomaszewski, and Christopher T. Green

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
billion gallons per day (Ggal/d)	43.81	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
liter per second (L/s)	0.2642	gallon per second (gal/s)
cubic kilometer per day (km^3/d)	264.2	billion gallon per day (Ggal/d)

Supplemental Information

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

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

Abbreviations

AMCL	Alternative maximum contaminant level
CEC	contaminants of emerging concern
EPA	U.S. Environmental Protection Agency
HBSL	health-based screening level
IWAA	Integrated Water Availability Assessment
IWS	Integrated Water Science
MCL	maximum contaminant level
PPCP	pharmaceutical and personal care product
TDS	total dissolved solid
UCMR	unregulated contaminant monitoring rule
USGS	U.S. Geological Survey
WMA	Water Resources Mission Area

Chemical Symbols

Al	aluminum
As	arsenic
Ba	barium
B	boron
Cd	cadmium
Ca	calcium
Cu	copper
Fe	iron
Pb	lead
Mg	magnesium
Mn	manganese
Hg	mercury
N	nitrogen
P	phosphorus
Se	selenium
Na	sodium
U	uranium
Zn	zinc

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Chapter A

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Purpose and Scope

An integrated water availability assessment for a region requires information about the demand for beneficial uses of water and an assessment of the water supply, which may be limited by the quality or quantity of water sources. Water quality may limit the beneficial use of a water source through natural processes, anthropogenic contamination, or environmental consequences of water use including treatment and return flow (fig. A1). For this report, "beneficial use" refers to human uses of a resource with emphasis on the benefits provided to individuals or to society, and "water use" refers to any human use of water resources. The predominant beneficial water use categories considered in this report are listed in table A1, including categories such as public supplies, domestic supplies, and irrigation. Water-quality considerations relevant to ecosystem services (benefits to people provided by ecosystems) are discussed separately in the companion Open-File Report "Knowledge Gaps and Opportunities in Water-Quality Drivers of Aquatic Ecosystem Health" (Harvey and others, 2024). In combination, these two reports address selected water-quality research topics that could contribute to improved assessments and predictions of water availability for a broad spectrum of human and ecosystem needs.

This report describes some of the scientific gaps that limit our ability to predict water-quality effects on water availability for beneficial uses across the United States. The presentation is organized into chapters A through E, which focus on A, introduction, B, salinity, C, geogenic constituents, D, contaminants of emerging concern, and E, nitrogen (N). Each chapter contains a selection of scientific gaps, approaches, and outcomes that could help guide research efforts by the U.S. Geological Survey (USGS) Water Resources Mission Area (WMA, https://www.usgs.gov/mission-areas/water-resources), other mission areas, and other national research efforts. It is emphasized that these chapters are not comprehensive, and new issues are likely to emerge; thus, it will be important to maintain broad-based expertise and flexibility to comprehensively address the long-term water-quality issues facing the Nation's water resources.

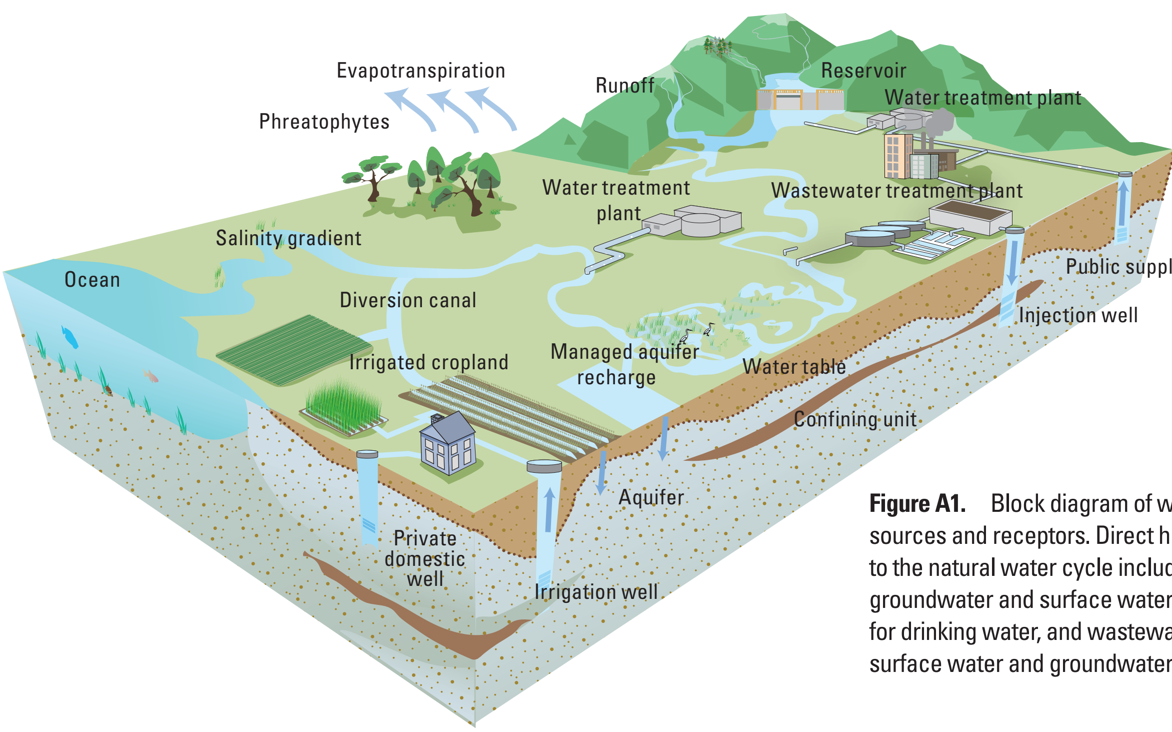


Figure A1. Block diagram of water cycle with sources and receptors. Direct human alterations to the natural water cycle include irrigation from groundwater and surface water, water withdrawal for drinking water, and wastewater inflow to surface water and groundwater.

Table A1. Common inflow water-quality limitations and outflow degradation for primary beneficial use categories in the United States.

[TDS, total dissolved solids; PPCP, pharmaceutical and personal care product.]

Use category	Most common inflow water-quality limitations	Outflow water-quality degradation
Public Supply	Trace elements, radionuclides, TDS, nitrate, microbes, hydrocarbons	Nutrients, biogenic[1], PPCPs, trace elements, microbes
Domestic	Trace elements, radionuclides, TDS, nitrate, microbes	Nutrients, biogenic, PPCPs
Irrigation	Crop specific trace elements, boron, TDS	Nutrients, pesticides, adjuvants[2], geogenic
Livestock	Trace elements, nitrate, TDS, pH, alkalinity	Nutrients, biogenic, pharmaceutical, food additives
Aquaculture	Temperature, mercury, trace elements, ammonium	Nutrients, biogenic, biocides, antibiotics, growth promoters
Industrial	Widely variable depending on the industrial process	Trace elements, acids and bases, solvents, starting materials, waste materials, byproducts, products
Thermoelectric	pH, hardness, alkalinity, iron, hydrogen sulfide, sulfate, silica, and TDS	Temperature, complexing agents, scrubber wash down
Mining	Minimal	Metals, hydrocarbons, acidity
Oil and gas development	Hardness and concentrations of barium, boron, iron, sulfate, and TDS	TDS, hydrocarbons, naturally occurring radioactive material, metals

[1]Such as endocrine disrupting compounds 17β-estradiol and estrone (see chapter D in this report "The Influence of Contaminants of Emerging Concern on Beneficial Uses of Water").

[2]Such as additives to enhance pesticide activity.

Beneficial Water Uses and Water-Quality Requirements

In 2015, the cumulative water use for the United States was approximately 322 billion gallons per day (Ggal/d), with 74 percent coming from surface water sources (Dieter and others, 2018). The largest withdrawals were used for cooling of thermoelectric power plants (133 Ggal/d) and irrigation of agricultural crops (118 Ggal/d), followed by golf courses, parks, and other landscapes (Dieter and others, 2018). The pie chart in fig. A2 shows the percentage of United States water use by category. Consumptive uses prevent immediate return of some or all of the intake water, for example, with evapotranspiration from irrigation use, incorporation of water into the products in industrial use, and drinking by humans and livestock. Water that is not consumptively used (for example, thermoelectric power plant cooling) is returned to the hydrologic environment via direct or indirect discharge to groundwater or surface water, with potential subsequent effects on downgradient water quality.

Each beneficial use has its own specific water-quality requirements, as illustrated in table A1. As a result, the distribution and relative magnitude of various water-quality constituents will affect water availability in different ways, depending on intended use and treatment options (Pick, 2011; McMahon and others, 2016; U.S. Environmental Protection Agency [EPA], 2018). For example, drinking-water use requires considering a large list of geogenic (geologic-sourced) and anthropogenic (human-sourced) constituents, which may be toxic, interfere with treatment efficacy, or affect distribution systems (https://www.epa.gov/awma/factsheets-water-quality-parameters). Water use for irrigation requires considering boron (B), iron (Fe), and total dissolved solids (TDS) concentrations as well as the sodium (Na) abundance relative to magnesium (Mg) and calcium (Ca) (Wilcox, 1955). Water use for livestock requires considering the pH, alkalinity, and concentrations of sulfate (SO_4^{2-}) and TDS (https://www.ndsu.edu/agriculture/extension/publications/livestock-water-quality). Thermoelectric cooling water requires considering pH, hardness (Mg plus Ca concentration), and concentrations of alkalinity, Fe, hydrogen sulfide (H_2S), SO_4^{2-}, silica (SiO_2), and TDS (Pan and others, 2018). Hardness and concentrations of barium (Ba), B, Fe, SO_4^{2-}, and TDS may limit the effectiveness of water used for oil and gas development (McMahon and others, 2016; see chapter C in this report "Geogenic Water-Quality Effects on Beneficial Uses of Water").

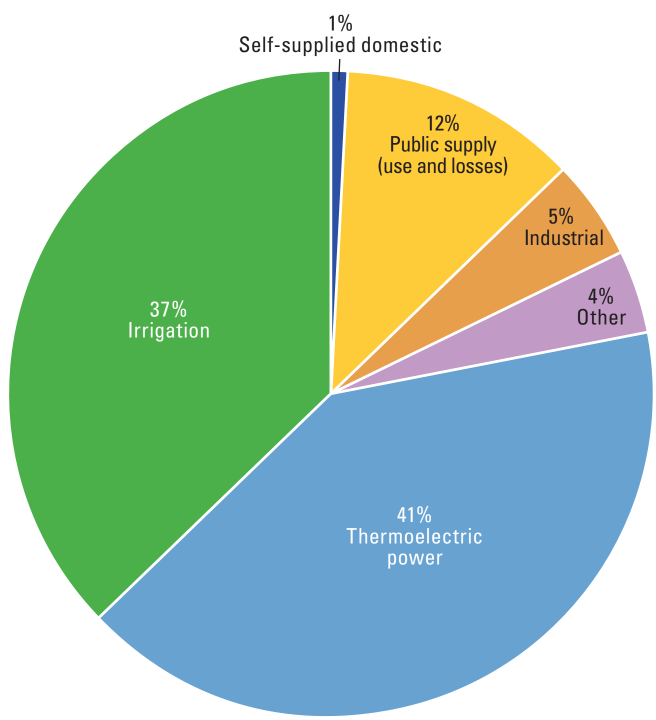


Figure A2. Pie chart of estimated percentage of United States water use per year by water-use category, based upon 2015 water use data obtained from Dieter and others (2018). %, percent.

Threats to Beneficial Uses of Water

Water availability depends on both water quantity and water quality (Evenson and others, 2013). Water availability limitations due to water quality can be caused by high concentrations of one or more categories of constituents. The following chapters of this report focus on salinity, geogenic constituents, contaminants of emerging concern (CEC), and nitrogen (N). These constituents are of concern for water quality because of their widespread sources, chemical properties and (or) toxicological effects. Salinity and salinization (see chapter B "Addressing Salinity Challenges to the Beneficial Uses of Water") have long been leading water-quality issues in the United States and globally (Vengosh, 2014), and urban-influenced watersheds have a multi-decadal trend of increasing salinity on a continental scale (Kaushal and others, 2018; Stets and others, 2020). Elevated concentrations of geogenic constituents (see chapter C "Geogenic Water-Quality Effects on Beneficial Uses of Water"), which commonly occur naturally, are among the most prevalent water contaminants in the United States and globally (DeSimone, 2009; DeSimone and others, 2015; Hug and others, 2020; Shaji and others, 2021). Municipal wastewater, industrial products and waste, and agricultural practices and waste are primary sources of CECs affecting freshwater environments (see chapter D "The Influence of Contaminants of Emerging Concern on Beneficial Uses of Water"). The CEC effects on beneficial uses are often more difficult to quantify than other constituent effects because of the uncertainty in their toxicity and acceptable threshold concentrations. Nitrate concentrations in groundwater and streams (see chapter E "Improving Predictions of Nitrogen Effects on Beneficial Uses of Water") are typically greater in agricultural areas than in urban or undeveloped settings (Burow and others, 2010; Dubrovsky and others, 2010) and are a major global concern for both direct and indirect effects on water quality and use (Böhlke, 2002; Bijay-Singh and Craswell, 2021).

All of these constituents are relevant to public and domestic drinking water supplies, which are two of the primary beneficial use categories. Trace elements, radionuclides, and nitrate are the constituents most commonly found at high concentration exceeding a human health benchmark in groundwater sources supplying drinking water (DeSimone, 2009; DeSimone and others, 2015) (table A2). Arsenic (As) and nitrate are among the constituents most likely to exceed EPA maximum contaminant levels (MCLs) in public water supplies (Allaire and others, 2018). Both surface water (fig. A3*A*) and groundwater (fig. A3*B*) are used for public water supply. In substantial portions of the country, domestic well water is the dominant or only potable drinking water source available to an estimated 42.5 million users (fig. A3*C*) (Dieter and others, 2018). In many areas, a combination of both water sources is used for public supply (fig. A3*D*).

Table A2. Exceedances of drinking-water thresholds for selected constituents in public and domestic supply wells in the conterminous United States.

[%, percent; µg/L, microgram per liter; HBSL, health-based screening level (Norman and others, 2018); UCMR, unregulated contaminant monitoring rule (U.S. Environmental Protection Agency [EPA], 2016); pCi/L, picocuries per liter; MCL, maximum contaminant level (EPA, 2018); NA, not available; AMCL, alternative maximum contaminant level (EPA, 2018); mg/L-N, milligrams per liter as nitrogen.]

Constituent	Public supply wells[1] (% high[2])	Domestic supply wells[3] (% high)	National/ Regional	Human health benchmark
Manganese	5	5	National	300 µg/L noncancer HBSL, UCMR
Arsenic	5	7	National	10 µg/L MCL
Lead-210/Polonium-210	4/1	2/5	National	NA (direct measure)[4] 15 pCi/L alpha radioactivity MCL (^{210}Po) 50 pCi/L beta radioactivity MCL (^{210}Pb)
Radium-226+Radium-228	3	2	Regional	5 pCi/L MCL
Radon-222	2	4	Regional	4,000 pCi/L (proposed AMCL)
Strontium	2	7	Regional	4,000 µg/L noncancer HBSL, UCMR
Iron	1	NA	National	4,000 µg/L noncancer HBSL
Nitrate	1	4	Regional	10 mg/L-N MCL
Uranium	1	2	Regional	30 µg/L MCL
Molybdenum	1	0.6	Regional	30 µg/L noncancer HBSL, UCMR
Cobalt	1	NA	Regional	2 µg/L noncancer HBSL, UCMR
Fluoride	1	1	Regional	4,000 µg/L MCL
Lithium	43	NA	National	10 µg/L noncancer HBSL
Lithium	4	NA	National	60 µg/L drinking water only threshold[5]

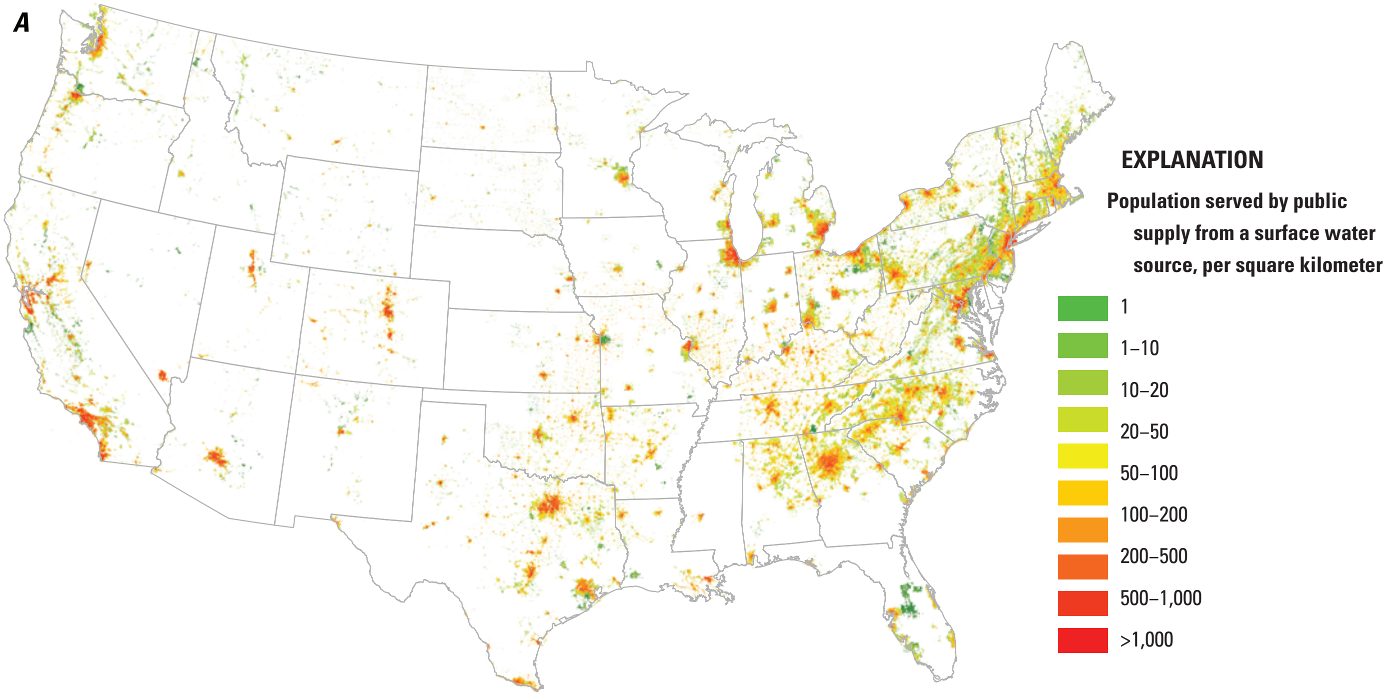
[1]Principal aquifers; public water system wells and equal-area assessment (Belitz and others, 2010, 2015, 2022), data in the U.S. Geological Survey (USGS) National Water Information System (USGS, 2021a).

[2]High-concentration exceeds a benchmark.

[3]Principal aquifers; domestic wells in networks, not equal area (DeSimone, 2009; DeSimone and others, 2015).

[4]Gross alpha and gross beta radioactivity measured.

[5]Assumes that 100% of exposure to lithium comes from drinking water (Lindsey and others, 2021).



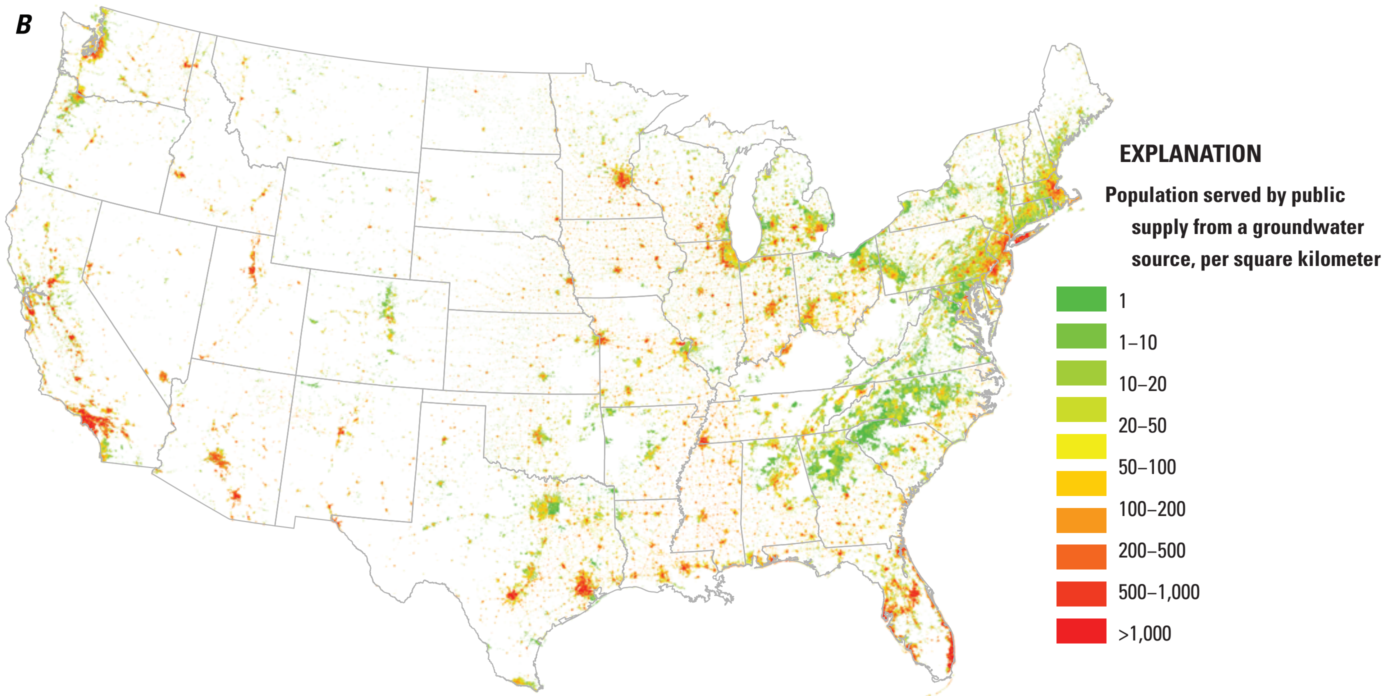
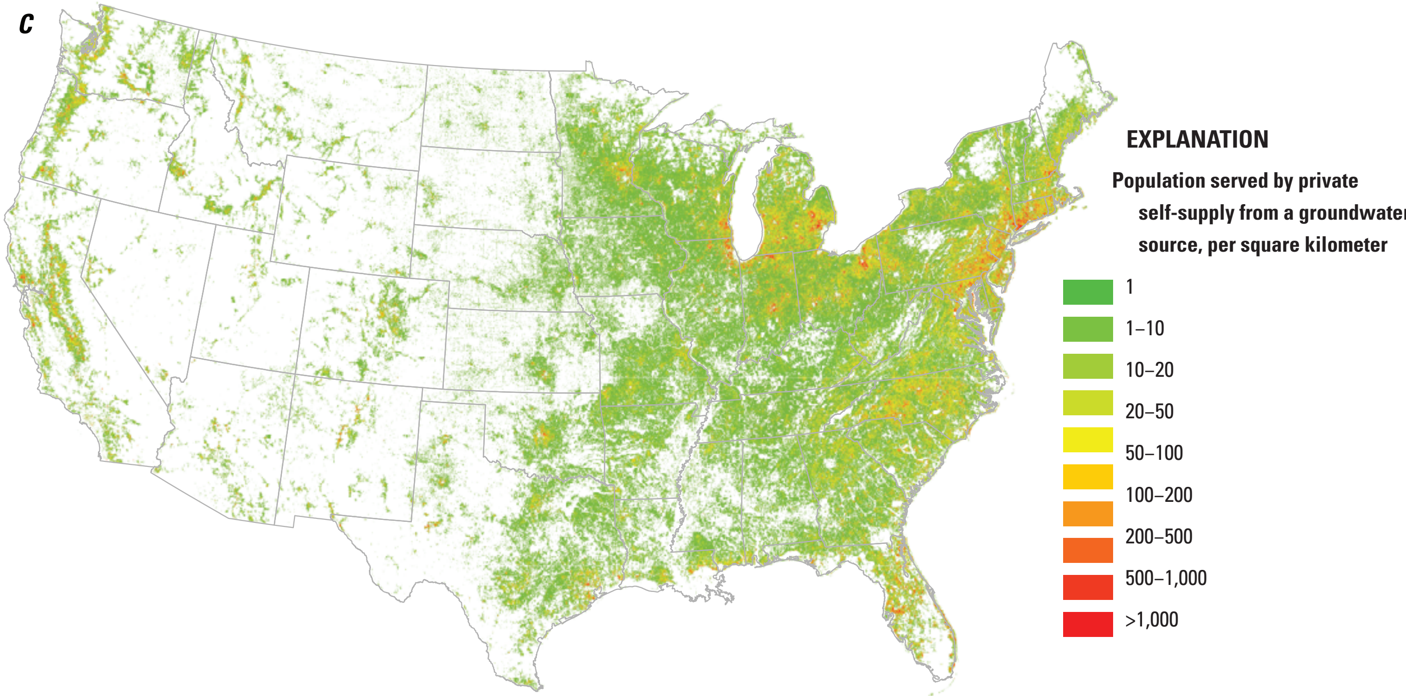


Figure A3. Maps of distribution of surface water and groundwater as sources of drinking water in the conterminous United States. *A*, Population served by a public supply from a surface-water source. *B*, Population served by a public supply from a groundwater source. *C*, Population served by a private (domestic) self-supplied groundwater source. *D*, Source of public supply: groundwater only, surface water only, or a mix of the two. Data from Johnson and others (2021).



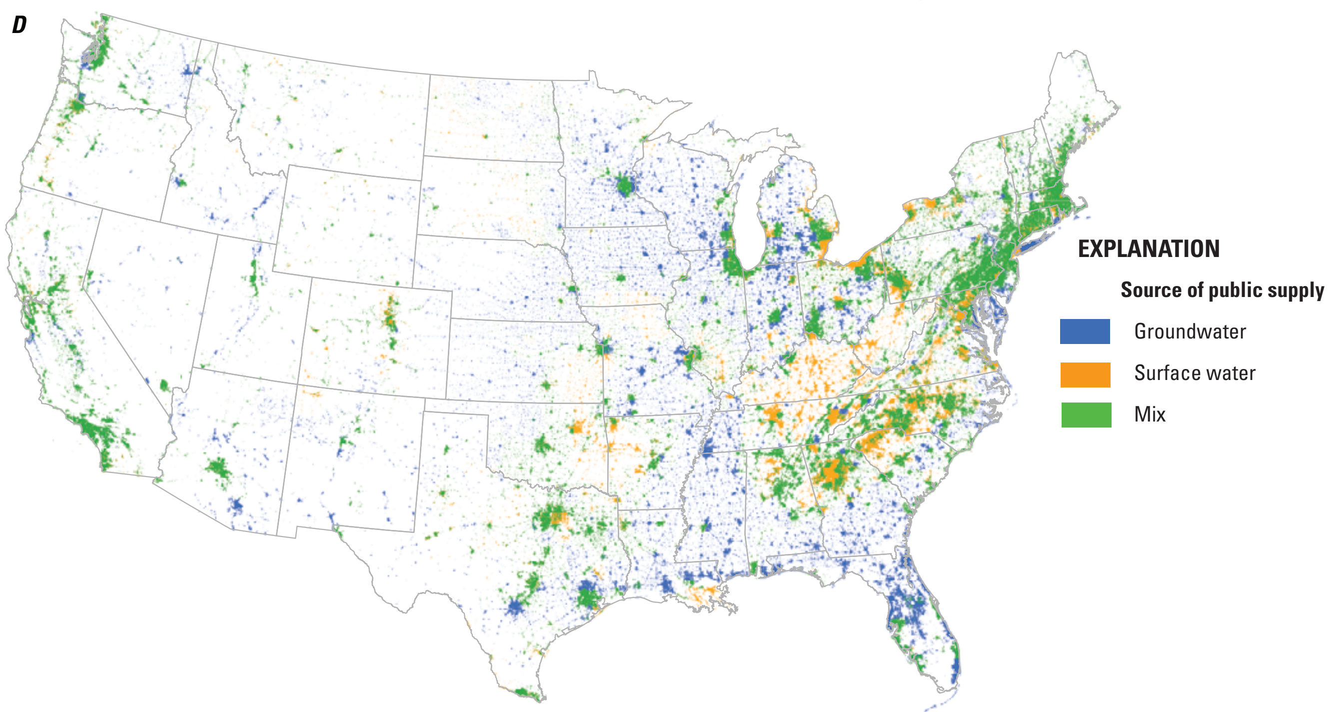


Figure A3.—Continued

There are many examples of water-quality concerns relating to water availability in the United States. For example, within the context of the USGS's Integrated Water Availability Assessment (IWAA) projects (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-availability-assessments-iwaas), selected drainage basins are being targeted for integrated water science studies to improve understanding of groundwater and surface water availability. USGS Integrated Water Science (IWS) basins are medium-sized watersheds (10,000–20,000 square miles [mi^2]) that represent a wide range of environmental, hydrologic, and landscape settings and human stressors of water resources. Some water-quality issues related to the first three of those study basins are described below.

In the Delaware River Basin and underlying aquifers, salinity is a primary concern. Salinity affects water quality and availability (see chapter B) where, for example, (1) the marine salt wedge traveling up the Delaware River enters public surface water supply intakes at low flow, (2) sea level rise leads to saltwater intrusion in public water supply and domestic wells, and (3) road salt contaminates fresh-water systems (Meyer and others, 2020; USGS, 2021b). Geogenic metals (Fe, manganese [Mn], aluminum [Al]) and radionuclides radon-222 [^{222}Rn] and polonium-210 [^{210}Po]) are also a concern in groundwater in this basin (Scott and others, 2019; Szabo and others, 2020).

In the streams and aquifers of the Upper Colorado River Basin, selenium (Se), mercury (Hg), uranium (U), ^{222}Rn, and geogenic nitrate limit water availability (Spahr and others, 2000; Conaway and others, 2005; Naftz and others, 2008; Vengosh, 2014). Salinity also poses a major challenge to water use, with estimated costs of hundreds of millions of dollars per year due to decreased crop yields, increased water treatment, degraded river health, clogged pipes, and damaged equipment (Vengosh, 2014). Mining waste contamination threatens water quality, particularly from increased acidity due to the weathering of exposed sulfide minerals, which mobilizes metals such as As, lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu).

The Illinois River Basin water resources are challenged by an overabundance of N and phosphorus (P) and harmful algal blooms that can result from excessive nutrient loads from urban and agricultural sources (Leland and Porter, 2000; Panno and others, 2008). Land-application of dredge sediment from the Chicago area (upper basin) to agricultural areas (lower basin) is redistributing metals and industrial chemicals that may contaminate water resources (Warner and others, 2003; Warner and Ayotte, 2015; Erickson and others, 2019; Szabo and others, 2020). High concentrations of nitrate, As, and radionuclides in the major aquifers in this basin (Mahomet, Glasford, glacial, and Cambrian-Ordovician system) also limit water availability (Groschen and others, 2001).

To assess, predict, and manage long-term risks to water availability in these, and other IWS basins, it is essential to understand sources, movement, and transformations of both natural and anthropogenic water-quality constituents throughout the combined natural and anthropogenic water cycle.

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