The Quality of Our Nation's Waters

Water Quality in the Glacial Aquifer System, Northern United States, 1993–2009

National Water-Quality Assessment Program

Circular 1352

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

Cover. Photographs by Kelly L. Warner, USGS, unless noted otherwise.

Background: Glacial deposits.

Foreground, left: City of Chicago (James Duncker, USGS); middle: corn field; right: little girl drinking water.

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By Kelly L. Warner and Joseph D. Ayotte

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SALLY JEWELL, Secretary

U.S. Geological Survey
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NAWQA

National Water-Quality Assessment Program

> *"The contaminant data and predictive models from the NAWQA Program for private and municipal water systems were essential for filling in the gaps in our understanding of the geography and timing of contaminant concentrations. Without this type of information, it's difficult to interpret what locations and populations are at risk from hazards such as arsenic and nitrate in drinking water, making it challenging for health scientists to promote risk reduction activities. A focus on continued NAWQA monitoring will be important as changes in population, land use, and climate affect our water resources."*
>
> —Matt Cahillane, New Hampshire Department of Health and Human Services
> Environmental Public Health Tracking Program

Photograph by Kelly L. Warner, USGS

Foreword

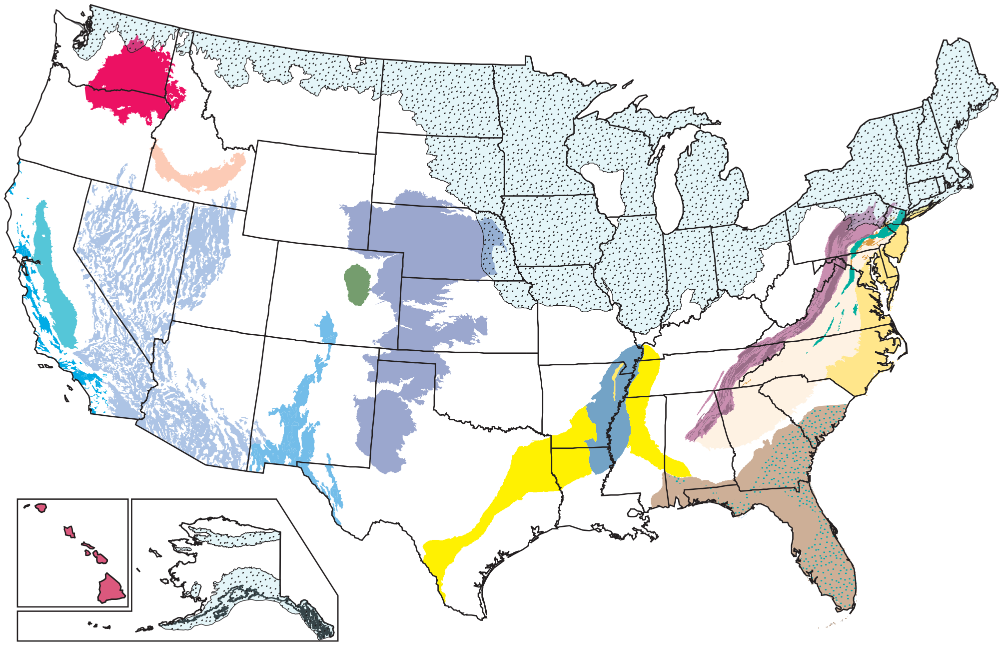
The United States has made major investments in assessing, managing, regulating, and conserving natural resources, such as water and a variety of ecosystems. Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources data and information to develop effective, science-based policies. Effective management of water resources also brings more certainty and efficiency to important economic sectors. Taken together, these actions lead to immediate and long-term economic, social, and environmental benefits that make a difference to the lives of millions of people (*http://water.usgs.gov/nawqa/applications/*).

Two decades ago, Congress established the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program to meet this need. Since then NAWQA has served as a primary source of nationally consistent information on the quality of the Nation's streams and groundwater, on ways in which water quality changes over time, and on the natural features and human activities affecting the quality of streams and groundwater. Objective and reliable data, systematic scientific studies, and models are used to characterize where, when, and why the Nation's water quality is degraded—and what can be done to improve and protect the water for human and ecosystem needs. This information is critical to our future because the Nation faces an increasingly complex and growing need for clean water to support people, economic growth, and healthy ecosystems. For example, NAWQA findings for public-supply wells, which provide water to about 105 million people, showed that 22 percent of source-water samples contained at least one contaminant at levels of potential health concern. Similarly, 23 percent of samples from domestic (or privately owned) wells, which supply untreated water to an additional 43 million people, also had contaminant levels of potential concern.

This report is one of a collection of publications that describe water-quality conditions in selected Principal Aquifers of the United States (*http://water.usgs.gov/nawqa/studies/praq/*). The collection is part of the series "The Quality of Our Nation's Waters," which describes major findings of the NAWQA Program on water-quality issues of regional and national concern and which provides science-based information for assessing and managing the quality of our groundwater resources. Other reports in this series focus on occurrence and distribution of nutrients, pesticides, and volatile organic compounds in streams and groundwater, the effects of contaminants and streamflow alteration on the condition of aquatic communities in streams, and the quality of untreated water from private domestic and public-supply wells. Each report builds toward a more comprehensive understanding of the quality of regional and national water resources (*http://water.usgs.gov/nawqa/nawqa_sumr.html*). All NAWQA reports are available online at *http://water.usgs.gov/nawqa/bib/*.

The information in this series primarily is intended for those interested or involved in resource management and protection, conservation, regulation, and policymaking at regional and national levels. In addition, the information should be of interest to those at a local level who wish to know more about the general quality of streams and groundwater in areas near where they live and how that quality compares with other areas across the Nation. We hope this publication will provide you with insights and information to meet your needs and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

Jerad Bales
Acting Associate Director for Water
U.S. Geological Survey



Principal Aquifers and Water-Quality Summary Reports

National summary of groundwater quality in Principal Aquifers—Circular 1360

🟪 **High Plains aquifer system**—Circular 1337

⬜ **Glacial aquifer system**—Circular 1352

🟨 **Northern Atlantic Coastal Plain surficial aquifer system**—Circular 1353

Piedmont, Blue Ridge, and Valley and Ridge aquifers—Circular 1354

🟧 Piedmont and Blue Ridge carbonate-rock aquifers

⬜ Piedmont and Blue Ridge crystalline-rock aquifers

🟪 Valley and Ridge siliciclastic-rock aquifers

🟪 Valley and Ridge carbonate-rock aquifers

🟩 Early Mesozoic basin aquifers

🟫 **Upper Floridan aquifer and overlying surficial aquifers**—Circular 1355

🟨 **Mississippi embayment–Texas coastal uplands aquifer system**—Circular 1356

🟦 Mississippi River Valley alluvial aquifer

🟩 **Denver Basin aquifer system**—Circular 1357

Southwest Principal Aquifers—Circular 1358

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🟥 Columbia Plateau basin-fill and basaltic-rock aquifers

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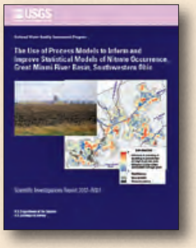
Introduction to This Report

This report contains the major findings of a regional assessment of water quality in the glacial aquifer system in the northern United States. It is one of a series of reports by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program that present major findings for Principal Aquifers, other aquifers, and major river basins across the Nation. In these reports, water quality is discussed in terms of local, State, regional, and national issues. Conditions in these aquifers are compared to conditions found elsewhere and to selected national benchmarks, such as those for drinking-water quality.

This report is intended for individuals working with water-resource issues in local, State, or Federal agencies, universities, public interest groups, or the private sector. The information will be useful in addressing current water-resource issues, such as drinking-water quality, source-water protection, and monitoring and sampling strategies. This report also will be useful for individuals who wish to know more about the quality of groundwater in areas near where they live and how that quality of water compares to the quality of groundwater in other areas across the region and the Nation.

Water-quality conditions in the glacial aquifer system summarized in this report are discussed in greater detail in other reports listed in the references. Detailed technical information, data and analyses, sample collection and analytical methodology, models, graphs, and maps that support the findings presented in this report in addition to reports in this series from other Principal Aquifers can be accessed from the national NAWQA Web site (*http://water.usgs.gov/nawqa/*).

Companion studies of these aquifers are discussed in the following reports.

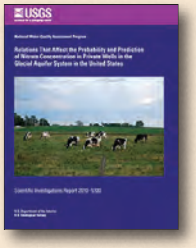


The Use of Process Models to Inform and Improve Statistical Models of Nitrate Occurrence, Great Miami River Basin, Southwestern Ohio

U.S. Geological Survey Scientific Investigations Report 2012–5001

By Donald A. Walter and J. Jeffrey Starn

(Also available at http://pubs.usgs.gov/sir/2012/5001/)



Relations That Affect the Probability and Prediction of Nitrate Concentration in Private Wells in the Glacial Aquifer System in the United States

U.S. Geological Survey Scientific Investigations Report 2010–5100

By Kelly L. Warner and Terri L. Arnold

(Also available at http://pubs.usgs.gov/sir/2010/5100/)

Chloride in Groundwater and Surface Water in Areas Underlain by the Glacial Aquifer System, Northern United States

U.S. Geological Survey Scientific Investigations Report 2009–5086

By John R. Mullaney, David L. Lorenz, and Alan D. Arntson

(Also available at http://pubs.usgs.gov/sir/2009/5086/)

Occurrence and Distribution of Iron, Manganese, and Selected Trace Elements in Ground Water in the Glacial Aquifer System of the Northern United States

U.S. Geological Survey Scientific Investigations Report 2009–5006

By George E. Groschen, Terri L. Arnold, William S. Morrow, and Kelly L. Warner

(Also available at *http://pubs.usgs.gov/sir/2009/5006/*)

Hypothetical Modeling of Redox Conditions Within a Complex Ground-Water Flow Field in a Glacial Setting

U.S. Geological Survey Scientific Investigations Report 2008–5066

By Daniel T. Feinstein and Mary Ann Thomas

(Also available at *http://pubs.usgs.gov/sir/2008/5066/*)

Hydrochemical Regions of the Glacial Aquifer System, Northern United States, and Their Environmental and Water-Quality Characteristics

U.S. Geological Survey Scientific Investigations Report 2008–5015

By Terri L. Arnold, Kelly L. Warner, George E. Groschen, James P. Caldwell, and Stephen J. Kalkhoff

(Also available at *http://pubs.usgs.gov/sir/2008/5015/*)

Occurrence of Uranium and ^{222}Radon in Glacial and Bedrock Aquifers in the Northern United States, 1993–2003

U.S. Geological Survey Scientific Investigations Report 2007–5037

By Joseph D. Ayotte, Sarah M. Flanagan, and William S. Morrow

(Also available at *http://pubs.usgs.gov/sir/2007/5037/*)

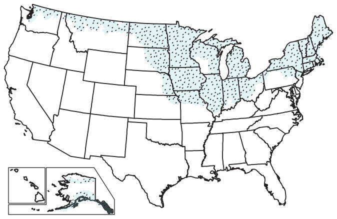
The Association of Arsenic With Redox Conditions, Depth, and Ground-Water Age in the Glacial Aquifer System of the Northern United States

U.S. Geological Survey Scientific Investigations Report 2007–5036

By Mary Ann Thomas

(Also available at *http://pubs.usgs.gov/sir/2007/5036/*)

Chapter 1: *Overview of Major Findings and Implications*



Forty-one million people—one in every six—living in the United States rely on the glacial aquifer system for drinking water. Withdrawals from the glacial aquifer system for public supply and for industrial use are the largest in the Nation and play a key role in the economic development of parts of 26 States, where the population has grown by about 15 million people over the last 40 years. Additionally, the glacial aquifer system provides drinking water for domestic use to individual homes and small communities in rural areas, especially in the highly agricultural Corn Belt area that overlies the glacial aquifer system.

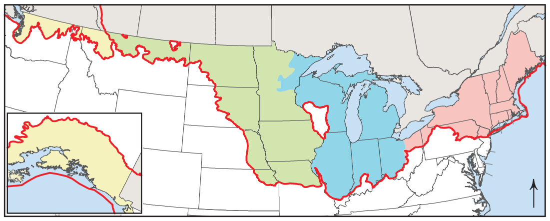
The quality of water in the glacial aquifer system has implications for human health and economic development. For example, public water suppliers that use the glacial aquifer system spent an estimated $29 million in 1999 to treat groundwater for elevated arsenic concentrations, which are a concern for human health. The expanding use of groundwater from the glacial aquifer system in areas such as suburban Chicago, where the groundwater demand is expected to double by 2050, highlights the increased importance of long-term management and sustainability planning.

The U.S. Geological Survey (USGS) assessment of water-quality conditions of the glacial aquifer system for the period 1993–2009 shows where, when, why, and how specific conditions affect groundwater across the aquifer and leads to science-based implications for assessing and managing the quality of this critical water resource.

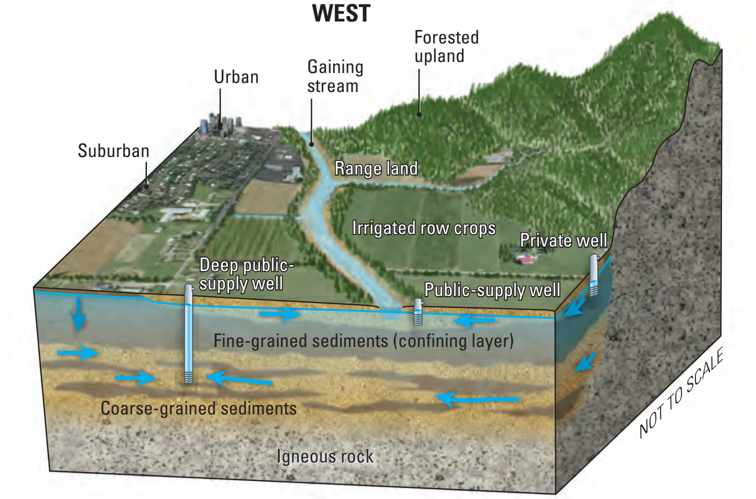
Monitoring groundwater quality in the glacial aquifer system leads to a better understanding of the science-based issues affecting this valuable drinking-water resource.

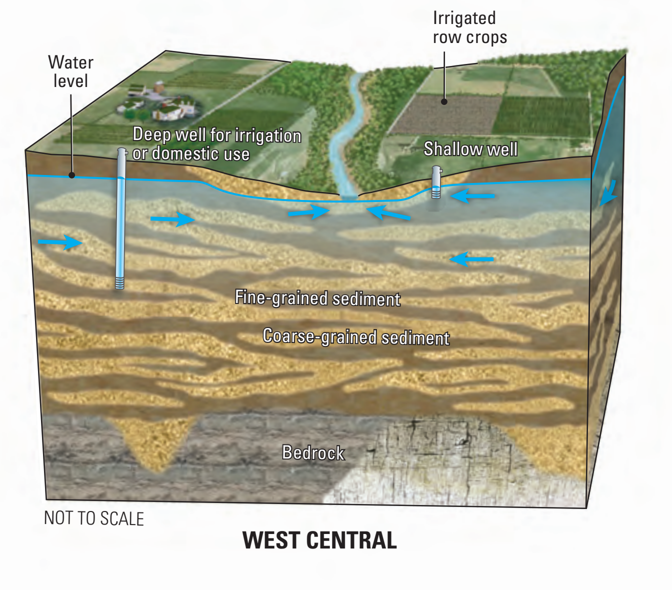
Photograph by Patrick C. Mills, USGS

Overview of Major Findings and Implications for the Glacial Aquifer System



The glacial aquifer system underlies much of the northern United States. About one-sixth (41 million people) of the United States population relies on the glacial aquifer system for drinking water. The primary importance of the glacial aquifer system is as a source of water for public supply to the population centers in the region, but the aquifer system also provides drinking water for domestic use to individual homes and small communities in rural areas. Withdrawals from this aquifer system for public supply are the largest in the Nation and play a key role in the economic development of parts of 26 States. Corn production has increased in the central part of the aquifer system over the last 10 years, and the increased production increases the need for water for agricultural use and the need for increased use of agrochemicals. Additionally, the steady increase in population (15 million people over the last 40 years) in urban and rural areas is resulting in an increased reliance on the glacial aquifer system for high-quality drinking water. The need to monitor, understand, and maintain the water quality of this valuable economic resource continues to grow.

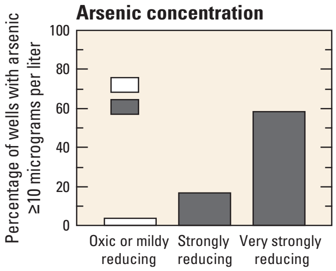




1

Contaminants from geologic sources—in particular arsenic and manganese—in groundwater used for drinking are a potential concern for human health

Manganese and arsenic are common constituents in sediments of the glacial aquifer system. Consumption of drinking water containing high levels of manganese and arsenic has been associated with neurological and carcinogenic effects, respectively. Concentrations of manganese and arsenic in the glacial aquifer system are among the highest in the country and are above a human-health benchmark in 11 percent of untreated drinking-water samples. These concentrations in groundwater are high in many parts of the glacial aquifer system because the water contains little or no dissolved oxygen—to a greater degree than in other principal aquifers—and this geochemical condition (called "anoxic") is associated with elevated concentrations of many other naturally occurring constituents. Treatment to lower concentrations of arsenic in groundwater can be costly and the burden is greatest for smaller communities where fewer people are available to bear the cost.



2

Concentrations of nitrate and pesticides in even in areas of intensive agriculture

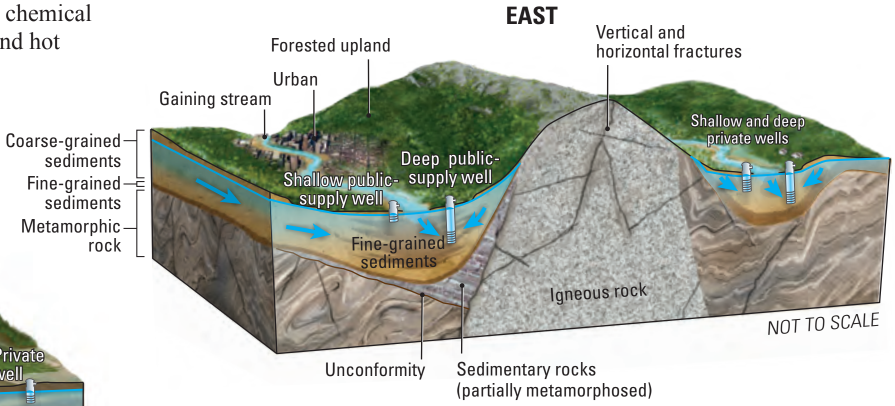
The glacial aquifer system is the shallowest aquifer
of the United States, and this area has a high use of agricultural
trations of nitrate in 90 percent of samples were lower than or
Contaminant Level of 10 milligrams per liter. Similarly, despite
concentrations of pesticides in 99 percent of samples were lower
human-health benchmarks. Concentrations of nitrate are low
of the glacial aquifer system in agricultural areas consists of
rich sediment that removes the nitrate by biogeochemical processes.
areas with fine-grained sediment are artificially drained with tile drains
water and discharge it to streams before it reaches the deeper aquifer. One
drainage is that it limits the contaminants that reach the water table by
nants to adjacent streams and rivers; an unintended consequence is
near streams and rivers can capture this contaminated streamwater.
grained sediments (sand and gravel) are near the land surface in the
in the country partly because nitrate-laden recharge water can infiltrate
concentrations in coarse-grained parts of the glacial aquifer system were

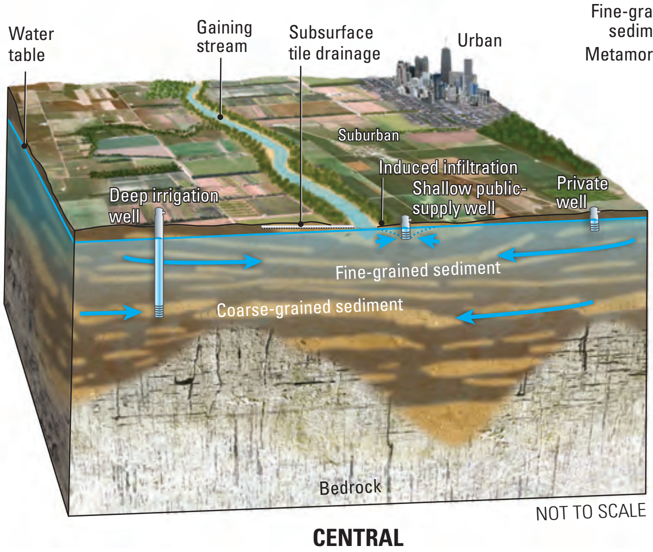
3 Chloride concentrations in groundwater are increasing in urban areas

The glacial aquifer system is the northernmost Principal Aquifer in the United States, where snow and ice in the winter drive the now common use of deicing salt (containing chloride) to maintain roadway safety. Since the 1970s, the use of deicing salt has increased threefold. The concentrations of chloride in recently recharged water exceeded the Secondary Maximum Contaminant Level (SMCL) of 250 milligrams per liter (mg/L) in more than 7 percent of samples in urban areas of the glacial aquifer system. The increase in chloride concentrations over the last two decades in urban areas is the largest in the Nation (more than 20 mg/L in some networks), prompting some communities to limit deicing salt use. Chloride in groundwater discharges to streams and increases the probability that concentrations in streamwater will exceed the chronic aquatic criterion (230 mg/L) and the SMCL (250 mg/L). Additionally, chloride in groundwater is not readily removed by natural chemical processes, so it stays in water and can cause water pipes and hot water systems to rust more easily.

Some areas of the glacial aquifer system have restricted use of road salt because of the susceptibility of the aquifer to contamination.

Photograph courtesy of Christopher S. Wheeler





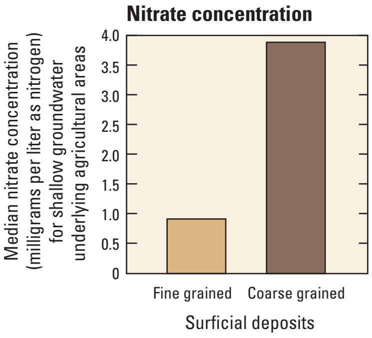
4 “Nuisance” constituents in groundwater from the glacial aquifer system could limit groundwater use

Constituents that affect the aesthetic quality of water, making it undesirable to drink or use for household needs but not necessarily a health concern, include iron, sodium, sulfate, and aluminum. These constituents occur naturally in groundwater and vary considerably depending on the mineral content of the aquifer sediments. The concern is that these constituents can make the water undesirable to drink because of taste and can add to the potential health effects of people with restricted (for example, low-sodium) diets. Twenty-five percent of water samples from all glacial wells sampled contained at least one contaminant at a concentration greater than the U.S. Environmental Protection Agency benchmarks for aesthetic quality, but 73 percent of untreated drinking-water samples had at least one constituent concentration above the benchmark for aesthetic quality. Two other measures of overall water quality are hardness (a measure of the concentration of calcium carbonate) and total dissolved solids. The central and west-central glacial aquifer system is noted for having hard water (77 percent of samples) with high dissolved solids. Groundwater is generally plentiful in the glacial aquifer system, but consumers may limit use based on aesthetic quality or may be forced to treat the groundwater at additional cost. Lastly, some constituents like dissolved solids, affect the aesthetic quality of groundwater and mobilize constituents of human-health concern.

Photograph courtesy of Culligan

groundwater were low in fine-grained sediment

underlying the Corn Belt
fertilizer. Yet concen-
equal to the Maximum
high pesticide use,
than or equal to their
in part because much
fine-grained, organic-
Additionally, agricultural
that capture infiltrated
consequence of artificial
delivering those contami-
that public-supply wells
By contrast, where coarse-
glacial aquifer system, concentrations of nitrate are some of the highest
rapidly through the coarse-grained sediments. As a result, high nitrate
most frequently measured in groundwater that was less than 10 years old.



Photographs from top to bottom: James J. Duncker, USGS; Brandon Curry, Illinois State Geological Survey; Anne Sharpe, private citizen; Gregory V. Steele, USGS

Overview of Major Findings *Water-Northern United States*

1 Contaminants from geologic sources — in particular arsenic and manganese — in groundwater used for drinking are a potential concern for human health.

Contaminants from geologic sources, most notably arsenic and manganese, were measured at concentrations of potential concern for human health in 20 percent of samples of untreated drinking water—more than three times as frequently as contaminants from human activities. Consumption of drinking water containing high levels of arsenic and manganese has been associated with carcinogenic and neurological effects. If radon is included, 50 percent of drinking-water samples contained a contaminant from geologic sources at a concentration of potential concern. Radon, a radioactive gas found in high concentrations in many parts of the glacial aquifer system, is a concern because it can be released into the air during showering or washing, increasing the exposure of homeowners to this known human carcinogen.

Concentrations of arsenic and manganese in the glacial aquifer system are among the highest in the Nation. The concentrations are high because groundwater in many parts of the glacial aquifer system contains little or no dissolved oxygen—a geochemical condition referred to as “anoxic.” Arsenic and manganese concentrations are higher in anoxic groundwater than in groundwater that contains dissolved oxygen (“oxic”). The highest concentrations of arsenic were measured in the deep groundwater of the central part of the glacial aquifer system, where much of the groundwater is anoxic.

Treatment to lower concentrations of arsenic in groundwater can be costly. The financial burden is greatest for small communities where fewer people are available to share the cost. Testing and treatment are required for public-supply wells, which are regulated under the Safe Drinking Water Act, but generally are not required for domestic-supply wells. The widespread detection of contaminants of natural origin in domestic-supply wells and the lack of regulation underscore the need for public education aimed at describing where contaminants are likely to be in groundwater and what testing and treatment options are available.

2 Concentrations of nitrate and pesticides in groundwater were low in fine-grained sediment even in areas of intensive agriculture.

The glacial aquifer system underlies the Corn Belt of the United States, where use of agricultural fertilizers and pesticides is among the highest in the Nation. Yet concentrations of nitrate and pesticides measured in groundwater in this area from 1993 through 2009 were surprisingly low—concentrations of nitrate in about 90 percent of samples did not exceed the nitrate Maximum Contaminant Level of 10 milligrams per liter (mg/L), and concentrations of pesticides in 99 percent of samples did not exceed their human-health benchmarks. These concentrations were low in part because much of the glacial aquifer system in agricultural areas consists of fine-grained, organic-rich sediment. As groundwater moves slowly through this sediment, nitrate is removed by a biogeochemical process called denitrification, and pesticides, to varying degrees, are removed from the water by adhering to the sediment

Quality Issues for the Glacial Aquifer System,

surfaces. However, much of the fine-grained agricultural land in the Corn Belt is artificially drained (through tile drains) to make the land suitable for farming. Tile drains intercept water and contaminants before they reach the water table and redirect them to adjacent streams. An unintended consequence of this practice is that public-supply wells that are near streams can capture contaminants delivered to streamwater by tile drains.

By contrast, some of the highest concentrations of nitrate in groundwater in the Nation were measured in those parts of the glacial aquifer system where coarse-grained sediments (sand and gravel) are near the land surface. In these types of sediments, nitrate is not removed by denitrification, and tile drains are not necessary for drainage, allowing nitrate to reach the water table. Where sediments are coarse-grained, nitrate concentrations in groundwater have been increasing over the last decade.

Even though fine-grained aquifer materials limit groundwater contamination from the land surface, large-scale land-use changes might make the aquifer vulnerable to contamination. For example, implementation of the 2005 Energy Policy Act, which calls for an increase in the use of biofuels from 9 billion gallons in 2009 to 36 billion gallons in 2022, has resulted in a projected increase in corn production and associated nitrogen-fertilizer use over the glacial aquifer system. Although biogeochemical processes currently limit concentrations of nitrate in groundwater, continued application of nitrogen fertilizers could exceed the capacity of these aquifers to naturally reduce nitrate concentrations over time.

3 Chloride concentrations in groundwater are increasing in urban areas.

In the northern United States, more salt is being used in the wintertime to make icy roads and streets safe for driving—since the 1970s, the use of deicing salt (which contains chloride) has increased threefold. Increases in chloride concentrations in groundwater in urban areas of the glacial aquifer system are the largest in the Nation—over the last two decades, groundwater chloride concentrations in the central and eastern regions of the glacial aquifer system have increased by more than 20 mg/L. During low-flow conditions, when groundwater is the dominant source of water to streams, high concentrations of chloride in groundwater can cause chloride in streams to exceed the chronic aquatic criterion (230 mg/L) developed to protect fish and other aquatic life.

Decreasing the use of salt to deice roads is controversial because public safety is involved, but high concentrations of chloride in groundwater have prompted some communities to reduce salt use by targeting when and where salt is applied and by investigating alternative chemical treatments. However, because groundwater moves slowly and natural chemical processes do not remove chloride from groundwater, it might take years to decades for these types of management actions to affect chloride concentrations in groundwater discharging to streams. Continued monitoring to track trends in chloride concentrations in urban groundwater and streams will provide feedback on the effectiveness of evolving best management practices for deicing-salt applications.

Photographs from top to bottom: Anne Sharpe, private citizen; Dana W. Kolpin, USGS; Alan M. Cressler, USGS; James J. Duncker, USGS

4 “Nuisance” constituents in groundwater from the glacial aquifer system could limit groundwater use.

Nearly three-quarters of samples from drinking-water wells contained what could be called a “nuisance” constituent at a concentration exceeding a Secondary Maximum Contaminant Level (SMCL). SMCLs are nonregulatory guidelines set by the U.S. Environmental Protection Agency for nuisance constituents in drinking water, which are those that do not cause adverse health effects, but that can impart an unpleasant taste or odor, cause undesirable effects such as skin or tooth discoloration, or damage plumbing. Iron, for example, causes red staining of laundry, dishes, and plumbing fixtures—concentrations of iron exceeded the SMCL of 300 micrograms per liter (µg/L) in more than half of samples from domestic-supply wells. Other nuisance constituents included chloride, sodium, sulfate, and aluminum. Elevated concentrations of nuisance constituents often are accompanied by high values of hardness and dissolved solids, which are indicators of poor water quality. Water was hard with high dissolved solids mostly in the central and west-central area of the glacial aquifer system, where aquifer sediments are derived in part from carbonate rocks and shale.

Although the glacial aquifer system provides a plentiful supply of potable groundwater, nuisance constituents prevent many consumers from using it for drinking. Some consumers choose to buy bottled water rather than drink tap water, incurring costs of hundreds of dollars each year. Water-treatment systems can remove nuisance constituents from groundwater but can be costly to install and maintain. The detection of nuisance constituents is a signal that other constituents—such as those of concern for human health—might also be present, and that testing for a broader range of constituents could be warranted to assess possible risks and to determine options for reducing risks.

Looking north from Copper Harbor, Michigan.

Photograph by Anne Sharpe, private citizen

Chapter 2: *NAWQA Approach to Assessing Water Quality*

Groundwater studies conducted by USGS NAWQA in the glacial aquifer system were designed to answer broad questions about the occurrence, fate, and transport of contaminants in aquifers used as sources of drinking water (see sidebar, Understanding study results, p. 8). This assessment of the glacial aquifer system provides a systematic and comprehensive regional analysis of water quality.

This chapter summarizes the study design used to investigate water quality in the glacial aquifer system.

Groundwater was collected from shallow monitoring wells beneath agricultural and urban areas to assess the effects of these activities on recently recharged groundwater in the glacial aquifer system.

Photograph by William S. Morrow, USGS

Assessing Water Quality in the Glacial Aquifer System

How does one go about characterizing the groundwater over an area as large as the 26 States covered by the glacial aquifer system? The approach taken by the USGS was to use different types of groundwater studies to gain a better understanding of how and why water quality varies. These groundwater studies are the building blocks of NAWQA's water-quality assessments of Principal Aquifers. Many studies of the Principal Aquifers were done, each with a different focus on information needs about groundwater quality and the natural and human-related factors that influence it (appendix 1). Groundwater studies designed to broadly assess water-quality conditions in aquifers used for drinking-water supply included analyses of samples from networks of randomly located monitoring and water-supply wells (see sidebar, What types of wells were sampled?, p. 9). Groundwater studies designed to characterize and explain the quality of recently recharged groundwater in agricultural and urban land-use settings included analyses of samples from mostly shallow monitoring wells that were installed as part of the NAWQA Program. Other studies focused on public water supplies or groundwater quality along individual flow paths.(1, 2, 3)

This Principal Aquifer assessment brings together results from all of the NAWQA groundwater studies in the glacial aquifer system. Throughout this assessment, the results are grouped as those that characterize the quality of groundwater used as a drinking-water supply and those that characterize the quality of groundwater that has been recently recharged in either an agricultural or an urban land-use setting. The entire glacial aquifer system is used for drinking-water supply, but most public and domestic-supply wells withdraw water from the deeper part of the aquifer, which contains groundwater that was recharged many years ago—in some cases long before any manmade chemicals were used on the land surface. The results of land-use studies allow us to evaluate the effects of recent human activities on groundwater quality and can provide an early warning for issues that might adversely affect drinking-water resources in the future. Land-use studies also can provide an indication of degradation or improvement in water quality related to changes in chemical use.

Understanding study results

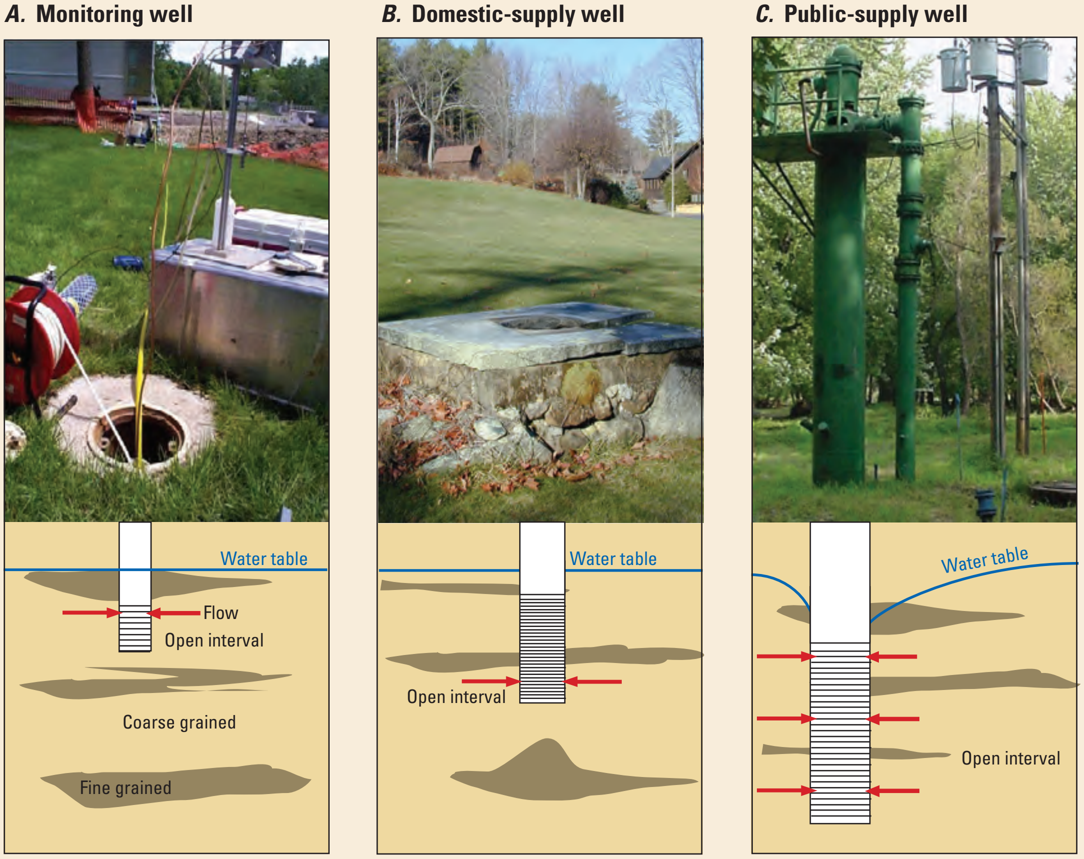
Important aspects of the NAWQA Principal Aquifer assessments:

- Water samples were collected at the wellhead (see sidebar, Anatomy of a well, p. 11) prior to any treatment. They represent the quality of the groundwater resource but not necessarily the quality of tap water.
- The focus of the assessments is the condition of the total resource, including groundwater in a wide range of hydrologic and land-use settings across the Nation, rather than conditions at specific sites with known water-quality concerns.
- The assessments are guided by a nationally consistent study design, and all assessments use the same methods of sampling and analysis. Findings apply to water quality of a particular aquifer but also contribute to the larger picture of how and why water quality varies regionally and nationally. This consistent approach helps to determine if a water-quality issue is isolated or widespread. (See *http://water.usgs.gov/nawqa/about.html* for more information.)
- The assessments focus on aquifers used for water supply or on shallow groundwater that underlies an area with a particular type of land use. Because the NAWQA groundwater study areas do not cover the full spatial extent of the targeted Principal Aquifer, the findings might not represent the effects of the full range of geology, climate, and land use present.
- Analytical methods used by USGS chemists for assessments of water quality in Principal Aquifers are designed to measure constituents at as low a concentration as possible. As a result, constituents frequently are detected at concentrations far below human-health benchmarks for drinking water (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 39). Low-level detections allow scientists to identify and evaluate emerging issues and to track contaminant levels over time.

What types of wells were sampled?

Untreated samples were collected from two types of drinking-water wells: domestic (private) wells and public-supply wells. Domestic-supply wells typically are shallower than public-supply wells and therefore pump water that is nearer to sources of manmade contaminants, such as fertilizers and pesticides, at the land surface. Domestic wells commonly are located in rural areas, so are more likely than public-supply wells to be vulnerable to contamination from agricultural chemicals. Public-supply wells generally pump water from deeper in the glacial aquifer system and tend to be located in suburban and urban areas, so are more likely than domestic-supply wells to be vulnerable to contamination from chemicals associated with urban activities. Public-supply wells have larger pumps and longer screened intervals than do domestic-supply wells and are pumped for longer periods of time. As a result, public-supply wells pump much larger volumes of water than do domestic-supply wells and so have much larger capture zones. Therefore public-supply wells potentially are more vulnerable than domestic-supply wells to manmade contamination from distant sources. If the amount of water withdrawn is large enough, it can change the flow direction and velocity of the groundwater, which can, in turn, affect the groundwater geochemistry and the constituents contained.(3) Routine testing of water from domestic-supply wells is not required and homeowners are responsible for testing, maintenance, and treatment of the water from their domestic-supply well. Water that is provided to consumers from public-supply wells is required to be tested on a routine basis to assure that the water meets Federal and State water-quality standards.

Some groundwater samples were collected from shallow monitoring wells. Monitoring wells are not pumped regularly—they are used for measuring water levels or occasionally collecting water samples, but are not used for drinking water, irrigation, or other purposes. Monitoring wells sampled in the NAWQA groundwater studies were installed to monitor the quality of recently recharged water.



Photographs by *(A)* Kelly L. Warner, USGS, *(B)* Joseph D. Ayotte, USGS, and *(C)* USGS.

Number of wells = 1, 022
Median depth = 25 feet
Median open interval = 5 feet
Median casing diameter = 2 inches
Maximum casing diameter = 8 inches

Number of wells = 481
Median depth = 80 feet
Median open interval = 5 feet
Median casing diameter = 5 inches
Maximum casing diameter = 45 inches

Number of wells = 174
Median depth = 125 feet
Median open interval = 25 feet
Median casing diameter = 16 inches
Maximum casing diameter = 60 inches

The sampling of *(A)* monitoring, *(B)* domestic, and *(C)* public-supply wells leads to a systematic understanding of the quality of water as it moves from the land surface to the water table, and finally to deeper parts of the aquifer used for drinking-water supply *(B and C)*. Note the differences in well construction between these three well types.

Photograph courtesy of Jassmit

Indianapolis is one of the major cities overlying the glacial aquifer system.

Photograph by Kelly L. Warner, USGS

Corn is a major crop in the agricultural land overlying the glacial aquifer system.

Aquifer (aq.ui.fer)—ăk’wə-fər

An underground layer of saturated permeable materials (rock, gravel, sand, or silt) that will yield a useful quantity of water to a well.

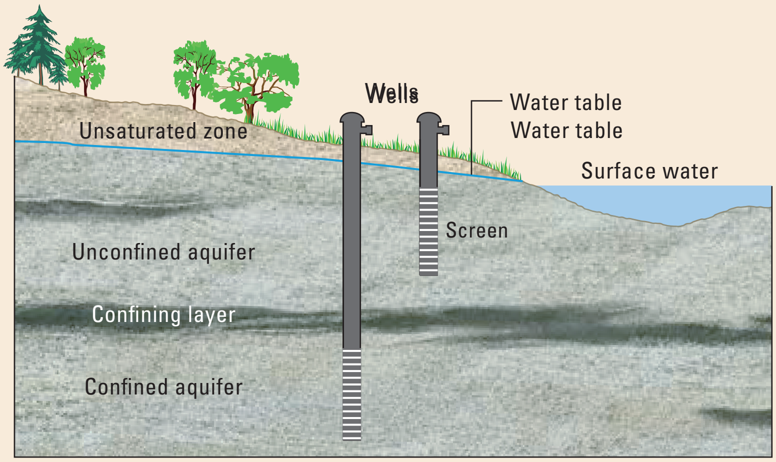
The **unsaturated zone** is the area below the land surface and above an aquifer. In addition to soil, rocks, and air, the unsaturated zone contains water from the land surface (such as rain) that is slowly moving downward to the water table of the aquifer.

An **unconfined aquifer** is bounded at its top by the water table, below which water fills all the pore spaces in the rock. Water from the land surface can move down into an unconfined aquifer.

A **confining layer** is a layer of material (often clay) through which water does not easily flow, creating a boundary between aquifers.

A **confined aquifer** is bounded at its top by a confining layer. Water enters or “recharges” confined aquifers where the confining layer is not present. Where the confining layer is not continuous or is breached (for example, by a well), flow between the unconfined and confined aquifer can occur.

The pressure within a confined aquifer can be greater than that in the overlying unconfined aquifer if the source of the water in the confined aquifer is at a higher elevation than the unconfined aquifer. In that case, water in a well in a confined aquifer will rise to a higher level than that in the overlying unconfined aquifer.

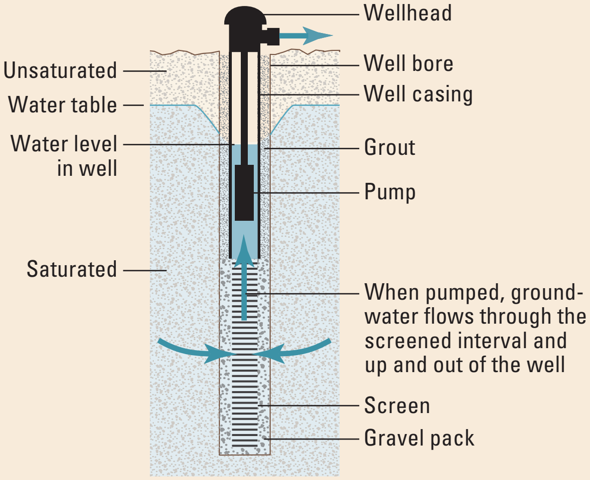


Sedimentary aquifer

Groundwater storage and flow between grains of sediment

Anatomy of a well

A well is simply a hole in the ground (well bore or borehole) from which water can be removed. The well bore is lined with a well casing, such as a pipe, to prevent the well bore from collapsing. The casing, along with a sealant (called grout), also prevents water from flowing into the well from the land surface or from parts of the aquifer where the water quality may be less desirable. The casing can be open at the bottom or perforated at a specific depth with a screen, to allow water to flow into the well where it can be pumped to the surface. Coarse sand or gravel (called sand pack or gravel pack) can be placed around the well screen to help improve the flow of water into the well. Some wells are cased only near the land surface, allowing water to flow into the well from nearly the entire length of the well bore.



To assess water-quality conditions of groundwater used as a drinking-water resource, one sample was analyzed from each of 655 randomly selected water-supply wells that had been used in different NAWQA studies—481 domestic-supply wells and 174 public-supply wells (table 2–1). The samples were analyzed for major and trace inorganic constituents, nutrients, volatile organic compounds (VOCs), and pesticides (see sidebar, NAWQA assessments use a wide range of geochemical data and site information, p. 14). Seventy-five percent of the drinking-water wells had been used in drinking-water studies designed to assess the deeper drinking-water resource, but because even the shallowest part of the glacial aquifer system is used for drinking-water supply, some public-supply and domestic-supply wells were used for studies of shallow, recently recharged water. Although the wells are distributed across much of the area overlying the aquifer, they are grouped only in NAWQA groundwater study areas (fig. 2–1), so some parts of the glacial aquifer system were not represented (fig. 2–2).

To assess the quality of recent groundwater recharge underlying agricultural and urban areas, groundwater samples were collected from mostly shallow monitoring wells installed by the USGS. The monitoring wells—with a median depth of 25 feet (ft) tap groundwater near the water table. The primary agricultural setting of the glacial aquifer system is areas of row crops, such as corn and soybeans that require fertilizer and pesticide applications. Most of the agricultural land is artificially drained to remove excess water, but in some areas where the soil is coarse-grained or the climate is more arid, such as Nebraska, the agricultural land is irrigated. The urban land-use settings where samples were collected were typical of those where many Americans work and live—areas of single- and multi-family residential and commercial development mostly in the suburbs. The suburbs represent the rapidly growing outskirts of cities where agricultural land is being converted to urban land use. The water quality of the samples collected in agricultural and urban areas is an indication of how the chemicals we use in day-to-day life—fertilizers, pesticides, solvents, and gasoline—might affect the quality of our future drinking-water resource.

Table 2–1. The objectives of the different studies determined the types of wells that were targeted for sampling in the glacial aquifer system. Drinking-water studies targeted wells screened at greater depths in the part of the aquifer used for drinking water, whereas land-use studies targeted water from wells screened just below the water table to assess recent recharge underlying agricultural and urban areas.

Study type	Drinking-water-supply wells		Monitoring wells	Other wells
	Public	Domestic		
Agricultural land use	1	9	492	7
Urban land use	8	0	353	5
Drinking water	40	450	53	25
Other (including special drinking-water studies and forested land-use studies)	125	22	124	0
Total wells by type	174	481	1,022	37


Photographs by William S. Morrow, USGS

Left, Wells, like this domestic-supply well, are sampled for water quality, and other measurements related to the water quality are collected. Here, a hydrologist carefully measures the water level in a domestic-supply well. Right, Public-supply wells pump higher volumes of water than domestic-supply wells. Shown here is a public-supply pumping facility in Illinois.

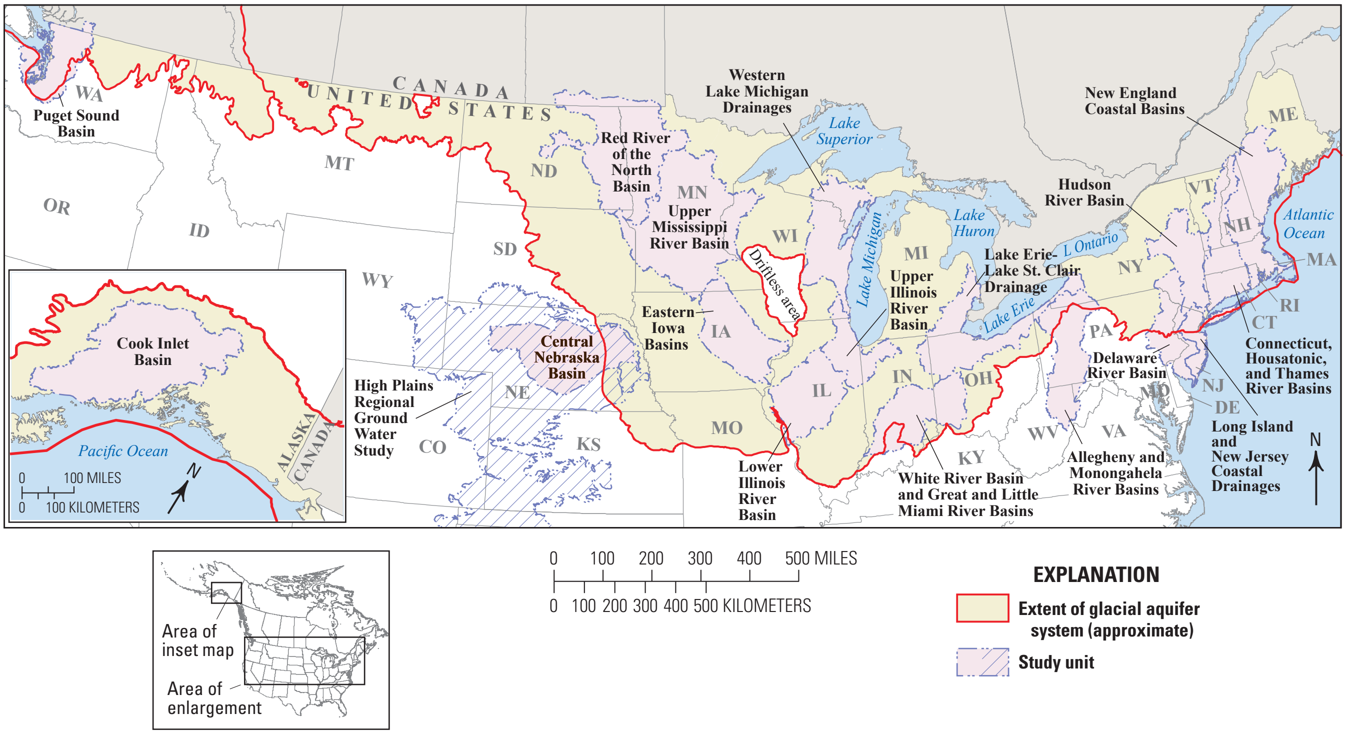


Figure 2–1. Wells sampled for the assessment of the water quality of the glacial aquifer system are within local NAWQA groundwater study areas (studies are named for the drainage-basin location). These studies cover about 79 percent of the area of the glacial aquifer system.

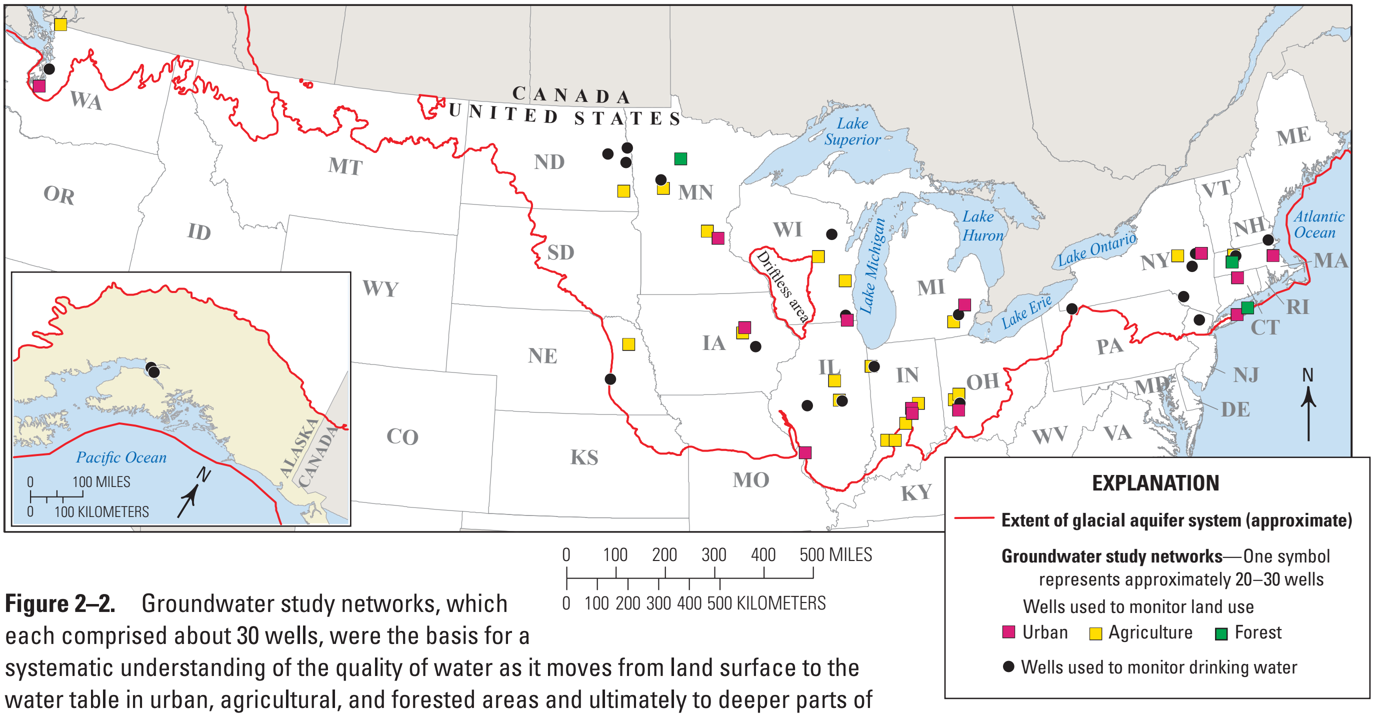


Figure 2–2. Groundwater study networks, which each comprised about 30 wells, were the basis for a systematic understanding of the quality of water as it moves from land surface to the water table in urban, agricultural, and forested areas and ultimately to deeper parts of the surficial aquifer that supply drinking water and base flow to streams.

NAWQA assessments use a wide range of geochemical data and site information

Constituents measured in samples from most wells	
Constituent group	**Examples**
Water-quality properties	pH, specific conductance, dissolved oxygen, temperature
Major ions (filtered)	Bromide, calcium, chloride, magnesium, sodium, sulfate
Trace elements (filtered)	Arsenic, boron, iron, manganese, selenium, uranium
Nutrients (filtered)	Ammonia, nitrate, phosphorus
Pesticides (filtered)	Herbicides, insecticides, fungicides
Volatile organic compounds	Solvents, gasoline hydrocarbons, refrigerants, trihalomethanes, fumigants
Organic carbon (filtered)	
Additional constituents measured in samples from some wells	
Constituent group	**Examples**
Radionuclides	Radon
Groundwater age tracers	Tritium, chlorofluorocarbons
Stable isotopes	Oxygen-18, hydrogen-2
Microorganisms	*Escherichia coli* and total coliforms
Additional site information	
Use of well Well depth Depth to water Well-construction data Principal Aquifer	Land-surface elevation at well Land use within a 500-meter (1,640-foot) radius buffer Estimates of nutrient inputs Estimates of pesticide use

Chemists at the USGS National Water Quality Laboratory analyze groundwater samples using an array of sophisticated techniques.

Additional information (often called “ancillary information”) about the well and surrounding environment complements the chemical data measured. This additional information often is key to making sense of the chemical data. For example, the information might be used to determine that shallow groundwater is more (or less) vulnerable to contamination than deep groundwater, that domestic wells are more (or less) vulnerable to contamination than public-supply wells, or that urban land use is associated with different types of groundwater contamination than is agricultural land use. Chemical data without accompanying ancillary data are much less useful for understanding factors that affect groundwater quality.

Chapter 3: *Environmental and Hydrogeologic Setting*

The vast expanse of the glacial aquifer system is the result of multiple advances of continental glaciers that left behind a nearly continuous, but remarkably heterogeneous, mixture of glacial sediments. These sediments—with their unique hydraulic properties and composition—give rise to complex patterns of flow, geochemical conditions, and, ultimately, groundwater quality. The hydrogeologic properties of the glacial sediments, along with pumping and other human modifications of the flow system, affect the movement of contaminants into and through the aquifer. Reactions between water and aquifer sediments and related biogeochemical processes within the aquifer determine whether contaminants that are released into the aquifer by human activities will persist or eventually degrade to less harmful compounds, and whether constituents from geologic sources will be released from aquifer materials into groundwater. The background information presented here sets the stage for a clearer understanding of contaminant distribution and the factors that affect where, when, why, and how contaminants enter the glacial aquifer system.

This chapter summarizes background information for the glacial aquifer system and provides the context for understanding findings about water-quality in this Principal Aquifer. The chapter covers the environmental and hydrogeologic setting, including population, land use, and water use.

Thick deposits of glacial sediment form the banks of a stream in Illinois.

Photograph by William S. Morrow, USGS

Environmental Setting

The glacial aquifer system covers nearly one million square miles (mi^2) across parts of 26 northern States from Maine to Washington and Alaska—about one-fourth of the area of the United States. For this study, the glacial aquifer system includes all unconsolidated aquifers of glacial origin north of the line of continental glaciation in the United States and Alaska. An area of about 20,000 mi^2 in southwestern Wisconsin, northwestern Illinois, and a small part of eastern Iowa is considered nonglaciated because of the absence of glacially derived sediments (see red outlined area in fig. 3–1). Parts of the glacial aquifer system have been given a variety of local names, including the glacial deposit aquifer, alluvial aquifers (where glacial sediments were eroded and redeposited by streams and rivers), and surficial aquifers.

The glacial aquifer system has been divided into four regions—west, west-central, central, and east—on the basis of similar fundamental environmental and hydrogeologic features, such as topography, precipitation, sediment texture, underlying geologic deposits, and the direction of glacial advance during the last ice age.(4) Distinct differences in the major-ion chemistry of groundwater from these four areas (5) along with regional differences in the hydrogeology and overlying land use partly explain differences in the concentrations of several commonly detected contaminants in the four areas of the glacial aquifer system that are the focus of subsequent sections of this report.

Topography influences the direction and time it takes groundwater to flow to a well or stream. Generally, groundwater moves faster in steep areas, but the rate of flow also depends on other factors, such as sediment thickness and hydraulic properties. Topography within the boundary of the glacial aquifer system is mountainous in the east and west regions and substantially flatter in the central and west-central regions (Midwest). Maximum elevations in the mountains of Maine and New Hampshire exceed 4,000 ft and more than 14,000 ft in Washington, but rarely exceed 1,000 ft in the midcontinent (fig. 3–2). The glacial sediments were laid down by streams or in glacial lakes mostly in the valleys in the mountainous terrain of the east and west regions, but can cover larger areas in the low-relief central and west-central regions. Although the central and west-central regions are predominantly flat, glacial features such as moraines and drumlins provide some local topographic relief.

The climate of most of the area overlying the glacial aquifer system is humid, although the plains of Nebraska, North and South Dakota, and Montana are semiarid. Annual precipitation averages range from more than 100 inches at high elevations along the northwestern coast and Alaska to less than 20 inches in North Dakota (fig. 3–3).

In the central and west-central regions, glaciation created large areas with little topographic relief. These areas, which feature rich soils and adequate drainage, are some of the most productive farmland in the world.

Photograph by William S. Morrow, USGS

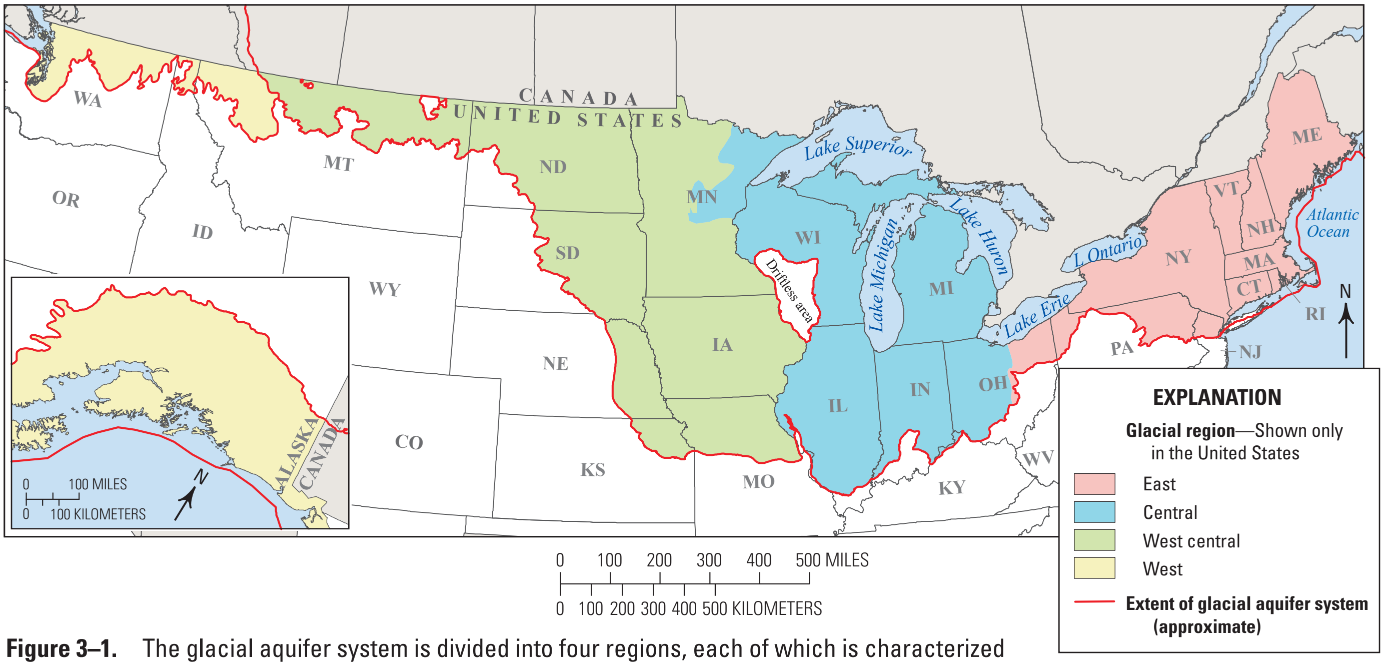


Figure 3–1. The glacial aquifer system is divided into four regions, each of which is characterized by similar physiography and hydrochemistry. The physiography affects the flow of water through the system, and the hydrochemistry affects the natural water quality.

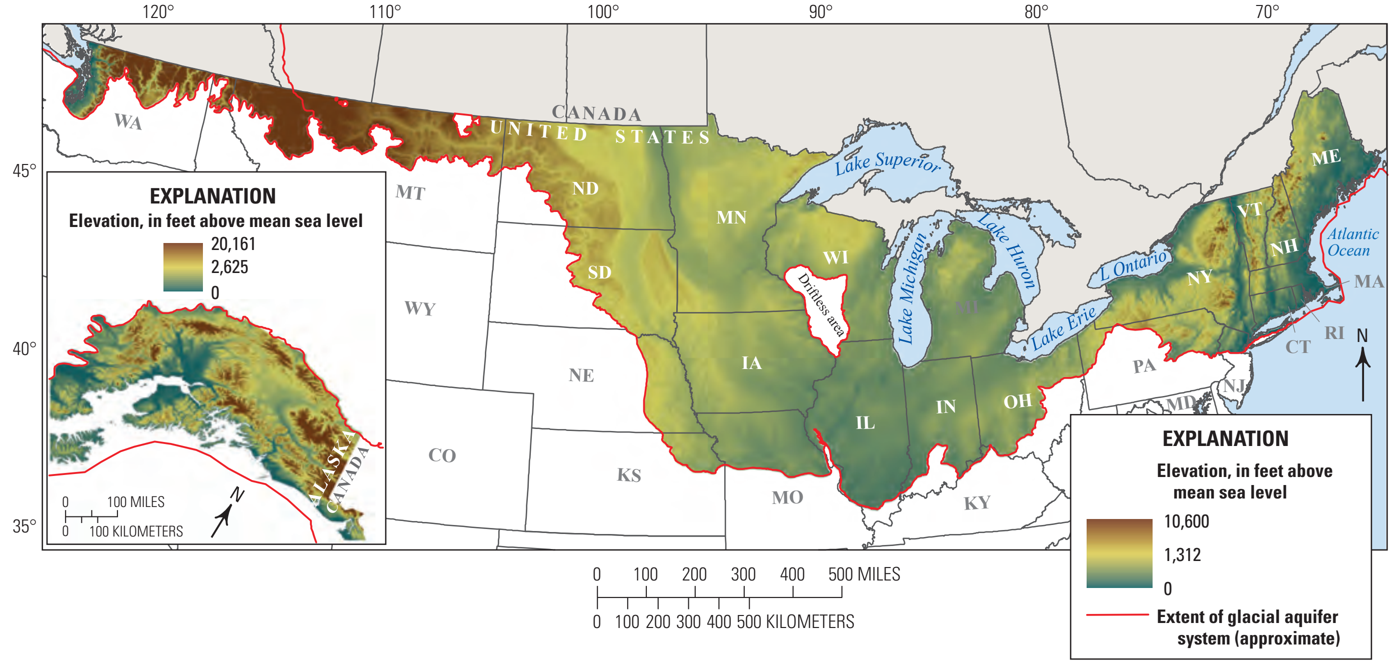


Figure 3–2. The topographic relief is less in the central and west-central regions of the glacial aquifer system than in the mountainous east and west. In the midcontinent, the glacial aquifer system is mostly continuous, although heterogeneous, whereas in the mountainous terrain of the western and eastern regions, the aquifer system is less continuous because it primarily occupies valleys.

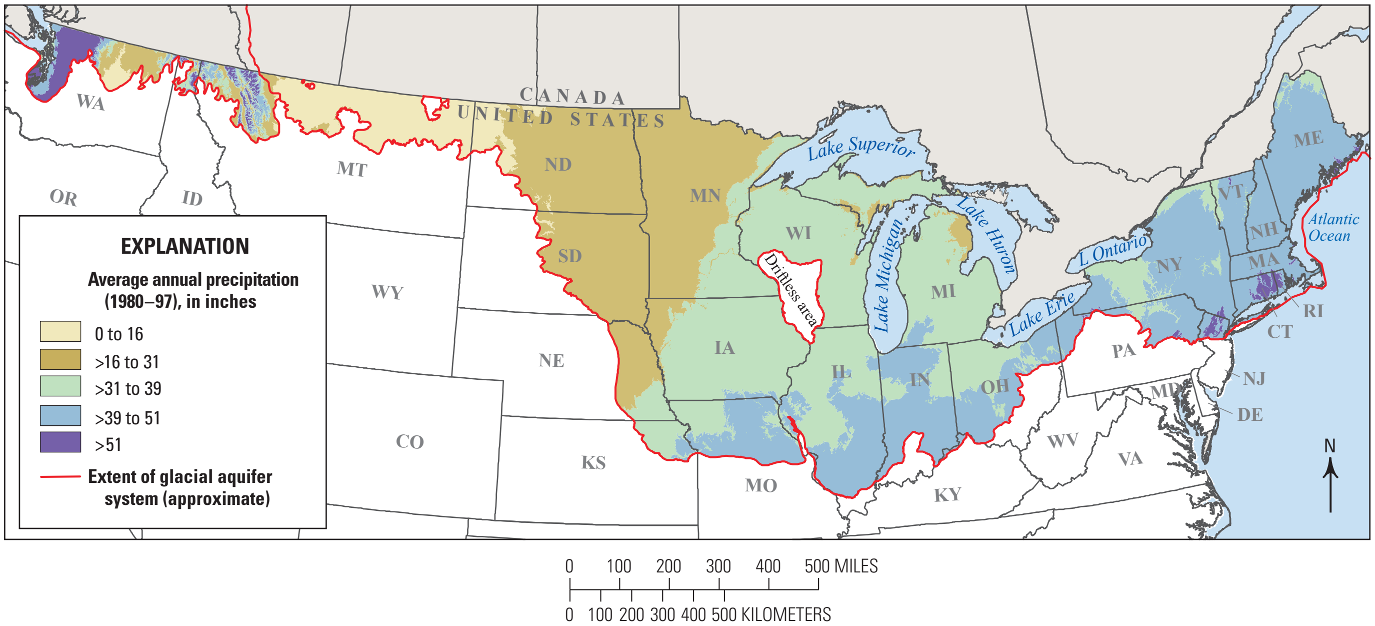


Figure 3–3. Annual precipitation is high near the east and west coasts and low in the west-central region. In areas where the glacial sediment is coarse-grained, water infiltrates readily, and high precipitation results in more groundwater recharge. In areas where the uppermost glacial sediment is fine grained, water does not easily infiltrate, so high precipitation results in more runoff to streams.

Texture and Lithology of Glacial Sediments

The movement of water and contaminants in the glacial aquifer system is influenced by aquifer properties, including the texture and lithology of the unconsolidated sediments, the amount and timing of recharge, and the length of time that the water is in contact with the glacial sediments (residence time). Generally, residence times are greater in the west-central part of the glacial aquifer system than in the east, in part because of greater depths to the water table, drier climatic conditions, and correspondingly lower rates of groundwater recharge.

The glacial aquifer system consists of unconsolidated sediments of various textures. The texture of those sediments can differ substantially across the landscape and with depth. The textures of sediments visible at the land surface are not always similar to those deeper in the aquifer from which wells pump water. A coarse-grained sand deposit deep in the aquifer can be separated from the land surface by layers of fine-grained sediments or by glacial till—unsorted gravel, sand, silt, and clay. Features such as these control flow through the aquifer and have a strong influence on the quality of groundwater.

Although the area of continental glaciation is nearly continuous across the northern United States, some of the glacial sediments are only marginally continuous and very thin, as in parts of Montana. In other areas, the glacial sediments are extensive and hundreds of feet thick, such as in northern Indiana. The texture, permeability, and depositional patterns of the glacial sediments control the movement of groundwater through the glacial aquifer system. For example, coarse-grained sand and gravel sediments, such as outwash, promote rapid rates of groundwater flow and can store large volumes of water for supply. Fine-grained and unsorted sediments, such as glacial till, inhibit flow and produce less water for supply (see sidebar, Glacial depositional processes affect groundwater flow and chemistry today, p. 19).

The texture of glacial sediments affects the flow of water through the aquifer and thus has a strong influence on the quality of groundwater.

Photograph by Gregory V. Steele, USGS

Photograph by Dana Kolpin, USGS

Left, Wheat field in the semiarid climate of the glacial aquifer system in Nebraska. Right, Forests and farms in the humid climate of the glacial aquifer system in the northeastern United States.

Glacial depositional processes affect groundwater flow and chemistry today

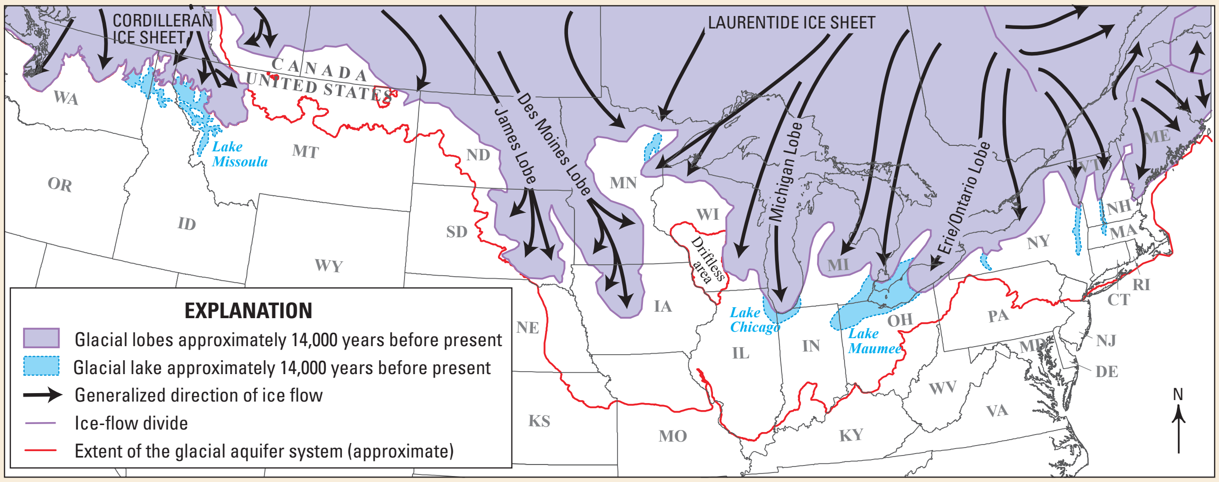
Glacial processes and different types of glacial depositional environments determine where and what type of glacial sediment is found on the landscape. The texture and permeability of the sediment also affect the movement of groundwater and transport of dissolved constituents in groundwater. Two large continental ice sheets, Cordilleran and Laurentide, covered parts of North America from about 1.6 million years ago until 10,000 years ago. The Cordilleran ice sheet extended into Washington, Idaho, and Montana, and the Laurentide ice sheet extended from Montana to Maine and as far south as Illinois and Missouri. As the ice sheet grew, it eroded the underlying bedrock and previously deposited glacial sediment. At the edges of the ice sheet, tongues of ice and sediment, called lobes, extended through many areas of the midcontinent (map).

The sediment deposited from continental ice sheets and associated ancient rivers and lakes formed the glacial aquifer system that today is one of the Nation's most valuable water supplies. In the eastern and western United States, the continental glaciers were thickest in the mountain valleys and left behind many glacial lakes as the ice retreated. In the midcontinent, preexisting stream valleys were further eroded by the ice, filled with sediment, and finally covered with a thick enough layer of younger glacial sediment to make the current landscape a flat layer of glacial sediment. These buried valleys, which are not visible at the land surface, often are an important source of deep groundwater.

The lithologic composition of the sediment deposited by the continental glaciers reflects the geology of the bedrock over which the ice moved. For example, glacial sediments that were derived from the erosion of comparatively soft limestone and shale are composed of fragments of those rocks, which contribute to the hard water that is widespread in the central regions of the glacial aquifer system. In contrast, the hard crystalline rocks of the east and west regions, which contain abundant silicate minerals such as quartz and feldspar, led to the deposition of glacial sediment that has little capacity to buffer low-pH recharge water.

Photograph by Joseph Ayotte, USGS

Sorted glacial sediment, such as outwash, has larger grained sediment at the bottom and smaller grained sediment at the top. Unsorted glacial sediment, such as till, contains a mix of grain sizes. Groundwater flows more easily through sorted outwash sediments.



Modified from Geological Survey of Canada[91]

Approximate location of the Cordilleran and Laurentide ice sheets and the glacial lobes, ice-flow divides, ice-flow direction, and select glacial lakes about 14,000 years before present. Erosion of the underlying bedrock by the overlying glacial lobes is the source of the thick sediments of the glacial aquifer system.

Hydrogeologic Setting

The wide array of glacial depositional processes resulted in a similarly wide variety of hydrogeologic settings across the glacial aquifer system, but there are some general patterns over large areas. Typical hydrogeologic settings and the distribution of glacial sediments within the four regions of the glacial aquifer system used in this report illustrate some of the general similarities within the regions (fig. 3–4).

The west region of the glacial aquifer system consists mostly of coarse-grained sediments in valleys and thick layers and lenses in flatter topography. In this region, water samples were collected primarily in the broad, coarse-grained aquifers of the Puget Sound Basin in Washington and the Cook Inlet Basin in Alaska. The underlying bedrock in the Puget Sound Basin consists of igneous and sedimentary rocks with little or no groundwater development.

The glacial aquifer system in the central and west-central regions is underlain primarily by carbonate rocks and shale, and

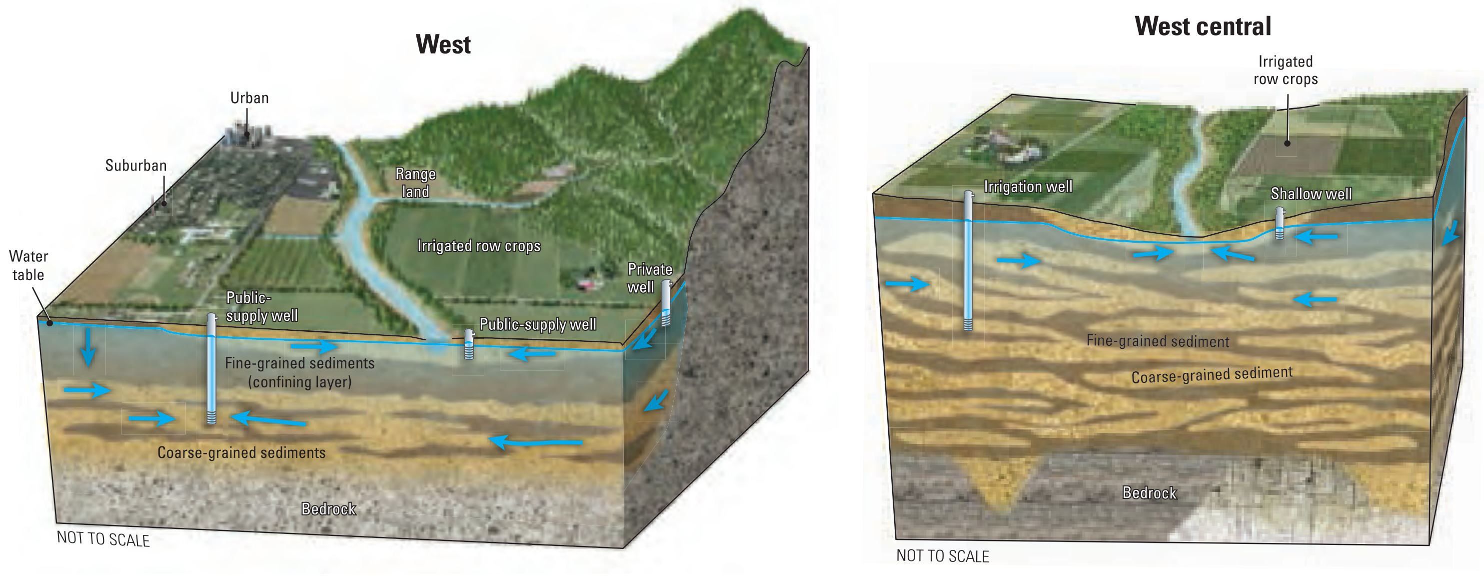
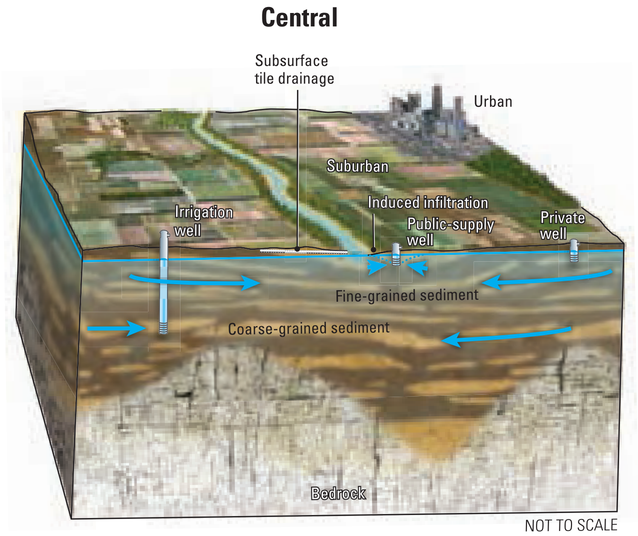


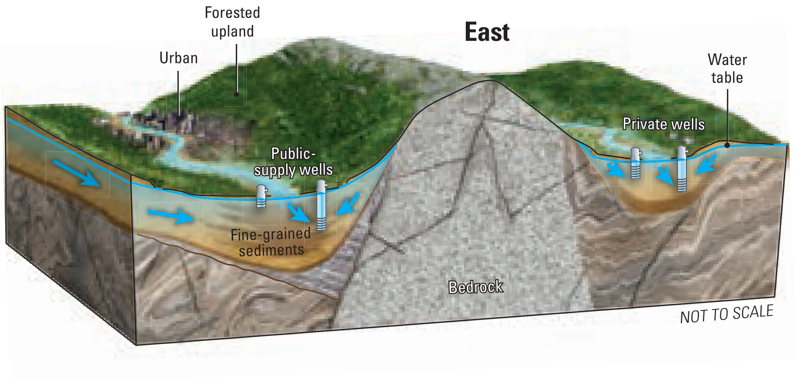
Figure 3–4. The distribution of different types of glacial sediments in the four regions of the glacial aquifer system affects the water quality. The minerals in the glacial sediments, to varying extents, reflect those of the underlying rocks. The sediments are coarser and silicic in the east and west, but the sediment in the west-central and central regions contains more fine-grained sediments that include carbonate material. Acidic water (pH less than 7) is associated with silicic sediment, and alkaline water (pH greater than 7) is associated with carbonate-rich sediment.

Characterization of glacial regions	West	West central
Topography	Mountainous	Flat
Precipitation	Arid/humid	Arid/humid
Thickness	Moderately thick	Thick
Characterization of sediment	Mixed—more coarse than fine	Mixed—more fine than coarse
Common bedrock	Crystalline	Shale and carbonate
Major glacial aquifer use	Drinking water and irrigation	Drinking water and irrigation
Characteristic land use	Forested and urban	Agricultural
Other Principal Aquifers underlying the glacial aquifer system		Cambrian-Ordovician aquifer Silurian-Ordovician aquifer Mississippian aquifers High Plains aquifer Lower Tertiary sandstone Upper Cretaceous sandstone

thick sequences of coarse- and fine-grained glacial sediments fill and obscure previously formed bedrock valleys. The Cambrian-Ordovician sandstone aquifer and the High Plains aquifer underlie parts of the glacial aquifer system in these regions. The unsorted, fine-grained till sediments are widely distributed and inhibit the movement of contaminants from the land surface down into these deeper underlying aquifers. By contrast, coarse-grained glacial sediments, which are the most productive for water supply, can act as a conduit for rapid transport of contaminants to deeper parts of the aquifer or to underlying aquifers.

In the east, the glacial sediments fill the many crystalline bedrock valleys and cover broad lower-lying areas with outwash sediments. Most of the region is covered by deposits of glacial till—that is marginally productive for water supply. The most productive glacial sediments are those that consist of sands and gravels without silt and clay—these generally are discontinuous and in low-lying areas. The glacial aquifer system in the east region is underlain primarily by crystalline bedrock aquifers and by the North Atlantic Coastal Plain aquifers.





	Central	East
	Flat	Mountainous
	Humid	Humid
	Thick	Moderately thin
	Mixed—more fine than coarse	Mixed—more coarse than fine
	Carbonate	Crystalline
	Drinking water	Drinking water
	Agricultural	Urban and forested
	Cambrian-Ordovician aquifer Silurian-Devonian aquifer Mississippian aquifer Pennsylvanian aquifer	New York–New England carbonate-rock aquifers New England crystalline aquifer Early Mesozoic basin aquifer

Population and Land Use

Approximately one-third (98 million people) of the United States population live in the area overlying the glacial aquifer system (as of 2011), and the population continues to grow (fig. 3–5). In 2000, an estimated 41 million people relied on the glacial aquifer system for drinking water.(4) The more heavily urbanized and densely populated parts of the glacial aquifer system include the metropolitan areas of New York City, Chicago, Detroit, Indianapolis, Columbus, Boston, Seattle, and Cleveland (fig. 3–6). Most of these cities use a combination of surface water and groundwater for water supply. Chicago, for example, uses Lake Michigan water for most of the city, but many of the fastest growing suburbs rely on groundwater. The glacial aquifer system also is an important resource for rural domestic supply. About 22 percent (8,820,000) of the 41 million people using the glacial aquifer system rely on domestic water supplies.(6)

Land use over the glacial aquifer system is mostly agricultural in the central and west-central regions and mostly undeveloped in the east and west. Land cover is mostly forested in the more mountainous east and west (fig. 3–7). Land use is commonly linked to the topography and underlying type of bedrock. For example, in areas where the bedrock is crystalline and the landscape is hilly to mountainous—such as the east and west coasts and northern Michigan, Wisconsin, and Minnesota—the land use is dominantly undeveloped, and cover is commonly forested; in the flat-lying areas underlain by deep sedimentary rocks, such as in the mid-continent, the land use is mostly agricultural.

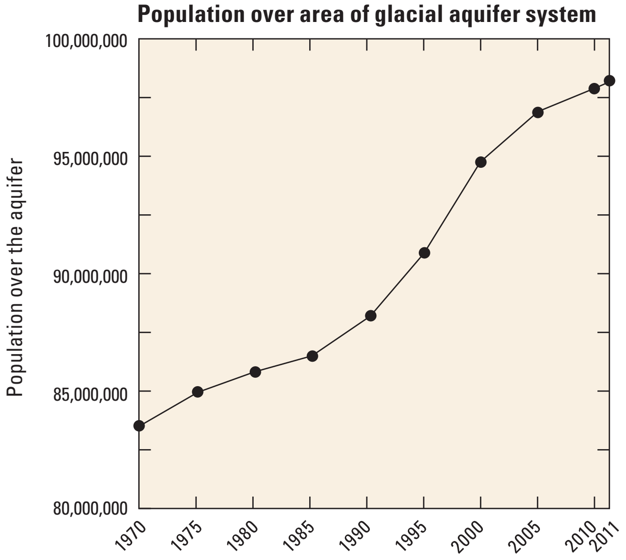
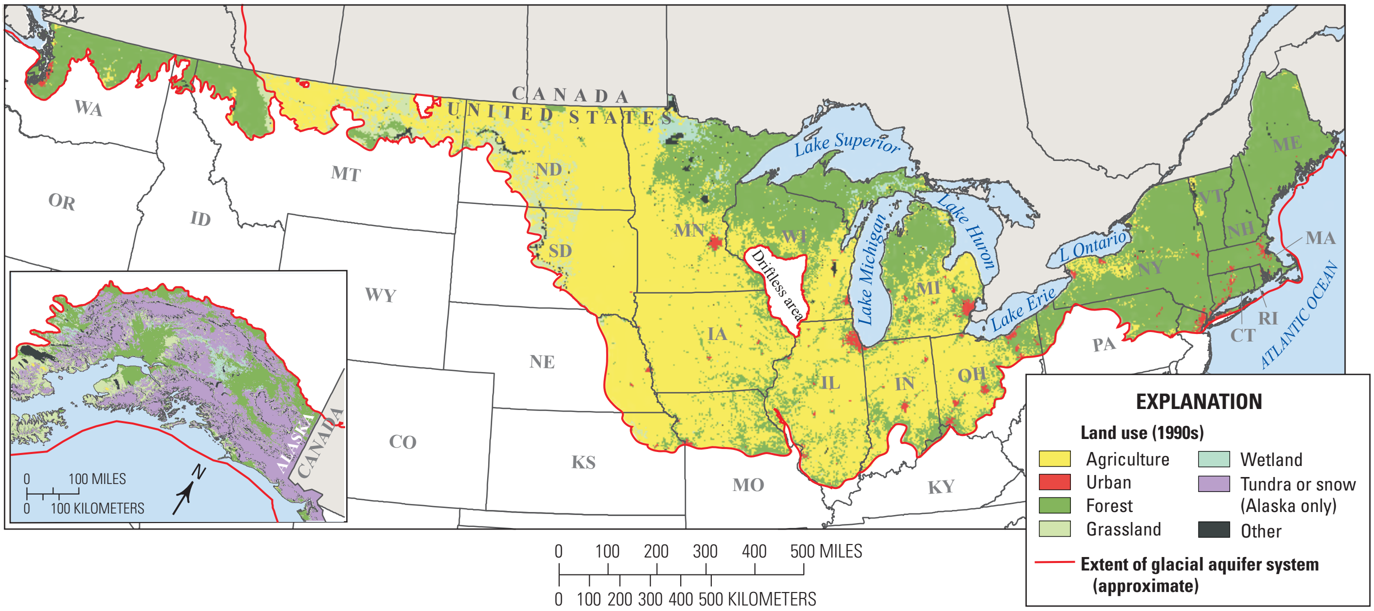


Figure 3–5. The glacial aquifer system is one of the most extensive and intensively used groundwater resources in the Nation, with over 98 million people living over the aquifer. As population grows, more and more people rely on groundwater resources for drinking-water supplies and other uses

Figure 3–6. Many large metropolitan areas overlie the glacial aquifer system. Although some large cities that overlie the glacial aquifer system, such as Chicago, Indianapolis, and New York, rely heavily on surface-water supplies, surrounding suburban areas commonly rely on groundwater pumped from the glacial aquifer system.



Modified from Hitt[92]

Figure 3–7. Land use overlying the glacial aquifer system is dominated by agriculture and undeveloped (forested) land. Urban areas overlie a relatively small percentage of the glacial aquifer system (4 percent), but represent a substantial demand for a high-quality groundwater supply.

Photograph by Patrick C. Mills, USGS

The areal density of contamination sources in urban areas is high because of the high density of people and industry.

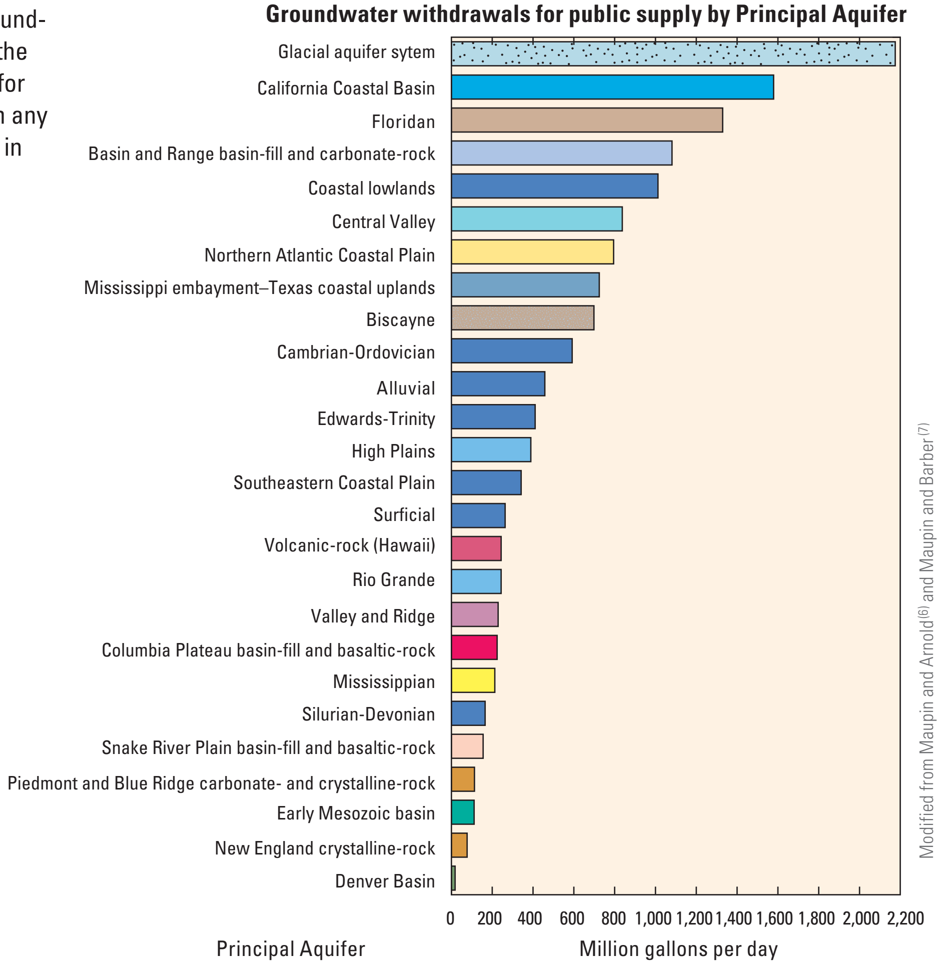
Water Use

Total withdrawals from the glacial aquifer system in 2000 were 3,560 million gallons per day, which constitutes almost 5 percent of total withdrawals from all aquifers in the United States,(7) and the need for more water is growing. The five Great Lakes are the centerpiece of the glaciated area and provide water for many cities, but in urban areas further from the lakes the glacial aquifer system is critical for economic growth.

The glacial aquifer system supplies more water for public supply than any other Principal Aquifer in the United States (fig. 3–8). Although the glacial aquifer system is used extensively for public water supply, other uses, for example irrigation and industry, also rely on the aquifer for water supply (fig. 3–9). The central region uses more than twice the amount of water for public supply than do any of the other three regions of the glacial aquifer system. In large cities, like Chicago, Boston, and New York City, the fast-growing suburbs are the primary users of the glacial aquifer system for public water supply. In Chicago, new and growing suburbs will increasingly use the glacial aquifer system for water supply because the withdrawals from Lake Michigan are approaching the limit set by a U.S. Supreme Court decree. Monitoring and maintaining water quality in the glacial aquifer system will be paramount for urban growth and sustainability.

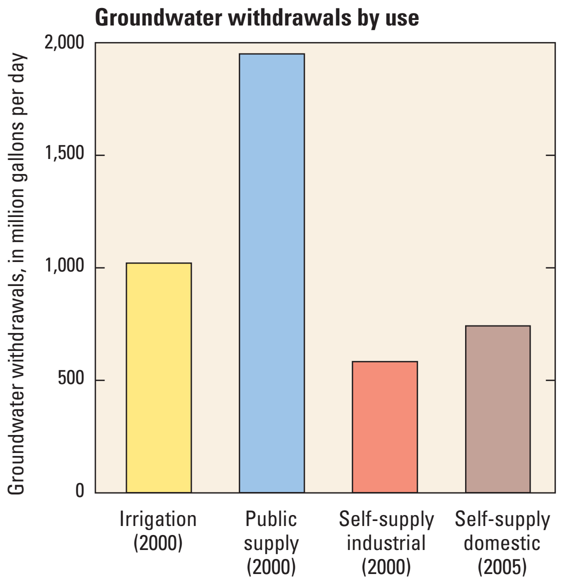
In some places, the glacial aquifer system is underlain by another Principal Aquifer and, in these areas, water-supply withdrawals may come from both aquifers. When the glacial aquifer system is hydraulically connected to an underlying aquifer, groundwater withdrawals can cause the groundwater from the two to mix, which can affect groundwater quality in both aquifers. Likewise, when wells are pumped near streams, the pumping can cause groundwater and surface water to mix (see sidebar, Enhancing groundwater supplies by inducing infiltration of river water, p. 26).

The glacial aquifer system is widely used for domestic water supply especially across large rural areas where the population density is low (fewer than 1,000 people per square mile) (fig. 3–10). The glacial aquifer system is used by a majority of people supplying their own water for domestic use in Illinois, Indiana, and Alaska.



Modified from Maupin and Arnold(6) and Maupin and Barber(7)

Figure 3–8. More groundwater is pumped from the glacial aquifer system for public supply than from any other Principal Aquifer in the United States.

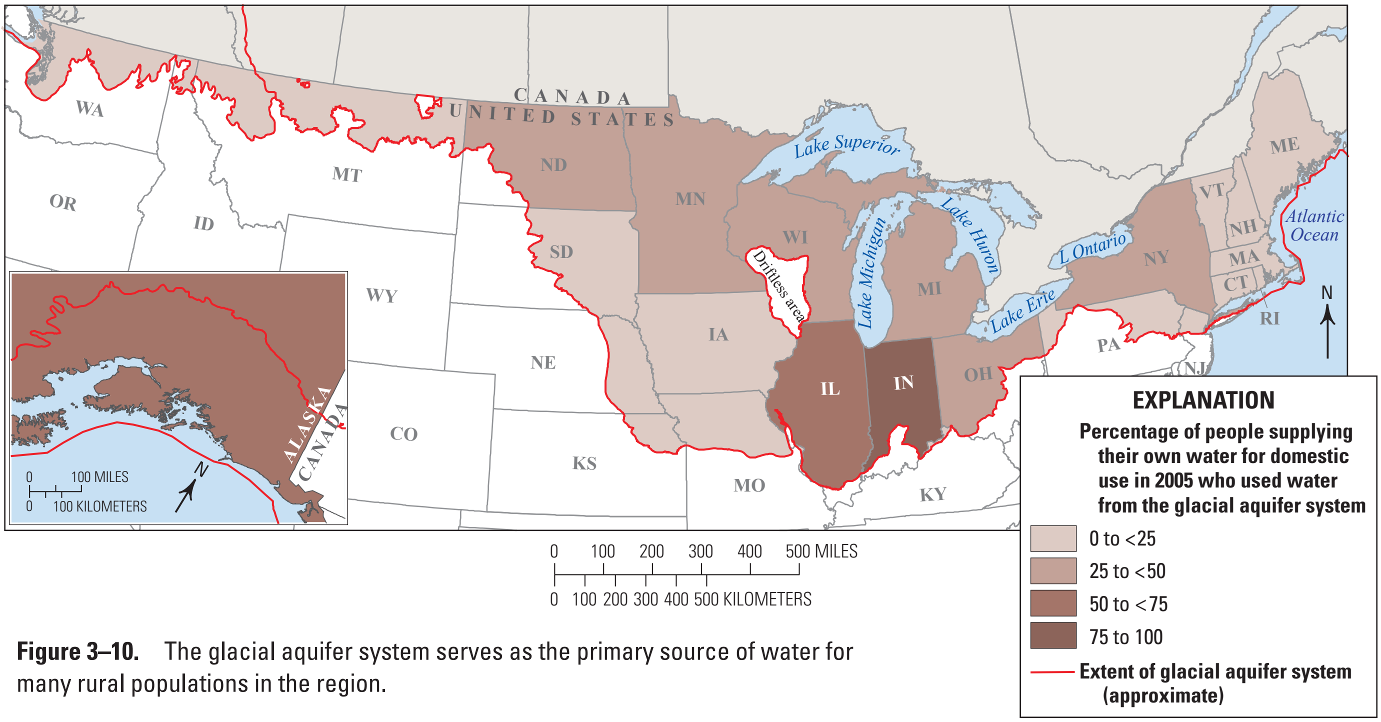


Modified from Maupin and Arnold[6] and Maupin and Barber[7]

Figure 3–9. Public supply is the primary use of groundwater from the glacial aquifer system, although most of the rural population relies on domestic-supply wells.

Photograph by Jennifer Sharpe, USGS

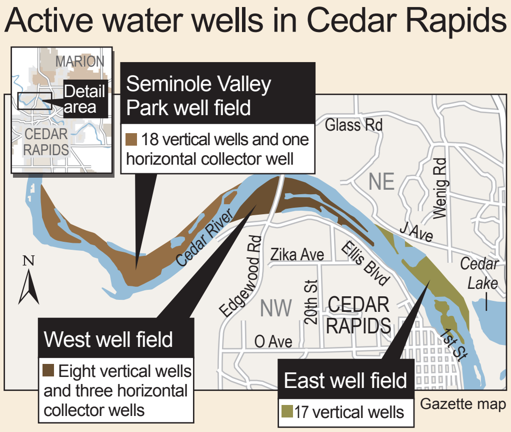
The amount of Lake Michigan water available for new allocations in Illinois is small relative to expected demand throughout the Chicago metropolitan region. The demand for groundwater is expected to double by 2050 (Tim Loftus, Chicago Metropolitan Agency for Planning, oral commun., October 10, 2012).



Water-use population from Maupin and Arnold,[6] modified for NH, ME, and MA/RI based on oral communication from Joseph Ayotte, Martha Nielson, and Leslie DeSimone (respectively), all of USGS, January 2012

Figure 3–10. The glacial aquifer system serves as the primary source of water for many rural populations in the region.

Enhancing groundwater supplies by inducing infiltration of river water

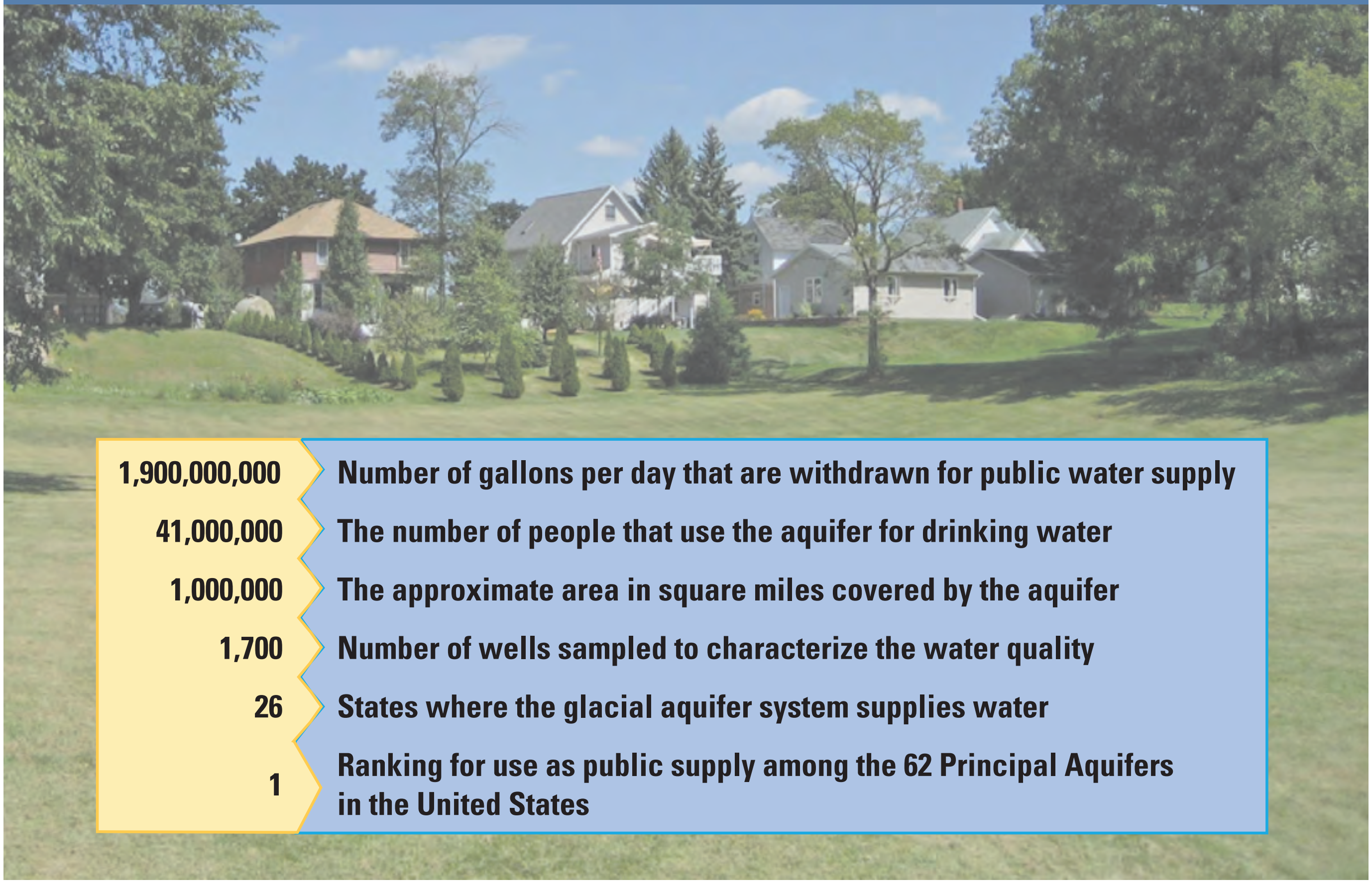


Wells near streams can yield larger quantities of water than other wells because, when the wells are pumped, water can be diverted from the stream to the well. With this benefit, however, comes the risk that floodwater can overtop well casings, shutting down pumps and introducing contaminants into the groundwater. Raising well casings to heights that floodwaters will not reach is one way to protect the water supply. The city of Cedar Rapids, Iowa, spent $2.1 million doing exactly that—raising the casings by 10 feet on its 43 water wells along the Cedar River. This change protects against well outages and direct contamination, particularly by microbial contaminants, but may not protect against chemical contaminants, such as certain pesticides that are transported in streamwater that moves through aquifer sediments to the pumping well (reproduced with permission from The Gazette, March 23, 2012, Cedar Rapids, Iowa).

Water pumped from wells near streams can contain additional contaminants.

Map and photograph republished with permission ©2012 SourceMedia Group, Cedar Rapids, Iowa

The glacial aquifer system at a glance



1,900,000,000	**Number of gallons per day that are withdrawn for public water supply**
41,000,000	**The number of people that use the aquifer for drinking water**
1,000,000	**The approximate area in square miles covered by the aquifer**
1,700	**Number of wells sampled to characterize the water quality**
26	**States where the glacial aquifer system supplies water**
1	**Ranking for use as public supply among the 62 Principal Aquifers in the United States**

Photograph by Kelly L. Warner, USGS

Chapter 4: *Natural Processes and Human Activities That Affect the Quality of Water*

Groundwater-flow rates, aquifer geochemistry, hydrologic modification, and contaminant releases affect groundwater quality in the glacial aquifer system. Understanding these processes and how they interact can improve our ability to interpret groundwater-quality patterns and trends and can lead to improved management of groundwater resources.

This chapter explains and discusses the hydrologic and geochemical processes and human activities that affect the movement and quality of groundwater in the glacial aquifer system.

Floodwaters can introduce contaminants to wells. Shown here is a flooded park along the Mississippi River near Rapid City, Illinois.

Photograph by Kelly L. Warner, USGS

Hydraulic Properties of the Aquifer Control Groundwater Flow Rates and Affect Water Quality

The glacial aquifer system is made up of unconsolidated sediments of gravel, sand, silt, and clay that formed from the periodic advance and retreat of large continental glaciers. The texture, grain size, and sorting of glacial sediments determine aquifer hydraulic properties, which affect groundwater-flow rates. These rates, in turn, affect the length of time water is in the aquifer, how long it interacts geochemically with the sediments, and the path it takes as it flows through the aquifer—all factors that affect the quality of groundwater.

Well-sorted coarse-grained sediments like outwash constitute the most productive part of the glacial aquifer system. Although outwash sediments represent only a small percentage of the land area overlain by glacial sediments, they are an important source for public water-supply systems. Glacial deltaic sediments also are well sorted and, where coarse-grained, also can be productive aquifers. Glacial lacustrine sediments, formed from sediment-laden meltwater in glacial lakes, commonly contain fine-grained silt and clay sediments that can impede groundwater flow, so these sediments rarely are used for public water supply.(8) The most extensive type of glacial sediment is glacial till. Glacial till includes a mixture of unsorted sediments of various grain sizes that can be clay rich and therefore less productive for water supply. Because of their low permeability, till sediments restrict groundwater flow and therefore the movement of contaminants from the land surface to more productive aquifers that might be beneath the till. However, despite their low permeability, till sediments in some parts of the glacial aquifer system, particularly rural areas, are the only source of water and are used extensively for domestic supply.

Aquifer Sediments Can Be a Source of Contaminants in Groundwater

Geochemical processes involving sorption and exchange reactions on glacial sediments, mineral dissolution, and precipitation reactions can cause constituents to be released from glacial sediments into groundwater and vice versa. Local geochemical processes, water-sediment reactions, and hydrogeologic and geochemical properties of the aquifer can play an important role in determining whether or not constituents become dissolved in groundwater and later are transported to wells or streams.

A source is necessary for a contaminant to be present in groundwater, but geochemical processes ultimately determine the fate of a contaminant in groundwater.

Whether or not groundwater contains constituents with geologic sources and at what concentrations depends on the composition of the sediments that compose the glacial aquifer system and the geochemical conditions within the aquifer. The minerals in the sediments largely reflect the composition of the underlying bedrock and the geologic terrains over which the glacial ice advanced. For example, glacial sediments associated with the James and Des Moines Lobes contain rock fragments and sediment derived from shale and sandstone; Huron Lobe sediments contain black shale and limestone (see sidebar, Glacial depositional processes affect groundwater flow and chemistry today, p. 19). Certain rock types, such as black shale, are naturally enriched in certain trace elements, such as arsenic or uranium. Also important is the presence or absence of organic carbon derived from plant remains such as wood fragments; this type of carbon plays a key role in determining the redox conditions in the aquifer. In addition, the geochemical conditions in the groundwater must be favorable for the contaminant to remain dissolved and can affect whether contaminants react with or degrade to other compounds.

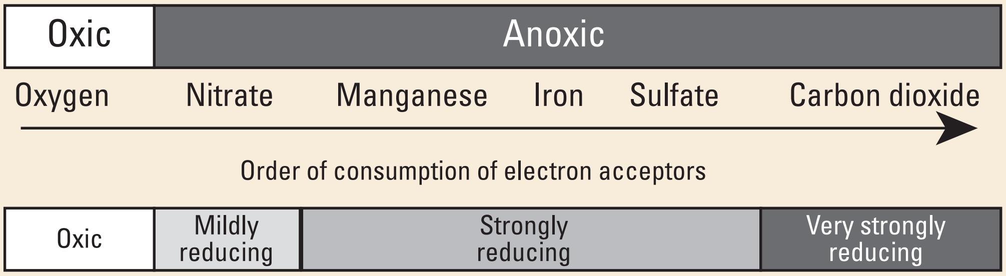
Hydraulic properties of sediment can vary greatly across the glacial aquifer system. One way to determine hydraulic properties at specific depth intervals is to collect subsurface samples (cores) of the aquifer material and analyze the distribution of grain sizes. Geochemical properties can be determined from chemical analysis of the sediment.

Redox Processes Can Remove Some Contaminants From Groundwater But Can Add Others

Reduction/oxidation (redox) processes affect the chemical quality of groundwater in the glacial aquifer system. Such reactions can contribute to the degradation of contaminants from human activities, such as nitrate and VOCs, but also can cause contaminants from geologic sources, such as arsenic or uranium, to be released into the groundwater or to precipitate onto sediment.(9) Determining the kinds of redox processes in the glacial aquifer system, documenting the spatial distribution of redox conditions, and understanding how redox affects concentrations of contaminants from geologic and human activities is important for assessing and predicting the quality of groundwater (see sidebar, How do redox reactions work?, below).

How do redox reactions work?

Reduction/oxidation (redox) processes require one chemical species that donates electrons and another chemical species that accepts those electrons. As a chemical species donates electrons it is “oxidized,” and as the other species accepts electrons it is “reduced.” Redox processes typically are facilitated by microbes (bacteria), which use the energy produced by the processes. In groundwater, organic carbon is the most common electron donor. If dissolved oxygen is present, it is the preferred electron acceptor, because reduction of dissolved oxygen produces more energy than reduction of other chemical species that commonly occur in groundwater. The atmosphere is the source of the dissolved oxygen, so the redox conditions in an aquifer near where recharge occurs usually are oxic (defined here as having a concentration of dissolved oxygen of at least 0.5 mg/L).



As groundwater moves through the aquifer along a flow path, the dissolved oxygen in the groundwater gradually is consumed by redox processes. Once all of the dissolved oxygen is consumed, other chemical species can accept electrons and become reduced. If nitrate is present, it will become the preferred electron acceptor until it in turn is completely consumed. This pattern continues, with manganese, iron, sulfate, and finally carbon dioxide acting as electron acceptors until they are consumed, in that order. This order of use of electron acceptors has important implications for the preservation, degradation, and even production of contaminants in groundwater. Because redox reactions occur in a sequence, it can take a long time for strongly reducing conditions to develop. For this reason, anoxic groundwater commonly is older than oxic groundwater, and, within the anoxic category, strongly reducing groundwater commonly is older than mildly reducing groundwater.

From a water-quality perspective, denitrification—the reduction of nitrate to nitrogen gas—is one of the most important redox processes that occurs in groundwater. Nitrate is a concern for human health and, where it discharges to surface water, can impair aquatic communities. Conversion of nitrate by denitrification to harmless nitrogen gas, the same gas we breathe in the atmosphere, is the primary way that nitrate is removed from water.

In the glacial aquifer system, most samples of groundwater were oxic, that is, containing at least 0.5 mg/L of dissolved oxygen (fig. 4–1). In the east and west regions, more than three-fourths of the water samples were oxic, largely because the sediments are relatively permeable and contain little organic matter. However, in the west-central and central regions of the glacial aquifer system, nearly half of the samples of groundwater were anoxic (containing less than 0.5 mg/L dissolved oxygen). This anoxia is partly due to the composition of the aquifer sediments, which have high clay content (which can impede groundwater flow) and contain abundant organic matter that microorganisms use to facilitate energy-producing redox reactions.

Because of the anoxic conditions in the central parts of the glacial aquifer system, contaminants such as nitrate are more likely to be reduced through denitrification. For example, near the Otter Tail River in Minnesota, little nitrate is reduced in the shallow, young, and oxic groundwater, but as groundwater moves into older anoxic water at greater depths in the aquifer, denitrification converts nitrate to inert nitrogen gas (fig. 4–2).(10) However, constituents such as arsenic, where present on iron oxide coatings on glacial sediments, can readily dissolve into groundwater under anoxic conditions.

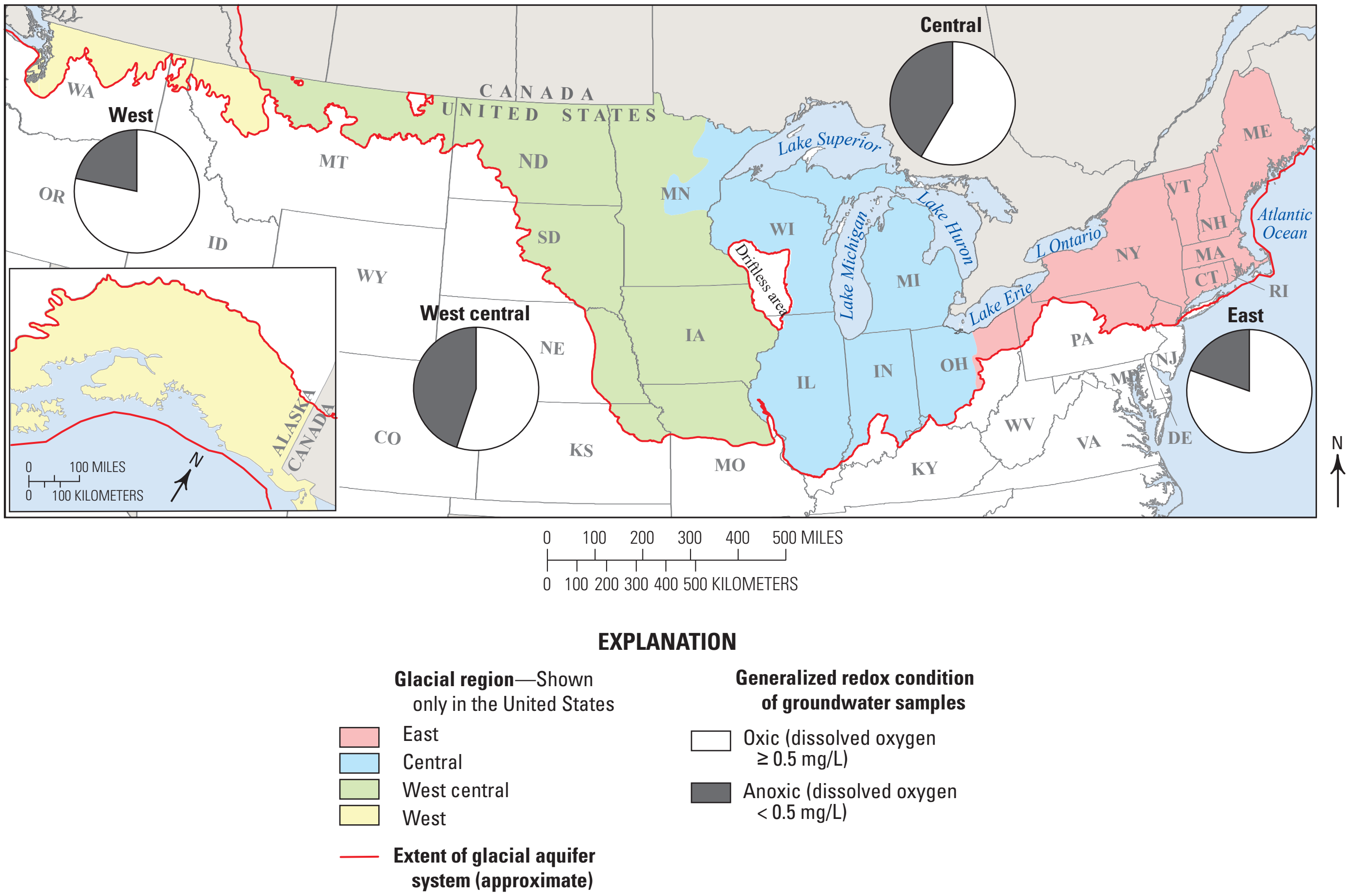


Figure 4–1. In the glacial aquifer system, redox conditions commonly were oxic in the east and west regions. In the central and west-central regions, however, nearly half of the samples were anoxic.

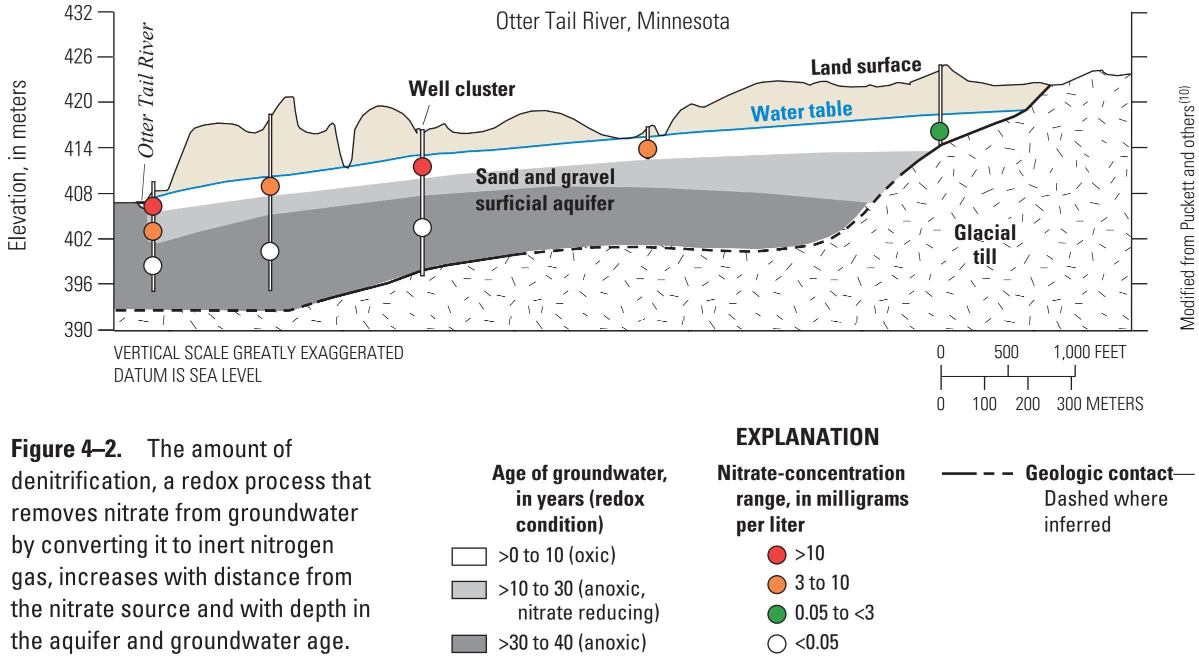


Figure 4–2. The amount of denitrification, a redox process that removes nitrate from groundwater by converting it to inert nitrogen gas, increases with distance from the nitrate source and with depth in the aquifer and groundwater age.

Groundwater pH Is an Important Geochemical Control on the Occurrence of Selected Trace Elements

Groundwater pH can affect the concentrations of many trace elements in groundwater, including cadmium, cobalt, copper, lead, nickel, and zinc. These trace elements commonly exist as positively charged ions, or cations, that are more likely to be adsorbed, or be attached, to metal oxide coatings on aquifer sediments at higher pH (fig. 4–3). At higher pH, the surface charge of metal oxides that commonly coat aquifer sediments becomes more negative, attracting the positively charged trace-element ions and decreasing the concentrations of those elements in groundwater.(11) Conversely, trace elements typically present as negatively charged anions, such as arsenic, chromium, selenium, and molybdenum, are released from oxide coatings as pH increases, resulting in higher concentrations of these trace elements in groundwater. The amount of a trace element that is adsorbed to aquifer sediments or dissolved in groundwater depends on the amounts of metal oxides and dissolved organic carbon present. Furthermore, at near-neutral pH (pH around 7) and under oxic conditions, metal oxide coatings (such as iron oxides) are stable, but under anoxic conditions (at the same pH), these coatings can dissolve, releasing into the groundwater any trace elements adsorbed to them. This important process affects arsenic concentrations in all regions of the glacial aquifer system.(12, 13)

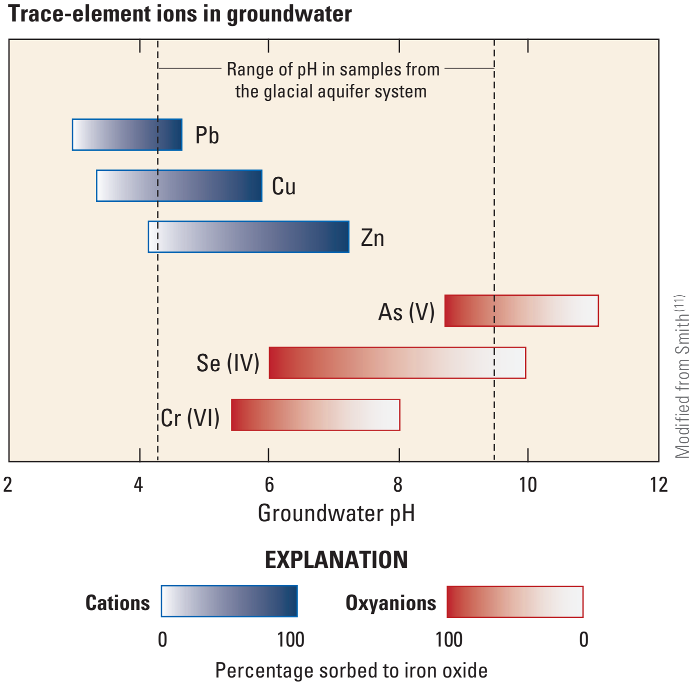


Figure 4–3. As pH increases, certain trace element cations (positively charged ions, in blue), such as lead (Pb), copper (Cu), and zinc (Zn), can be adsorbed to iron oxide coatings on glacial sediments, whereas oxyanions (negative ions that contain oxygen, in red) of chromium (Cr), selenium (Se), and arsenic (As) can be desorbed (detached) from glacial sediments and are released into groundwater with increasing pH.

Ion Exchange Affects the Concentrations of Contaminants in Groundwater

In a process called “ion exchange,” ions adsorbed to clays, metal oxide coatings, or organic material are released and replaced with ions that were in the groundwater. For example, sodium on the surface of clay minerals can be exchanged for calcium and magnesium in groundwater. This exchange decreases the hardness of the water but increases the sodium concentration in the water (see sidebar, Treating hard water, below). The process also can proceed in reverse, depending on the concentrations of the ions dissolved in the water and other factors. Where groundwater in the glacial aquifer system in the northeastern United States has high concentrations of dissolved sodium as a result of contamination from deicing salt, the exchange of sodium in groundwater for other cations on aquifer sediments has been reported (14) (see Chapter 7 section entitled Chloride). Ion exchange also can cause trace elements such as arsenic and chromium to be released from sediments into groundwater.

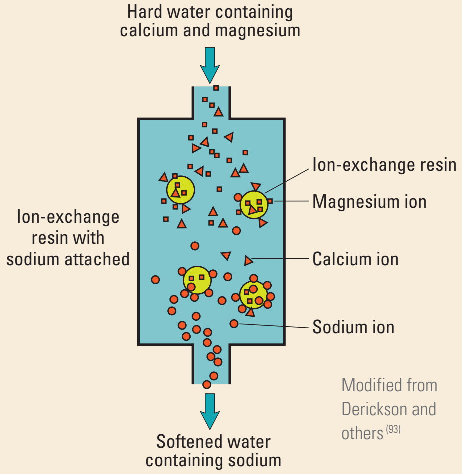
Precipitation and Dissolution of Minerals Change Groundwater Chemistry

Redox conditions are an important control on whether minerals will be dissolved in the groundwater, potentially at high concentrations, or precipitate as solids onto the sediment. For example, under anoxic conditions, metal oxide minerals that coat the aquifer sediments dissolve, releasing iron and manganese into the groundwater.(9) Concentrations of iron and manganese in the glacial aquifer system commonly exceed water-quality standards (SMCLs) established for aesthetic (nuisance) considerations, such as unpleasant taste and staining of laundry and plumbing fixtures. When metal oxide minerals dissolve, other elements such as arsenic that were previously adsorbed to these coatings also can be released into the groundwater. Similarly, when sediments derived from limestone or dolomite dissolve, calcium, magnesium, and bicarbonate ions are released into groundwater. The resulting bicarbonate ions can form aqueous complexes—molecules that include water—with elements such as uranium, increasing the uranium concentration in the groundwater (see Chapter 6 section entitled Uranium and Radon).

Treating hard water

Water softeners commonly are used to reduce the high concentrations of calcium and magnesium ions (the primary sources of hardness in water) in groundwater in the central and west-central regions of the glacial aquifer system. Water softeners work by replacing the calcium and magnesium (or iron) ions in household water with sodium ions. The softeners contain plastic resin that is coated with sodium ions (from salt). As water passes over the resin, calcium and magnesium ions in the water are absorbed by the resin, releasing the sodium ions. Once the resin is saturated with calcium and magnesium, the device rinses the resin with a high concentration of salt solution (brine), which removes the calcium and magnesium ions from the resin and replaces them once again with sodium ions. The excess brine, along with the calcium and magnesium ions, is sent down the drain. The initial cost of water softeners ranges from $1,500 to $3,000, and the devices require about $100 per year to maintain.(75) The savings from water softening, however, which increases the lifetime of plumbing and heating fixtures, can outweigh the costs.

Softening process



Modified from Derickson and others (93)

High concentrations of calcium and magnesium in groundwater are exchanged for sodium during the softening process. The softened water contains sodium instead of the hard-water ions of calcium and magnesium. When the sodium on the resin is depleted, and the resin is saturated with calcium and magnesium ions, a sodium-brine rinse washes these ions away (to a drain), and the resin is recharged with sodium ions.

Geochemistry and Groundwater Quality Are Related to Groundwater Age

Many of the geochemical processes that affect groundwater quality continue over a long period of time. The longer the water is in contact with aquifer materials, the greater the degree to which geochemical processes can change the pH, dissolved oxygen content, and concentration of dissolved solids of the groundwater.

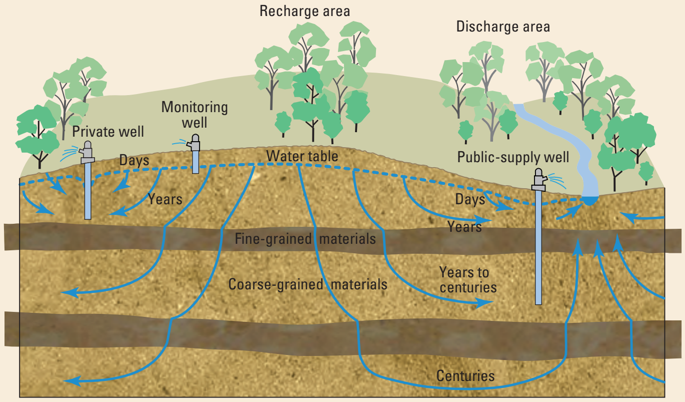
The age of a sample of groundwater indicates when the water entered the aquifer as recharge. In this report, groundwater is characterized as “young” or “old”; young groundwater is defined as water that was recharged within the past 50–60 years—recharged after 1952, or following atomic-bomb testing—and old groundwater is defined as water that was recharged more than 50–60 years ago (see sidebar, What is groundwater age?, below).

Groundwater age increases as the groundwater moves away from the point of recharge, either laterally or deeper into the aquifer. Groundwater in the glacial aquifer system can be many months to many hundreds of years old. Groundwater age is controlled in part by the hydraulic properties of the glacial aquifer system, which affect flow rate. Groundwater age also is controlled by the amount of recharge the aquifer receives, which, like hydraulic properties, affects the groundwater-flow rate. Most parts of the glacial aquifer system are in humid-climate regions. In these areas, the aquifer receives large amounts of recharge in the form of precipitation. In humid areas underlain by coarse-grained glacial sediment, groundwater moves through the aquifer quickly and is mostly young, whereas in drier climates or parts of the glacial aquifer system dominated by fine-grained sediments, groundwater moves slowly and can be hundreds or thousands of years old. Older groundwater has had more time to interact with aquifer sediment than has younger groundwater, and this interaction causes changes to the groundwater chemistry that generally are predictable. For example, as young groundwater in the glacial aquifer system becomes old, it tends to evolve from oxic to anoxic, moderate to higher pH, and lower to higher concentrations of dissolved solids. Older groundwater from wells that are screened in the deep parts of the glacial aquifer system generally has these characteristics, all of which can affect groundwater quality.

Concentrations of nitrate and arsenic in groundwater illustrate the effects of groundwater age. Nitrate, a contaminant that is introduced by humans at the land surface, is more common in wells that tap shallow, young groundwater than in wells that tap deep, older groundwater, because nitrate degrades under the anoxic conditions more prevalent in deep, old groundwater (fig. 4–2). By contrast, arsenic, a contaminant that can be derived from geologic sources and that dissolves readily under anoxic conditions, is more common in deep, old groundwater.

What is groundwater age?

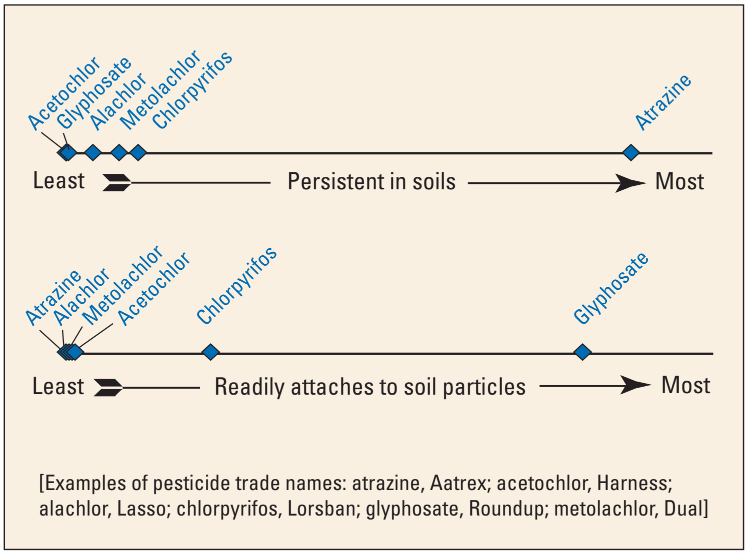
Groundwater age refers to the time elapsed since recharge water reached the groundwater table and became isolated from the atmosphere.(94, 95) The term “age” is sometimes qualified with the word “apparent” to signify that the accuracy of the determined age depends on many variables. Groundwater age can provide information on the susceptibility of the aquifer to contamination from chemicals related to human activities, because recently recharged groundwater is more likely to be contaminated than groundwater that is hundreds of years old. Many chemicals related to human activities have no natural sources and were developed only during the last 60 years or so; these chemicals are unlikely to be detected in groundwater older than that. Estimates of groundwater age can be made by measuring the concentrations of compounds and radioactive substances that infiltrated into the ground with the water and travelled to the sampling point.(96, 97) Generally speaking, groundwater ages of less than 60 years (recharged after 1952) are classified as “young” in the Principal Aquifers described in this series of Circulars. Groundwater ages generally increase with depth in the aquifer. Some contaminants, like nitrate, are common in young groundwater, whereas other contaminants, like arsenic, are common in older groundwater. The youngest groundwater is at or just below the water table. Groundwater can be many months (in coarse-grained sediments) to hundreds of years old (in fine-grained sediments), depending on aquifer hydraulics and flow paths. Because public-supply wells pump water at very high rates, groundwater is captured from many flow paths, and as a result, the water pumped from the well can be a mixture of water of different ages and, in some cases, can include water captured from streams.



NOT TO SCALE

Pesticides That Do Not Readily Adhere to Soils Are Frequently Detected in Groundwater

Although pesticide compounds are most common in streams and groundwater in areas with the highest rates of pesticide use, the likelihood that a pesticide compound will be measured in groundwater also depends on how long it takes for the pesticide to degrade and whether it can readily adhere to soil particles.(15) The widely used pesticide atrazine does not degrade rapidly in soils (fig. 4–4) and dissolves readily in water and, as a result, atrazine is one of the most frequently detected pesticides in streams and groundwater.(15) Glyphosate, by contrast, degrades more rapidly and attaches much more readily to soil particles. For this reason, when it is applied at similar rates, glyphosate is detected less frequently in streams and groundwater than is atrazine. Many pesticides degrade to other compounds with chemical characteristics that are different from those of the pesticide originally applied. Metolachlor, alachlor, and acetochlor, for example, are heavily used and degrade most rapidly in soils, but their degradation products last comparatively longer than the parent compound and are more soluble—therefore, they are more frequently detected in groundwater than are the pesticides originally applied(15, 16, 17) (see Chapter 7 section entitled Pesticides).



[Examples of pesticide trade names: atrazine, Aatrex; acetochlor, Harness; alachlor, Lasso; chlorpyrifos, Lorsban; glyphosate, Roundup; metolachlor, Dual]

Modified from Baker and others(57)

Figure 4–4. The chemical characteristics of a pesticide determine whether that pesticide breaks down rapidly in soil (is not persistent) and whether it attaches to soil particles rather than being transported in water. Atrazine degrades slowly in aerobic soil and does not readily attach to soil particles; it therefore is commonly detected in groundwater. Glyphosate, by contrast, readily attaches to soil particles and degrades more rapidly than atrazine; glyphosate, therefore, is less commonly detected in groundwater than is atrazine.

Groundwater Pumping Can Cause Mixing of Groundwater

Pumping water from supply wells can lower water levels, which in turn can alter groundwater flow near wells and cause groundwater from different parts of the aquifer to mix.(3, 18) If waters from those different parts of the aquifer system have different redox conditions, then mixing of the two can lead to mixed redox conditions in the area affected by pumping. The pumping-induced mixing of groundwater of different ages and chemistries can have the unintended consequence of changing redox conditions, causing chemical constituents that were adhered to or incorporated into the aquifer sediments to dissolve into the groundwater.(19) For example, if pumping causes deep, anoxic groundwater to flow to a part of the aquifer where arsenic is adsorbed to iron oxides, the iron oxides can dissolve, releasing the associated arsenic to the groundwater.

A mixture of young and old groundwater can occur in locations where only old water is expected when groundwater flow paths are short-circuited, allowing water from various depths to flow quickly to a well (fig. 4–5). In the glacial aquifer system, the natural fractures and cracks in fine-grained tills and discontinuities in fine-grained layers can provide those pathways. Additionally, deep, long, or multiple-screen wells that are not being pumped can serve as conduits for groundwater, allowing contaminants in shallow parts of the aquifer to reach deep parts relatively quickly.(20) Similarly, gray water (wastewater from laundry, dishwashing, and bathing) that is introduced into the groundwater through underground structures can find short-circuit flow paths.(21)

High-volume pumping of supply wells can also cause the direction of groundwater flow to change. In some cases, this change in flow direction can cause contaminated groundwater—such as wastewater from leaking sewer lines, water from a stream (induced infiltration), or shallow groundwater—to flow toward the supply well. For example, high-volume pumping of municipal-supply wells screened in the glacial aquifer system in Wisconsin caused diversion of contaminated water to the well, and human enteric virus was detected in the groundwater pumped.(22) Pumping of water from the glacial aquifer system, if substantial enough, also can cause sideways or upward migration of groundwater from adjacent or underlying bedrock aquifers into the glacial aquifer system.(23)

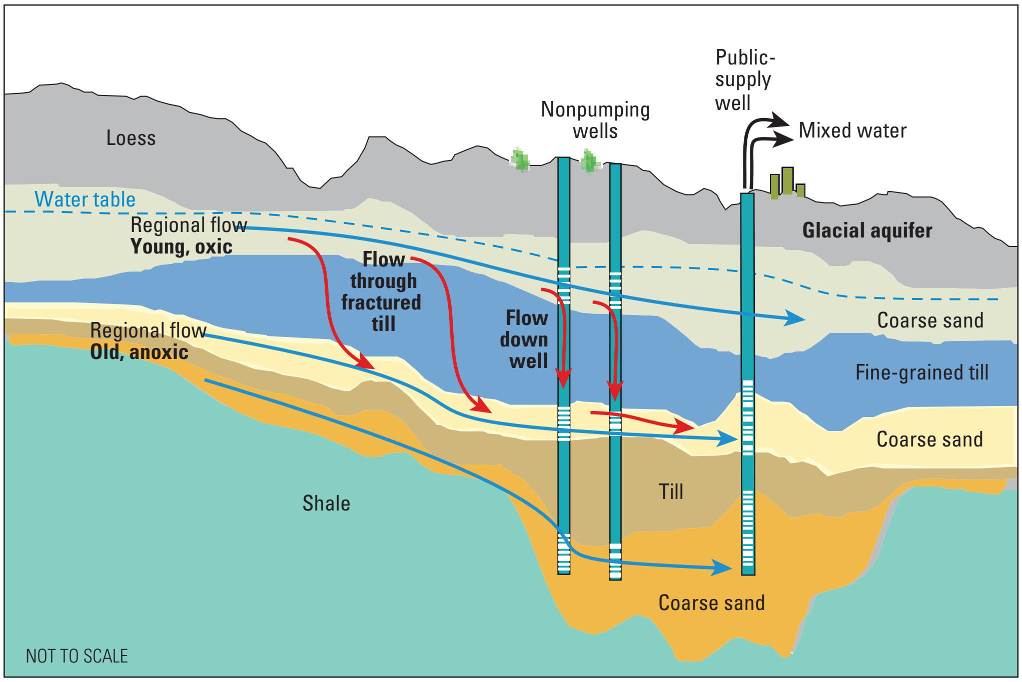


Figure 4–5. Redox conditions (oxic or anoxic), groundwater age (young or old), and short-circuited flow paths (flow up or down well bores or through cracks in fine-grained layers) are three important factors to consider in assessing the vulnerability of public-supply wells to contamination.

Artificial Drainage Can Redirect Contaminants to Streams

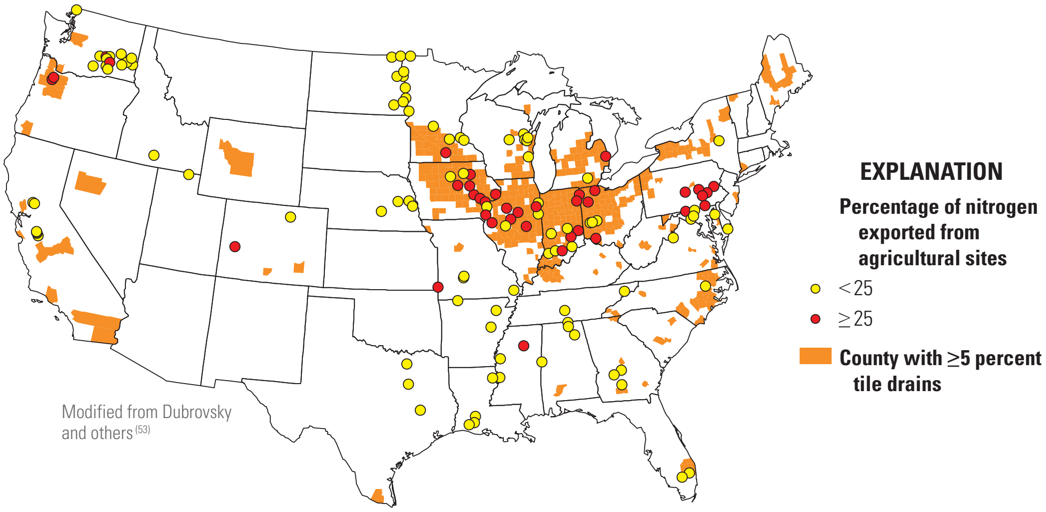
Artificial drainage of fine-grained sediments in agricultural areas makes the soil more productive for crops by removing excess water from the soil zone. This practice decreases recharge to the aquifer and therefore the amount of fertilizer and pesticides that normally would infiltrate down to the water table. Although artificial drainage can improve groundwater quality, it can degrade streamwater quality.

In the central region of the glacial aquifer system where precipitation is abundant, glacial sediments are fine-grained and therefore poorly drained. These two factors combined result in excess water into and onto farm soils, so artificial drainage is required to effectively cultivate corn, soybeans, and other crops (fig. 4–6). Precipitation on the land surface is rerouted to streams by tile drains and ditches, preventing water from infiltrating and reducing the overall amount of recharge to the aquifer.

An unintended effect of artificial drainage is that not only water but also excess nutrients and pesticides are rerouted to streams. As a result, a smaller amount of nutrients and pesticides reaches the water table, but a larger amount is delivered to streams. Elevated concentrations of these contaminants in streams increase their loading to receiving waters such as the Gulf of Mexico. In some instances, these chemicals are still delivered to the groundwater, albeit by a circuitous route: downstream supply wells placed near stream banks can capture water from nearby streams. This practice, called "induced infiltration," also can draw in the elevated concentrations of nutrients and pesticides from these streams (see sidebar, Induced infiltration—Surface-water quality affects groundwater quality, p. 84).

Photograph by Dana Kolpin, USGS

Figure 4–6. Photograph, Subsurface drains, commonly referred to as "tile drains" (the white pipe with water flowing into the ditch is the endpoint of a tile drain), remove excess water from the soil root zone, thereby transporting associated agricultural chemicals to drainage ditches and nearby streams.(57) Map, Tile drains have been installed throughout much of the Corn Belt of the United States in the central region of the glacial aquifer system, which improves groundwater quality but raises concentrations of nitrogen and pesticides in streams.



Modified from Dubrovsky and others(53)

Chapter 5: *Quality of the Groundwater Resource Used for Drinking*

More than 22 percent of samples from drinking-water wells that rely on groundwater from the glacial aquifer system contained at least one constituent at a concentration that exceeded its human-health benchmark. At least one constituent from geologic sources, such as arsenic, manganese, strontium, uranium, selenium, and molybdenum, was present at a concentration of concern for human health in 26 percent of public-supply and 18 percent of domestic-supply wells. A constituent derived from human activities, such as a VOC or pesticide, exceeded its benchmark in 3 percent or fewer of public-supply or domestic-supply wells (table 5–1), although low-level concentrations of these compounds were widespread.

This chapter identifies and discusses constituents that were detected at a concentration greater than or near a human-health benchmark in water from drinking-water supply wells tapping the glacial aquifer system.

Photograph by Jennifer B. Sharpe, USGS

Contaminants From Geologic Sources Are a Greater Concern Than Those From Human Activities

In samples from drinking-water wells, concentrations of contaminants from geologic sources were five times more likely to exceed their human-health benchmarks than were concentrations of contaminants from human activities (fig. 5–1). Arsenic and manganese—which both originate from geologic sources—exceeded their respective human-health benchmarks in 11 percent of samples from drinking-water wells (table 5–2). The percentage of samples with a concentration of arsenic greater than its Maximum Contaminant Level (MCL) of 10 µg/L was similar for public-supply and domestic-supply wells, whereas concentrations of manganese exceeded its benchmark of 300 µg/L in almost twice as many public-supply wells (17 percent) as domestic-supply wells (9 percent). Radon exceeded its proposed MCL of 300 picocuries per liter (pCi/L) in half of the drinking-water-supply wells sampled; however, exceedances of the proposed Alternate Maximum Contaminant Level (AMCL) (4,000 pCi/L) were rare.

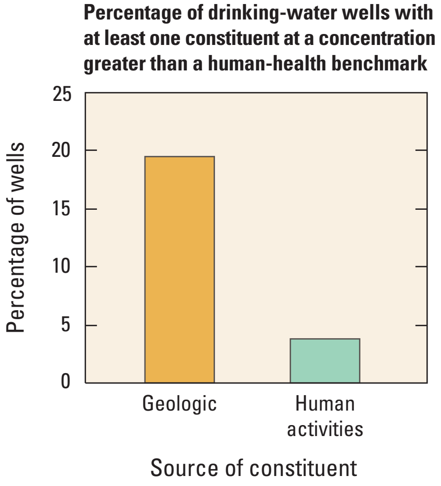


Figure 5–1. Drinking-water wells were five times more likely to have a contaminant derived from geologic sources that exceeded a human-health benchmark than a contaminant derived from human activities.

Arsenic and manganese—which both originate from geologic sources—exceeded respective human-health benchmarks in 11 percent of samples from drinking-water wells.

What is a contaminant?

Contaminants have a wide range of sources, both manmade and geologic. Most organic chemicals in groundwater that are of concern for human health are manmade. In contrast, most inorganic constituents in groundwater have geologic or other natural sources, although their concentrations in groundwater may be altered by human activities, such as irrigation and groundwater pumping. Some contaminants have both manmade and natural sources. For example, nitrate in groundwater has many natural sources, but nitrate concentrations in groundwater underlying agricultural and urban areas commonly are higher than in other areas because of contributions from sources associated with human activities.

But what exactly is a contaminant? The word means different things to different people. For example, a contaminant is defined by the Safe Drinking Water Act (SDWA) as “any physical, chemical, biological, or radiological substance or matter in water” (see *http://www.epw.senate.gov/sdwa.pdf*). This broad definition of contaminant includes every substance that may be found dissolved or suspended in water—everything but the water molecule itself. This is not a very practical definition because this would imply that all water is “contaminated.” Pure water that has nothing dissolved in it does not occur naturally—not even rainfall is pure water, because it contains, at a minimum, some dissolved gases.

The U.S. Environmental Protection Agency defines a contaminant as “Any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil” (see *http://epa.gov/region04/superfund/qfinder/glossary.html*). This definition is more practical and allows both manmade constituents and those with geologic sources in water to be defined as contaminants. However, it does not define what “adverse” means, and what may be adverse in one way might be beneficial in another. In this circular, a contaminant is defined as any physical, chemical, biological, or radiological substance or matter in groundwater that is manmade or that impairs the use of water for its intended purpose. Impairment is determined by comparing a measured concentration to benchmarks or guidelines. By this definition, all manmade compounds, such as pesticides and volatile organic compounds, are contaminants because they do not occur naturally in groundwater. If a constituent with a geologic source, such as arsenic, occurs in drinking water at a concentration above its human-health benchmark, it also is considered a contaminant.

Human-health benchmarks and other guidelines used in this assessment

Concentrations of constituents measured for this assessment were compared to human-health benchmarks to place study findings in the context of human health. The benchmarks are threshold concentrations in water above which the concentration of a contaminant in drinking water could adversely affect human health. Human-health benchmarks were available for about two-thirds of the 290 constituents and properties measured for the Principal Aquifer assessments (appendix 2). Two types of human-health benchmarks were used: U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) (*http://water.epa.gov/drink/contaminants/index.cfm*) and U.S. Geological Survey (USGS) Health-Based Screening Levels (HBSLs). MCLs are legally enforceable drinking-water standards that specify the maximum permissible level of a constituent in water that is delivered to any user of a public water system(118) (values used in this report were current as of February 2012). Although MCLs are used to regulate the quality of drinking water only from public-supply sources, they also are useful for evaluating the quality of water from domestic and monitoring wells. An MCL was available for 53 of the constituents measured. For some constituents for which an MCL has not been established, the USGS, in collaboration with the USEPA and others, developed non-enforceable HBSLs by using standard USEPA methods for establishing drinking-water guidelines and current toxicity information(99, 100) (values used in this report were current as of February 2012; see *http://water.usgs.gov/nawqa/HBSL*). An HBSL was available for 135 constituents measured. Radon has neither an MCL nor an HBSL, but two MCLs have been proposed. Copper and lead have USEPA action levels rather than an MCL.

In addition to human-health benchmarks, non-health-based guidelines—Secondary Maximum Contaminant Levels (SMCLs)—were available for some of the constituents measured in this assessment. The SMCLs are non-enforceable guidelines for concentrations of "nuisance" constituents in drinking water that can cause unwanted cosmetic effects, such as skin or tooth discoloration; aesthetic effects, such as unpleasant taste, odor, or color; or technical effects, such as corrosion or sedimentation of plumbing or reduced effectiveness of water treatment.(98)

Concentrations greater than one-tenth of a human-health benchmark were used in this assessment to indicate which contaminants occurred, either individually or as mixtures, at concentrations that approach those of potential concern for human health, and to identify contaminants that might warrant additional monitoring and study. The criterion of one-tenth of a benchmark is consistent with various State and Federal practices for reporting contaminant occurrence in groundwater and for identifying contaminants of potential human-health concern (for example, see U.S. Environmental Protection Agency;(101) New Jersey Department of Environmental Protection(102)).

Screening-level assessments, such as this one, provide perspective on the potential relevance of detected contaminants to human health and can help in planning future studies.(100) They are not designed to evaluate specific effects of contaminants on human health and are not a substitute for comprehensive risk assessments. It is important to note that occurrence of a contaminant at a concentration greater than its benchmark does not mean that adverse effects are certain to occur, because the benchmarks are conservative (protective) and source-water samples were collected prior to any treatment or blending that could alter contaminant concentrations in finished drinking water. There are water-treatment options, such as charcoal filtration, that can be used to lower the concentration of the contaminant to below the benchmark before the water is consumed.


Photograph by Kelly L. Warner, USGS

The glacial aquifer system is used for drinking water by more than 41 million people.

Human-Health Concerns: Contaminants From Human Activities

Contaminants from human activities, such as nitrate, pesticides, and VOCs, were detected frequently in groundwater samples but at low concentrations that rarely exceeded human-health benchmarks (table 5–1). Nitrate was measured at concentrations greater than 1 mg/L as nitrogen (N), which is one-tenth of the MCL, in 30 percent of samples from drinking-water wells, most of which were domestic-supply wells. Nitrate exceeded the MCL (10 mg/L as N) in only 2.9 percent of those samples (table 5–2). All glacial aquifer system domestic-supply wells sampled in which nitrate concentrations exceeded 10 mg/L as N contained predominantly young, oxic groundwater.(25) Young groundwater tapped by shallow domestic-supply wells is more vulnerable to nitrate contamination than deeper groundwater because young groundwater is nearer to the land surface (where nitrate is applied) and often oxic. Some domestic-supply wells tap the deep groundwater that is farther from the source of nitrate and commonly is anoxic—as a result, nitrate, if detected at all in these wells, generally is at low concentrations.

One or more pesticide compounds were detected in 33 percent of samples from drinking-water wells, but concentrations rarely exceeded a threshold level of 0.2 µg/L. This threshold is the highest common screening level for laboratory results; therefore, pesticide concentrations were compared at this threshold, unless otherwise noted. Only one pesticide, dieldrin, was measured at a concentration that exceeded its human-health benchmark, and that was in fewer than 1 percent of samples (table 5–2). Breakdown products of atrazine, the pesticide with the highest rate of application, were detected in 18 percent of samples from drinking-water wells, but generally at concentrations less than 0.2 µg/L (see Chapter 7 section entitled Pesticides)—15 times lower than the atrazine MCL of 3 µg/L. Pesticides were detected in about 33 percent of all wells and in nearly 50 percent of shallow wells used for monitoring groundwater underlying agricultural land, but concentrations were low (mostly less than 0.2 µg/L).

> *Nitrates, pesticides, and VOCs are commonly detected in water from domestic and public-supply wells but seldom exceed drinking-water standards—unlike arsenic, manganese, and other trace elements.*

The VOCs that exceeded a human-health benchmark in drinking-water wells were tetrachloroethene (fig. 5–2), 1,2 dichloropropane, and trichloroethene, each in less than 1 percent of wells. Tetrachloroethene, also known as perchloroethylene or PCE, was the most frequently detected VOC and was detected primarily in shallow groundwater underlying urban areas. Tetrachloroethene is a manmade chemical that is widely used in the dry cleaning of fabrics and also is used for degreasing metal parts and in manufacturing other chemicals. (See sidebar, Low-level volatile organic compound occurrence in the Midwest and Northeast, p. 41.)

Bacteria, such as coliform and *Escherichia coli* (*E. coli*), in groundwater can indicate the presence of surface sources of contamination, which might be expected in the glacial aquifer system where the water table is near the land surface.(26) Surprisingly, these bacteria were detected less frequently in domestic-supply wells in the glacial aquifer system, despite its shallow water table, than in domestic-supply wells in other aquifer systems across the Nation.(27) This unexpected result might be associated with the abundance of fine-grained materials that can filter out bacteria in the glacial aquifer system.

Table 5–1. Percentage of selected samples with one or more trace elements, VOCs, pesticides, nitrate, or radon exceeding existing or proposed human-health benchmarks in the glacial aquifer system wells sampled by the NAWQA Program, 1992–2003, by primary water use.

[Percentages shown in shaded cells are higher than national average for NAWQA samples; VOC, volatile organic compound; MCL, Maximum Contaminant Level]

Study type	Drinking-water supply wells				Monitoring wells		Other wells		All wells	
	Public		Domestic							
	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark
Trace element	121	**26**	479	**18**	1,006	**27**	37	22	1,643	**24**
VOC	134	**3.0**	389	0.3	702	**1.7**	28	0.0	1,253	1.4
Pesticide	136	1.5	436	0.0	980	1.3	34	0.0	1,586	1.0
Nitrate	121	1.7	458	3.0	1,002	**13**	35	6.0	1,616	**10**
Radon*	68	75	356	45	450	58	20	35	894	54

* U.S. Environmental Protection Agency proposed MCL is 300 picocuries per liter in water.

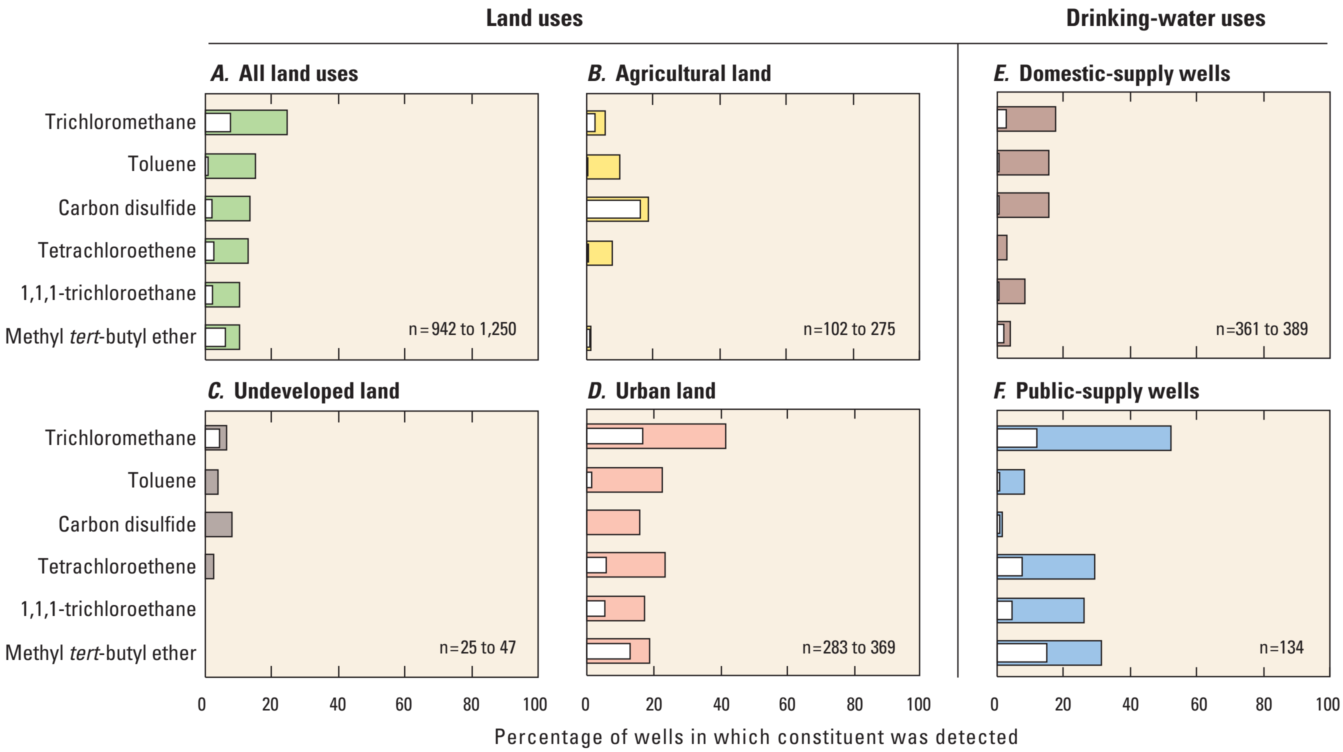


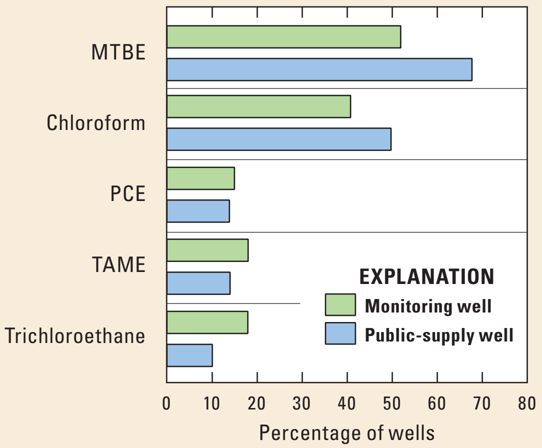
Figure 5–2. Volatile organic compounds (VOCs) were detected in more than 20 percent of all wells, but concentrations were low. The greatest frequency of detections and highest concentrations were in shallow groundwater underlying urban areas and in samples of groundwater from public-supply wells.

EXPLANATION

- ■ **Detected at any concentration**
- ☐ **Detected at a concentration ≥ 0.2 µg/L**

Low-level volatile organic compound occurrence in the Midwest and Northeast

Volatile organic compounds (VOCs) were detected commonly in shallow groundwater in the glacial aquifer system, although, like pesticides, concentrations generally were low. Some VOCs, such as chloroform (trichloromethane), were widely detected. Chloroform, which is associated with the breakdown of chemicals used for disinfection of water supplies, was detected in shallow groundwater beneath most urban areas. Chloroform was detected in nearly 25 percent of 43 shallow wells (17 domestic wells and 26 monitoring wells) in the Midwest near Chicago, Illinois.(103) Chloroform in domestic wells could result from treating the well with chlorine bleach to kill bacteria, and chloroform in monitoring wells might be related to the use of chlorinated water from a public water utility for landscape and lawn watering. Other VOCs, such as methyl *tert*-butyl ether (MTBE), were detected only in some regions. MTBE was detected primarily in the Northeast, where air-quality attainment regulations led to widespread use of this fuel oxygenate in gasoline. MTBE has largely been replaced by ethanol. In the densely populated Northeast, MTBE was the most commonly detected VOC in groundwater, along with chloroform, 1,1,1-trichloroethane, *tert*-amyl methyl ether (TAME), and perchloroethylene (PCE).



Methyl *tert*-butyl ether and chloroform were the most frequently detected volatile organic compounds at concentrations ≥0.05 microgram per liter in shallow, recently recharged groundwater in the Northeast.

Table 5–2. Summary comparison of the water-quality data from the glacial aquifer system to human-health benchmarks by primary water use.

[HHB, human-health benchmark; —, not applicable; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; HBSL, Health-Based Screening Level; MCL, Maximum Contaminant Level; AMCL, Alternative Maximum Contaminant Level; N, nitrogen; for radon >300 pCi/L and for dieldrin, 1/10 of the benchmark was below laboratory reporting limits and therefore no data are shown; for radon >4,000 pCi/L, 1/10 of the benchmark is close to the 300 pCi/L benchmark and therefore no data are shown; >, greater than; see appendix 3 for National comparisons]

Constituent	Benchmark		All glacial aquifer wells			Drinking-water wells			Wells monitoring agricultural land use			Wells monitoring urban land use		
			Number of samples	Percentage of samples with concentrations exceeding		Number of samples	Percentage of samples with concentrations exceeding		Number of samples	Percentage of samples with concentrations exceeding		Number of samples	Percentage of samples with concentrations exceeding	
	Type	Value		HHB	1/10 HHB		HHB	1/10 HHB		HHB	1/10 HHB		HHB	1/10 HHB
Contaminant primarily from geologic sources														
Manganese	HBSL	300 µg/L	1,641	18	52	600	11	50	503	19	53	355	24	55
Arsenic	MCL	10 µg/L	1,060	7.0	36	457	11	46	283	3.5	31	258	4.3	24
Uranium	MCL	30 µg/L	1,167	2.0	13	475	1.3	11	334	3.3	20	258	0.8	8.1
Molybdenum	HBSL	40 µg/L	1,057	1.0	20	460	0.2	20	278	3.6	29	258	0.8	8.5
Selenium	MCL	50 µg/L	1,057	1.0	4.9	460	0.7	4.8	278	2.5	10	258	0.0	0.8
Strontium	HBSL	4,000 µg/L	864	0.8	22	376	1.3	31	208	1.0	23	225	0.0	8.9
Boron	HBSL	6,000 µg/L	890	0.0	12	386	0.0	14	213	0.0	12	243	0.0	8.2
Radon	Proposed MCL	300 pCi/L	894	54	—	424	50	—	215	54	—	169	64	—
Radon	Proposed AMCL	4,000 pCi/L	894	0.1	—	424	0.2	—	215	0.0	—	169	0.0	—
Contaminant primarily from human activities														
Nitrate, as N	MCL	10 mg/L	1,616	10	43	579	2.9	30	503	23	58	356	4.2	52
Tetrachloroethene	MCL	5 µg/L	1,196	0.6	1.9	494	0.6	1.2	260	0.0	0.0	338	1.2	5.0
1,2-dichloropropane	MCL	5 µg/L	1,249	0.2	0.6	522	0.2	0.6	260	1.1	2.7	347	0.0	0.3
Trichloroethene	MCL	5 µg/L	1,246	0.2	1.4	522	0.4	1.1	257	0.0	0.0	347	0.3	3.2
Benzene	MCL	5 µg/L	1,247	0.2	0.3	523	0.0	0.0	257	0.0	0.0	347	0.9	1.2
1,2-dibromoethane	MCL	0.05 µg/L	1,250	0.1	0.1	523	0.0	0.0	260	0.4	0.4	347	0.0	0.0
1,2-dichloroethane	MCL	5 µg/L	1,246	0.1	0.2	523	0.0	0.2	260	0.0	0.0	344	0.3	0.3
1,2-dibromo-3-chloropropane	MCL	0.2 µg/L	1,250	0.1	0.1	523	0.0	0.0	260	0.0	0.0	347	0.3	0.3
Vinyl chloride	MCL	2 µg/L	1,250	0.1	0.3	523	0.0	0.0	260	0.0	0.0	347	0.3	1.2
Dieldrin	HBSL	0.002 µg/L	871	1.6	—	279	0.9	—	346	1.2	—	191	4.2	—
Fipronil	HBSL	0.1 µg/L	539	0.2	0.2	248	0.0	0.0	109	0.0	0.0	143	0.7	0.7
Atrazine	MCL	3 µg/L	1,586	0.1	1.4	572	0.0	0.0	502	0.2	3.0	354	0.0	1.1

Concerns for General Use: Nuisance Constituents Deter Use of Groundwater for Drinking

The presence of nuisance constituents at concentrations greater than their SMCLs can deter people from using groundwater even though the water is considered safe to drink. At concentrations exceeding the SMCLs, nuisance constituents in drinking water can give drinking water an unpleasant taste or odor, cause undesirable effects such as skin or tooth discoloration, or damage plumbing. In the glacial aquifer system, the nuisance constituents iron, manganese, chloride, sulfate, and aluminum and the properties of pH and dissolved solids were measured at concentrations that exceeded their SMCLs (table 5–3). The concentration of at least one nuisance constituent exceeded its SMCL in almost 75 percent of samples from drinking-water wells. The reasons for the exceedances of these non-health-related guidelines are discussed in Chapter 6.

Groundwater from three out of four drinking water wells in the glacial aquifer system had nuisance constituents at concentrations above the SMCL.

Table 5–3. Summary comparison of water-quality data from the glacial aquifer system with nuisance benchmarks for selected wells by primary water use.

[mg/L, milligrams per liter; µg/L, micrograms per liter; SMCL, Secondary Maximum Contaminant Level]

Property or constituent	Benchmark		All glacial aquifer system wells		Drinking-water wells		Wells monitoring agricultural land use		Wells monitoring urban land use	
	Type	Value	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark	Number of samples	Percentage of samples exceeding benchmark
Properties of water										
Low pH	SMCL	6.5	1,642	18	607	13	501	12	351	29
High pH	SMCL	8.5	1,642	0.5	607	0.8	501	0.2	351	0.0
Total dissolved solids	SMCL	500 mg/L	1,632	24	596	19	503	21	353	42
Hard water	Threshold	120 mg/L	1,602	77	598	74	486	88	342	72
Constituent										
Chloride	SMCL	250 mg/L	1,636	2.3	597	1.5	502	0.6	355	6.8
Sulfate	SMCL	250 mg/L	1,637	2.4	597	2.0	503	3.2	355	1.7
Manganese	SMCL	50 µg/L	1,641	45	600	39	503	48	355	47
Iron	SMCL	300 µg/L	1,641	30	600	43	503	22	355	21
Aluminum*	SMCL	50 µg/L	1,046	1.9	454	0.7	278	1.1	257	5.1
Aluminum*	SMCL	200 µg/L	1,046	0.9	454	0.0	278	0.0	257	3.5

*SMCL for aluminum is a range from 50 to 200 µg/L.

Photograph by Kelly L. Warner, USGS

Urban encroachment on agricultural land may affect groundwater quality.

Chapter 6: *Understanding Where and Why Constituents From Geologic Sources Occur*

This chapter describes the sources of and factors that affect concentrations of arsenic, manganese, uranium, radon, iron, and major ions in groundwater in the glacial aquifer system.

Human-health benchmarks for constituents from geologic sources, such as arsenic, manganese, radon (proposed benchmark), and uranium, were exceeded far more frequently than those for contaminants from human activities (appendix 3). Additionally, high concentrations of dissolved solids and sodium—which also originate from geologic sources—impair the use of groundwater. Concentrations of constituents from geologic sources, unlike concentrations of contaminants from human activities, generally were higher in deeper groundwater, which is used for drinking, than in shallow groundwater. The following sections focus on where and why contaminants from geologic sources are detected in groundwater.

Boulders from glacial deposits line a New Hampshire stream.

Photograph by P. Ryan Jackson, USGS

Arsenic

Concentrations of arsenic in groundwater from deep parts of the aquifer—the parts commonly tapped by drinking-water wells—exceeded the arsenic MCL of 10 µg/L in 11 percent of samples. In shallow parts of the aquifer, concentrations of arsenic in groundwater were 2 to 3 times less likely to exceed the MCL. Where groundwater is anoxic and alkaline (pH >7)—conditions common in the central and west-central regions of the glacial aquifer—more than 20 percent of samples contained arsenic at concentrations greater than the MCL. The risk of having arsenic in groundwater can be assessed regionally across the glacial aquifer system; however, on a well-to-well basis, the concentration of arsenic in groundwater is difficult to predict.

33
As
75

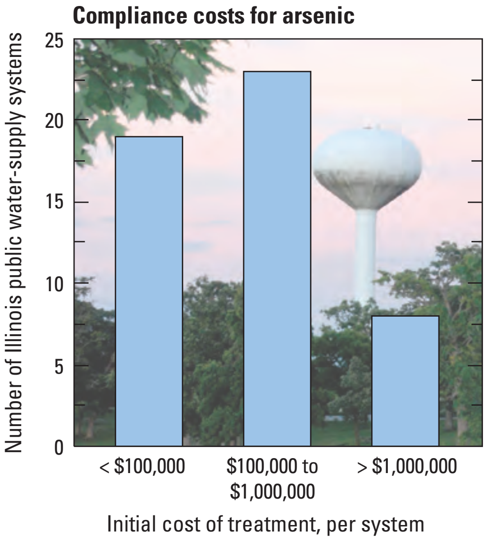
Arsenic is a trace element found in aquifer materials and can also come from pesticide application or industrial waste. Long-term exposure to arsenic in drinking water is related to elevated risks of cancer and skin damage.

Arsenic is a known human carcinogen and is increasingly being linked to other adverse human-health outcomes. Health effects from exposure to arsenic in drinking water include increased risk for bladder, skin, kidney, and lung cancers, and increased risk for diabetes and heart disease. Research on the health effects of low-to-moderate concentrations of arsenic caused the U.S. Environmental Protection Agency (USEPA) in 2006 to lower the MCL from 50 to 10 µg/L. One State, New Jersey, has a drinking-water standard for arsenic of 5 µg/L.

Removing arsenic from groundwater to meet drinking-water standards comes with substantial costs. The Illinois Environmental Protection Agency has estimated that the initial cost to reduce arsenic concentrations to below the MCL of 10 µg/L for 50 of the community-water supplies with elevated arsenic concentrations in Illinois (fig. 6–1) could reach a total of $40 million dollars, with the highest costs associated with small community supplies.(28) Domestic-supply wells typically are not regulated for arsenic or other contaminants, and owners of domestic-supply wells are solely responsible for testing and treating their water.

Arsenic exceeds its MCL in 11 percent of domestic-supply wells, but because these wells are generally not regulated, the water is not routinely tested. As a result, people using domestic-supply wells could be drinking water with elevated arsenic concentrations.

The dominant sources of arsenic in groundwater in the glacial aquifer system are the iron and manganese oxides that coat the glacial sediments.(29) The presence or absence of arsenic-bearing metal oxides is related to the source of the sediments, redox conditions in the aquifer, and the original arsenic-bearing minerals. Concentrations of arsenic in glacial sediments reflect the lithology (bedrock type) over which the major glacial ice lobes flowed(30) and the type of bedrock underlying the current location of glacial sediments.(12) For example, in areas where the glacial sediments are derived from arsenic-rich marine shales and redox conditions favor the release of arsenic to groundwater, the groundwater tends to have high arsenic concentrations. The former positions and directions of movement of the glacial ice lobes relative to the underlying bedrock provide clues to the general composition and geochemistry of the glacial sediments left behind after the glacial ice retreated; however, the presence of glacial sediment with high amounts of arsenic can be highly variable, especially at the local scale.



Modified from Warner and others(28)

Figure 6–1. The projected initial cost of remediating arsenic in a community-water supply in Illinois can exceed a million dollars.

Arsenic in Drinking Water Is a Concern for Human Health

Concentrations of arsenic in groundwater from about 7 percent of all wells sampled in the glacial aquifer system exceeded the MCL of 10 µg/L. Concentrations in samples from the deep part of the glacial aquifer system, which is used for drinking water, more frequently exceeded the MCL (11 percent of samples) than in samples from the shallower part of the system (fig. 6–2*A*), likely because most drinking-water wells tap deep, anoxic groundwater. The difference in exceedances of the arsenic MCL in domestic and public-supply wells was small—the MCL was exceeded in 11 percent of domestic-supply wells and 10 percent of public-supply wells. Nationally, concentrations of arsenic exceeded the MCL in 10 and 7 percent of NAWQA samples from public- and domestic-supply wells, respectively.(27, 31) However, the percentages of wells with concentrations of arsenic greater than the MCL differed between groundwater from shallow monitoring wells and deeper drinking-water wells within each region of the glacial aquifer system (fig. 6–2*B*), primarily because of differences in sources and geochemistry. Concentrations of arsenic in drinking-water wells in the west and central regions of the glacial aquifer system exceeded the MCL in 17 and 14 percent of samples, respectively. (See sidebar, High levels of arsenic in the Mahomet glacial aquifer, p. 48.)

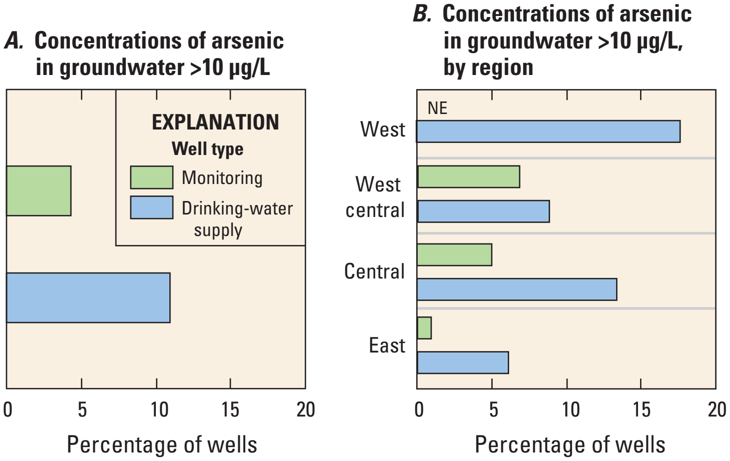
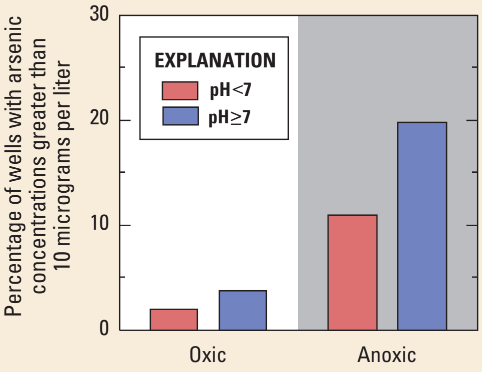


Figure 6–2. *A*, Drinking-water wells in the glacial aquifer system that tap deep groundwater more frequently contained arsenic at concentrations exceeding the MCL of 10 micrograms per liter than did monitoring wells that tap shallow groundwater. *B*, Drinking-water wells in the west and central regions of the glacial aquifer system more frequently contained arsenic at concentrations exceeding its MCL than did drinking-water wells in the west-central and east regions. [NE, no exceedances]

Anoxic and alkaline conditions mobilize arsenic in groundwater

Although arsenic in the glacial aquifer system is derived originally from the breakdown of pyrite and other arsenic-bearing minerals, a substantial proportion of arsenic is adsorbed (attached) to iron and manganese oxides that coat glacial sediments, and redox and pH are important controls on the solubility of arsenic associated with these coatings.(12, 13, 29) Under anoxic conditions, arsenic is in its reduced state, arsenite (AsIII). Arsenite is not strongly adsorbed to iron and manganese oxides and can dissolve in the groundwater (see Chapter 4 on geochemical processes). Additionally, under anoxic conditions, the oxides themselves may dissolve, releasing any attached arsenic to the groundwater. Under oxic conditions, arsenic is in its oxidized state of arsenate (AsV). Typically, arsenate is strongly adsorbed to iron and manganese oxides, resulting in lower dissolved arsenic concentrations in groundwater. However, arsenate adsorption depends on pH and decreases with higher (more alkaline) pH of groundwater. As a result, alkaline pH conditions (pH ≥7) increase the overall concentration of arsenic dissolved in groundwater. Values of pH in groundwater in the glacial aquifer system range from 4.3 to 9.5, and the median pH is 7.1. The longer the time since groundwater was recharged, the greater the likelihood that the water is anoxic and alkaline, both of which lead to higher concentrations of arsenic and more exceedances of its human-health benchmark.

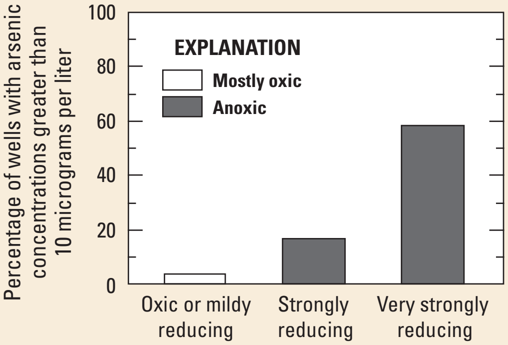


Groundwater samples that were anoxic (dissolved oxygen <0.5 mg/L) and alkaline (pH ≥7) most frequently had concentrations of arsenic greater than the MCL of 10 µg/L. The simple and inexpensive measurement of dissolved oxygen and pH in groundwater can provide a helpful indication of the likelihood of elevated arsenic concentrations.

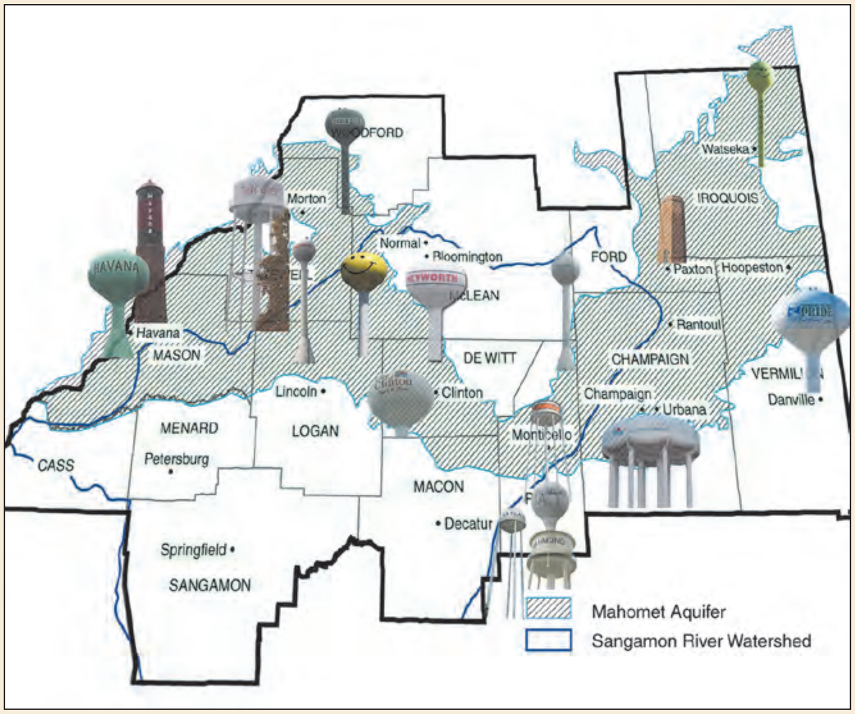
High levels of arsenic in the Mahomet glacial aquifer

Anoxic conditions, especially when strongly reducing (see sidebar, How do redox reactions work?, p. 29), can result in high concentrations of arsenic in groundwater.(12, 13, 108) An example of this is the groundwater in the deep, confined Mahomet aquifer in Illinois (central region) where water used to supply domestic wells is strongly reducing—a condition favorable for releasing arsenic from geologic sources in the glacial sediment to groundwater. In this aquifer, more than 65 percent of groundwater samples that were very strongly reducing had concentrations of arsenic that exceeded the MCL of 10 micrograms per liter.(12) More than 900,000 people live in the Mahomet aquifer region, and the population of communities using or considering use of the Mahomet aquifer totals more than 274,000.(109) Zones of low concentrations of arsenic in the Mahomet aquifer vary with location and depth. Identification of low-concentration zones could help reduce treatment costs and ultimately costs to consumers.

Deep buried-basin or buried-bedrock-valley aquifer sediments with organic carbon sources, such as those associated with buried paleosols (ancient soils), are likely to have high groundwater arsenic concentrations similar to those in the Mahomet aquifer. Thick glacial sediments in other regions of the glacial aquifer system, such as in Alaska and Minnesota, also have groundwater with high arsenic concentrations that result from strongly reducing conditions, affecting domestic and public-supply wells.



Concentrations of arsenic greater than the MCL of 10 μg/L have been measured more frequently in very strongly reducing groundwater than in strongly reducing, mildly reducing, or oxic groundwater. Most of the very strongly reducing groundwater was from deep wells in the Mahomet aquifer in central Illinois.



Reprinted with permission from the Mahomet Aquifer Consortium

The Mahomet aquifer supplies water to many communities in central Illinois. The Mahomet aquifer is widely used as indicated by the water towers. If concentrations of arsenic are greater than the MCL, communities must take action to reduce the arsenic concentration.

Redox and pH Are Key Factors Affecting Arsenic Concentrations in Groundwater

Redox and pH influence the frequency of detection and concentration of arsenic in groundwater. In the glacial aquifer system, the combination of anoxic and alkaline (pH ≥7) conditions is the most favorable for high concentrations of arsenic in groundwater (fig. 6–3) (see sidebars, Anoxic and alkaline conditions mobilize arsenic in groundwater, p. 47, and Landfill leachate can change redox and mobilize arsenic, p. 50).

In most regions, redox has a greater influence on the mobilization of arsenic at concentrations greater than or equal to 1 µg/L than does pH. Patterns illustrating this effect can be seen in regional graphs characterizing arsenic frequencies of detection. In all regions but the west-central region, arsenic was most frequently detected in wells tapping groundwater that was both anoxic and slightly alkaline.

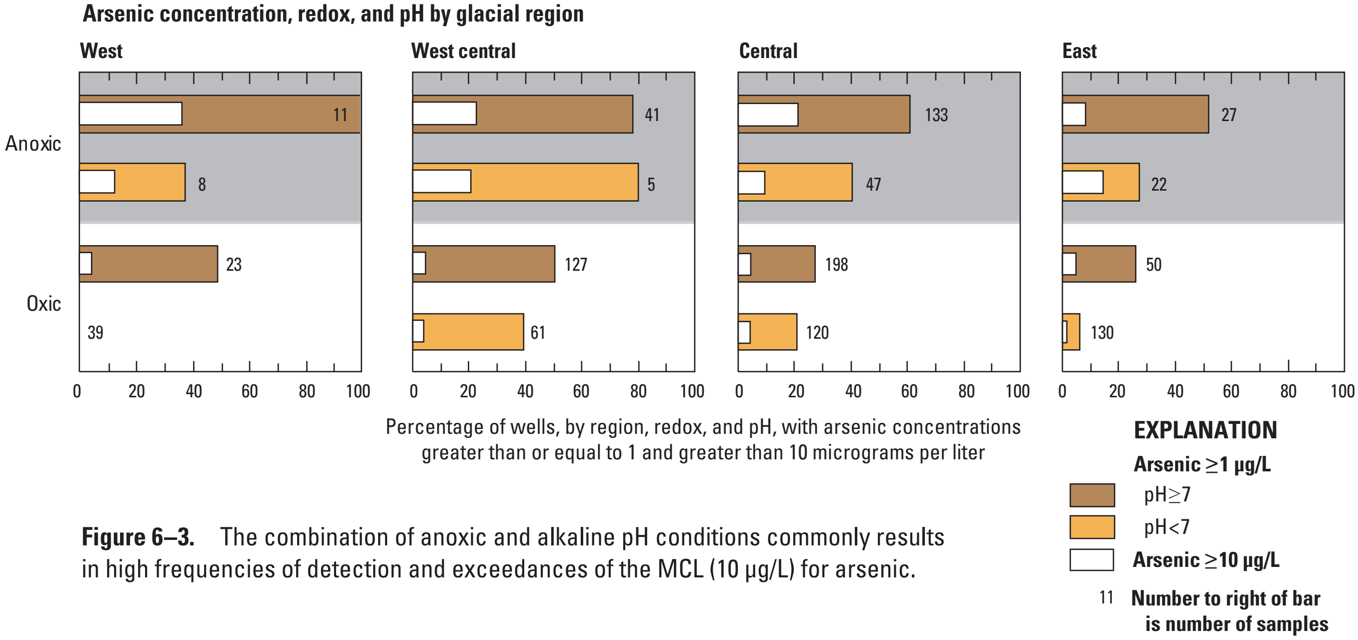


Figure 6–3. The combination of anoxic and alkaline pH conditions commonly results in high frequencies of detection and exceedances of the MCL (10 µg/L) for arsenic.

What If the MCL for Arsenic Were Lowered?

The USEPA considered a range of potential MCLs in developing the Arsenic Rule, including MCLs of 3, 5, and 10 µg/L.(32) The lower limit of 3 µg/L was considered because it is as close as is feasible to the MCL Goal (the concentration at which no known or anticipated adverse health effects would be expected) of zero.(32) About 9 million people use domestic-supply wells that withdraw water from the glacial aquifer system.(6) About 11 percent of those domestic-supply well users (an estimated 1 million people) obtain drinking water with arsenic concentrations greater than the MCL. This number would increase to 28 percent (an estimated 2.5 million people) if an MCL of 3 µg/L were adopted (table 6–1). Some governments have lowered the enforceable thresholds for protection of human health to levels below USEPA standards and World Health Organization Agency guidelines. In Denmark, for example, the human-health benchmark is 5 µg/L, as is the benchmark established by the State of New Jersey in 2004.

Table 6–1. Percentages of samples from drinking-water wells containing concentrations of arsenic greater than 10, 5, 3, and 1 micrograms per liter.

[µg/L, micrograms per liter; >, greater than]

Arsenic threshold (µg/L)	West	West central	Central	East	Overall
>10	18	9	13	6	11
>5	26	30	22	10	21
>3	29	52	27	11	28
>1	62	73	43	24	45

For public and domestic drinking-water suppliers, removing arsenic from groundwater to a concentration lower than the current MCL of 10 µg/L would substantially increase the costs to consumers. For example, the average annual cost (1999 dollars) for treating public groundwater supplies to meet the current MCL of 10 µg/L is an estimated $31.85 per household, whereas treating to 3 µg/L would cost an estimated $41.34—about a 30 percent increase.(32) Additionally, these costs are higher per person for small suppliers than for larger ones, further increasing the costs for some users. These estimated costs, however, do not account for any potential health benefits savings.

Landfill leachate can change redox and mobilize arsenic

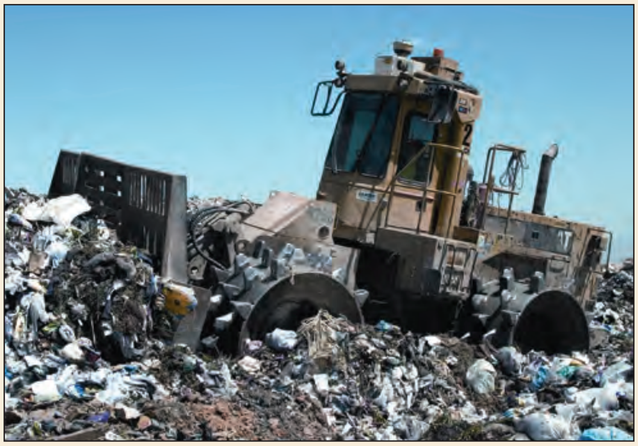
Landfill leachate, volatile organic compounds (VOCs), and human-induced changes to the natural flow system—such as pumping for water supply—can change redox conditions and cause arsenic from geologic sources within glacial aquifer sediment to dissolve in groundwater. In domestic and public-supply wells, contaminants from geologic sources were detected more frequently at concentrations of concern than were manmade contaminants, such as nitrate, VOCs, and pesticides.(31, 76) Potential contaminants that are a component of the solid aquifer material can be released from sediments and rocks to groundwater if the geochemical conditions are favorable.

Leachate from beneath landfills can cause groundwater, which typically is oxic in sandy parts of the aquifer, to become anoxic. The chemistry of the groundwater changes because landfill leachate contains large amounts of organic carbon—as microorganisms break down organic carbon, they consume dissolved oxygen in the groundwater, creating anoxic conditions. This process releases arsenic from the sediments to the groundwater, and, as a result, arsenic concentrations are elevated in groundwater flowing from the landfill.(104)

Photographs by (left) Joseph Ayotte, USGS; (right) Denis Leblanc, USGS

The color of aquifer sediment provides clues about the redox conditions and even potential arsenic concentrations in the groundwater. Under oxic conditions, iron oxides coat aquifer sediment, giving it a rusty red color. Arsenic adheres to the oxides, so concentrations in groundwater tend to be low. Under anoxic conditions, the sediments are a gray color and arsenic can easily desorb from the coatings. Further, the dissolution of the oxides releases additional arsenic into the groundwater, so concentrations tend to be high.

For example, leachate from the Saco Landfill in Maine has caused groundwater to become anoxic, and concentrations of arsenic in groundwater flowing away from the landfill exceed the MCL.(105) Although the source of the arsenic is the aquifer material and not the contents of the landfill, the presence of a landfill can cause elevated arsenic concentrations in groundwater.(106)



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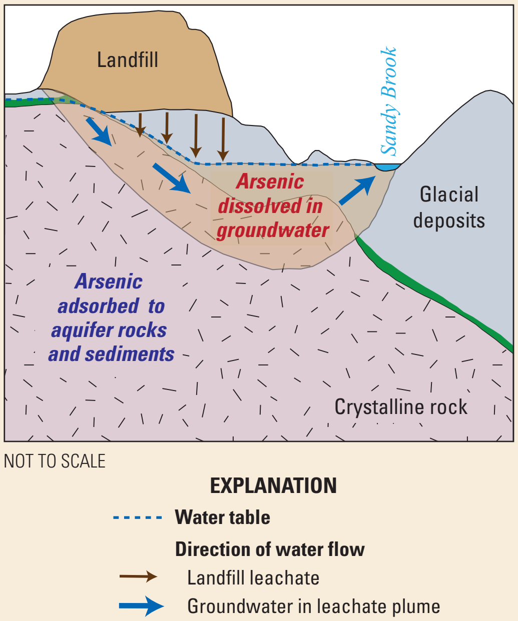


Modified from Stollenwerk and Colman (105)

Left, Compacting trash at a landfill. Right, Leaching of landfill waste creates anoxic conditions that can cause arsenic on aquifer sediments to dissolve and contaminate groundwater.

Other Constituents and Properties That Affect Water Use

Seventy-three percent of water samples from the glacial aquifer system contained at least one nuisance constituent—a constituent that causes water to taste or smell bad; stain teeth, laundry, or plumbing fixtures; or corrode or clog pipes—at a concentration greater than its USEPA benchmark (SMCL) for these constituents. Although elevated concentrations of nuisance constituents, such as iron, hardness, and dissolved solids, are not health concerns, they make the water unappealing for drinking and can be costly for home maintenance. High iron concentrations (exceeding the SMCL) were measured in nearly one-half of the water samples from domestic-supply wells. Across the glacial aquifer system, nearly three-quarters of drinking-water samples were classified as hard water—almost all drinking-water wells in the central and west-central regions had hard water, compared to 40 percent or fewer in the west and east regions.

The presence of nuisance constituents can be unpleasant and costly

Many constituents in groundwater can make the water undesirable to use or drink. Dissolved iron in groundwater can stain laundry, sinks, bathtubs, and toilets a brownish red, and can degrade plumbing and heating systems. Iron also gives drinking water an unpleasant taste, rendering it undrinkable for many well owners. Manganese often co-occurs with iron and causes many of the same problems. Hard water—defined by high concentrations of calcium and magnesium—causes water pipes and fixtures to become coated with scale, limits the ability of soaps and detergents to form suds, and can cause premature failure of plumbing and heating fixtures. The dissolved solids concentration is a measure of all dissolved substances in water and indicates the general quality of the water—a high dissolved solids concentration makes water taste disagreeably salty and often indicates the presence of other more harmful constituents from geologic sources.

Treatment for these nuisance constituents can be an expensive additional household cost. Median costs for installation and annual maintenance of water-treatment equipment can be on the order of $2,000 and $200, respectively (Pierce Rigrod, New Hampshire Department of Environmental Services, written commun., 2012). However, letting poor water quality go untreated, which decreases the useful lifetime of plumbing and fixtures, can have even higher long-term costs.

High iron concentrations make water undesirable to use

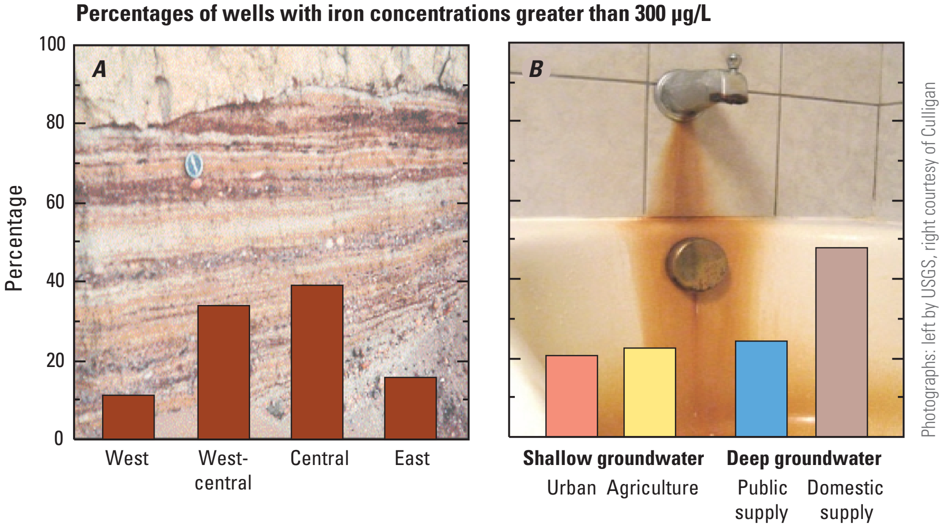
Because of the abundance of iron in the environment and its release to groundwater under anoxic and near-neutral pH conditions, iron was detected in the majority of groundwater samples from the glacial aquifer system. Iron concentrations, however, varied widely by glacial region, with the highest concentrations in the west-central and central regions (fig. 6–4*A*). Concentrations of iron exceeded the SMCL of 300 µg/L nearly twice as often in groundwater from domestic-supply wells than in either public-supply wells or shallow groundwater, although the reason for this finding is unclear (fig. 6–4*B*). About half of domestic-supply wells had iron above the SMCL. Low concentrations of iron can be treated relatively inexpensively with a water softener but higher concentrations may require more sophisticated chemical or physical treatment at a greater cost. Many homeowners are faced with deciding whether or not to treat their water for iron, and some well owners opt to use other water sources, such as bottled water or prepared beverages.

Iron in groundwater can indicate the presence of constituents of concern for human health. Because strongly reducing geochemical conditions favor enhanced solubility and transport of both iron and arsenic, high concentrations of iron in wells can indicate possible high concentrations of arsenic (see Chapter 6 section entitled Arsenic). Iron in groundwater has been associated with high concentrations of arsenic and manganese in Illinois and elsewhere in the Midwest.(12, 13, 28) This finding is of particular concern for domestic-supply well owners, because nearly half of domestic-supply wells sampled had concentrations of iron that exceeded the iron SMCL. Wells with high concentrations of iron were five times more likely to have concentrations of arsenic that exceeded the MCL of 10 µg/L than wells with iron concentrations less than the SMCL (fig. 6–5).

26
Fe
55.85

Iron is a common mineral in geologic materials. Iron is a nuisance constituent in water because of odor, taste, and discoloration.

More than half of the groundwater samples from domestic wells had concentrations of iron that exceeded the SMCL.



Photographs: left by USGS, right courtesy of Culligan

Figure 6–4. *A,* High concentrations of iron that exceed the nuisance level of 300 µg/L were more common in the west-central and central regions, where many glacial aquifer deposits contain iron. *B*, Domestic-supply wells have water with high concentrations of iron more than twice as often as do higher-yielding public-supply wells.

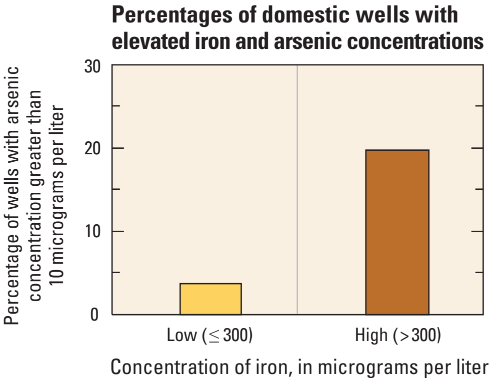


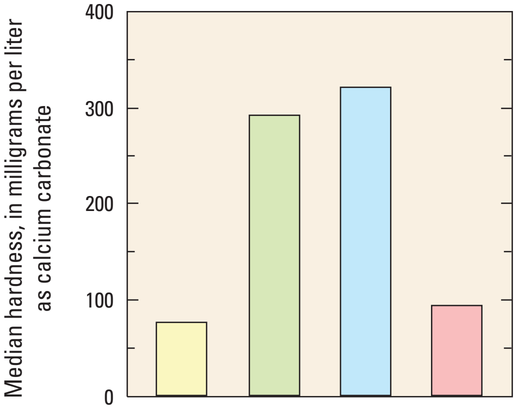
Figure 6–5. Domestic-supply wells with high concentrations of iron (brown bar, right) were five times more likely to have arsenic concentrations exceeding the MCL of 10 µg/L than were wells with low concentrations of iron (yellow bar, left). Concentrations of iron that exceed the SMCL of 300 µg/L—a condition that is easily seen by the naked eye when water in a glass has a slightly yellow or brown color—can be a visible indicator of potentially high concentrations of arsenic.

Hardness and dissolved solids are much greater in some regions

The hardness of a water sample is one measure of the amount of impurities in groundwater. Although historically many definitions have been used,[(33)] hardness is generally defined by the concentrations of the divalent cations—ions with a positive charge of 2 such as calcium and magnesium—which are the principal contributors to hardness in most groundwater. Hardness in water reduces the effectiveness of soap to form suds and increases the tendency for scale deposits to develop in water heaters and pipes, causing inefficient heating and reduced water flow.

The median hardness of samples from drinking-water wells in the glacial aquifer system is 258 mg/L as calcium carbonate ($CaCO_3$). Water with less than 60 mg/L of hardness is considered “soft” (11 percent of drinking-water well samples in the glacial aquifer system); water with more than 120 mg/L is considered “hard” (74 percent of drinking-water well samples); and water with more than 180 mg/L is considered “very hard” (64 percent of drinking-water well samples).[(33)] Hardness in groundwater is related, in part, to the source rock that formed the glacial sediments in a given area, but also can be affected by the long-term addition of agricultural amendments such as lime. Median concentrations of hardness in groundwater used for drinking water in the central and west-central regions of the glacial aquifer system were much higher than those in the east and west regions (fig. 6–6*A*). Water is hard in areas that are underlain by soluble rock types such as carbonates and shale. About 95 percent of the samples in the central and west-central glacial aquifer system regions, which are generally underlain by carbonate rocks, were hard or very hard (fig. 6–6*B*). In these regions, hardness can exceed 3,000 mg/L as $CaCO_3$ and is a nuisance for domestic water users. In the east and west glacial regions, which commonly are underlain by crystalline rocks, less than 40 percent of the water was hard.

***A.* Median hardness in drinking water by region**



***B.* Likelihood that drinking water is hard by region**

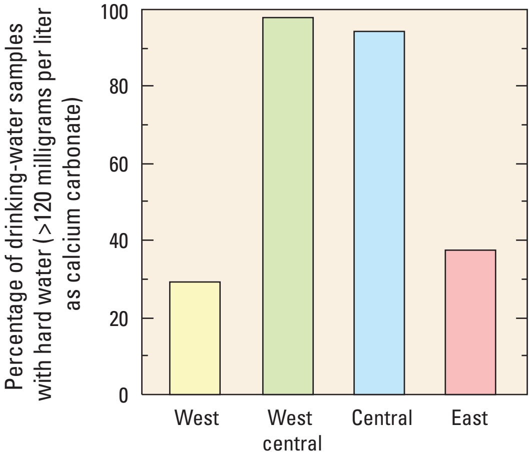


Figure 6–6. *A,* Median concentrations of hardness in drinking water in the west-central and central regions were about three times higher than those in the west and east regions. *B,* More than 90 percent of the samples from drinking-water wells in the central and west-central regions were hard. The prevalence of hard water in the west-central and central regions is caused in part by the abundant, easily dissolvable calcium and magnesium minerals in glacial sediments in those regions. In the west and east regions, glacial sediments were derived more typically from igneous and metamorphic rocks; the calcium and magnesium minerals in igneous and metamorphic rocks are less soluble than the same minerals in carbonate rocks.

Photograph used with permission from www.livingwaterllc.com

Calcium and magnesium ions tend to precipitate as mineral solids on the surfaces of pipes and especially on the hot heat-exchanger surfaces of boilers. The resulting buildup of scale can impede water flow in pipes and reduce the efficiency of heating elements.

The highest concentration of dissolved solids and hardness are in the central and west-central regions of the glacial aquifer system.

Like hardness, the percentage of samples with concentrations of dissolved solids that exceed the SMCL (500 mg/L for dissolved solids) was about four times higher in the west-central and central regions than in the east and west regions (fig. 6–7*A*). Carbonate-rich glacial sediments derived from underlying limestone and shale bedrock in the central and west-central regions are partially responsible for the high dissolved solids in these regions, although human activities including road deicing and septic system leakage might also play a role. The shallow groundwater underlying urban areas had the highest median concentration of dissolved solids—450 mg/L—and the greatest frequency of concentrations exceeding the SMCL—42 percent (fig. 6–7*B*). The many human sources of dissolved solids include roadway deicing salt, water softeners, and fertilizer and other lawn-care products. These sources are most common in urban and suburban areas.

In the glacial aquifer system, concentrations of dissolved solids and hardness generally are correlated. The exception is the east region, where high dissolved solids concentrations were primarily a result of high concentrations of chloride (34) from sources such as deicing salts, water softening, and septic leachate.

High concentrations of dissolved solids can indicate the presence of arsenic, uranium, and other trace elements derived from geologic sources in groundwater. The same factors—increasing residence time, geochemical weathering, and evaporative concentration—that increase concentrations of dissolved solids in groundwater also increase concentrations of contaminants derived from geologic sources (aquifer material).(27) For this reason, samples with multiple contaminants exceeding a human-health benchmark were more likely to have high concentrations of dissolved solids (fig. 6–8). Contaminants from human activities, such as nitrate, pesticides, or VOCs, also can be present, but concentrations of these above human-health benchmarks were rare compared to those from geologic sources.

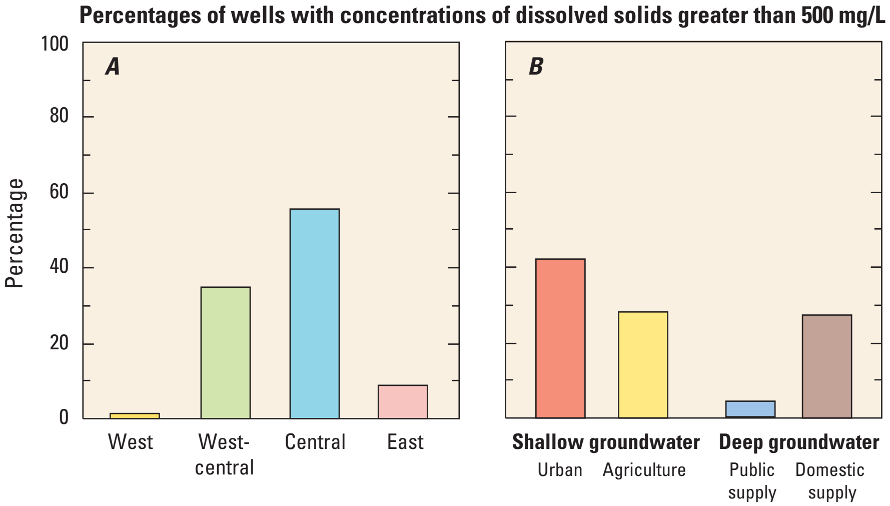


Figure 6–7. *A*, The percentage of groundwater samples with concentrations of dissolved solids that exceeded the SMCL of 500 mg/L was four or more times higher in the west-central and central regions of the glacial aquifer system than in the west and east regions. *B*, The percentage of samples exceeding the SMCL was highest for samples of shallow groundwater underlying urban areas.

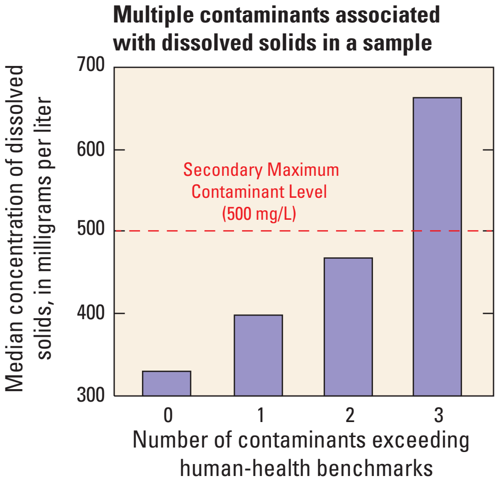


Figure 6–8. The presence of multiple contaminants in groundwater that are of concern for human health is strongly related to concentrations of dissolved solids.

Manganese

Concentrations of manganese—an emerging concern because of potential adverse effects on children's intellectual function—exceeded the human-health benchmark of 300 µg/L in 18 percent of wells sampled in the glacial aquifer system. The percentage was highest in the west-central region, where the benchmark was exceeded in water from almost one-half (46 percent) of public-supply wells and almost one-quarter (22 percent) of domestic-supply wells. Manganese concentrations were highest where the groundwater was anoxic or pH was slightly acidic—conditions that are common in the glacial aquifer system. Elevated manganese concentrations in groundwater also can indicate the presence of high concentrations of other trace elements, such as arsenic and uranium, particularly in the west-central and central regions.

Manganese is a trace element essential for human health. Although food, rather than drinking water, is the primary source of exposure for people,(35) recent research on childhood intellectual function conducted in Quebec, Canada, reported an association between ingestion of high concentrations of manganese in drinking water and declines in children's IQ (intelligence quotient or intellectual function).(36) A similar study in Bangladesh showed that high concentrations of manganese in drinking water were associated with lower IQs.(37)

Concentrations of manganese in samples of groundwater in the glacial aquifer system exceeded the human-health benchmark of 300 µg/L in 18 percent of shallow groundwater sampled, compared to 11 percent nationally. Although concentrations typically were highest in samples of shallow groundwater (fig. 6–9*A*), concentrations varied by region and by well type (fig. 6–9*B*). Concentrations of manganese in about 25 percent of drinking-water wells sampled in the west-central region exceeded the benchmark, but the concentrations in monitoring wells were even greater. In all regions except the west, concentrations of manganese were greater than the benchmark more often in wells that tapped the shallow groundwater than the groundwater from drinking-water wells.

25
Mn
55

Manganese is a trace element found in aquifer materials and some industrial wastes. Manganese has a human-health benchmark of 300 µg/L because of neurological effects.

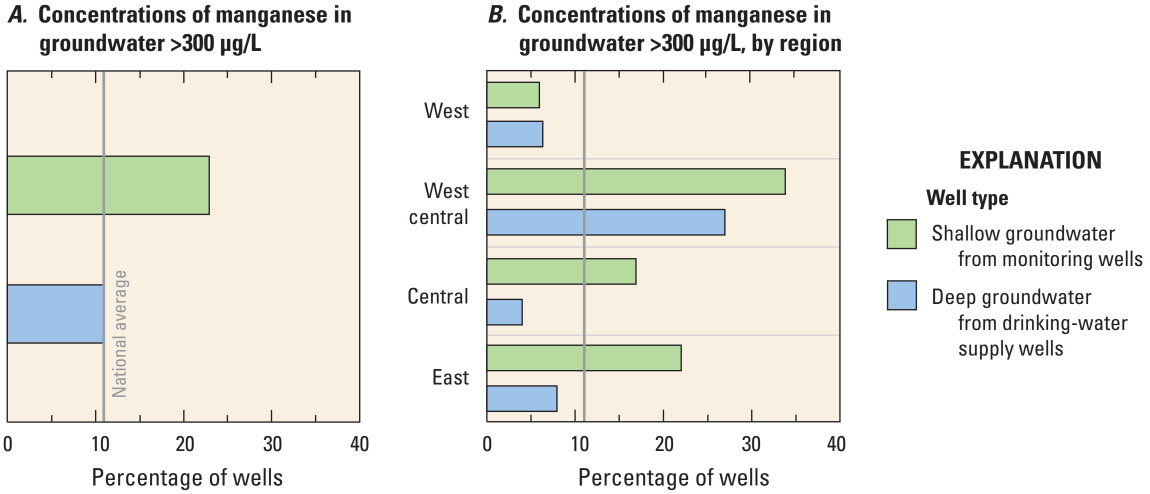


Figure 6–9. The percentage of wells with concentrations of manganese in groundwater that exceeded the human-health benchmark of 300 µg/L was *(A)* greatest for shallow monitoring wells, and *(B)* greatest in the west-central region of the glacial aquifer system.

Anoxic conditions and acidic pH release manganese from sediments into groundwater

Although many parts of the glacial aquifer system contain sediments that are enriched in manganese,(17) concentrations of manganese in groundwater are controlled by redox conditions and pH. Manganese oxides that appear as coatings on aquifer sediments are common and may serve as the source of manganese in groundwater from the glacial aquifer system. The release of manganese from aquifer sediments into groundwater increases as groundwater becomes more anoxic.(33) For this reason, the presence of dissolved manganese often is used as an indicator of the redox conditions of groundwater (see sidebar, How do redox reactions work?, p. 29)

Manganese in drinking water is a human-health concern because of potential adverse effects on children's intellectual function. Manganese concentrations are above the human-health benchmark over a wide range of groundwater depths.

Manganese also is more soluble in groundwater that has neutral to slightly acidic pH,(33) a property which is consistent with the observation that the highest human-health benchmark exceedance rate for manganese was associated with groundwater that was both anoxic and had a slightly acidic pH (fig. 6–10). As groundwater moves deeper into the aquifer and becomes increasingly anoxic, manganese concentrations might be expected to increase. However, because the mobility of manganese also is affected by pH, manganese can be present at high concentrations in shallow, young groundwater, which commonly is acidic. As a result, manganese concentrations can be above the human-health benchmark over a range of groundwater depths.

Figure 6–10. The percentage of groundwater samples with concentrations of manganese greater than the human-health benchmark of 300 µg/L was highest for groundwater that was anoxic and that had slightly acidic pH (pH <7). The percentage of groundwater samples with concentrations of manganese above the benchmark was nearly three times higher for anoxic samples than for oxic samples and nearly two times higher for acidic samples than for alkaline samples (pH ≥7).

Percentage of samples with manganese concentrations >300 micrograms per liter vary by pH and redox

pH	Redox	
	Anoxic	Oxic
<7 Slightly acidic	41%	16%
≥7 Slightly alkaline	25%	10%

Manganese dissolved in anoxic, sewage-contaminated groundwater flows to the shore of this pond on Cape Cod, Massachusetts. Where the manganese comes into contact with the oxygen in the atmosphere, it oxidizes and precipitates, forming the dark-colored manganese oxide coatings on sediments along the shoreline.

Photograph by D.R. LeBlanc, USGS

The degree to which redox and pH were related to manganese solubility varied across the regions of the glacial aquifer system (fig. 6–11). For example, in the west-central region, samples that were anoxic more frequently contained manganese at concentrations above the human-health benchmark than did oxic samples, as might be expected, and pH had a smaller effect. In the central region, however, manganese concentrations were more strongly related to pH than to redox conditions—higher concentrations were most commonly associated with acidic water, and rates of exceedance of the benchmark were similar for anoxic and oxic groundwater.

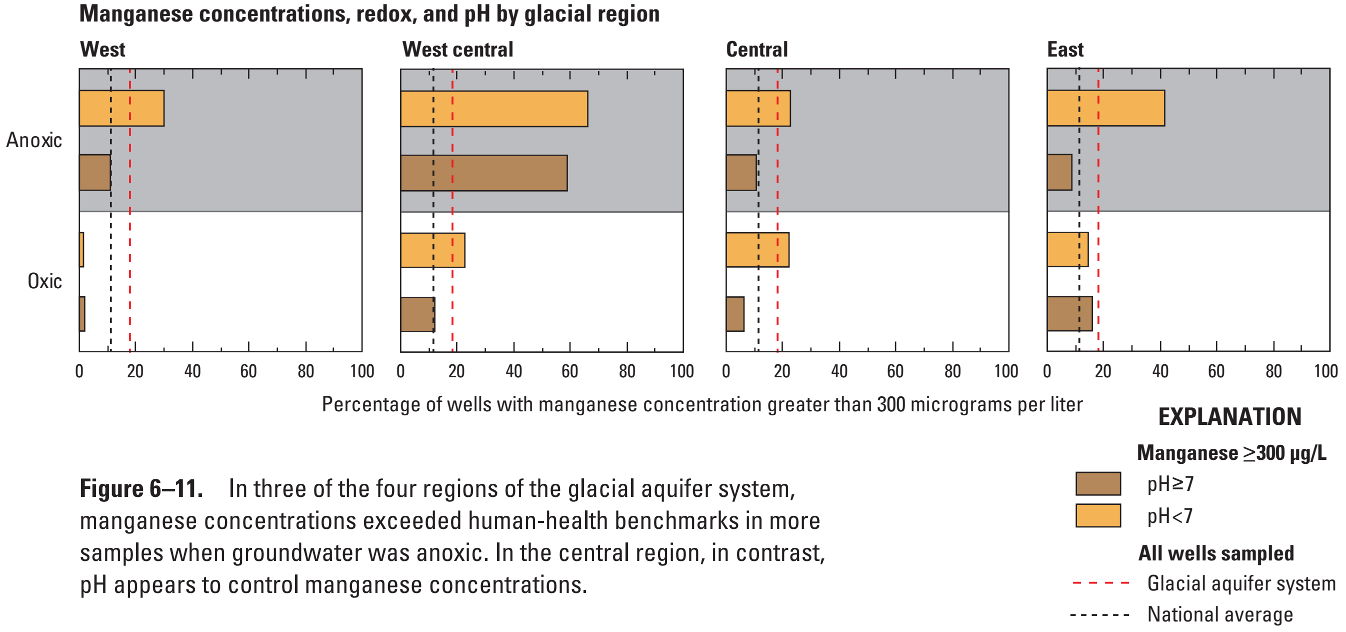


Figure 6–11. In three of the four regions of the glacial aquifer system, manganese concentrations exceeded human-health benchmarks in more samples when groundwater was anoxic. In the central region, in contrast, pH appears to control manganese concentrations.

High manganese concentrations in drinking water and implications for human health

Manganese concentrations were above the human-health benchmark of 300 µg/L in samples from 11 percent of drinking-water wells in the glacial aquifer system. In the west-central region, however, manganese concentrations in 46 percent of public- and 22 percent of domestic-supply well samples exceeded the benchmark (fig. 6–12), possibly reflecting a more abundant source of manganese in the aquifer sediment. Public- and domestic-supply wells in the glacial aquifer system as a whole are similar in depth, but in the west-central region, public-supply wells tend to be substantially deeper than domestic-supply wells (the median depth is 292 ft for public-supply wells and 80 ft for domestic-supply wells)—conditions are more strongly reducing in deeper groundwater.

High concentrations of manganese also were prevalent in deep groundwater in the other regions of the glacial aquifer system. Aquifer-wide, concentrations of manganese in samples from domestic-supply wells (median 26 µg/L and range less than 1 to 2,900 µg/L) and public-supply wells (median 44 µg/L and range less than 1 to 1,767 µg/L) were similar to those reported in a study on childhood IQ impairment in Quebec, where the median concentration of manganese in tap water was 34 µg/L (range 1 to 2,700 µg/L).(36)

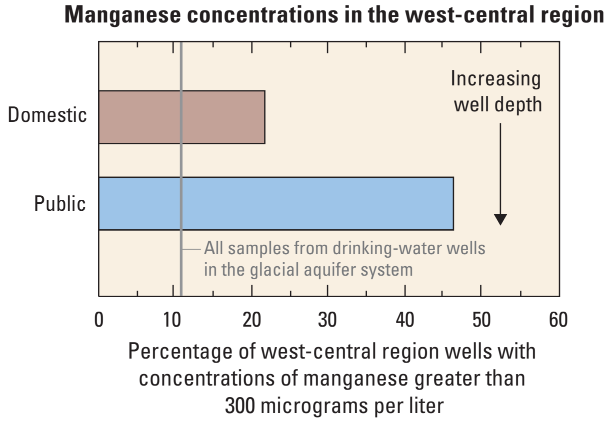


Figure 6–12. Concentrations of manganese exceeded the human-health benchmark more frequently in wells in the west-central region than in the glacial aquifer system as a whole (gray line). The benchmark was exceeded in almost half of the public-supply wells, about twice as often as in domestic-supply wells. Public-supply wells in this region are about four times deeper than domestic-supply wells, so groundwater conditions are more frequently anoxic.

Uranium and Radon

Concentrations of uranium in groundwater exceeded the USEPA MCL of 30 µg/L in 20 percent of public-supply and 3 percent of domestic-supply well samples in the west-central region of the glacial aquifer system, and exceedances were common in groundwater with high alkalinity. Uranium concentrations were commonly elevated in high-sulfate waters, possibly indicating the presence of uranium-bearing geologic source materials such as Cretaceous marine shale in glacial sediments. Concentrations of radon, a daughter product of uranium decay, exceeded the proposed USEPA MCL of 300 pCi/L in 53 percent of the wells sampled but rarely exceeded the proposed alternative MCL of 4,000 pCi/L.

Uranium and radon can cause adverse health effects in humans. For those exposed to uranium on the job, such as uranium miners, health effects include renal (kidney) toxicity.(38, 39) Little is known, however, about the long-term health effects of exposure to low-level environmental uranium through ingestion of drinking water, although long-term health risks may be a result of uranium's toxicity and not its cancer-causing potential.(40) Recent epidemiology studies indicate that uranium, like some other heavy metals, can act as an endocrine disruptor in mammals exposed to it in the environment.(41, 42, 43)

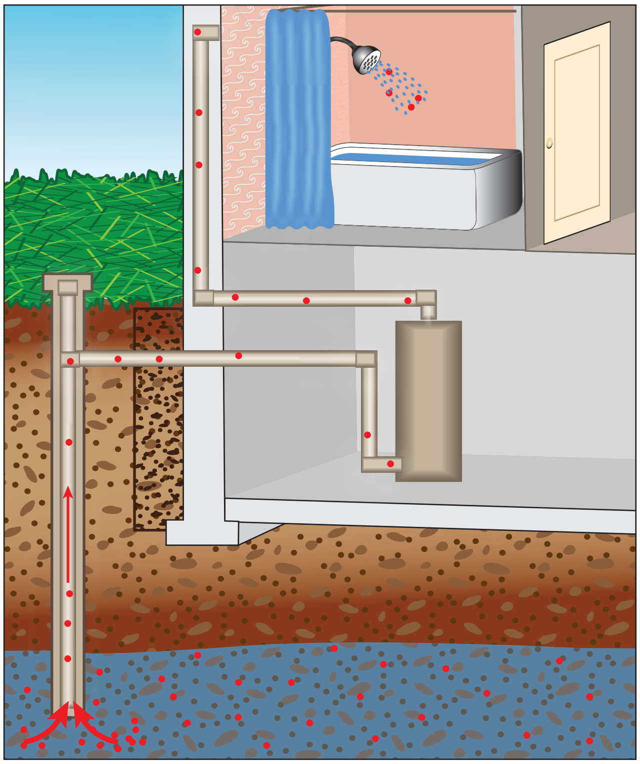
Exposure to radon has been recognized as the second leading cause of lung cancer in the United States behind cigarette smoking.(44) Health risks associated with radon are primarily from inhalation of radon in indoor air. Most radon in air enters homes through the foundation, but some is released from groundwater when it is used for showering and washing clothes.

92
U
238

Uranium is a radioactive element found in aquifer sediment. Drinking water with uranium at levels above the MCL has been associated with increased risk of cancer and kidney toxicity.

86
Rn
222

Radon is an element that results from the radioactive decay of uranium in aquifer materials. Radon in drinking water is associated with lung cancer and stomach cancer.



Modified from Otton and others(107)

In addition to radon that is derived from soils, radon gas can enter the home by degassing from groundwater used for water supply.

Concentrations of uranium were highest in the west-central region, but concentrations of radon were high across the entire glacial aquifer system

Although uranium was present at low concentrations in samples of groundwater from all regions of the glacial aquifer system, concentrations exceeded the MCL of 30 µg/L in about 2 percent of all wells sampled and only 1 percent of drinking-water wells (table 5–2). All of the concentrations exceeding the MCL were in samples from the west-central region—7 percent of monitoring wells and 6 percent of drinking-water wells sampled in that region contained uranium at a concentration exceeding the MCL (fig. 6–13*A*). Among drinking-water wells in the west-central region, uranium exceeded the MCL in 20 percent of public-supply wells but in only 3 percent of domestic-supply wells.

Radon concentrations in groundwater exceeding the USEPA proposed MCL of 300 pCi/L were measured in drinking-water and shallow monitoring wells. In the east, more than 70 percent of the groundwater samples from drinking-water wells had radon concentrations greater than 300 pCi/L (fig. 6–13*B*). In the northern part of the east region, some concentrations of radon in groundwater approached, but were less than, 4,000 pCi/L—the USEPA proposed alternative MCL. Only one sample, in New England, exceeded the alternative MCL. Concentrations of radon exceeded the USEPA proposed MCL of 300 pCi/L in groundwater from more than 55 percent of shallow monitoring wells in the glacial aquifer system and, with the exception of the east region, were higher in monitoring wells than in drinking-water supply wells.

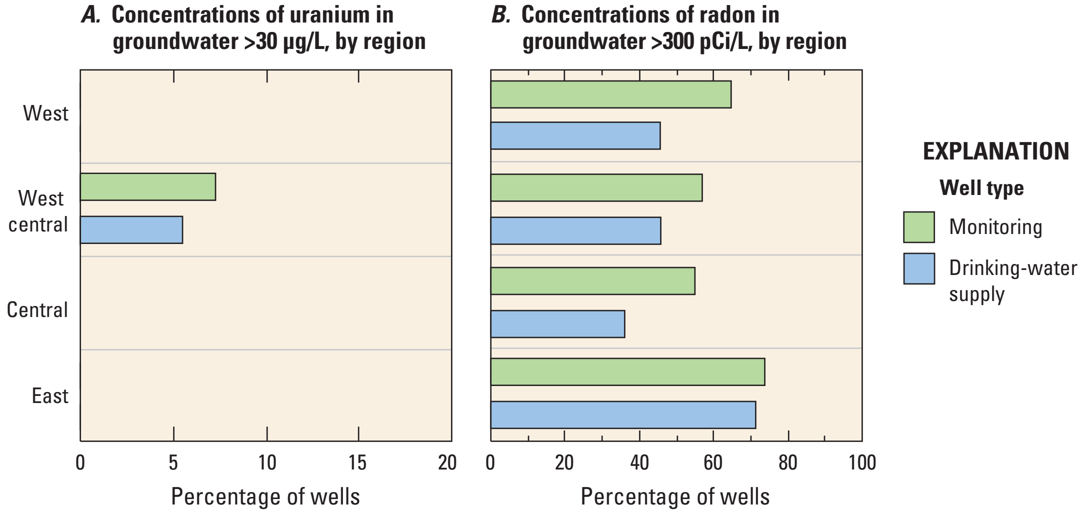


Figure 6–13. *A*, Concentrations of uranium exceeded the MCL of 30 µg/L in groundwater only in the west-central region of the glacial aquifer system. *B*, Concentrations of radon exceeded the USEPA proposed MCL of 300 pCi/L in all regions of the glacial aquifer system and in wells of all depths—shallow monitoring wells and deep drinking-water wells.

Aquifer sediments are a source of uranium

Uranium-containing rock and mineral fragments in glacial sediments are the primary source of dissolved uranium in groundwater. The minerals that contain uranium and the amount they contain are related to the types of rocks from which the glacial sediments were derived. The origin of the glacial ice and the direction it moved can be useful in characterizing differences in the types of bedrock that served as the source of material that now makes up the glacial sediments (see sidebar, Glacial depositional processes affect groundwater flow and chemistry today, p. 19).

In the west-central region of the glacial aquifer system, sediments containing fragments of shale can contain substantial quantities of uranium, resulting in concentrations in groundwater that exceed human-health benchmarks. Glacial sediment near the southern terminus of the glacial aquifer system near Nebraska also can include loess, or windblown sediments, from the west that contain uranium. This kind of information can be used to evaluate differences in groundwater uranium concentrations on a regional scale.(45)

Radon is derived from the radioactive decay of uranium, but radon and uranium do not necessarily co-occur in groundwater. The reason is that uranium is transported in groundwater as a reactive dissolved ion (or complex), and whether or not it remains dissolved in water depends on geochemical conditions. Radon, however, is present as an inert (nonreactive) gas that is very soluble in groundwater under all geochemical conditions; however, its short half-life of 3.8 days limits how far it can travel in groundwater.

Photograph by D.P. Schwert, North Dakota State University

Glacial outwash deposits containing shale fragments (dark material) in Barnes County, North Dakota. Shale in this region can be enriched in uranium and can be a source of uranium in groundwater.

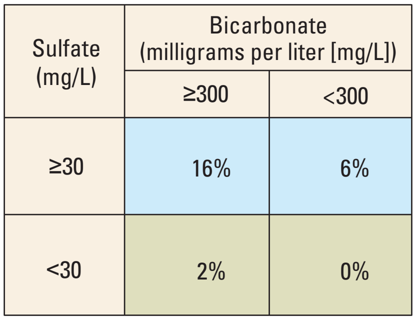
Geochemistry affects uranium and radon in groundwater in the glacial aquifer system

A major factor affecting whether uranium is dissolved in and transported with groundwater is the ability of uranium to form soluble complexes with other ions, such as bicarbonate. Uranium is more soluble in oxic groundwater; however, if uranium forms complexes with other ions, particularly bicarbonate ions, it remains dissolved in water over a wide range of redox and pH conditions.(33) The presence of sulfate (at concentrations greater than 30 mg/L) can indicate that aquifer sediments may be derived in part from shale, which, if enriched in uranium, can lead to increased concentrations of uranium in groundwater.

Uranium exceeded its MCL only in wells in the west-central region of the glacial aquifer system, most commonly in those samples with elevated bicarbonate and sulfate concentrations (fig. 6–14). In the glacial aquifer system, particularly the west-central region, concentrations of bicarbonate and sulfate are related to the types of rocks that were the source of the glacial sediment. For example, the glacial sediments deposited by the James and Des Moines Lobes (see sidebar, Glacial depositional processes affect groundwater flow and chemistry today, p. 19) were derived in part from Late Cretaceous-age sedimentary rocks like shale, some of which contain abundant carbonate and sulfide minerals; these shales also are enriched in uranium.(46, 47) In some parts of the glacial aquifer system where groundwater conditions are strongly anoxic, such as the deep anoxic groundwater in the Mahomet aquifer in Illinois, uranium solubility can be greatly diminished. In this part of the aquifer, concentrations of uranium were less than 1 µg/L in all 30 wells sampled.(48)

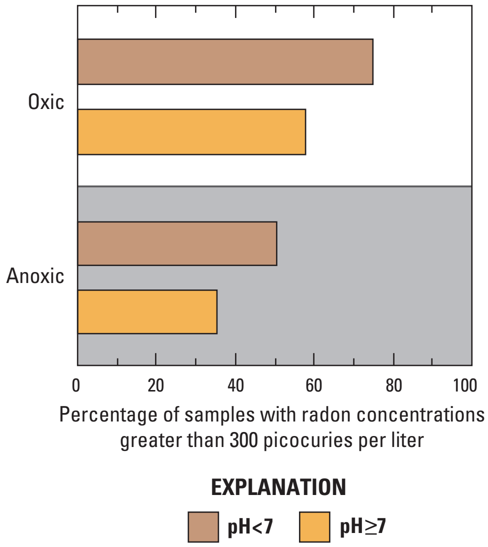
Although radon itself is not geochemically controlled, concentrations of radon were greatest in groundwater that was oxic and slightly acidic (fig. 6–15). The reason might be related in part to redox and pH controls on the solubility of radium-226 (^{226}Ra), from which radon is directly derived; therefore, geochemical conditions in the aquifer can indirectly affect radon concentrations in groundwater. Concentrations of radon under oxic and slightly acidic conditions might be high because there is more ^{226}Ra, which adsorbs to iron oxide sediment coatings under oxic groundwater conditions. Alternatively, these geochemical conditions may lead to increased emanation of radon from its source, ^{226}Ra.(49, 50, 51)

Percentage of samples with uranium concentrations >30 micrograms per liter in the west-central region



Sulfate (mg/L)	Bicarbonate (milligrams per liter [mg/L])	
	≥300	<300
≥30	16%	6%
<30	2%	0%

Figure 6–14. Wells in the west-central region were most likely to contain concentrations of uranium greater than the MCL of 30 µg/L if they also contained elevated concentrations of sulfate and bicarbonate. The co-occurrence with bicarbonate is because formation of uranium-bicarbonate complexes keeps uranium dissolved in water. Sulfate is an indicator of glacial aquifer sediments derived in part from uranium-bearing sulfide-rich marine shale.



Elevated radon concentrations vary by pH and redox

Figure 6–15. High concentrations of radon were associated with slightly acidic pH and oxic groundwater conditions.

Uranium and radon in drinking water and implications for water supply

Untreated water captured by public- and domestic-supply wells in the glacial aquifer system can contain concentrations of uranium that exceed the USEPA MCL of 30 µg/L, particularly in the west-central region (table 6–2). Although concentrations of uranium greater than the MCL in deep groundwater used for drinking-water supplies were relatively infrequent, many parts of the glacial aquifer system had groundwater uranium concentrations that were between 3 and 30 µg/L, indicating more widespread low-level occurrence—this was true particularly for domestic-supply wells.

Well depth and type of well may be important factors affecting concentrations of uranium in drinking water from the west-central region. For example, uranium exceeded the MCL in only 3 percent of samples from low-volume, relatively shallow domestic-supply wells (median depth 80 ft) but exceeded the MCL in 20 percent of samples from high-volume, deep public-supply wells (samples primarily from wells of median depth 292 ft in eastern Nebraska and North Dakota) (table 6–2).

Concentrations of radon in groundwater in all parts of the glacial aquifer system are a concern: the median concentration from all samples was 340 pCi/L—slightly higher than the proposed USEPA MCL of 300 pCi/L. In the east, groundwater concentrations of radon were greatest, exceeding the proposed MCL in nearly two-thirds of domestic-supply wells and nearly all public-supply wells sampled (table 6–3). Only in rare cases, however, did concentrations of radon in water from drinking-water wells in the east exceed the USEPA proposed AMCL of 4,000 pCi/L.

Table 6–2. Percentages of samples from drinking-water wells with concentrations of uranium greater than the USEPA MCL of 30 micrograms per liter and 3 micrograms per liter in source water.

[µg/L, micrograms per liter]

Well type	West	West central	Central	East
		Greater than 3 µg/L		
Domestic	0	27	4	7
Public	0	73	0	2
All drinking-water wells	0	33	2	5
		Greater than 30 µg/L		
Domestic	0	3	0	0
Public	0	20	0	0
All drinking-water wells	0	6	0	0

Table 6–3. Percentages of samples from drinking-water wells with concentrations of radon greater than the proposed USEPA MCL of 300 picocuries per liter and the proposed USEPA AMCL of 4,000 pCi/L in source water.

[pCi/L, picocuries per liter]

Well type	West	West central	Central	East
		Greater than 300 pCi/L		
Domestic	58	45	34	63
Public	44	100*	53	92
All drinking-water wells	46	46	36	71
		Greater than 4,000 pCi/L		
Domestic	0	0	0	1
Public	0	0*	0	0
All drinking-water wells	0	0	0	1

* Based on only one sample.

Chapter 7: *Understanding Where and Why Contaminants Associated With Human Activities Occur*

Contaminants released at the land surface infiltrate to the water table and move to deeper parts of the aquifer commonly used for drinking water or to surface water, such as streams. Nitrate and pesticides are the most common contaminants in groundwater underlying agricultural areas, and chloride is the most common contaminant in groundwater underlying urban areas. Characteristics of the glacial sediments and related geochemical conditions inhibit the transport of some contaminants and enhance the transport of others.

This chapter describes the sources of and factors that affect contaminants derived from human activities, such as nitrate, chloride, and pesticides in the glacial aquifer system.

Human modifications of the environment, such as irrigation, tile drains, and urbanization, have changed the pathways and rates by which nitrogen moves through the glacial aquifer system.

Background photograph by Patrick Mills, USGS; foreground photographs, left by Dana Kolpin and right by Derek Jensen

Nitrate

Despite high rates of fertilizer application, concentrations of nitrate in the glacial aquifer system are low in the deep groundwater commonly used for drinking. Shallow groundwater (less than 100 ft deep) is more vulnerable to nitrate contamination, particularly in areas where the overlying sediments are coarse-grained. The presence of coarse-grained sediment and a lack of organic carbon leads to oxic conditions, in which nitrate is stable. High nitrate concentrations in shallow groundwater can contribute nutrients to streams, where it can impair aquatic life. Despite a tenfold increase in the application of nitrogen in agricultural areas over the last 60 years, significant increasing trends in nitrate in groundwater are uncommon.

Nitrate in drinking water has been implicated in several human health problems, including methemoglobinemia (commonly called “blue-baby syndrome”) and specific cancers and reproductive problems, although more research is needed to verify some of these associations.(52) Groundwater can be an important contributor of nitrate to surface water that is used for drinking. Elevated concentrations of nitrate in surface water can also lead to a variety of direct and indirect adverse effects on water quality, including hypoxia (a condition of low oxygen), harmful algal blooms, and associated taste and odor problems.

Nitrate, the most common form of nitrogen in groundwater, originates from many human, animal, and natural sources, including chemical fertilizer, manure, atmospheric deposition, human waste, and decomposition of organic debris. Fertilizer is a major source of nitrogen in all four regions of the glacial aquifer system, but application rates of nitrogen fertilizer are highest in the west-central and central regions (the Corn Belt) (fig. 7–1). The use of nitrogen fertilizers in the United States, primarily in the Corn Belt, has increased tenfold over the last 60 years.(53) The Corn Belt, which comprises Illinois, Indiana, Iowa, Nebraska, Ohio, and parts of adjoining States, is the area of the Great Plains and the Midwest where corn and soybeans are the principal crops; corn production could increase if corn were used for biofuels as well as for animal feed (see sidebar, Biofuel production and water quality, p. 66). Low concentrations of nitrogen from geologic sources have been identified in a few areas, such as in the loess sediments of Nebraska.(54)

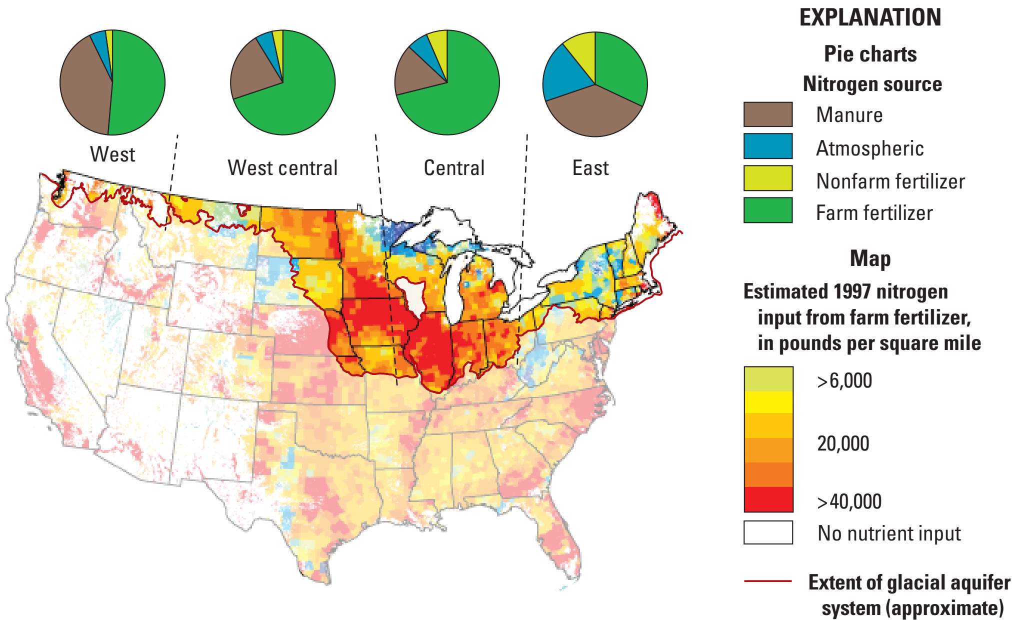


Figure 7–1. Farm fertilizer is the major source of nitrogen in all regions of the glacial aquifer system except the east, where the input of nitrogen from manure is slightly higher. The rates of commercial fertilizer applications of nitrogen in the country are highest in the agricultural areas of the central and west-central regions.

Nitrate contamination of groundwater is greatest at shallow depths

Although public-supply wells mostly tap the deeper parts of the glacial aquifer system for water supply, the shallow glacial aquifer system commonly is used for domestic drinking-water supply. Two-thirds (66 percent) of domestic-supply wells are less than 100 ft deep, and some wells are as shallow as 12 ft. Fifty-eight percent of samples of shallow groundwater underlying agricultural areas contained nitrate concentrations greater than 1 mg/L as N, the background concentration for the glacial aquifer system.(55) Median concentrations of nitrate in groundwater were higher in shallow wells tapping groundwater underlying agricultural and urban areas than in groundwater from deeper drinking-water wells (fig. 7–2).

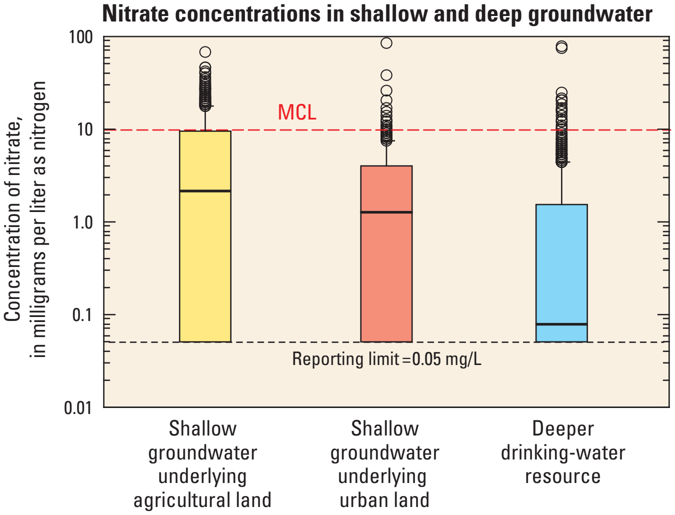


Figure 7–2. The median nitrate concentrations for samples of groundwater underlying agricultural land and urban land (median well depth of 25 ft) were significantly higher than those for samples of groundwater from drinking-water wells (median depth of 80 ft for domestic-supply and 125 ft for public-supply wells). However, many domestic-supply wells use water from the shallow aquifer system. Nitrate concentrations in at least one sample from each well category were greater than the MCL of 10 mg/L as N.

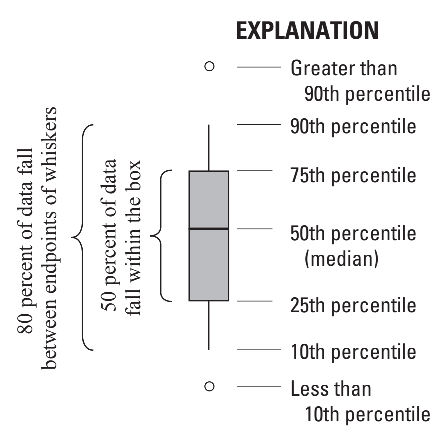
Boxplots

Boxplots are used to illustrate how results are distributed within a group. The "box" ranges from the 25th to the 75th percentile and represents 50 percent of the data. The horizontal line in the middle of the box is the median value—one-half of the values in the group are greater than the median and one-half are less.

Percentiles describe the percentage of values in a group that are less than the given value: 25 percent of the values in a group are less than the 25th percentile; 75 percent of the values in a group are less than the 75th percentile. The median is also the 50th percentile.

If, for example, the 75th percentile for the measured concentration of a contaminant in a group of wells is equal to the human-health benchmark for that contaminant, then 75 percent, or three-fourths, of the wells have a concentration of that contaminant less than the benchmark, and 25 percent, or one-fourth, have a concentration greater than the benchmark.

The "whiskers" (vertical lines) in these figures extend to the 10th and 90th percentiles; box and whiskers together represent 80 percent of the data. Values greater than the 90th or less than the 10th percentiles are shown as individual points (outliers).



Nitrate concentrations in groundwater underlying coarse-grained sediments exceeded the MCL more frequently than groundwater underlying fine-grained sediments because fine-grained sediments impede the transport of nitrate to groundwater.

Shallow groundwater (less than 100 ft deep) is more susceptible to nitrate contamination in areas where the overlying sediments are coarse-grained than where sediments are fine-grained (fig. 7–3). Coarse-grained sediments enhance rapid transport of water through the aquifer, allowing little time for denitrification. Fine-grained sediments slow the transport of groundwater and are often rich in organic matter—factors that favor the development of anoxic conditions and denitrification.(56) The median nitrate concentration for samples of anoxic groundwater was near zero, regardless of the magnitude or type of nitrogen input (fig. 7–4). Fine-grained sediments contain nutrients essential for agriculture, but drain poorly. Drainage commonly is improved by the installation of tile drains, which divert nitrate-rich excess recharge to streams. Tile drains, ditches, and other forms of artificial drainage thus contribute to higher nitrate concentrations in streams, but may lower concentrations of nitrate in groundwater.(57) Streams, however, can be a source of nitrate to nearby drinking-water wells that pump water from streams through aquifer sediment to augment supply.

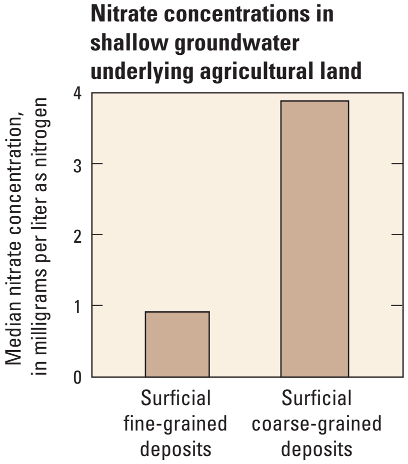


Figure 7–3. Shallow groundwater (less than 100 ft deep) in agricultural areas is more susceptible to nitrate contamination where the overlying sediments are coarse-grained than where sediments are fine-grained.

Biofuel production and water quality

The Renewable Fuels Standard created as part of the 2005 Energy Policy Act was amended to increase the use of biofuels in the United States. The target was to increase the annual total of biofuels from 9 billion gallons in 2009 to 36 billion gallons by 2022 to compose about 13 percent by volume of all transportation fuels. Large increases in biofuel use would require a substantial increase in production of corn, possibly by using improved corn varieties with higher yield, expanding corn planting into nontraditional corn growing areas, or increasing the amount of continuous corn planting. All of these practices would lead to increased use of nutrients and pesticides in the part of the United States in the area where use of these chemicals is already highest—the Corn Belt. Concern is growing that these changes in agriculture practices would result in increased ecological and economic costs.(111) The increased volume of fertilizer placed on the fields could increase the amount of nitrogen transported to groundwater. Although denitrification and artificial drainage of agricultural land currently keep concentrations of nitrate in groundwater in the glacial aquifer system relatively low, continued application of nitrogen fertilizers could exceed the capacity of these aquifers to naturally reduce nitrate concentrations. Additionally, nitrate loading to streams and rivers can be expected to increase, which could have an adverse effect on the quality of water pumped from wells that capture substantial amounts of river water through induced infiltration and of downstream receiving waters such as the Gulf of Mexico.

Photograph by Kelly L. Warner, USGS

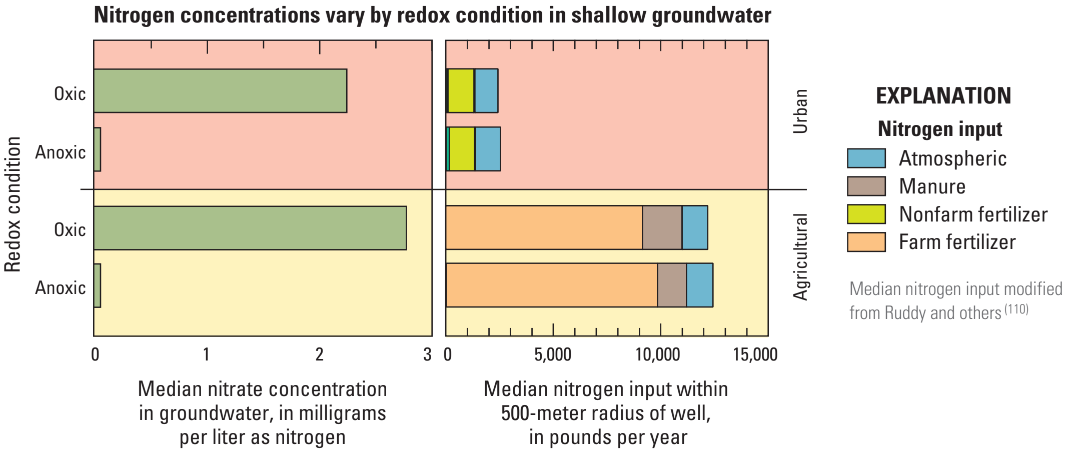


Figure 7–4. Nitrate concentrations were higher in oxic groundwater (water with at least 0.5 milligram per liter dissolved oxygen) than in anoxic groundwater (water with less than 0.5 milligram per liter dissolved oxygen), regardless of land use or nitrogen source. The median nitrate concentration is similar in groundwater underlying urban and agricultural land regardless of source.

Many of the factors that affect the presence and transport of nitrate in groundwater are related to one another (fig. 7–5). For example, grain size and residence time are related because groundwater flows relatively rapidly through coarse-grained sediments. Residence time in turn is related to redox condition, with longer residence times required for the development of anoxic conditions and therefore denitrification (see sidebar, How do redox reactions work?, p. 29). Coarse-grained glacial sediment also tends to be carbon-poor, which inhibits the development of anoxic conditions. In contrast, groundwater flow is slower through fine-grained sediment, which tends to be richer in organic carbon—the longer residence time and organic carbon contribute to development of anoxic conditions, which in turn promote higher rates of denitrification.(58)

Although rates of denitrification are higher in the glacial aquifer system than in many other aquifer systems, the assimilation capacity of the glacial aquifer system—the amount of nitrate that it can transform through denitrification to inert nitrogen gas—might be limited. If the assimilation capacity is exceeded, nitrate concentrations in the deeper parts of the aquifer could increase as shallow groundwater with high nitrate concentrations moves downward.(2) This process could impair the quality of water from drinking-water wells, which typically tap the deeper parts of the aquifer.

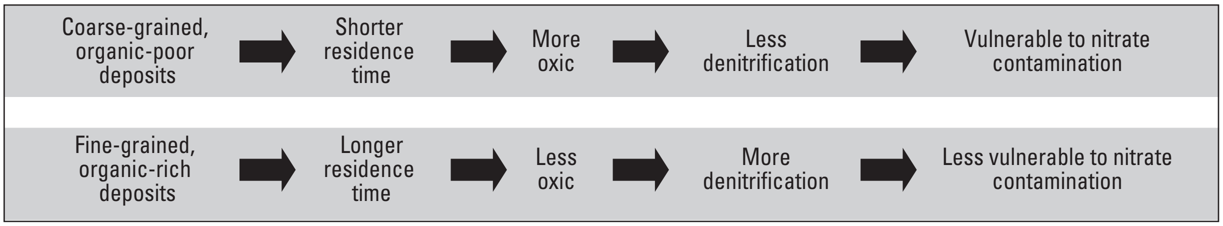


Figure 7–5. Nitrate concentration in groundwater is related to many interdependent factors that affect the stability of nitrate in the glacial aquifer.

Nitrate in drinking water

Concentrations of nitrate in groundwater from deep domestic and public-supply wells are three to four times less likely to exceed the nitrate MCL (10 mg/L as N) than in shallow groundwater beneath agricultural and urban areas. Median concentrations of nitrate in domestic-supply (less than 0.06 mg/L as N) and public-supply wells (0.5 mg/L as N) were low. Groundwater samples from domestic and public-supply wells had lower concentrations of nitrate than did samples of shallow groundwater underlying agricultural and urban areas primarily because of the greater depth of the drinking-water wells, for which redox conditions are more often anoxic (fig. 7–6).

Nitrate concentrations in groundwater from public and domestic-supply wells were greater than the nitrate MCL in wells mostly less than 100 ft deep, where redox conditions are more often oxic. The groundwater in mostly domestic-supply wells less than 50 ft deep was predominantly oxic and had the highest concentrations of nitrate. A statistical model developed to identify the vulnerability of domestic supplies to nitrate contamination demonstrated that the high concentrations of nitrate in domestic-supply wells depended on whether or not there was a source of nitrogen and on the characteristics of the domestic-supply well, such as diameter and depth of the well screen (55) (see sidebar, Large-diameter wells, p. 69).

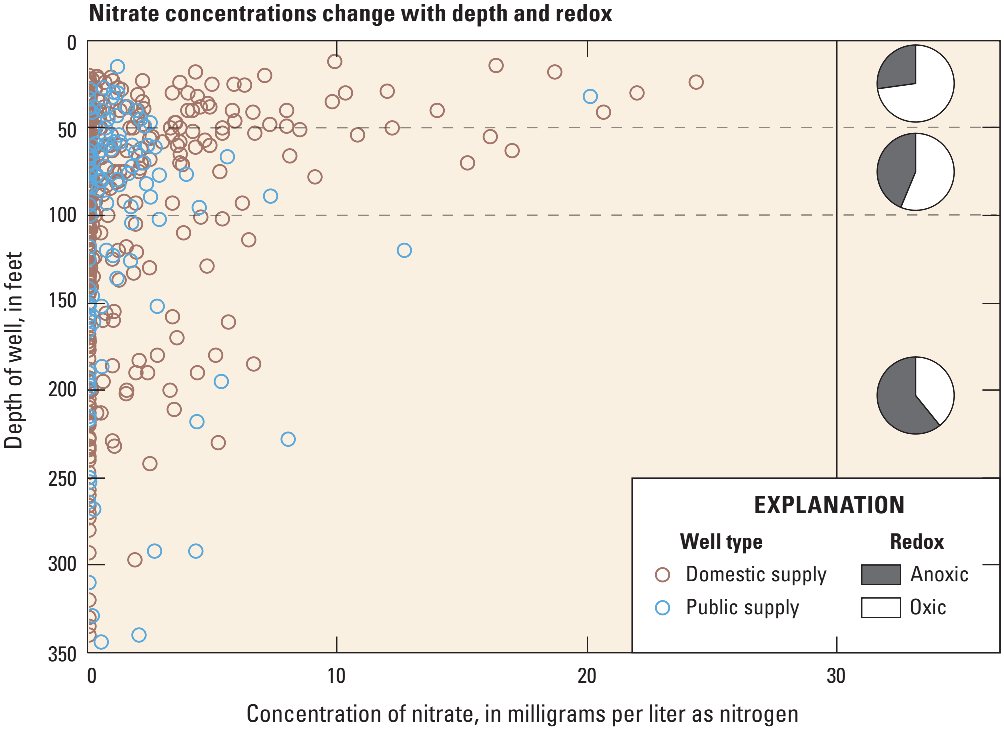
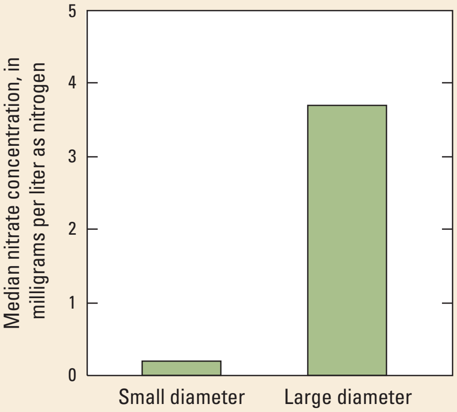


Figure 7–6. The highest concentrations of nitrate in drinking water were in wells that were shallower than 50 ft below land surface, where redox conditions mostly are oxic. As well depth increases, redox conditions become increasingly anoxic, increasing the likelihood that nitrate will be removed by denitrification.

Concentrations of nitrate exceeding the MCL are uncommon (less than 3 percent) in drinking water from the glacial aquifer system.

Large-diameter wells

Large-diameter (greater than 24 inches) domestic-supply wells are common in areas where the permeability of the glacial sediment is low, so movement of groundwater into the well is slow. The large volume inside these wells allows water to be stored within the well for short-term use. The large diameter of these wells, however, seems to increase their vulnerability to nitrate contamination. The median nitrate concentration for 15 large-diameter domestic-supply wells sampled in Illinois, Connecticut, and North Dakota was almost 30 times higher than that for smaller diameter domestic-supply wells that pumped water from a similar depth. A model simulation that estimated the probability of nitrate contamination in domestic-supply wells found that well diameter was a significant factor contributing to concentrations of nitrate greater than 4 mg/L as N.(55)



Photograph by Joseph D. Ayotte, USGS

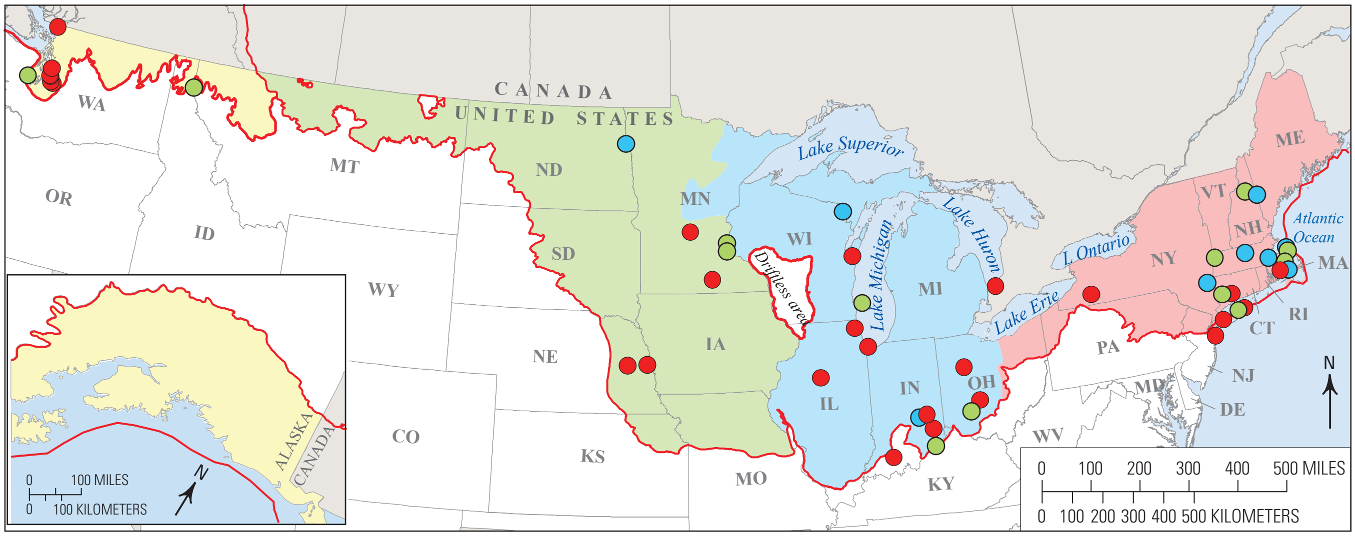
Groundwater in large-diameter, shallow (up to 50 feet deep), domestic-supply wells had much higher median nitrate concentrations than in smaller diameter wells that pumped water from the same depth. Although the results from only 15 large-diameter and 75 small-diameter wells were compared, the difference in median nitrate concentrations was statistically significant.

Groundwater can be a source of nitrate to streams

Nitrate from groundwater contributes to the total nitrate carried by many streams that overlie the glacial aquifer system. In three-quarters of the 48 streams monitored by NAWQA, 30 percent or more of the total nitrate in the stream comes from base flow that is attributed to groundwater discharge.(59) Streams in the glacial aquifer system area ultimately deliver nitrate to large water bodies, from Puget Sound in the west, to the Great Lakes in the upper Midwest, and to the Gulf of Mexico in the south, where the nitrate contributes to harmful algal blooms and seasonal hypoxia.

Nitrate-laden groundwater can take decades to move through the glacial aquifer system to streams. A study of several streams in the glaciated area found that nitrate in base flow of streams with coarse-grained sediments, where dissolved oxygen is relatively high, is mostly from nitrate-laden groundwater.(60) The nitrate-laden groundwater, however, may be decades old when it discharges to the stream; high nitrate levels in some streams in the glacial area may be sustained for decades regardless of current management practices. At a local scale, management practices aimed at controlling nutrient loads to streams, such as allocations of total maximum daily loads (TMDLs), ideally would account for contributions of nitrate from groundwater in addition to those from overland flow—but many local practices do not. The contribution of nitrate from groundwater is a substantial part of the picture but often is overlooked.

The concentration of nitrate in many streams during low flow—when most of the streamflow is derived from groundwater, including water from tile drains—exceeds USEPA-recommended nutrient criteria for the protection of aquatic life (fig. 7–7). Six ecoregions, each with its own USEPA nutrient criterion related to streams, overlie the glacial aquifer system. The nitrogen criterion for protection of aquatic life was most often exceeded in streams in the central region, even though this region has the highest nitrogen criterion in the Nation (2.18 mg/L as N). The regional criterion was least often exceeded in the east region, even though this region has a much lower nitrogen criterion (0.04 mg/L as N).

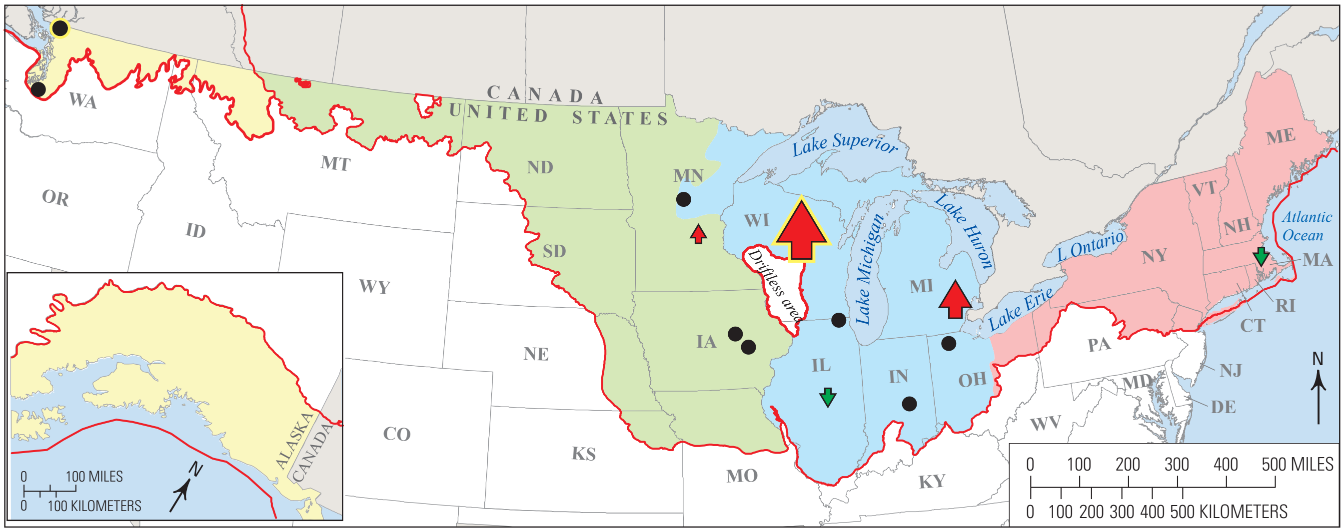


Modified from Spahr and others(59)

Figure 7–7. Recommended values of nutrient criteria for the protection of aquatic life in streams were exceeded during base flow, when groundwater is a major contributor to streamflow.

Concentrations of nitrate in groundwater show few trends

Concentrations of nitrate in groundwater did not change during the period 1988–2010 in many parts of the glacial aquifer system, but in a few areas concentrations increased significantly (61) (see sidebar, How does NAWQA investigate trends in groundwater quality?, below). The trends were not related to the type of land use—concentrations increased in samples from shallow groundwater underlying agricultural land in Wisconsin and from shallow urban monitoring wells in Michigan and Minnesota. Concentrations decreased in samples from drinking-water wells in Illinois and from shallow urban monitoring wells in Massachusetts (fig. 7–8).



Modified from Lindsey and Rupert (61)

EXPLANATION

Glacial region—Shown only in the United States

🟥 East
🟦 Central
🟩 West central
🟨 West

Extent of glacial aquifer system (approximate)

Statistically significant change in median nitrate concentrations between the first and second samples from a group of wells, in milligrams per liter as nitrogen—Yellow outlines indicate that the median nitrate concentration of the second sample is greater than the drinking-water standard of 10 milligrams per liter

Direction of change Increase	Decrease	Magnitude of change
▲	▼	Less than 0.1
▲	▼	0.1 to 0.5
▲	▼	Greater than 0.5

● No significant change in median nitrate concentrations between the first and second samples from a group of wells

Figure 7–8. Nitrate concentrations in the glacial aquifer system increased significantly in three well networks and declined slightly in two well networks during the period 1988–2010.

How does NAWQA investigate trends in groundwater quality?

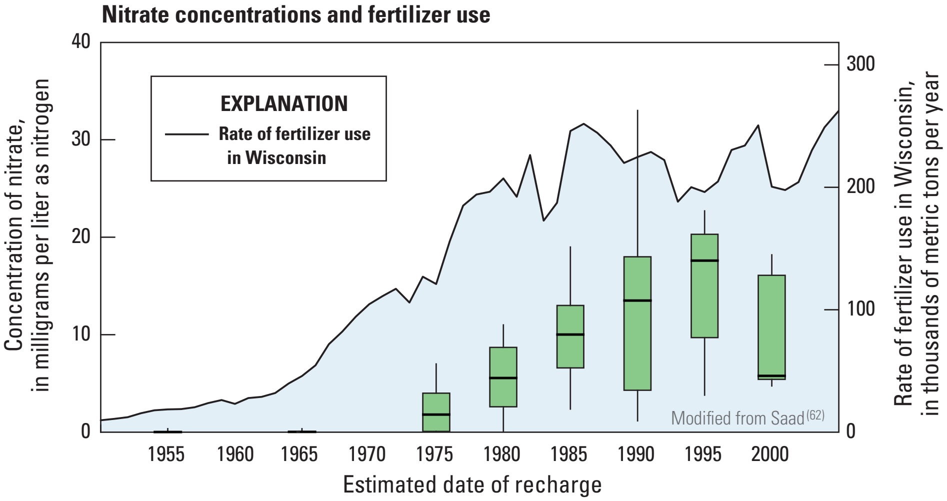
A trend is a change in groundwater quality over time. How do we know if the variation that we see in sequential groundwater-quality measurements is a trend? How can data from individual wells be interpreted in terms of regional-scale—or national-scale—changes in groundwater quality?

To answer these questions, data from more than 300 wells in 13 groundwater studies in the glacial aquifer system were analyzed as part of a NAWQA study on decadal trends.(61) NAWQA's approach used results from groundwater studies of 20 to 30 wells each, which were sampled for a large number of constituents at about 10-year intervals. The paired samples for each well were compared, and the numbers of wells with increasing or decreasing concentrations were analyzed with statistical methods to determine whether concentrations in the study area increased, decreased, or remained the same over the 10-year period. The decadal-scale sampling data were supplemented with sampling a subset of wells in each study every 2 years. Because it assessed trends for groups (networks) of wells, the NAWQA approach minimized the influence of variability at individual wells. Groundwater changes slowly, so decadal sampling was adequate to detect statistically significant trends in nitrate concentrations in the glacial aquifer.

The largest recorded change was for the agricultural area in Wisconsin, where the median nitrate concentration increased by more than 0.5 mg/L over 10 years and now exceeds the MCL of 10 mg/L as N.(61) The increases in Wisconsin likely are related to both source and aquifer characteristics. This is an area where applications of nitrogen fertilizer have increased (fig. 7–9), where aquifer sediments are coarse-grained, and where groundwater is mostly oxic.(62)

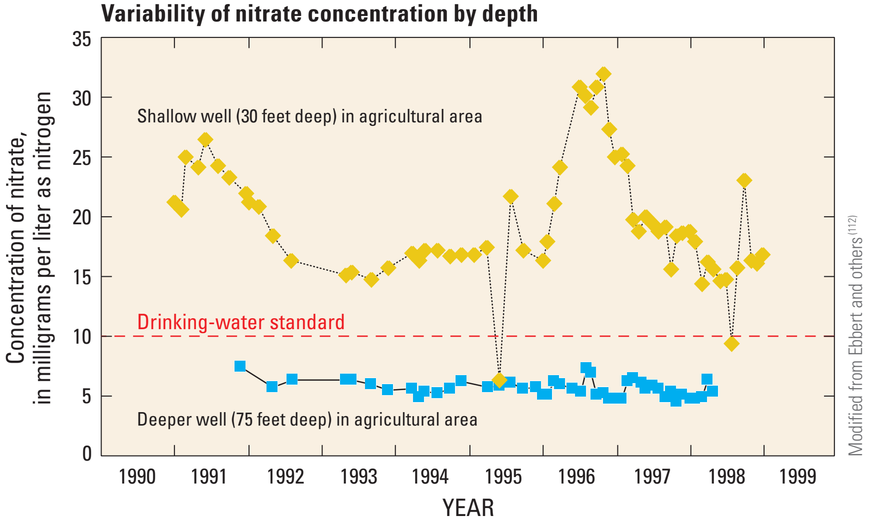
Groundwater in one other network of wells in the glacial aquifer system—in northwestern Washington State—had a median concentration of nitrate that exceeded the MCL. For these wells, however, nitrate concentrations did not change significantly over the 10-year period. Even if the median nitrate concentration for a well network does not change, the concentrations at a single well, especially shallow wells, can vary greatly over short time periods (fig. 7–10); this variation complicates the evaluation of trends. The water quality of deeper drinking-water wells varies less over time. Nitrate concentrations that exceeded 10 mg/L as N in most domestic-supply wells in the glacial aquifer system did not change or decreased over a 10-year period.(61)

The overall percentage of all samples with concentrations of nitrate that exceeded the MCL (10 mg/L as N) increased by 1 percent over the past 10 years for samples that were oxic—a condition typical of groundwater in coarse-grained sediments. The percentage of anoxic samples with concentrations of nitrate greater than 10 mg/L as N remained low and did not change over the decade.


Nitrate concentrations and fertilizer use

Modified from Saad(62)

Figure 7–9. The pattern of increasing nitrate concentrations in groundwater in Wisconsin mirrors the increasing trend in nitrogen fertilizer use. The downward trend in nitrate concentrations after the estimated date of recharge in the mid-1990s could be real or an artifact of the small number of samples available to represent water that recharged after the mid-1990s.


Variability of nitrate concentration by depth

Modified from Ebbert and others(112)

Figure 7–10. Nitrate concentrations in a shallow domestic-supply well were higher and more variable than those in a deeper well in the glacial aquifer system near Puget Sound. Monitoring the variability of nitrate concentrations in shallow wells is important because a single sample cannot provide a picture of how nitrate concentrations fluctuate.

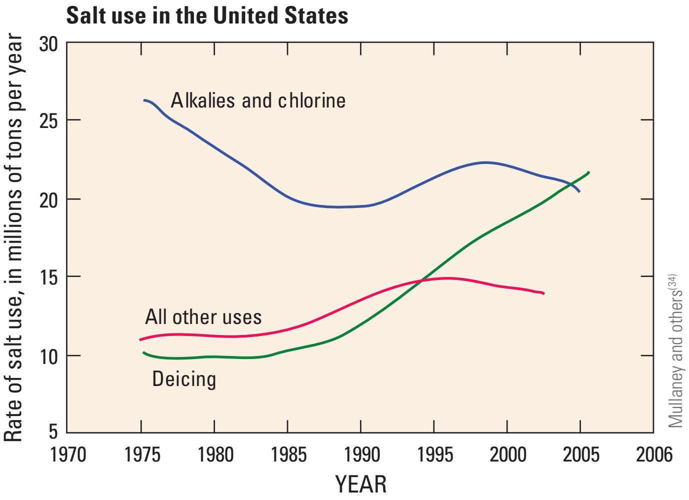
Chloride

Chloride in samples of shallow urban groundwater, where the highest chloride concentrations were measured, exceeded the SMCL of 250 mg/L in 7 percent of wells. Chloride in groundwater from the glacial aquifer system is derived largely from human activities, primarily sodium chloride (salt), which is used commonly for deicing roadways. Discharges of chloride-laden groundwater to streams increase the probability that chloride in streams will exceed the chronic aquatic criterion of 230 mg/L, especially during dry periods when the groundwater contributes most of the streamflow.

The use of salt (sodium chloride, calcium chloride, and magnesium chloride) has increased measurably in the United States since 1950, and most of the increase has been primarily for the deicing of roads, parking lots, and other impervious surfaces during winter months(63) (fig. 7–11). Not surprisingly, high concentrations of chloride and sodium in groundwater from the glacial aquifer system have been related to urban land use, where deicing with salt is a common practice.(64–68) Chloride in groundwater of the glacial aquifer system also has other sources in addition to deicing salt, such as water softeners, septic systems, animal waste, fertilizers, and water treatment.

17
Cl
35

Chlorine is present in minerals as chloride—a familiar example is halite (sodium chloride), which is used as table salt. Chloride typically is present in very small amounts in most aquifer materials. Runoff from roads that have been treated with road salt, agricultural drainage, and saltwater encroachment all can cause elevated concentrations of chloride in groundwater.



Mullaney and others(34)

Figure 7–11. Use of salt for deicing has more than doubled since the 1980s. In 2005, the two largest uses of salt were the industrial production of alkalies and chlorine for cleaning and disinfection products, and deicing. [Salt use by industry is compiled by the Bureau of Mines and the U.S. Geological Survey from industry reports.]

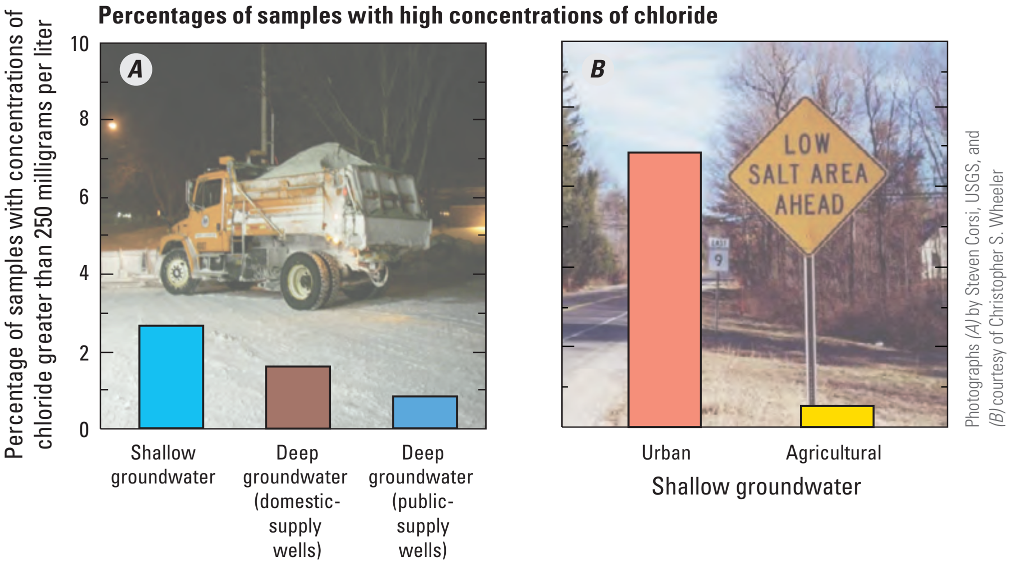
Photograph courtesy of MeltSnow.com

In some areas of the glacial aquifer system, the use of road salt is restricted because of the susceptibility of the aquifer to contamination. This photograph shows a truck applying salt brine.

Shallow groundwater in urban areas is vulnerable to chloride contamination

Concentrations of chloride exceeded the SMCL of 250 mg/L more frequently in samples of shallow groundwater than in samples of deep groundwater used as a drinking-water supply (fig. 7–12*A*). The highest concentrations of chloride were measured in shallow groundwater in urban areas and other areas where salt use is high, and there were with no major differences by region in the glacial aquifer system. Chloride exceeded the SMCL in about 7 percent of shallow urban groundwater samples (fig. 7–12*B*). This exceedance may be cause for concern as shallow groundwater with high chloride concentrations migrates to deeper parts of the aquifer used for public supply. Chloride is a conservative constituent—it is not readily removed by natural chemical processes and seldom reacts with other constituents. Therefore, as shallow groundwater moves downward into the aquifer over time, the potential increases for transporting chloride to the deeper groundwater used for drinking-water supplies. The evidence is minimal, however, that chloride has contaminated deep groundwater on a widespread basis in the glacial aquifer system—concentrations of chloride in groundwater from domestic-supply wells exceeded the SMCL of 250 mg/L in only 1.6 percent of samples, compared to 2.1 percent nationally.(69) Groundwater from public-supply wells had even lower concentrations of chloride than did domestic-supply wells (possibly resulting from dilution associated with higher pumping rates or generally greater well depths) and exceeded the SMCL in water samples from fewer than 1 percent of wells.

Chloride is present in minerals—a familiar example is halite (sodium chloride), which is used as table salt. Chloride usually is present in very small amounts in most aquifer materials. Runoff from roads that have been treated with road salt, agricultural drainage, and saltwater encroachment all can cause elevated concentrations of chloride in groundwater.



Photographs (*A*) by Steven Corsi, USGS, and (*B*) courtesy of Christopher S. Wheeler

Figure 7–12. *A*, The percentage of wells with concentrations of chloride in groundwater that exceeded the SMCL of 250 mg/L was higher for wells monitoring shallow groundwater underlying urban and agricultural areas than for deep drinking-water wells, and *B*, was particularly high for wells monitoring shallow groundwater in urban areas. Because chloride is not removed from groundwater by natural processes, discharge of chloride-laden shallow groundwater can be a dominant source of chloride to streams.

Concentrations of chloride in groundwater are increasing

Chloride concentrations in shallow groundwater have increased over time. Data from samples collected about 10 years apart (1990s and 2000s) indicate that concentrations of chloride in groundwater in the glacial aquifer system had increased significantly, with the greatest increases in the east and central regions (fig. 7–13).

Of the 5 well networks (30 wells each) nationally in which chloride concentrations increased by more than 20 mg/L over the last decade,(61) 4 were in the glacial aquifer system. Of the 13 well networks monitored for trends in the glacial aquifer system—3 monitoring deep groundwater, 5 monitoring shallow groundwater beneath agricultural land, and 5 monitoring groundwater beneath urban land—6 had a statistically significant increase in chloride concentration.

The chloride likely is from sources that include deicing salt, water-softening salt, and sewage and animal waste. The ratio of chloride to bromide concentrations indicates the source of chloride in samples from areas where concentrations are increasing.(34) Although the specific sources of the chloride are unclear, it is evident that contributions from human activities are related to the increases of chloride concentrations in groundwater. This upward trend of chloride concentrations in groundwater is a potential concern for aquatic ecosystems, because of the discharge of chloride-laden shallow groundwater to streams, and for the users of water from the shallow glacial aquifer system.

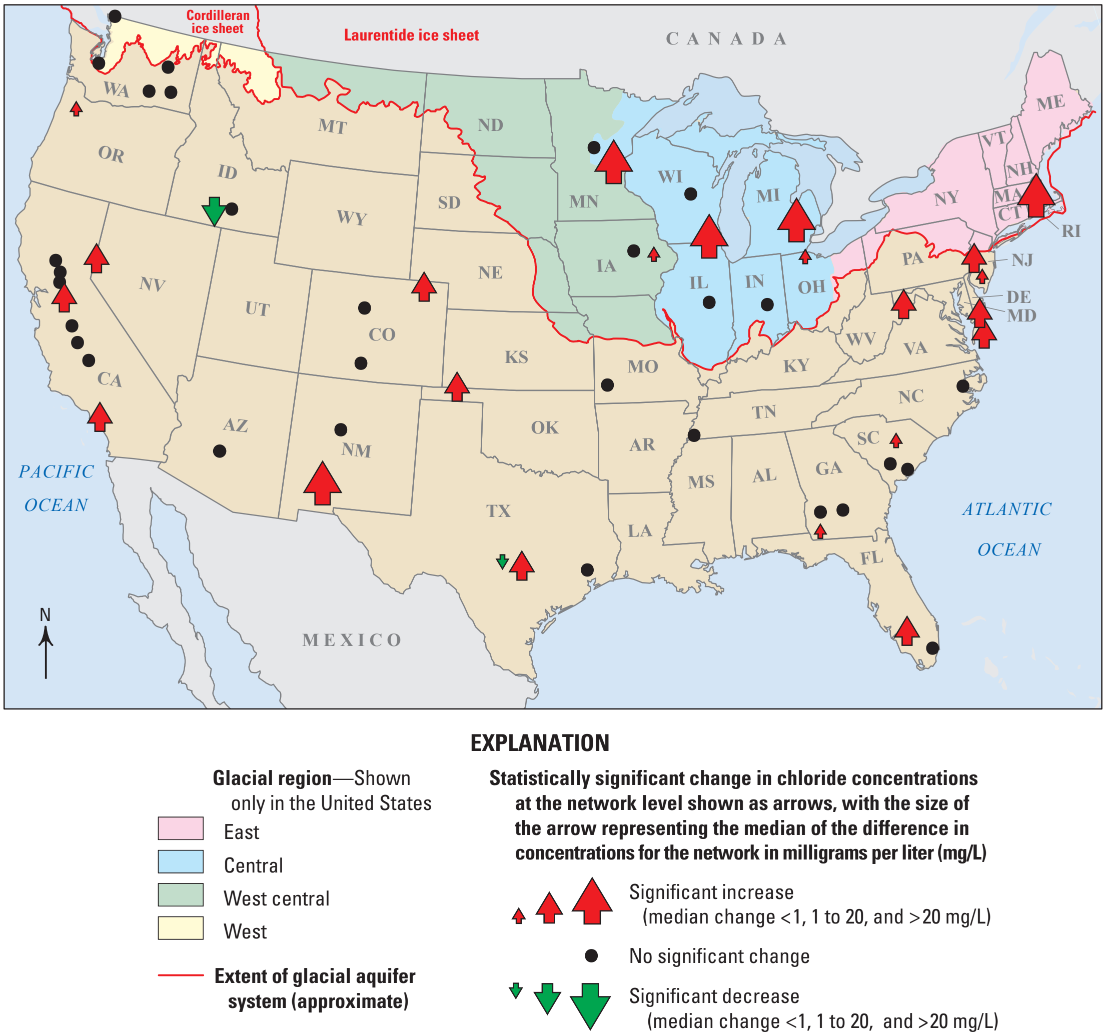


Figure 7–13. Concentrations of chloride in groundwater (median concentrations from 30 well networks) are increasing over time (red arrows) primarily in networks near urban areas. The largest median increases in chloride concentrations in the country are in the glacial aquifer system.

Chloride in groundwater affects concentrations of chloride in streams

Chloride in streams is derived from the inflow of groundwater with high concentrations of chloride and from direct surface runoff and wastewater discharge. During dry conditions and at sites with no major wastewater discharges, groundwater discharge makes up most of the streamflow (base flow). Under these conditions, concentrations of chloride in streamwater reflect the concentrations of chloride in the groundwater flowing to the stream. In glacial aquifer streams, the median concentration of chloride was 81 mg/L in stream base-flow samples from urban areas, 21 mg/L from agricultural basins, and 3.5 mg/L from undeveloped (forested) basins,(34) indicating that the greatest contribution of chloride to streams is from urban sources.

Chronic aquatic criteria have been developed for streams to protect fish and other aquatic life. In some urban areas, groundwater with elevated chloride concentrations contributes to exceedances of the chronic aquatic criteria.

During dry conditions, high concentrations of chloride in groundwater discharging to streams can cause concentrations of chloride in the stream to exceed the chronic aquatic criterion (CAC) of 230 mg/L—a criterion developed to protect fish and other aquatic life. Concentrations of chloride in groundwater were greater than the CAC (for streams) in 8 percent of wells sampled in urban areas. Not surprisingly, chloride concentrations at 15 of 100 streamflow-monitoring sites (12 urban and 3 agricultural) overlying the glacial aquifer system exceeded the CAC at least once during the sampling period, which was generally monthly for 3 to 13 years.(34)

Concentrations of chloride in streamwater during low-flow conditions (except at sites where there are major wastewater discharges) can be used to predict where maximum chloride concentrations during winter and spring will exceed the CAC (fig. 7–14). In streams that overlie the glacial aquifer system, the maximum measured chloride concentrations were greater than 230 mg/L in samples from sites at which base-flow chloride concentrations were greater than about 100 mg/L.(34) Streams with high concentrations of chloride in base-flow samples were most likely to have chloride concentrations that exceeded the recommended criterion during the winter months preceding high flows associated with snowmelt. After snowmelt begins, chloride concentrations in the streamwater become diluted by increased runoff.(34) Concentrations of chloride were elevated mostly at urban stream sites.

Photograph by James J. Duncker, USGS

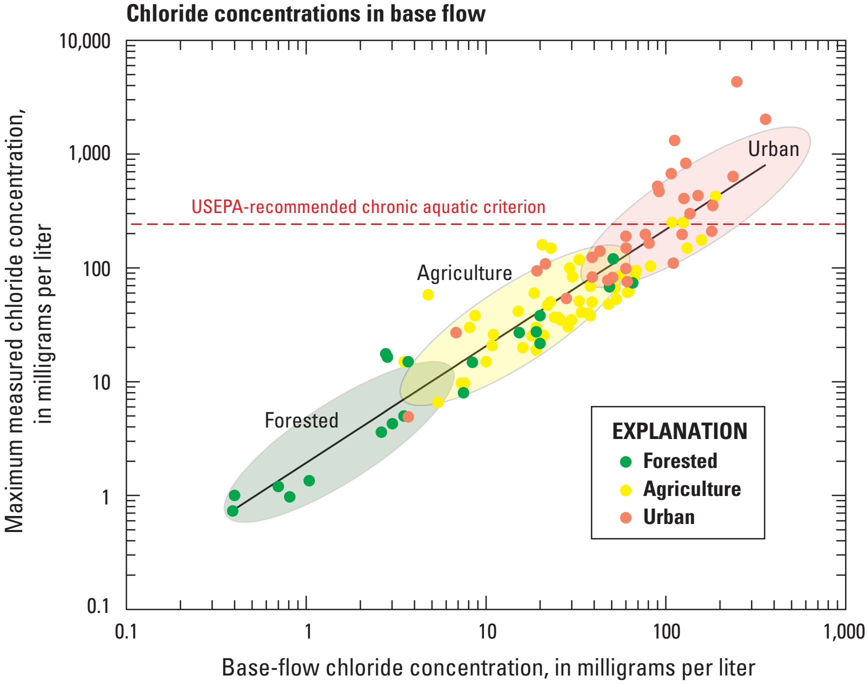


Figure 7–14. Chloride concentrations in groundwater underlying urban areas were higher than those in groundwater underlying agricultural or forested areas. Concentrations of chloride in streamwater during low-flow conditions can be used to predict where maximum chloride concentrations will exceed the chronic aquatic criterion.

Pesticides

Pesticide compounds (including herbicides) were widely detected in groundwater from the glacial aquifer system, but concentrations generally were low (< 0.2 µg/L) despite intensive use in some areas. Fine-grained aquifer sediments in the Corn Belt, where pesticide-application rates are high, limit the movement of groundwater and any pesticides it contains and promote degradation of those pesticides. Where aquifer sediments are coarse, pesticides and their degradates (compounds that form as the original pesticide breaks down) were detected more frequently in groundwater than where sediments are fine. In some cases, concentrations of pesticide degradates exceeded the concentrations of the original pesticide. The extensive use of artificial drainage of agricultural land in the Corn Belt decreases the amount of pesticides that reach the aquifer, but increases the transport of pesticides to streams. In some areas, pesticide compounds transported to streams are captured by downstream supply wells; pesticides were detected three times as often in groundwater pumped from public-supply wells near streams draining the Corn Belt than from public-supply wells farther from streams.

Adverse human-health effects from pesticide compounds, such as atrazine, in drinking water have had limited study but suggest cause for concern—including potential cancer, damage to the nervous system, and possible adverse effects on birth outcomes. The USEPA determined in 2000 that atrazine is not likely to cause cancer in humans.(70) However, atrazine was banned by the European Union in 2004 because of its persistence in groundwater at concentrations greater than 0.1 µg/L.(71) Some studies have shown associations between adverse reproductive outcomes in humans and concentrations of triazine compounds, which include atrazine, ranging from 0.1 to more than 2 µg/L in drinking water.(72, 73) Groundwater can be an important source of pesticides to streams, particularly during dry periods when the proportion of streamflow composed of groundwater discharge is at its maximum; this can lead to the exposure of aquatic organisms to potentially harmful levels of pesticides.(24, 74)

Although pesticides are detected frequently in the glacial aquifer system, they are nearly always measured at concentrations well below human-health benchmarks. The pesticides atrazine (and its degradate deethylatrazine), metolachlor, simazine, prometon, and bentazon were among the pesticides detected most frequently in groundwater, but fewer than 5 percent of samples contained one of these compounds at a concentration above the common assessment level of 0.2 µg/L—a level that is many times lower than any human-health benchmark.

In special studies specifically designed to look for pesticide degradates primarily in the Corn Belt region of the glacial aquifer system, the degradates were detected more commonly than the pesticide originally applied. For these special studies, 8 of the 15 most frequently detected pesticide compounds in groundwater from wells in the Corn Belt were degradates of five high-use pesticides applied to corn and soybeans: atrazine, metolachlor, acetochlor, alachlor, and dimethenamid. Even when the concentration of any one pesticide in a well was low (less than 0.2 µg/L), the sum of the concentrations of all pesticides and associated degradates commonly (in more than 60 percent of samples tested) exceeded 1 µg/L in groundwater samples from some settings.

Detection of pesticides at low concentrations is widespread

Two groups of pesticides stand out because they have been detected most frequently both across the glacial aquifer system and within the Corn Belt: the triazine pesticides (for example, atrazine) and the chloroacetanilide pesticides (for example, metolachlor). This result is not surprising because pesticides from these two groups, particularly atrazine and metolachlor, were the pesticides most heavily applied (on an annual basis) during the period when groundwater samples were collected.(15) Atrazine and its breakdown product deethylatrazine also were among the most frequently detected pesticide compounds in water from public- and domestic-supply wells nationwide.(76, 77) Although the frequency of pesticide occurrence is not uniform across the glacial aquifer system because of differences in rates of use and areal distribution, atrazine and deethylatrazine were detected at or above the common assessment level of 0.2 µg/L in samples from wells in the Corn Belt States in about 2 percent of samples—about the same frequency as for all samples in the glacial aquifer system (fig. 7–15*A*). Pesticides were detected at very low concentrations in 40 to 50 percent of shallow groundwater samples from wells in agricultural areas, but seldom (fewer than 10 percent of samples) at concentrations above the common assessment level of 0.2 µg/L (fig. 7–15*B*).

Pesticides were detected at very low concentrations in almost 50 percent of shallow groundwater samples from wells in agricultural areas, but seldom at higher concentrations.

Pesticides have been detected in the shallow groundwater under all land-use settings and in domestic and public-supply wells. Some pesticides were detected in water samples from wells in undeveloped land; however, no detections of pesticide compounds were at a concentration greater than 0.2 µg/L (fig. 7–15*C*).The frequent detection of low concentrations of pesticides in shallow groundwater in undeveloped areas indicates that pesticides are transported out of agricultural areas by wind or rain during or after application.(78) The detection of pesticides in samples from domestic-supply wells reflects the extensive use of triazine compounds in rural areas where domestic-supply wells are common. The detection of pesticides in samples from public-supply wells (fig. 7–15*F*), which largely are in urban areas, is similar to the urban land-use signature (fig. 7–15*D*). However, one exception is for public-supply wells near streams—these wells may capture pesticides that have been transported from agricultural land (see sidebar, Enhancing groundwater supplies by inducing infiltration of river water, p. 26).

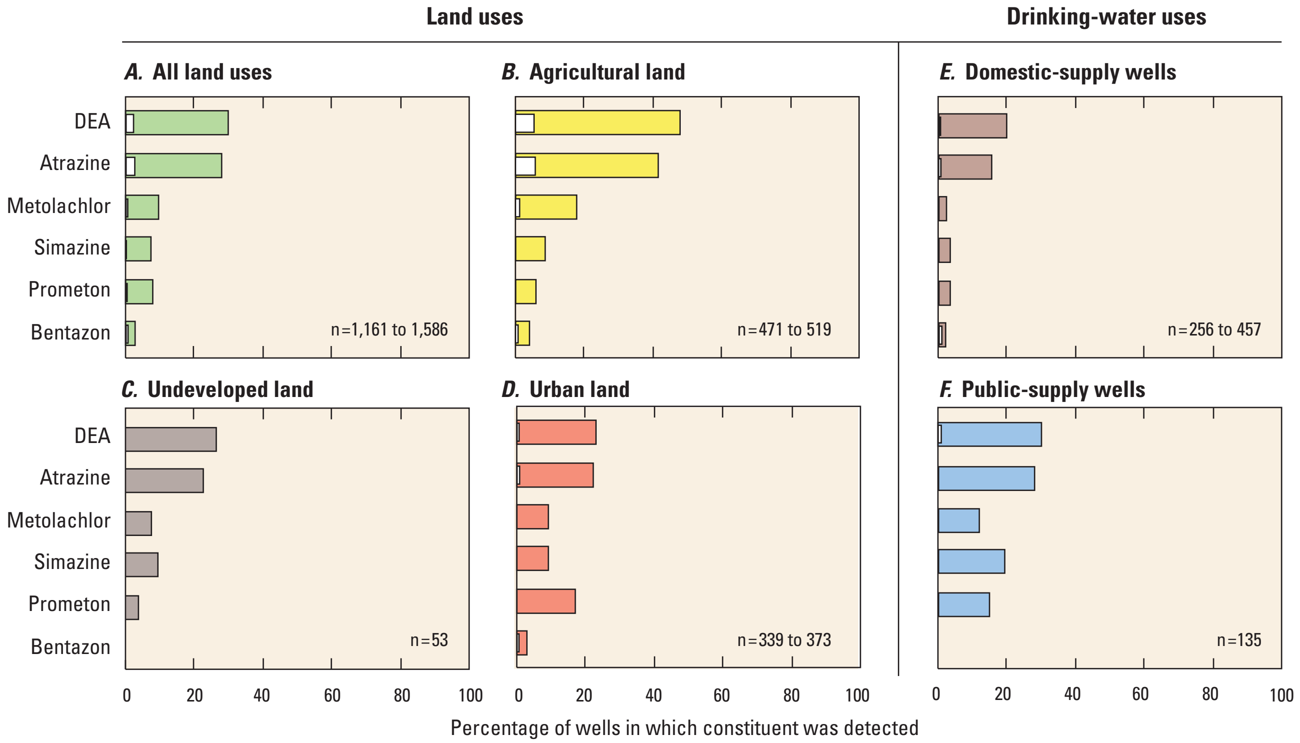


Figure 7–15. *A,* The six pesticide compounds shown were those detected most frequently in samples from the entire glacial aquifer system. The pesticide atrazine and its primary degradate, deethylatrazine (DEA), were the pesticide compounds detected most frequently in groundwater samples from the glacial aquifer system. *B,* The highest percentages of samples containing a pesticide were from shallow monitoring wells in agricultural settings. *C,* Pesticides were detected in samples collected from wells on undeveloped land, but no concentrations equaled or exceeded 0.2 µg/L. *D,* The highest percentage of samples containing prometon was collected in urban settings. *E,* Samples from domestic-supply wells contained primarily triazine compounds; *F,* but many types of compounds were detected in samples from public-supply wells.

EXPLANATION

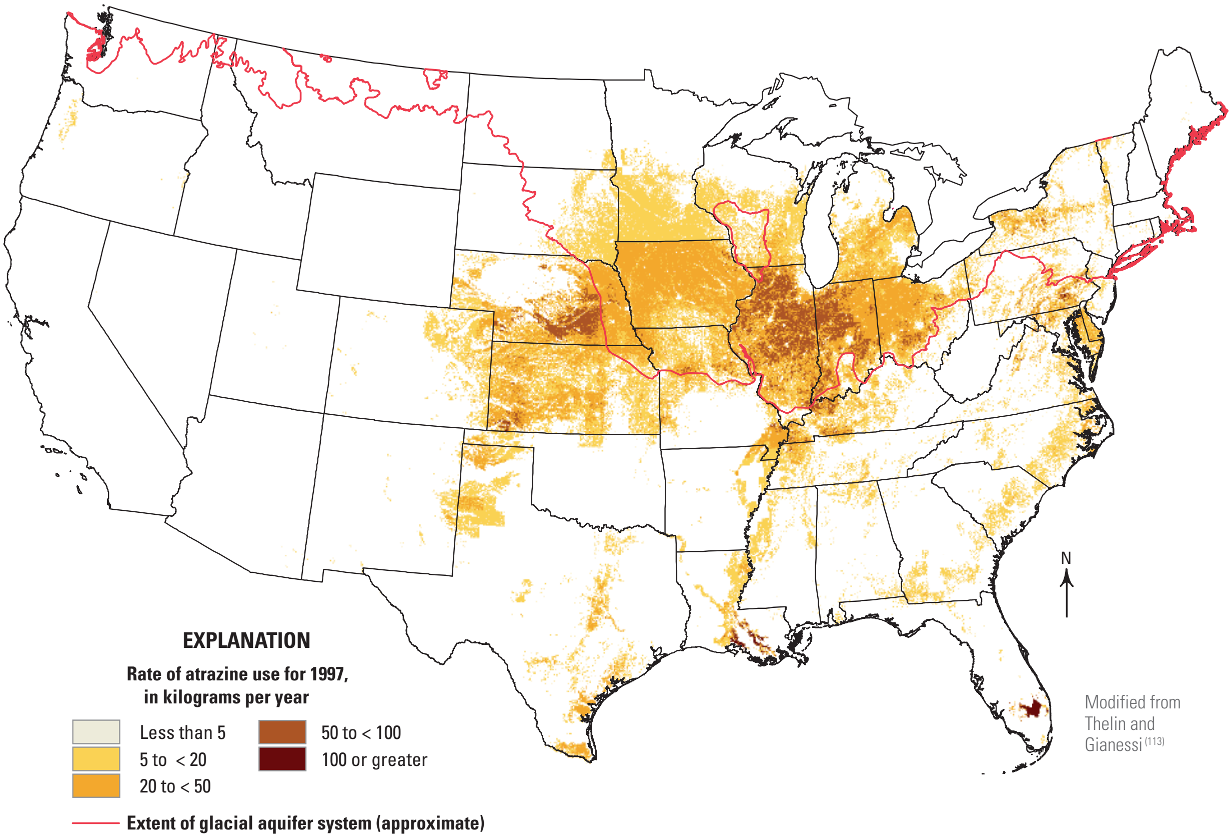
■ Detected at any concentration

☐ Detected at a concentration ≥ 0.2 micrograms per liter

Pesticide use in the Corn Belt is higher than elsewhere in the Nation

In general, the use of pesticides such as atrazine, metolachlor, alachlor, and acetochlor is higher in the Corn Belt than in other parts of the Nation.(15) More than 200 pounds of atrazine and metolachlor per square mile of cropland, for example, were applied annually during the late 1990s.

Atrazine, the most heavily applied pesticide during the 1990s, is used extensively in the Corn Belt States of Illinois, Indiana, Iowa, Nebraska, and Ohio, as well as parts of adjoining States, most of which overlie the glacial aquifer system (fig. 7–16). Atrazine-application rates remained essentially constant from 1992 to 2001 in the Corn Belt, even though some other aspects of pesticide use changed; among the changes were declines in the use of metolachlor and alachlor and the introduction of acetochlor and subsequent increases in its use.(15) More recent information suggests that this pattern was consistent through 2006, with steady use of atrazine and decreased use of metolachlor and acetochlor in the Corn Belt region of the United States.(79) Glyphosate use increased and in 2007 surpassed that of atrazine in the United States.(80) Glyphosate is used extensively with genetically modified pesticide-tolerant crops but also around homes and in other nonagricultural areas.



Modified from Thelin and Gianessi(113)

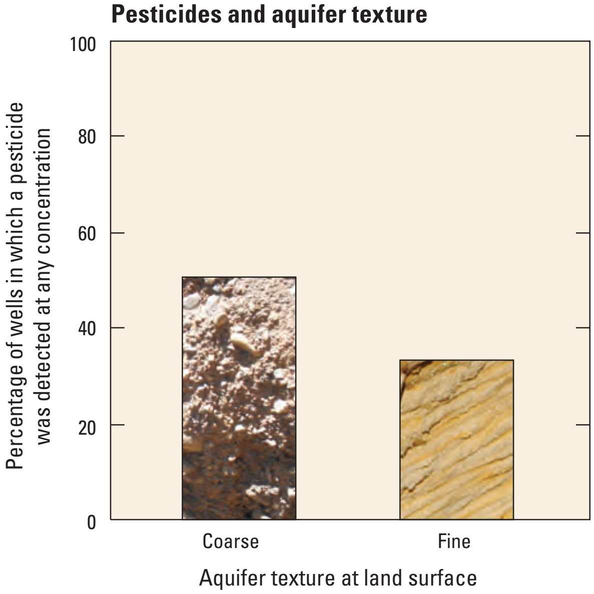
Figure 7–16. Atrazine use in the conterminous United States (1997 data). The heaviest application rates are in the Corn Belt States (Ohio, Indiana, Iowa, Illinois, eastern Nebraska, and parts of adjoining States).

Pesticide detections in groundwater are related to permeability of aquifer sediments

Pesticides are most likely to enter groundwater from agricultural and urban pesticide application, although the specific pesticides used and the amount and timing of the applications differ between agricultural and urban settings and among different regions.(15) Generally, the greater the application rate — the amount used on a given area of land in a year — the more likely it is that elevated concentrations of pesticides will be measured in groundwater.(15, 81) However, in the glacial aquifer system, this is not always the case because of the range in permeability of overlying soils and underlying aquifer sediments, which can inhibit pesticide transport. Also, the artificial drainage of poorly drained cropland in many parts of the glacial aquifer system diverts pesticide-laden recharge from shallow groundwater to streams. Pesticides were detected more frequently in wells in areas with coarse aquifer materials at the land surface than in areas with fine aquifer materials at the land surface (fig. 7–17). Coarse materials allow rapid infiltration of recharge or irrigation water, which can contain dissolved pesticide compounds.(82)

In the Corn Belt, as in other parts of the United States, the predicted detection of atrazine in shallow groundwater was found to depend not solely on the amount of pesticide use but also on soil characteristics and the amount of artificially drained land (see sidebar, Predicted atrazine concentrations in shallow groundwater were highest where aquifer sediments were coarse-grained, p. 81). For example in Illinois, total pesticide concentrations were higher in wells completed in coarse-grained aquifer sediments than in wells completed in fine-grained till, despite similar pesticide application rates.(83)

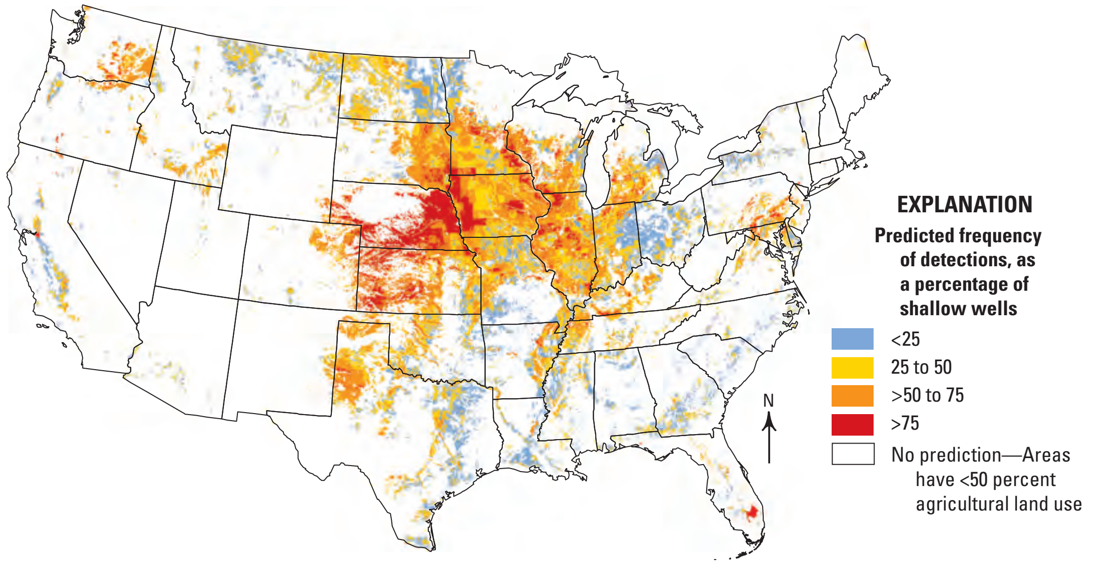
Figure 7–17. Pesticides were detected more commonly in groundwater that flows through coarse-grained sediments than through fine-grained sediments.



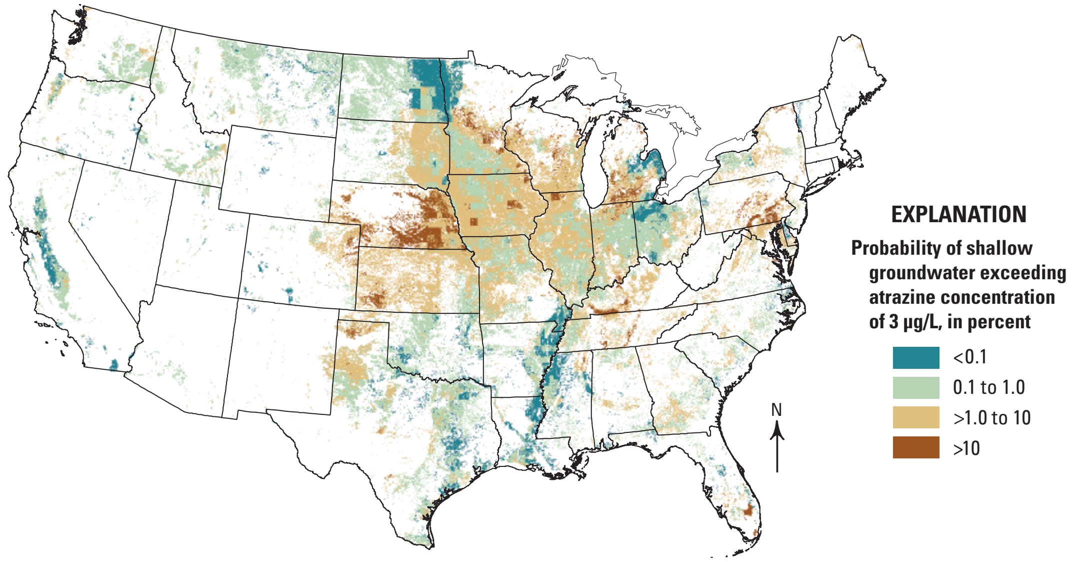
Predicted atrazine concentrations in shallow groundwater were highest where aquifer sediments were coarse-grained

Atrazine application rates, amount of agricultural land use, amount of drained land, soil water-holding capacity, and vertical soil permeability combine to indicate where atrazine will be detected in shallow groundwater. A statistical model using data on these factors predicted that most of the atrazine detections in U.S. groundwater would be in the Corn Belt region of the glacial aquifer system—especially where sediments are most permeable, such as along the Iowa and Nebraska border.(82)

Another statistical model predicted that the chance of atrazine concentrations exceeding the MCL of 3 µg/L is less than 10 percent in most parts of the glacial aquifer system, even where application rates are high. Several factors combine to reduce concentrations of atrazine, such as artificial drainage of agricultural land and fine-grained aquifer materials.(114)



On the basis of a predictive model that incorporated atrazine application rates and factors related to soil permeability, atrazine is most likely to be detected in shallow groundwater in the Corn Belt region of the United States.



Concentrations of atrazine compounds in shallow groundwater are likely to exceed the MCL of 3 µg/L in only a few locations. Even in the Corn Belt, where application rates are high, the chance of atrazine concentrations exceeding the MCL was less than 10 percent.

Pesticide degradation rates affect concentrations in groundwater

Pesticides eventually degrade (break down) in the environment, and the rate at which a pesticide degrades affects its concentration in groundwater. For any pesticide, the degradation rate is indicated by its half-life—the time it takes for half of the original amount of the compound to degrade. Some pesticides have long half-lives and, therefore, can persist in the environment for years to decades. Atrazine has a relatively long half-life in soil (146 days). The long half-life and its high use rate might explain why atrazine was the most commonly detected pesticide in glacial aquifer system wells (fig. 7–18*A*); alachlor and acetochlor, which were seldom detected, have half-lives of 20 days or less.(15)

In the Corn Belt region, degradates of metolachlor, alachlor, and acetochlor were detected in wells as or more frequently than the pesticide originally applied (fig. 7–18*B*). One of the degradates of metolachlor, metolachlor ethane sulfonic acid, was detected at or above a concentration of 0.2 µg/L in more than 30 percent of water samples from wells and more than 30 times more frequently than metolachlor itself. In groundwater in the Corn Belt, the six most frequently detected pesticide compounds were degradates (fig. 7–19).

Pesticide degradates can be transported more readily in groundwater than many parent compounds. For example, deethylatrazine, a degradate of atrazine, is about 100 times more soluble in water than atrazine and about 10 times less likely to adsorb to soil particles.(84) Many other degradates from a range of pesticide classes are at least 10 times less likely than the pesticide originally applied to adsorb to soils.(85) Although some pesticide degradates have lower toxicity than the original pesticide, others are just as toxic.

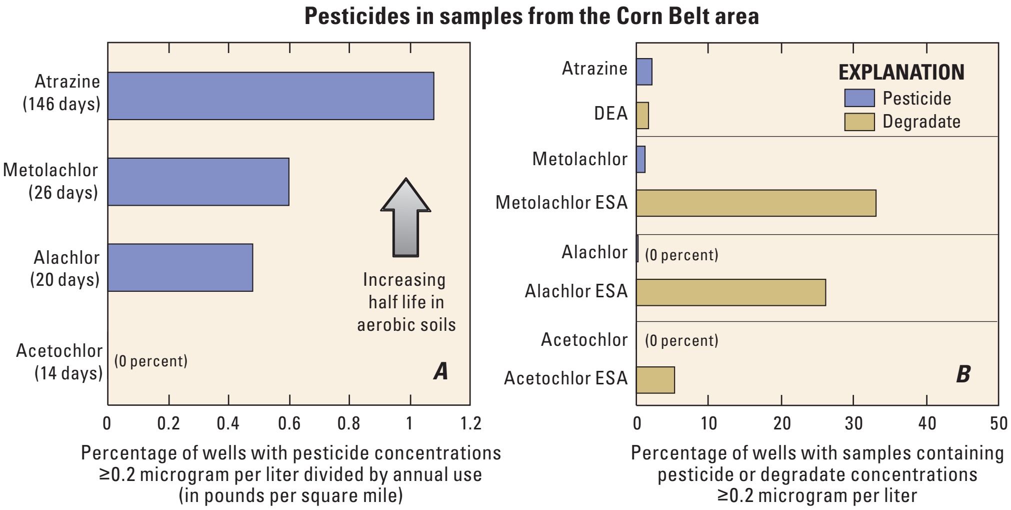
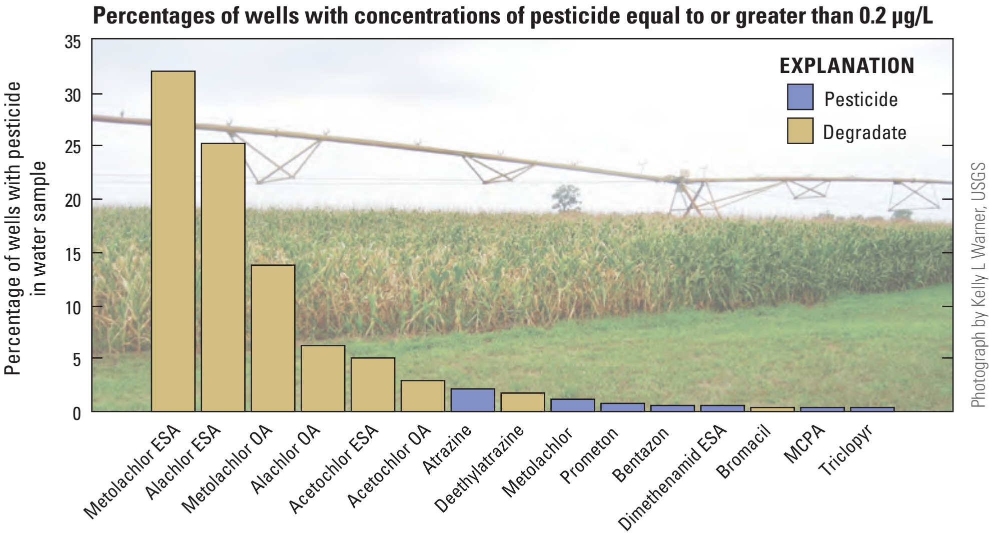


Figure 7–18. *A*, In samples from monitoring and drinking-water wells in the Corn Belt, pesticides with longer half-lives were detected more frequently per pound of annual use than those with shorter half-lives. *B*, Some pesticide degradates in Corn-Belt samples were detected much more frequently than the pesticide originally applied. [DEA, deethylatrazine; ESA, ethane sulfonic acid]



Photograph by Kelly L Warner, USGS

Figure 7–19. Many pesticide degradates were detected far more frequently than the pesticide originally applied in samples of groundwater from the Corn Belt. [OA, oxanilic acid; ESA, ethane sulfonic acid]

What are the implications of public-supply wells capturing water from nearby streams?

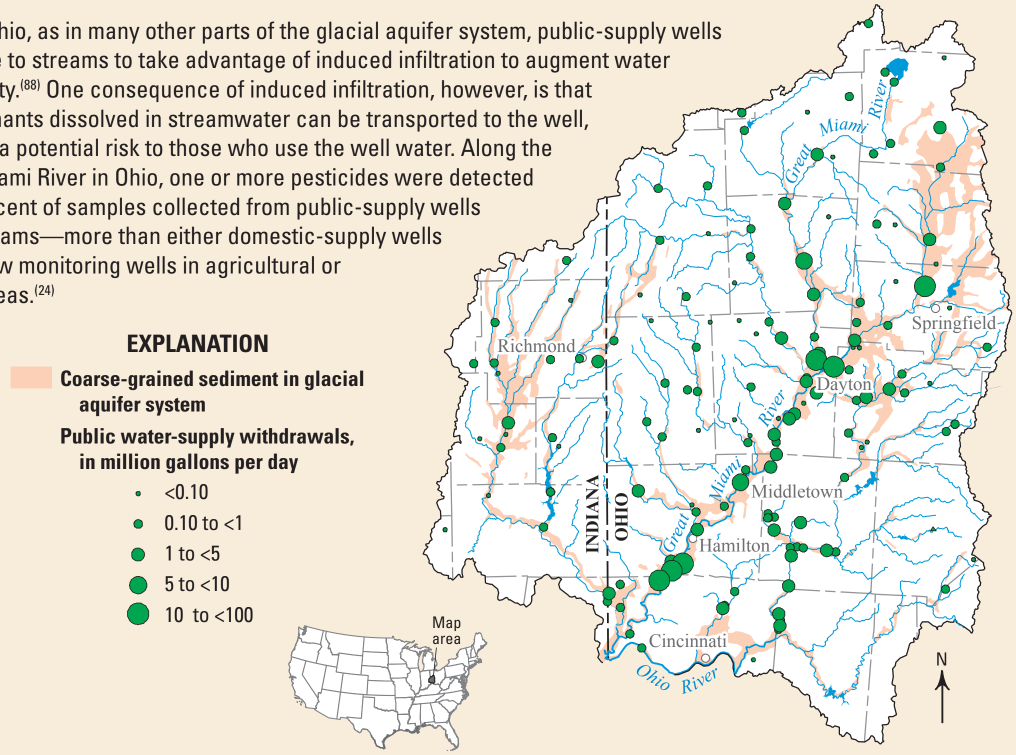
Pesticide occurrence was widespread, not just in groundwater, but also in streams in the glacial aquifer system, particularly in the Corn Belt.(15) Surface water can transport pesticides to groundwater by several mechanisms. For example, periodic flooding of streams can deliver pesticides to the groundwater system through a process referred to as bank storage. As water levels in the stream become greater than those in the adjacent aquifer, water flows from the stream to the aquifer. Extensive flooding also can inundate flood plains that directly overlie the aquifer with pesticide-contaminated flood waters.(86, 87) Pesticides can then move laterally or downward into the groundwater and eventually reach supply wells.

In many parts of the glacial aquifer system, the most productive public-supply wells are in stream valleys and often close to streams in order to take advantage of induced infiltration, whereby water flows from the stream to the well in response to pumping. Most high-capacity supply wells in the glacial aquifer system are along major streams, such as the Great Miami River and its tributaries in Ohio (88) (see sidebar, Samples from high-yield wells along the Great Miami River in Ohio frequently contain pesticides, below). This practice can cause pesticides in surface water to contaminate the groundwater (see sidebar, Induced infiltration—Surface-water quality affects groundwater quality, p. 84). As water moves from the stream through its bank to a supply well, it can be filtered; the process of filtration can remove or reduce the concentrations of many contaminants, such as suspended sediment and waterborne pathogens. However, dissolved contaminants, such as pesticides, can be captured by the supply wells.(24, 89)

Public-supply wells near streams are common in the glacial aquifer system. Pesticides are more likely to be detected in public-supply wells near streams than in wells further from streams.

Samples from high-yield wells along the Great Miami River in Ohio frequently contain pesticides

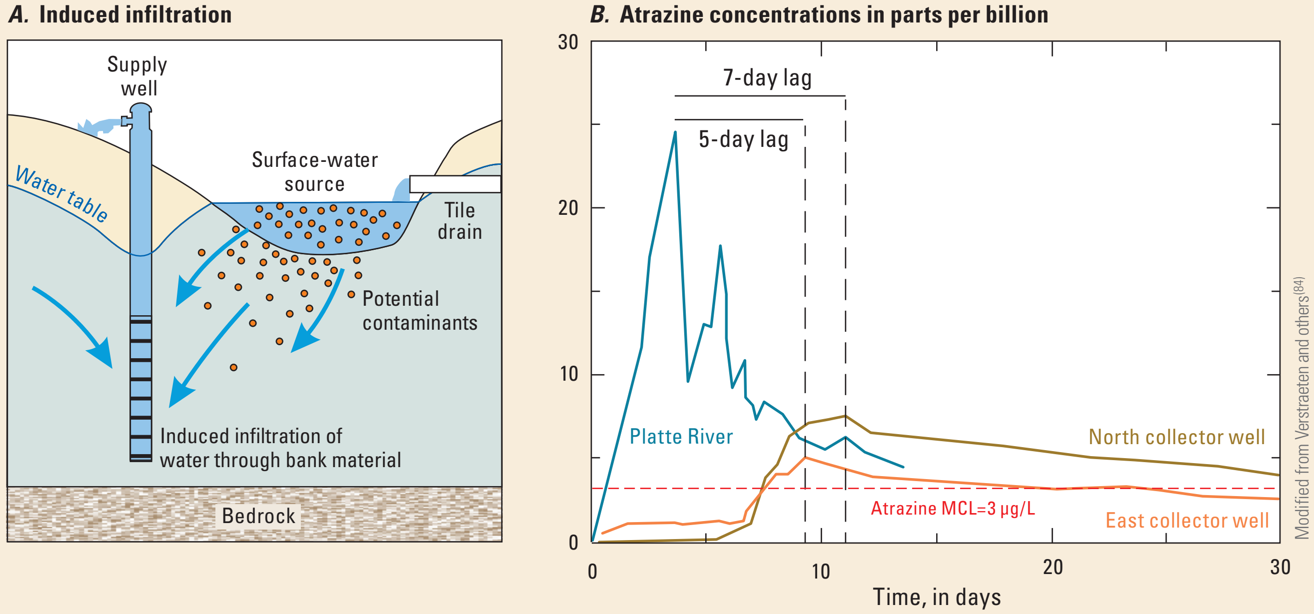
In Ohio, as in many other parts of the glacial aquifer system, public-supply wells are close to streams to take advantage of induced infiltration to augment water availability.(88) One consequence of induced infiltration, however, is that contaminants dissolved in streamwater can be transported to the well, creating a potential risk to those who use the well water. Along the Great Miami River in Ohio, one or more pesticides were detected in 60 percent of samples collected from public-supply wells near streams—more than either domestic-supply wells or shallow monitoring wells in agricultural or urban areas.(24)



Public-supply wells along the Great Miami River and its tributaries capture streamwater through induced infiltration—a process that also can lead to the capture of stream-borne pesticides.

Induced infiltration—Surface-water quality affects groundwater quality

A public-supply well near a stream can capture pesticides in streamwater. Temporal patterns of pesticide occurrence in the well mimic those in the stream, evidence that stream-borne pesticides can be an important contaminant source for some public-supply wells.[84, 115, 116] Where public-supply wells are downstream of artificially drained agricultural areas or other areas of heavy pesticide use, concentrations of pesticides in the streamwater and ultimately the water captured by the supply well can exceed 3 micrograms per liter. Contamination of public water supplies from induced infiltration can be especially troublesome when the timing of pesticide applications coincides with hydrologic events that increase direct runoff.


A. **Induced infiltration**

B. **Atrazine concentrations in parts per billion**

Modified from Verstraeten and others[84]

A, Induced infiltration can pull contaminants in surface water, such as pesticides, into public-supply wells. *B*, Concentrations of the pesticide atrazine in the Platte River, although much subdued, peaked 5 and 7 days later in the two public-supply wells adjacent to the river. This relation demonstrates that bank filtration might not be an effective strategy for removal of water-soluble pesticides, such as atrazine, from contaminated surface water.[117]

In some parts of the glacial aquifer system, pesticides were more likely to be detected in wells near streams than in wells farther from streams. For 53 public-supply wells in the Corn Belt (mostly in Ohio), pesticides were detected in about 75 percent of wells less than approximately 650 ft from a stream, but were detected in fewer than 25 percent of wells more than 650 ft from a stream (fig. 7–20). Furthermore, the median number of pesticide compounds in samples from public-supply wells near streams was three but for wells farther from a stream was only one (fig. 7–21). The relation suggests that pesticides could be a concern for public-supply wells along streams elsewhere in the glacial aquifer system.

The concentrations of some pesticides has declined in streams, resulting in part from declines in use.(79, 81, 90) However, these declines often are offset by increases in the concentrations of newly introduced pesticides, which can lead to more and different mixtures of pesticides in the environment. The amount and timing of the pesticide applications and of long-term changes in rainfall and runoff patterns can enhance or reduce this effect.(74, 83) The types and concentrations of pesticides in groundwater under the influence of surface water will change in response to introduction of new pesticides, changing land-use practices, and climate changes.

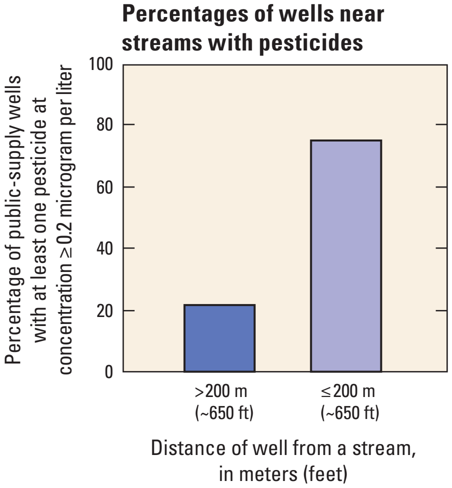


Figure 7–20. In 53 public-supply wells in the Corn Belt, pesticide compounds were detected three times more frequently in samples from wells within approximately 650 feet of a stream than in wells more than 650 feet from a stream.

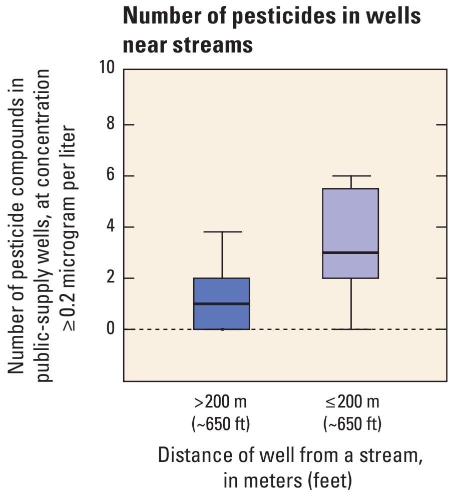
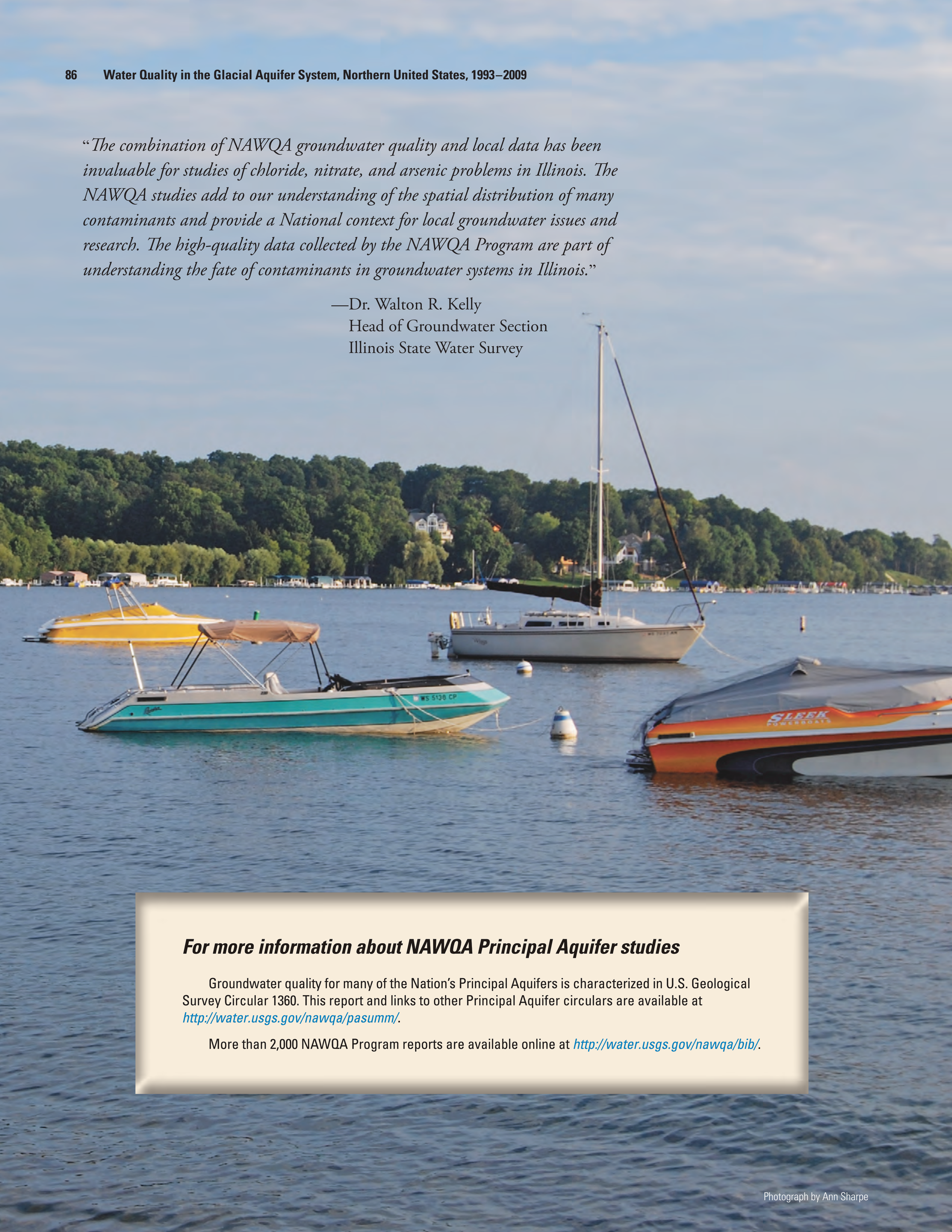


Figure 7–21. Mixtures of pesticide compounds were detected more frequently in water from public-supply wells near streams than farther from streams in the Corn Belt States of the Midwest.

> *“The combination of NAWQA groundwater quality and local data has been invaluable for studies of chloride, nitrate, and arsenic problems in Illinois. The NAWQA studies add to our understanding of the spatial distribution of many contaminants and provide a National context for local groundwater issues and research. The high-quality data collected by the NAWQA Program are part of understanding the fate of contaminants in groundwater systems in Illinois.”*
>
> —Dr. Walton R. Kelly
> Head of Groundwater Section
> Illinois State Water Survey



For more information about NAWQA Principal Aquifer studies

Groundwater quality for many of the Nation’s Principal Aquifers is characterized in U.S. Geological Survey Circular 1360. This report and links to other Principal Aquifer circulars are available at *http://water.usgs.gov/nawqa/pasumm/*.

More than 2,000 NAWQA Program reports are available online at *http://water.usgs.gov/nawqa/bib/*.

Photograph by Ann Sharpe

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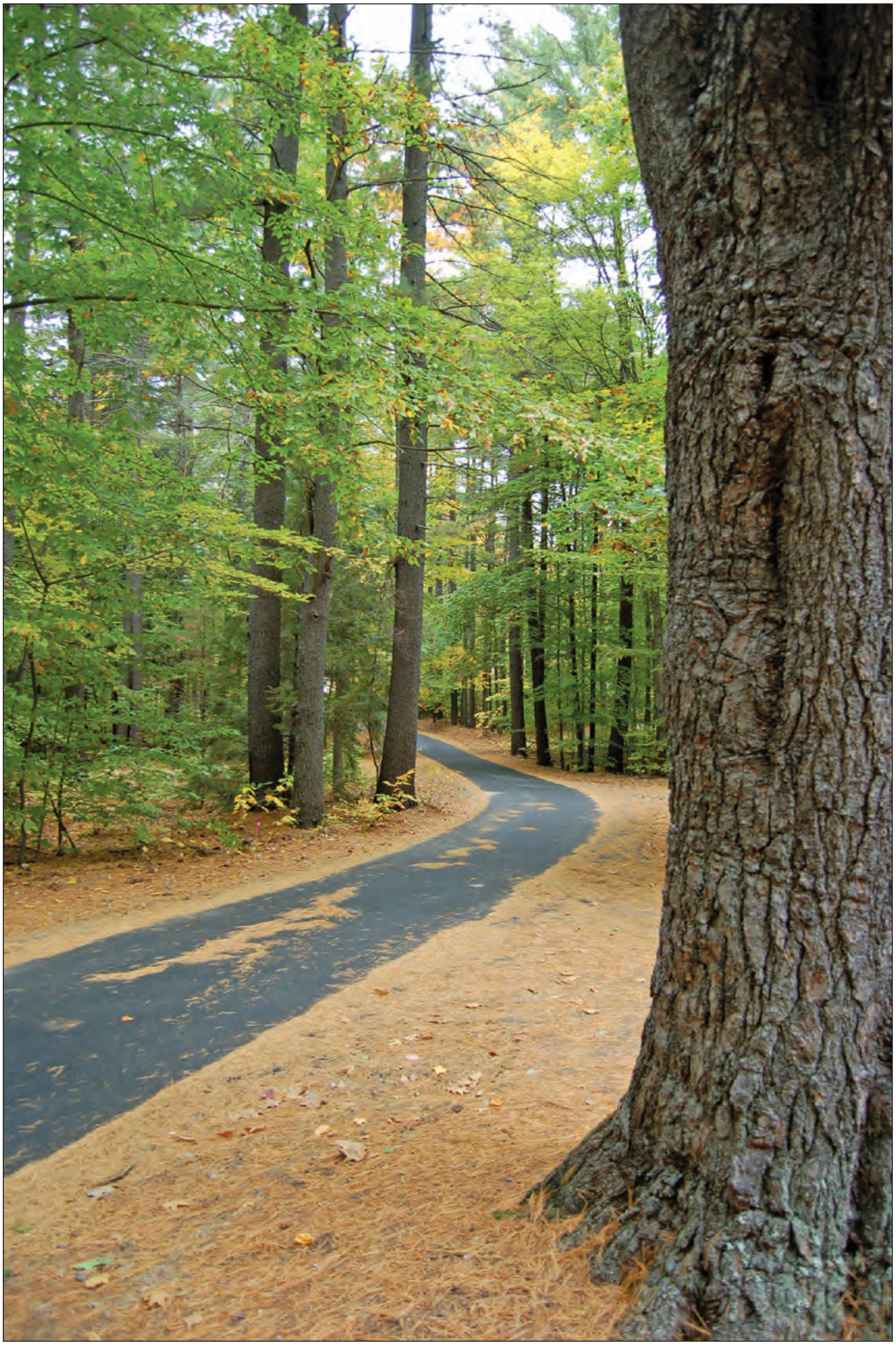


Photograph by P. Ryan Jackson, USGS

Glossary

A

alluvial aquifer An aquifer composed of unconsolidated material, such as sand and gravel, deposited by a river or other flowing water.

anoxic Water with no dissolved oxygen or a very low concentration (less than 0.5 milligram per liter) of dissolved oxygen.

apparent groundwater age The time elapsed since the recharge water became isolated from the atmosphere. The term "age" is normally qualified with the word "apparent" to signify that the accuracy of the determined age depends on many variables.

aquifer A geologic formation, group of formations, or part of a formation that contains a sufficient amount of saturated permeable material (for example, soil, sand, gravel and (or) rock) to yield substantial quantities of water to wells and springs.

artificial drainage *See* tile drain.

B

background concentration A concentration of a substance in a particular environment that corresponds to minimal influence by human (anthropogenic) sources or activities.

base flow Groundwater seepage into a stream or river. The continual contribution of groundwater to streams or rivers is an important source of streamflow between rain events.

bedrock General term for consolidated (solid) rock that underlies soils or other unconsolidated material.

C

carbonate rock or bedrock Rocks, such as limestone or dolostone, that are composed primarily of minerals, such as calcite and dolo mite, containing the carbonate ion (CO_3^{2-}).

cation An ion or group of ions that has acquired a positive charge by loss of one or more electrons.

common assessment level A single concentration threshold used to establish an equal basis for comparing detection frequencies among multiple chemicals. Use of a common assessment level avoids biases in detection frequencies caused by one compound having a lower detection level than another. Also sometimes referred to as a "common detection level."

constituent A chemical or biological substance in water, sediment, or biota that can be measured by an analytical (laboratory) method.

contaminant For the purposes of this report, any manmade compound at any concentration, or any constituent with a geologic source measured at a concentration exceeding the designated human-health benchmark.

crystalline rocks Igneous or metamorphic rocks consisting wholly of crystals or fragments of crystals. Granite and schist are examples of crystalline rocks.

D

degradate A compound formed by the transformation of a parent compound, typically an organic contaminant or another degradate, by chemical, photochemical, or biological reactions.

degradation The breakdown of a compound to a chemically simpler compound by abiotic or biotic processes.

deltaic sediments Sediment deposited in a delta, characterized by well-developed local crossbedding and by a mixture of sand, clay, and the remains of aquatic organisms and organic matter.

denitrification The bacterial reduction of dissolved nitrate to nitrogen gas. Denitrification is the primary process by which nitrate can be eliminated naturally in groundwater.

discharge The rate of flow of surface water or groundwater past a given point at a given moment, expressed as volume per unit of time. Also, the outflow from an aquifer, spring, or well or up through a streambed.

dissolution The process of dissolving a solid (mineral) into a homogeneous solution (water). Dissolution reactions result in the addition of ions to water as minerals react with water. Common dissolution reactions include dissolution of carbonate rock (limestone or dolomite) and incongruent dissolution of silicate minerals (feldspar) by carbonic acid (H_2CO_3).

domestic well A privately owned well that typically serves one home and supplies water for human consumption and other homeowner uses.

drinking-water standard or guideline A threshold concentration in a public drinking-water supply designed to protect human health or to identify acceptable concentrations of constituents that cause unpleasant tastes, odors, or colors in the water.

E

exchange reaction *See* ion exchange.

F

flow path The route or pathway of water flowing through the hydrologic system. Typically refers to subsurface (groundwater) flow.

G

groundwater Water that exists beneath the land surface, but most commonly refers to water in fully saturated soils and geologic formations.

groundwater age *See* apparent groundwater age.

groundwater discharge The flow of water from the saturated zone, for example, from a spring or a well or as seepage to surface water.

groundwater recharge The infiltration of water to the saturated zone. Also refers to water that reaches the water table by infiltration of precipitation or irrigation water through the unsaturated zone or by seepage of water from surface-water bodies, such as streams and lakes.

H

half-life The time required for the concentration of a compound in a given environmental medium to be reduced to one-half of its original value by one or more processes, such as degradation or transport into another environmental medium.

Health-Based Screening Level (HBSL) An estimate of concentration (for a noncarcinogen) or concentration range (for a carcinogen) in water that (1) may be of potential human-health concern, (2) can be used as a threshold value against which measured concentrations of contaminants in ambient groundwater samples can be compared, and (3) is consistent with U.S. Environmental Protection Agency Office of Water methodologies.

herbicide A chemical pesticide designed to control or destroy plants, weeds, or grasses.

human-health benchmark A threshold concentration above which the concentration of a contaminant in drinking water could have adverse effects on human health. Treatment or other measures can be used before the water is consumed to lower the concentration of the contaminant below the benchmark.

hydraulic properties Those properties of rock or sediment that govern the infiltration of water and the capacity to hold, transmit, and deliver water.

hydrogeologic setting A unit with common hydrogeologic characteristics and therefore common susceptibility to contamination; a composite description of all the major geologic and hydrologic factors that affect and control the movement of groundwater into, through, and out of an area.

hydrogeology The geologic and hydrologic features that control the movement of water, solutes, and small particles through the subsurface.

I

igneous rock Rock that solidified from molten (melted) or partly molten material. Granite is an example of an igneous rock.

induced infiltration Recharge to groundwater by infiltration of water from the land surface as a result of the lowering of the groundwater head below the surface-water level, for example, by pumping.

infiltration Movement of water, typically downward, into soil or porous rock.

ion exchange The replacement of ions attached to the surface of a solid by ions that were in water. Ion-exchange reactions commonly occur between water and ions attached to clay particles.

L

lacustrine sediments Geologic deposits formed at the bottom or along the edge of a pond or lake.

land-use study A study by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program to assess the effects of a specific land-use type (generally agricultural or urban) on groundwater quality, in most cases by sampling groundwater from monitoring wells that tap water from or near the water table.

lithology The physical character of a rock on the basis of color, structure, mineralogical composition, grain size, and other characteristics.

loess A deposit of silt that is produced by the erosion of outwash and transported by wind.

M

Maximum Contaminant Level (MCL) Maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCLs are enforceable standards established by the U.S. Environmental Protection Agency.

median The middle or central value in a distribution of data ranked in order of magnitude such that one-half of the data are higher than the median and one-half are lower. The median is also called the 50th percentile.

metamorphic rock Rock derived from mineralogical, chemical, or structural changes to preexisting rocks in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the Earth's crust. Gneiss and schist are examples of metamorphic rocks.

methemoglobinemia A health condition characterized by reduced ability of the blood to carry oxygen. Infants are most affected. One of the most common causes is nitrate in drinking water. Also called "blue baby syndrome."

milligrams per liter (mg/L) A unit expressing the concentration of a chemical constituent as weight (milligrams) of constituent per unit volume (liter) of water; equivalent to one part per million in most streamwater and groundwater. One thousand micrograms per liter (µg/L) is equivalent to 1 mg/L.

monitoring well A well used to measure water quality or groundwater levels continuously or periodically. Not typically used as a source of drinking water. Sometimes referred to as an "observation well."

N

nitrate An ion consisting of one nitrogen atom and three oxygen atoms (NO_3^-). Nitrate is a plant nutrient and is very mobile in soils.

nutrient An element or compound essential for animal and plant growth. Common nutrients include nitrogen, phosphorus, and potassium, such as are found in fertilizer.

O

organic carbon Carbon that originates from plants or animals and is bound in an organic compound.

organic matter Matter resulting from the decay of a plant or an animal and containing organic carbon compounds. Organic matter is rich in nutrients and is an essential component of soils.

organic compound A chemical compound containing the element carbon. A few types of carbon-containing compounds, including oxides of carbon (such as carbon dioxide, or CO_2), are not considered to be organic. Organic compounds include petroleum products, solvents, and many pesticides.

outwash A load of sediment, consisting of sand and gravel that is deposited by meltwater in front of a glacier.

oxic Water with a concentration of dissolved oxygen greater than or equal to 0.5 milligram per liter.

oxidation The loss of electrons by a chemical species as a result of transfer to another chemical species, typically dissolved oxygen. The species donating electrons is "oxidized."

oxyanion A group of atoms consisting of three or four anions (usually oxygen) surrounding a central cation and having an overall negative charge, for example, chlorite (ClO_3^-).

P

permeability A measure of the relative ease with which a porous or fractured medium can transmit groundwater. Rock formations that transmit fluids readily are described as permeable.

permeable Capable of transmitting liquids or gases through pores or openings.

pesticide Any substance, organic or inorganic, used to kill plant or animal pests.

pH A measure of the acidity (pH less than 7) or alkalinity (pH greater than 7) of a solution; a pH of 7 is neutral. Formally defined as the logarithm of the reciprocal of the hydrogen ion concentration (activity) of a solution.

precipitation Any or all forms of water particles that fall from the atmosphere, such as rain, snow, hail, and sleet. Also, the process in which a solid is formed from a fluid supersaturated with dissolved ions.

Principal Aquifer A regionally extensive aquifer or aquifer system that has the potential to be used as a source of potable water. A Principal Aquifer can be composed of one or more major aquifers.

public-supply well A privately or publicly owned well that provides water for public use to (1) a community water system, (2) a transient noncommunity water system, such as a campground, or (3) a nontransient, noncommunity system, such as a school.

R

radioactive decay The spontaneous emission of particles (alpha or beta) and gamma rays from an atom with an unstable nucleus (radionuclide).

recently recharged groundwater Groundwater that was recharged after 1952, as indicated by tritium concentrations greater than 0.5 tritium unit.

recharge The addition of water to the saturated zone naturally by precipitation or runoff or artificially by spreading or injection. Also, the water that is added.

reduction The gain of electrons by a chemical species, typically dissolved oxygen, as a result of transfer from another chemical species. The species accepting electrons is “reduced.” Once all of the dissolved oxygen has been reduced, other chemical species can accept electrons, following the most energetically favorable order.

reduction-oxidation (redox) Chemical reactions that involve the transfer of electrons from one chemical species to another, resulting in a change in the valence state of the species. Redox processes in groundwater often are microbially facilitated.

residence time The average amount of time that a solute, particle, organism, or other entity spends within a given environmental medium, such as a lake, groundwater, and the atmosphere.

runoff Excess rainwater or snowmelt that is transported to streams by flow over the land surface.

S

saturated The condition in which all the pores (voids, interstices) within a material are filled with a liquid, typically water.

Secondary Maximum Contaminant Level (SMCL) Guidelines set by the U.S. Environmental Protection Agency for concentrations of “nuisance” constituents in drinking water that may cause unwanted effects, such as unpleasant taste, color, or odor; discoloration of skin or teeth; or corrosion or staining of plumbing fixtures. Public drinking-water systems are recommended but not required to comply with these guidelines.

sedimentary rocks Rocks composed of particles derived from the erosion or weathering of preexisting rocks or from chemical precipitation from water. Sandstone and limestone are examples of sedimentary rocks.

sorption The general process by which solutes, ions, and colloids become attached to solid matter.

subsurface The region of earth materials beneath the land surface that encompasses the soil and unsaturated and saturated zones.

susceptibility A measure of the ease with which a contaminant in water enters and moves through an aquifer; a characteristic of the aquifer and overlying material and hydrologic conditions independent of the chemical characteristics of the contaminant and its sources.

T

tile drain A drain installed to collect subsurface water and route it to a drainage ditch, stream, or wetland. Originally constructed using short segments of clay or cylindrical concrete “tiles” and installed manually, modern tile drains typically are corrugated, perforated plastic pipes installed 3 to 6 feet below the soil surface by mechanical trenchers.

till Poorly sorted unconsolidated geologic material deposited by glaciers, commonly having low permeability unless fractures or other interconnected openings for flow are present.

trace element An element found in only minor amounts (concentrations less than 1.0 milligram per liter) in water or sediment; includes arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc.

U

unconsolidated sediment Deposit of loosely bound sediment that typically fills topographically low areas.

V

volatile organic compound (VOC) An organic chemical that has a high vapor pressure relative to its water solubility. VOCs include components of gasoline, fuel oils, lubricants, organic solvents, fumigants, some inert ingredients in pesticides, and some by-products of chlorine disinfection.

vulnerability The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer. The vulnerability of a groundwater resource to contamination depends both on the intrinsic susceptibility of the resource and on the locations and types of human and geologic sources of contaminants, locations of wells, and the characteristics of the contaminant(s).

W

water table The upper surface of the saturated zone below which all voids (spaces) are filled with water.

Appendixes 1–3

Appendix 1. How Does Land Use Affect Groundwater Quality? How Does Water Quality Change as it Moves Through an Aquifer? What Is the Quality of the Drinking-Water Resource?

NAWQA groundwater assessments include different types of studies, specifically designed to answer questions such as these.

- Land-use studies sampled water from water-table monitoring wells installed in urban and agricultural areas to assess the effects of these land uses on the quality of the underlying groundwater. Although not usually used for drinking, this water supplies recharge to the deeper aquifer system.
- Flow-path studies investigate how water quality changes as it moves along a groundwater flow path. Samples were collected from wells installed along a groundwater flowpath (*http://pubs.usgs.gov/circ/circ1112/flowpath.html*).
- Major aquifer studies provide a broad overview of the quality of the deeper aquifer system used for drinking-water supply. Most of the wells sampled were domestic wells that were distributed across a large area in a mixture of land uses.
- Vulnerability studies were designed to assess the vulnerability of water delivered by public-supply wells to contamination from natural and manmade contaminants. Samples were collected from multiple depths in public-supply wells to determine where and how contaminants from different sources enter the wells and how natural processes and human activities affect water quality (*http://oh.water.usgs.gov/tanc/NAWQATANC.htm*).
- Source-water-quality assessment studies sampled water from public-supply wells to understand occurrence of unregulated manmade chemicals in the groundwater resources that serve large numbers of people (*http://water.usgs.gov/nawqa/swqa/*).

Results of these studies were reinforced by locating some of the studies within the boundaries of larger studies. For example, the recharge areas for flow-path studies were located within the boundaries of the land-use studies to provide information on the quality of the recharge. In turn, the boundaries of the land-use studies were located within the boundaries of the major aquifer studies to provide information on how the quality of the recharge affects that of the deeper groundwater.

Each study sampled water from a network of a few to as many as 30 wells. Data from these studies were available for the Principal Aquifer assessments.

Table A1–1. NAWQA Cycle 1 and Cycle 2 groundwater-sampling study units and networks in the glacial aquifer.—Continued

[—, no second decadal sample]

Study unit and network name	Study component	Network purpose	Initial decadal sample	Second decadal sample	Number of wells	Monitoring	Domestic supply	Public supply	Other
Allegheny and Monongahela River Basin									
almnsus2	Major aquifer study	Characterize groundwater used for drinking	1996	—	30	0	30	0	0
Central Nebraska Basin									
cnbrluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	2003	—	29	29	0	0	0
cnbrrefpa1	Reference network	Characterize background water-quality conditions	2003	—	2	2	0	0	0
Connecticut, Housatonic, and Thames River Basins									
conndwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2003	—	15	0	0	15	0
connlusag1	Land-use study	Characterize shallow groundwater underlying agricultural area	1995	—	40	40	0	0	0
connlusfo1	Land-use study	Characterize shallow groundwater underlying forested area	1995	—	40	40	0	0	0
connlusrc1	Land-use study	Characterize shallow groundwater underlying urban area	2003	—	28	27	0	0	1
connlusur1	Land-use study	Characterize shallow groundwater underlying urban area	1995	—	40	40	0	0	0
connsus2	Major aquifer study	Characterize groundwater used for drinking	2002	—	30	0	28	0	2
Cook Inlet Basin									
cooksus1a	Major aquifer study	Characterize groundwater used for drinking	1999	—	29	0	22	4	3
cooksus1b	Major aquifer study	Characterize groundwater used for drinking	1999	—	5	0	0	5	0
Delaware River Basin									
delrsus3	Major aquifer study	Characterize groundwater used for drinking	2001	—	16	1	12	0	3
Eastern Iowa Basins									
eiwaluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1997	2007	31	31	0	0	0
eiwalusrc1	Land-use study	Characterize shallow groundwater underlying urban area	1997	—	30	30	0	0	0
eiwaspcg1	Special study	Characterize groundwater affected by surface water	1998	—	27	27	0	0	0
eiwasus2	Major aquifer study	Characterize groundwater used for drinking	1998	2007	32	0	32	0	0

Table A1–1. NAWQA Cycle 1 and Cycle 2 groundwater-sampling study units and networks in the glacial aquifer.—Continued

[—, no second decadal sample]

Study unit and network name	Study component	Network purpose	Initial decadal sample	Second decadal sample	Number of wells	Monitoring	Domestic supply	Public supply	Other
Hudson River Basin									
hdsnlusag1	Land-use study	Characterize shallow groundwater underlying agricultural area	1995	—	14	14	0	0	0
hdsnlusur1	Land-use study	Characterize shallow groundwater underlying urban area	1993	—	28	18	0	8	2
hdsnsus1	Major aquifer study	Characterize groundwater used for drinking	1995	—	2	0	1	0	1
hdsnsus3	Major aquifer study	Characterize groundwater used for drinking	2006	—	30	0	27	0	3
High Plains Regional Groundwater Study									
hpgwdwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2003	—	15	0	0	15	0
hpgwsus4	Major aquifer study	Characterize groundwater used for drinking	2003	—	30	0	30	0	0
Lake Erie–Lake St. Clair Drainage Areas									
leriluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1998	—	30	30	0	0	0
lerilusrc1	Land-use study	Characterize shallow groundwater underlying urban area	1997	2006	35	35	0	0	0
lerirefot1	Land-use study	Characterize background water-quality conditions	2007	—	2	2	0	0	0
lerispcg1	Special study	Characterize drinking-water resource (domestic wells) underlying an urban area	1997	—	26	0	22	4	0
lerisus1	Major aquifer study	Characterize groundwater used for drinking	1998	2007	31	0	30	0	1
Long Island and New Jersey Coastal Drainage Areas									
linjdwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2007	—	15	0	0	15	0
linjlusfo2	Land-use study	Characterize shallow groundwater underlying forested area	1996	—	2	2	0	0	0
linjlusrc2	Land-use study	Characterize shallow groundwater underlying urban area	2006	—	30	30	0	0	0
linjsus1	Major aquifer study	Characterize groundwater used for drinking	1997	—	1	0	1	0	0

Table A1–1. NAWQA Cycle 1 and Cycle 2 groundwater-sampling study units and networks in the glacial aquifer.—Continued

[—, no second decadal sample]

Study unit and network name	Study component	Network purpose	Initial decadal sample	Second decadal sample	Number of wells	Monitoring	Domestic supply	Public supply	Other
Lower Illinois River Basin									
lirbdwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2007	—	16	0	0	16	0
lirbluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1997	—	28	28	0	0	0
lirbluscr2	Land-use study	Characterize shallow groundwater underlying agricultural area	1997	—	29	29	0	0	0
lirblusrc1	Land-use study	Characterize shallow groundwater underlying urban area	2005	—	26	26	0	0	0
lirbsus1	Major aquifer study	Characterize groundwater used for drinking	1996	2007	31	0	27	1	3
lirbsus2	Major aquifer study	Characterize groundwater used for drinking	1996	—	30	0	28	1	1
New England Coastal Basins									
necblusrc1	Land-use study	Characterize shallow groundwater underlying urban area	1999	2010	34	34	0	0	0
necbreffo1	Reference network	Characterize background water-quality conditions	2005	—	2	2	0	0	0
necbsus3	Major aquifer study	Characterize groundwater used for drinking	2001	—	30	0	0	29	1
Puget Sound Basin									
pugtdwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2005	—	15	0	0	15	0
pugtluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1998	2006	25	20	4	1	0
pugtlusrs1	Land-use study	Characterize shallow groundwater underlying urban area	1998	2005	27	27	0	0	0
pugtrefcr1	Reference network	Characterize background water-quality conditions	2006	—	1	1	0	0	0
pugtreffo1	Reference network	Characterize background water-quality conditions	1998	2005	1	1	0	0	0
pugtsus1	Major aquifer study	Characterize groundwater used for drinking	1996	—	30	1	29	0	0

Table A1–1. NAWQA Cycle 1 and Cycle 2 groundwater-sampling study units and networks in the glacial aquifer.—Continued

[—, no second decadal sample]

Study unit and network name	Study component	Network purpose	Initial decadal sample	Second decadal sample	Number of wells	Monitoring	Domestic supply	Public supply	Other
Red River of the North Basin									
rednlusag1	Land-use study	Characterize shallow groundwater underlying agricultural area	1994	—	26	23	2	0	1
rednlusag2	Land-use study	Characterize shallow groundwater underlying agricultural area	1993	—	20	20	0	0	0
rednsus1	Major aquifer study	Characterize groundwater used for drinking	1995	—	29	23	5	0	1
rednsus2	Major aquifer study	Characterize groundwater used for drinking	1995	—	25	9	15	0	1
rednsus3	Major aquifer study	Characterize groundwater used for drinking	1995	—	15	12	3	0	0
rednsus5	Major aquifer study	Characterize groundwater used for drinking	1995	—	34	7	25	0	2
Upper Illinois River Basin									
uirbluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1999	—	29	29	0	0	0
uirblusrc1	Land-use study	Characterize shallow groundwater underlying urban area	2000	2010	27	27	0	0	0
uirbsus1	Major aquifer study	Characterize groundwater used for drinking	2001	—	27	0	27	0	0
uirbsus2	Major aquifer study	Characterize groundwater used for drinking	2000	—	23	0	23	0	0
Upper Mississippi River Basin									
umisdwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2005	—	15	0	0	15	0
umisluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1998	2006	37	29	3	0	5
umislusfo1	Land-use study	Characterize shallow groundwater underlying forested area	1998	—	15	15	0	0	0
umislusrc1	Land-use study	Characterize shallow groundwater underlying urban area	1996	2006	34	32	0	0	2
Western Lake Michigan Drainage Areas									
wmiclusag1a	Land-use study	Characterize shallow groundwater underlying agricultural area	1994	—	26	26	0	0	0
wmiclusag2	Land-use study	Characterize shallow groundwater underlying agricultural area	1994	2002	34	34	0	0	0

Table A1–1. NAWQA Cycle 1 and Cycle 2 groundwater-sampling study units and networks in the glacial aquifer.—Continued

[—, no second decadal sample]

Study unit and network name	Study component	Network purpose	Initial decadal sample	Second decadal sample	Number of wells	Monitoring	Domestic supply	Public supply	Other
Western Lake Michigan Drainage Areas—Continued									
wmicreffo1	Reference network	Characterize background water-quality conditions	2002	—	2	2	0	0	0
wmicsus2	Major aquifer study	Characterize groundwater used for drinking	2003	—	28	0	25	0	3
White River Basin and Great and Little Miami River Basins									
miamluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	2000	—	27	26	0	0	1
miamluscr1a	Land-use study	Characterize shallow groundwater underlying agricultural area	2000	—	8	8	0	0	0
miamlusrc1	Land-use study	Characterize shallow groundwater underlying urban area	2001	—	26	26	0	0	0
miamrefot1	Reference network	Characterize background water-quality conditions	2001	—	2	2	0	0	0
miamspcb1	Special study	Characterize groundwater affected by surface water	1999	—	15	0	0	15	0
miamsus1	Major aquifer study	Characterize groundwater used for drinking	1999	—	30	0	30	0	0
whitluscr1	Land-use study	Characterize shallow groundwater underlying agricultural area	1994	2002	26	26	0	0	0
whitluscr2	Land-use study	Characterize shallow groundwater underlying agricultural area	1995	—	20	20	0	0	0
whitluscr3a	Land-use study	Characterize shallow groundwater underlying agricultural area	1995	—	24	24	0	0	0
whitluscr3b	Land-use study	Characterize shallow groundwater underlying agricultural area	1995	—	6	6	0	0	0
whitlusur1a	Land-use study	Characterize shallow groundwater underlying urban area	1995	—	25	25	0	0	0
whitlusur1b	Land-use study	Characterize shallow groundwater underlying urban area	1995	—	3	3	0	0	0
whmidwgs1	Source-water-quality assessment	Characterize the source water for communities using public supply	2003	—	15	0	0	15	0
whmirefot1	Reference network	Characterize background water-quality conditions	2002	—	1	1	0	0	0

Appendix 2. Water-Quality Properties and Constituents Measured and Complete Data Archive for 1993–2009

The complete data archive is available at *http://pubs.usgs.gov/circ/1360/.*

Table A2–1. Water-quality constituents sampled in Cycle 1 and Cycle 2 networks.

[✔, planned sampling; —, not planned; ss, selected sites; LC/MS, Liquid Chromatography/Mass Spectrometry; best method for age dating was used in about 25 percent of these networks beginning in 2001; pCi/L, picocuries per liter; CFC, chlorofluorocarbon]

Constituent group	Drinking-water resource	Shallow groundwater underlying urban land	Shallow groundwater underlying agricultural land	Source water for communities
Field measurement	✔	✔	✔	✔
Major inorganics	✔	✔	✔	✔
Nutrients	✔	✔	✔	✔
Dissolved organic carbon	✔	✔	✔	✔
Trace elements in water				
Trace elements	✔	✔	✔	✔
Radon	✔	—	—	—
Radium isotopes (226, 228 only)	ss	—	—	—
Gross alpha and beta	ss	—	—	—
Pesticides				
General pesticides (*http://pubs.usgs.gov/circ/1360/*)	✔	✔	✔	✔
LC/MS (2050 replacement)	—	ss	ss	ss
Acetamide degradates	—	ss	ss	ss
Glyphosate	—	ss	ss	ss
Volatile organic compounds (VOCs)				
VOCs (with nontarget compounds)	✔	✔	ss	ss
Gasoline oxygenate degradation products	—	—	—	—
Microbes				
Bacteria (*E. coli* and total coliform)	✔	—	—	—
Coliphage	✔	—	—	—
Age dating				
Tritium (1 pCi/L)	✔	—	—	—
Tritium (0.3 pCi/L)	✔	—	—	—
CFCs	—	✔	✔	✔
Sulfur hexafluoride (SF_6) plus dissolved gases	—	✔	✔	✔
Dissolved gases	—	✔	✔	✔
Tritium/helium	—	✔	—	—
Well-cutting samples				
Organic carbon	—	✔	—	—
Particle size	—	✔	—	—
Soil pH (field)	—	✔	—	—

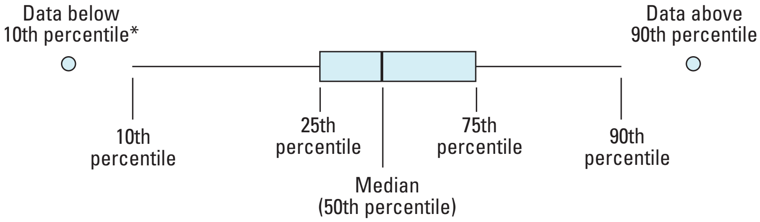
Appendix 3. Water Quality of the Glacial Aquifer System in a National Context

Principal Aquifer (number of samples)

(NA) Wells of this type were not sampled for this constituent

U.S. Environmental Protection Agency contaminant levels for drinking water

- - - - - **MCL** Maximum Contaminant Level
- - - - - **SMCL** Secondary Maximum Contaminant Level
- - - - - **PMCL** Proposed Maximum Contaminant Level
- - - - - **AMCL** Proposed Alternative Maximum Contaminant Level



* Data below laboratory reporting limits are not shown.

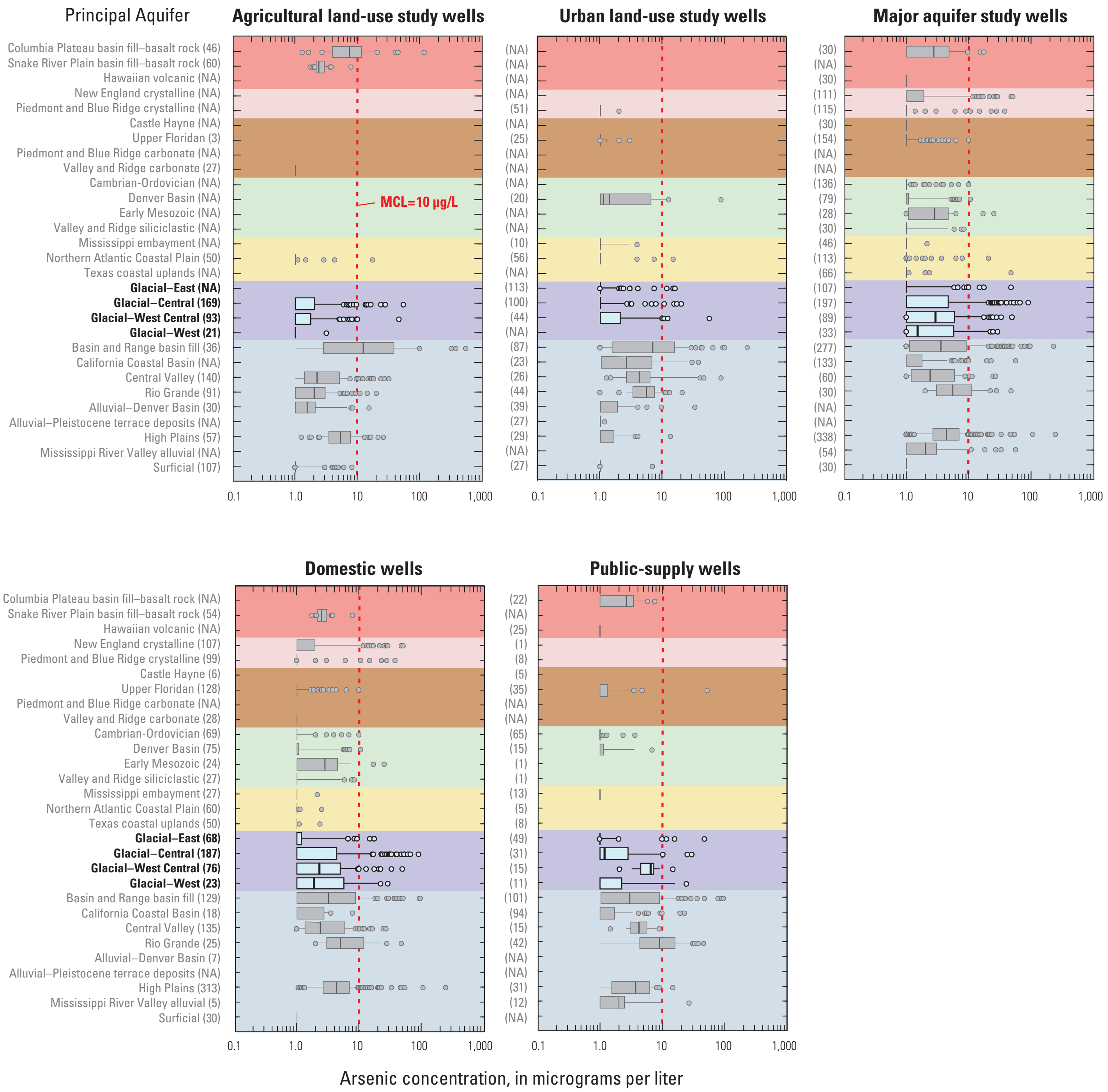
Lithology

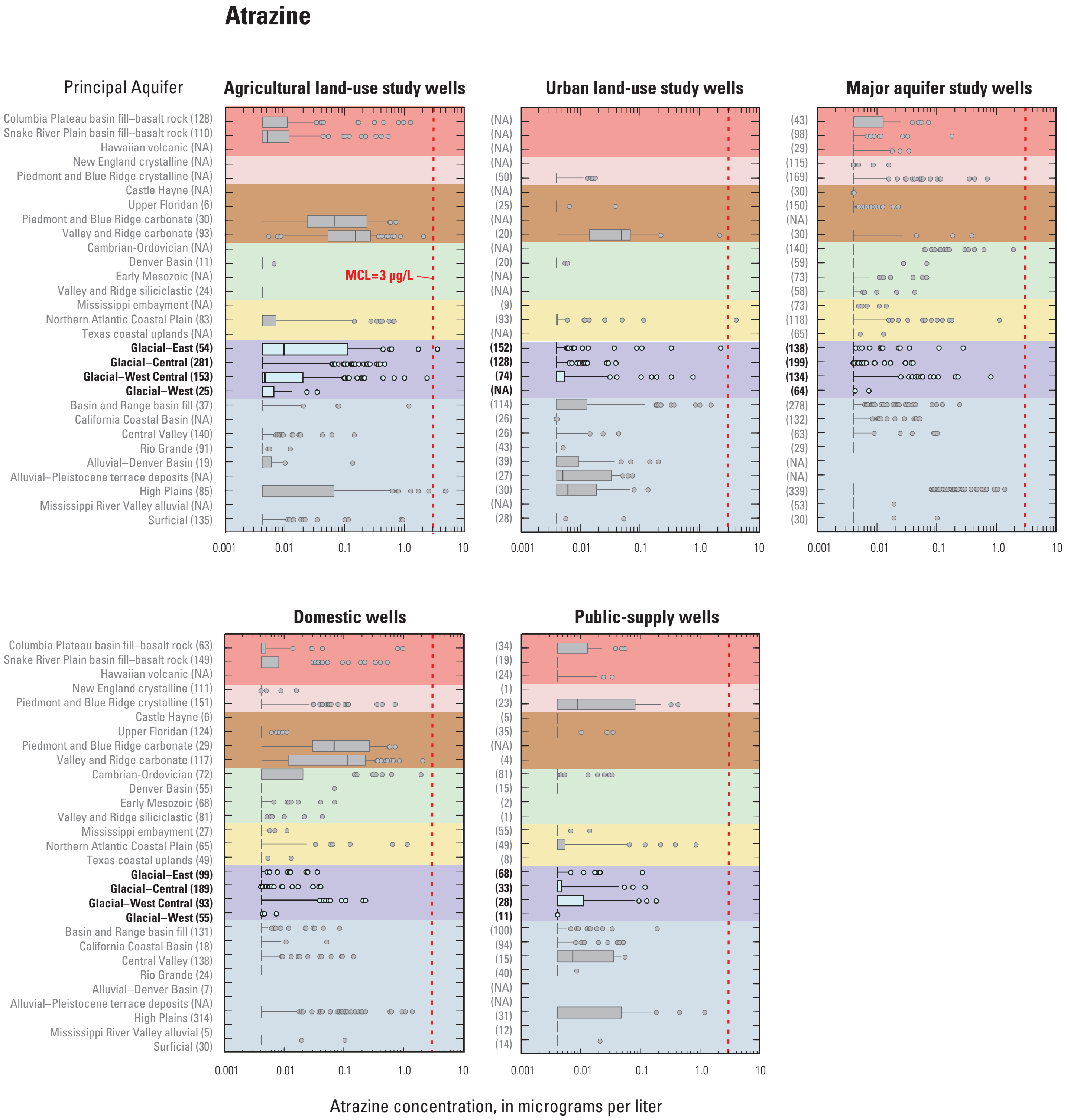
🟥 Basalt and volcanics**
⬜ Crystalline
🟫 Carbonate
🟩 Sandstone
🟨 Semiconsolidated sand and gravel
🟪 Glacial unconsolidated sand and gravel
🟦 Unconsolidated sand and gravel (nonglacial)

This appendix shows graphical comparisons of chemical concentrations (1991 to 2010) for selected inorganic and organic constituents of potential health or aquatic-life concern in selected Principal Aquifers of the United States. For each constituent, the concentration data are grouped according to five well types: agricultural land-use study wells (includes shallow agricultural monitoring wells), urban land-use study wells (includes shallow urban monitoring wells), major aquifer study wells, domestic wells, and public-supply wells. For each well type, the aquifers also are grouped according to aquifer lithology: basalt and volcanics,** crystalline, carbonate, sandstone, semiconsolidated sand and gravel, glacial unconsolidated sand and gravel, and unconsolidated sand and gravel (nonglacial). Data for a particular compound were not plotted if there were fewer than 10 samples for a particular well network in a Principal Aquifer; not all Principal Aquifers for which data were available are shown. Note that analytical detection limits varied among the constituents and that the number of samples for a constituent can vary greatly between Principal Aquifers. The data used in this appendix and boxplots for additional constituents are available at *http://pubs.usgs.gov/circ/1360/*.

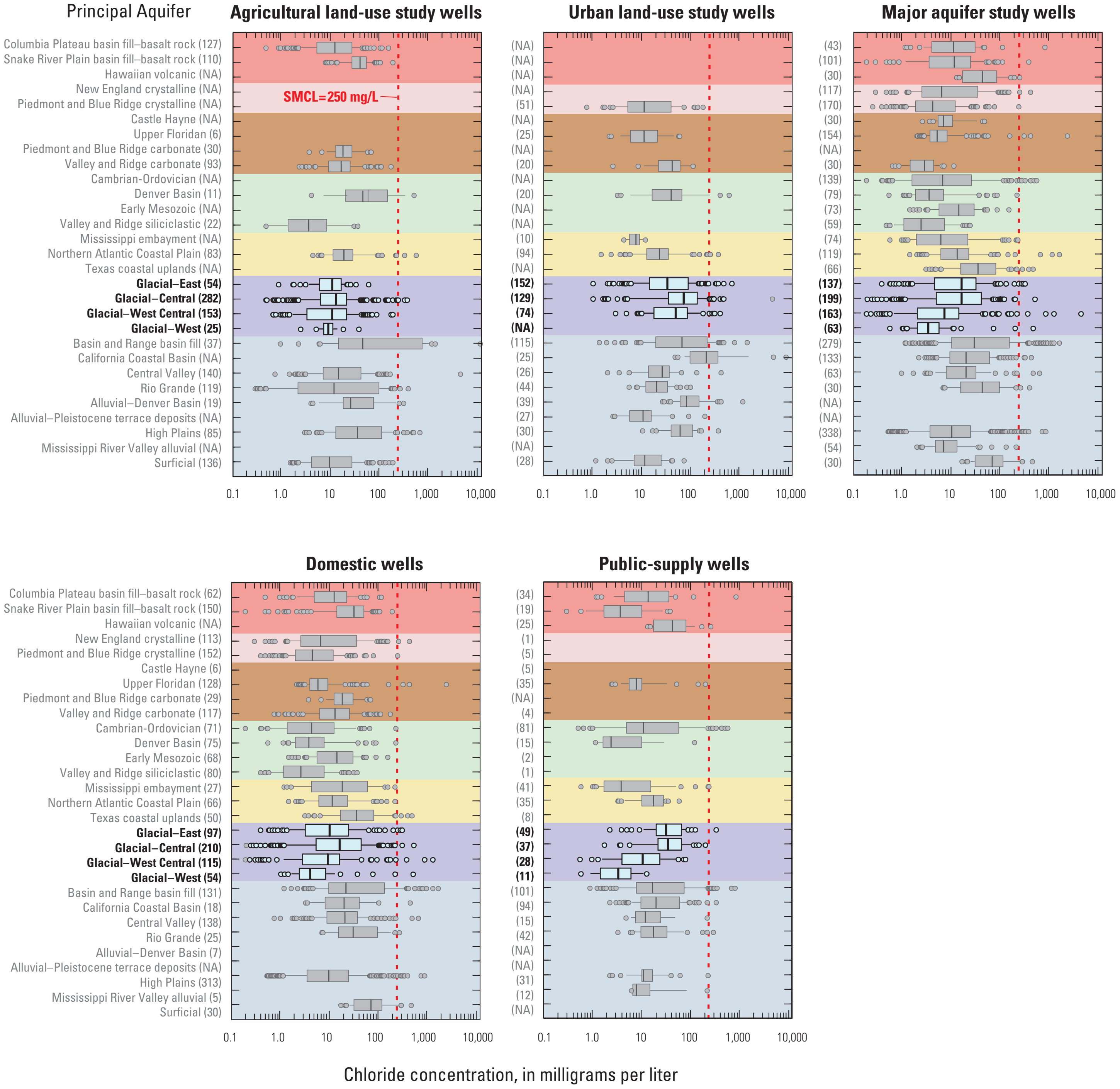
** Note: Two of the Principal Aquifers in this group include limited samples from basin-fill aquifers within the extent of the basaltic aquifer.

Arsenic

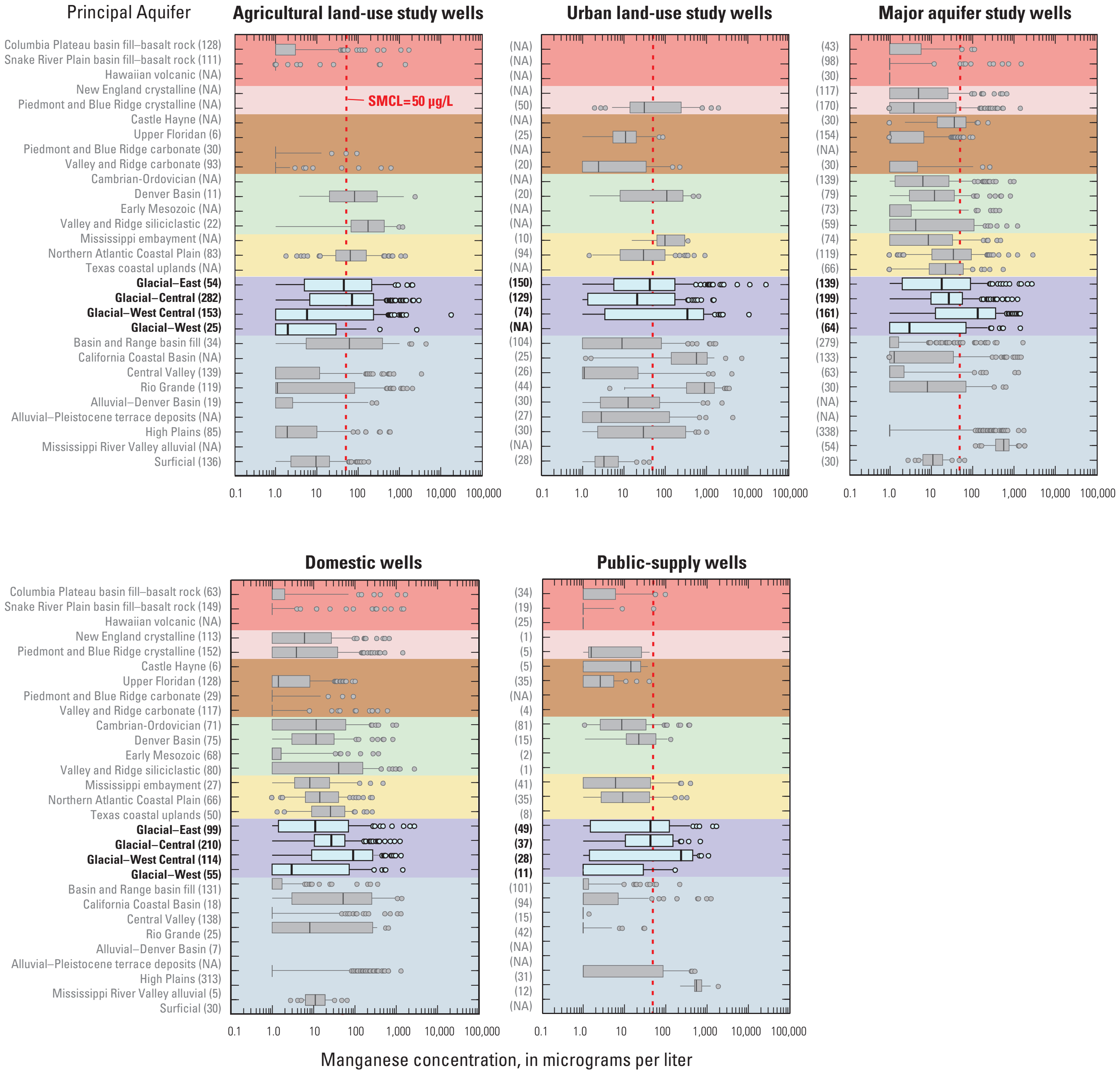

Principal Aquifer
Agricultural land-use study wells
Urban land-use study wells
Major aquifer study wells
Columbia Plateau basin fill–basalt rock (46)
Snake River Plain basin fill–basalt rock (60)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (NA)
Castle Hayne (NA)
Upper Floridan (3)
Piedmont and Blue Ridge carbonate (NA)
Valley and Ridge carbonate (27)
Cambrian-Ordovician (NA)
Denver Basin (NA)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (NA)
Mississippi embayment (NA)
Northern Atlantic Coastal Plain (50)
Texas coastal uplands (NA)
Glacial–East (NA)
Glacial–Central (169)
Glacial–West Central (93)
Glacial–West (21)
Basin and Range basin fill (36)
California Coastal Basin (NA)
Central Valley (140)
Rio Grande (91)
Alluvial–Denver Basin (30)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (57)
Mississippi River Valley alluvial (NA)
Surficial (107)
MCL=10 µg/L
(NA) (NA) (NA) (NA) (51) (NA) (25) (NA) (NA) (NA) (20) (NA) (NA) (10) (56) (NA) (113) (100) (44) (NA) (87) (23) (26) (44) (39) (27) (29) (NA) (27)
(30) (NA) (30) (111) (115) (30) (154) (NA) (NA) (136) (79) (28) (30) (46) (113) (66) (107) (197) (89) (33) (277) (133) (60) (30) (NA) (NA) (338) (54) (30)
0.1 1.0 10 100 1,000
Domestic wells
Public-supply wells
Columbia Plateau basin fill–basalt rock (NA)
Snake River Plain basin fill–basalt rock (54)
Hawaiian volcanic (NA)
New England crystalline (107)
Piedmont and Blue Ridge crystalline (99)
Castle Hayne (6)
Upper Floridan (128)
Piedmont and Blue Ridge carbonate (NA)
Valley and Ridge carbonate (28)
Cambrian-Ordovician (69)
Denver Basin (75)
Early Mesozoic (24)
Valley and Ridge siliciclastic (27)
Mississippi embayment (27)
Northern Atlantic Coastal Plain (60)
Texas coastal uplands (50)
Glacial–East (68)
Glacial–Central (187)
Glacial–West Central (76)
Glacial–West (23)
Basin and Range basin fill (129)
California Coastal Basin (18)
Central Valley (135)
Rio Grande (25)
Alluvial–Denver Basin (7)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (313)
Mississippi River Valley alluvial (5)
Surficial (30)
(22) (NA) (25) (1) (8) (5) (35) (NA) (NA) (65) (15) (1) (1) (13) (5) (8) (49) (31) (15) (11) (101) (94) (15) (42) (NA) (NA) (31) (12) (NA)
0.1 1.0 10 100 1,000
Arsenic concentration, in micrograms per liter


Atrazine
Principal Aquifer
Agricultural land-use study wells
Urban land-use study wells
Major aquifer study wells
Columbia Plateau basin fill–basalt rock (128) (NA) (43)
Snake River Plain basin fill–basalt rock (110) (NA) (98)
Hawaiian volcanic (NA) (NA) (29)
New England crystalline (NA) (NA) (115)
Piedmont and Blue Ridge crystalline (NA) (50) (169)
Castle Hayne (NA) (NA) (30)
Upper Floridan (6) (25) (150)
Piedmont and Blue Ridge carbonate (30) (NA) (NA)
Valley and Ridge carbonate (93) (20) (30)
Cambrian-Ordovician (NA) (NA) (140)
Denver Basin (11) (20) (59)
Early Mesozoic (NA) (NA) (73)
Valley and Ridge siliciclastic (24) (NA) (58)
Mississippi embayment (NA) (9) (73)
Northern Atlantic Coastal Plain (83) (93) (118)
Texas coastal uplands (NA) (NA) (65)
Glacial–East (54) (152) (138)
Glacial–Central (281) (128) (199)
Glacial–West Central (153) (74) (134)
Glacial–West (25) (NA) (64)
Basin and Range basin fill (37) (114) (278)
California Coastal Basin (NA) (26) (132)
Central Valley (140) (26) (63)
Rio Grande (91) (43) (29)
Alluvial–Denver Basin (19) (39) (NA)
Alluvial–Pleistocene terrace deposits (NA) (27) (NA)
High Plains (85) (30) (339)
Mississippi River Valley alluvial (NA) (NA) (53)
Surficial (135) (28) (30)
MCL=3 µg/L
0.001
0.01
0.1
1.0
10
Domestic wells
Public-supply wells
Columbia Plateau basin fill–basalt rock (63) (34)
Snake River Plain basin fill–basalt rock (149) (19)
Hawaiian volcanic (NA) (24)
New England crystalline (111) (1)
Piedmont and Blue Ridge crystalline (151) (23)
Castle Hayne (6) (5)
Upper Floridan (124) (35)
Piedmont and Blue Ridge carbonate (29) (NA)
Valley and Ridge carbonate (117) (4)
Cambrian-Ordovician (72) (81)
Denver Basin (55) (15)
Early Mesozoic (68) (2)
Valley and Ridge siliciclastic (81) (1)
Mississippi embayment (27) (55)
Northern Atlantic Coastal Plain (65) (49)
Texas coastal uplands (49) (8)
Glacial–East (99) (68)
Glacial–Central (189) (33)
Glacial–West Central (93) (28)
Glacial–West (55) (11)
Basin and Range basin fill (131) (100)
California Coastal Basin (18) (94)
Central Valley (138) (15)
Rio Grande (24) (40)
Alluvial–Denver Basin (7) (NA)
Alluvial–Pleistocene terrace deposits (NA) (NA)
High Plains (314) (31)
Mississippi River Valley alluvial (5) (12)
Surficial (30) (14)
0.001
0.01
0.1
1.0
10
Atrazine concentration, in micrograms per liter

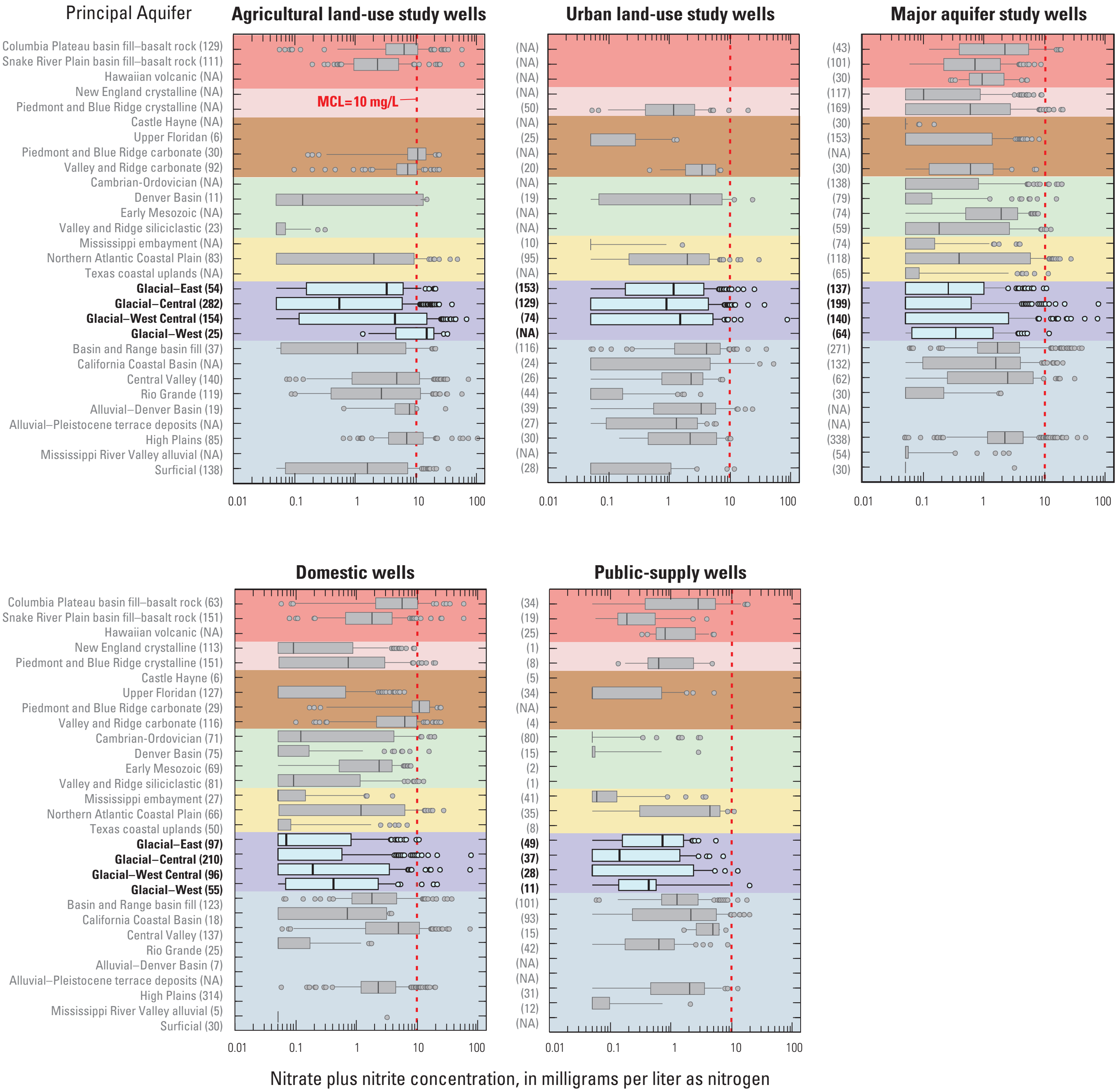
Chloride


Principal Aquifer
Agricultural land-use study wells
Urban land-use study wells
Major aquifer study wells
Columbia Plateau basin fill–basalt rock (127)
Snake River Plain basin fill–basalt rock (110)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (NA)
Castle Hayne (NA)
Upper Floridan (6)
Piedmont and Blue Ridge carbonate (30)
Valley and Ridge carbonate (93)
Cambrian-Ordovician (NA)
Denver Basin (11)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (22)
Mississippi embayment (NA)
Northern Atlantic Coastal Plain (83)
Texas coastal uplands (NA)
Glacial–East (54)
Glacial–Central (282)
Glacial–West Central (153)
Glacial–West (25)
Basin and Range basin fill (37)
California Coastal Basin (NA)
Central Valley (140)
Rio Grande (119)
Alluvial–Denver Basin (19)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (85)
Mississippi River Valley alluvial (NA)
Surficial (136)
SMCL=250 mg/L
(NA) (NA) (NA) (NA) (51) (NA) (25) (NA) (20) (NA) (20) (NA) (NA) (10) (94) (NA) (152) (129) (74) (NA) (115) (25) (26) (44) (39) (27) (30) (NA) (28)
(43) (101) (30) (117) (170) (30) (154) (NA) (30) (139) (79) (73) (59) (74) (119) (66) (137) (199) (163) (63) (279) (133) (63) (30) (NA) (NA) (338) (54) (30)
0.1
1.0
10
100
1,000
10,000
Domestic wells
Public-supply wells
Columbia Plateau basin fill–basalt rock (62)
Snake River Plain basin fill–basalt rock (150)
Hawaiian volcanic (NA)
New England crystalline (113)
Piedmont and Blue Ridge crystalline (152)
Castle Hayne (6)
Upper Floridan (128)
Piedmont and Blue Ridge carbonate (29)
Valley and Ridge carbonate (117)
Cambrian-Ordovician (71)
Denver Basin (75)
Early Mesozoic (68)
Valley and Ridge siliciclastic (80)
Mississippi embayment (27)
Northern Atlantic Coastal Plain (66)
Texas coastal uplands (50)
Glacial–East (97)
Glacial–Central (210)
Glacial–West Central (115)
Glacial–West (54)
Basin and Range basin fill (131)
California Coastal Basin (18)
Central Valley (138)
Rio Grande (25)
Alluvial–Denver Basin (7)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (313)
Mississippi River Valley alluvial (5)
Surficial (30)
(34) (19) (25) (1) (5) (5) (35) (NA) (4) (81) (15) (2) (1) (41) (35) (8) (49) (37) (28) (11) (101) (94) (15) (42) (NA) (NA) (31) (12) (NA)
0.1
1.0
10
100
1,000
10,000
Chloride concentration, in milligrams per liter

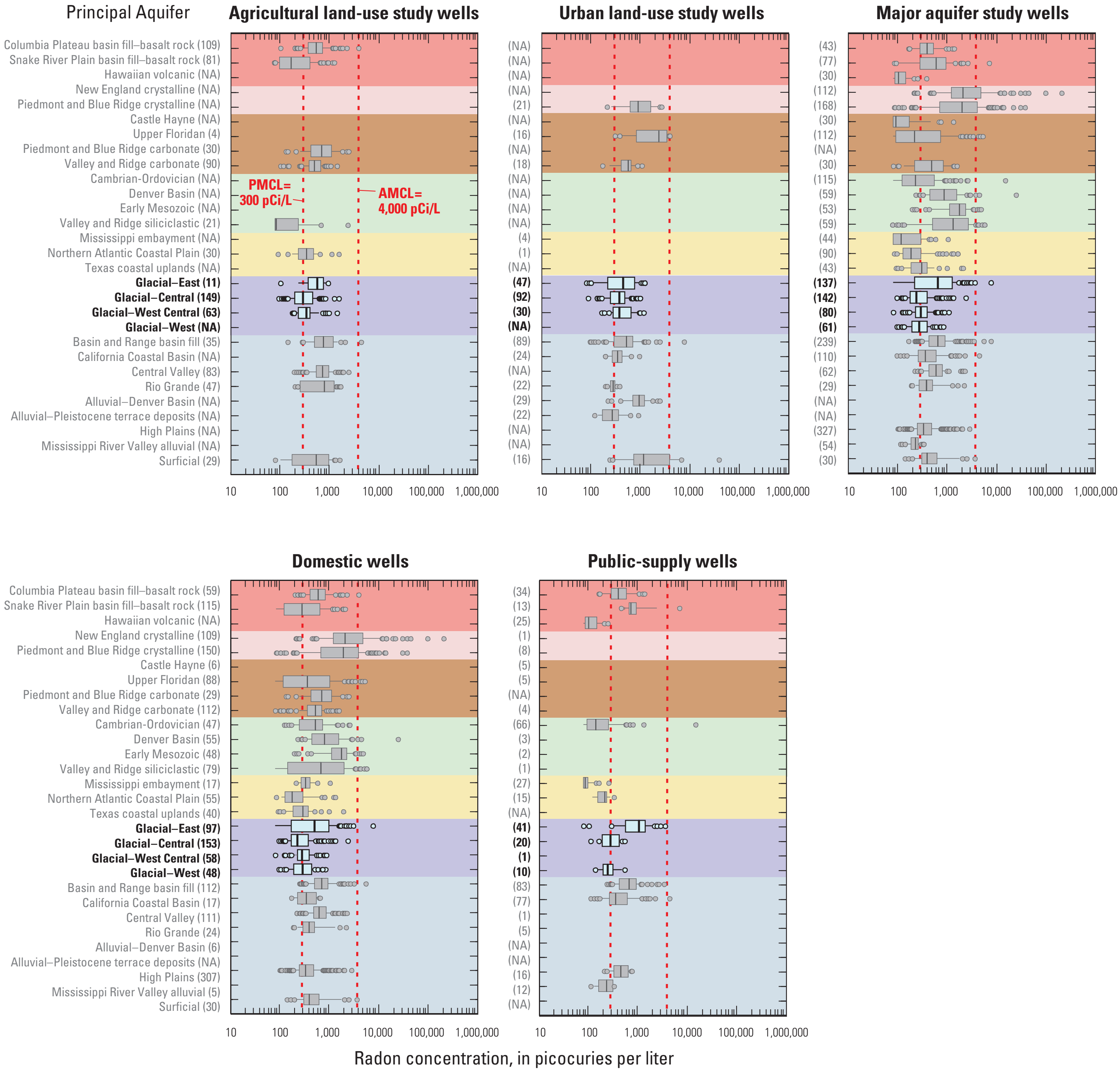
Manganese


Principal Aquifer
Agricultural land-use study wells
Urban land-use study wells
Major aquifer study wells
Columbia Plateau basin fill–basalt rock (128)
Snake River Plain basin fill–basalt rock (111)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (NA)
Castle Hayne (NA)
Upper Floridan (6)
Piedmont and Blue Ridge carbonate (30)
Valley and Ridge carbonate (93)
Cambrian-Ordovician (NA)
Denver Basin (11)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (22)
Mississippi embayment (NA)
Northern Atlantic Coastal Plain (83)
Texas coastal uplands (NA)
Glacial–East (54)
Glacial–Central (282)
Glacial–West Central (153)
Glacial–West (25)
Basin and Range basin fill (34)
California Coastal Basin (NA)
Central Valley (139)
Rio Grande (119)
Alluvial–Denver Basin (19)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (85)
Mississippi River Valley alluvial (NA)
Surficial (136)
SMCL=50 µg/L
(NA) (NA) (NA) (NA) (50) (NA) (25) (NA) (20) (NA) (20) (NA) (NA) (10) (94) (NA) (150) (129) (74) (NA) (104) (25) (26) (44) (30) (27) (30) (NA) (28)
(43) (98) (30) (117) (170) (30) (154) (NA) (30) (139) (79) (73) (59) (74) (119) (66) (139) (199) (161) (64) (279) (133) (63) (30) (NA) (NA) (338) (54) (30)
0.1 1.0 10 100 1,000 10,000 100,000
Domestic wells
Public-supply wells
Columbia Plateau basin fill–basalt rock (63)
Snake River Plain basin fill–basalt rock (149)
Hawaiian volcanic (NA)
New England crystalline (113)
Piedmont and Blue Ridge crystalline (152)
Castle Hayne (6)
Upper Floridan (128)
Piedmont and Blue Ridge carbonate (29)
Valley and Ridge carbonate (117)
Cambrian-Ordovician (71)
Denver Basin (75)
Early Mesozoic (68)
Valley and Ridge siliciclastic (80)
Mississippi embayment (27)
Northern Atlantic Coastal Plain (66)
Texas coastal uplands (50)
Glacial–East (99)
Glacial–Central (210)
Glacial–West Central (114)
Glacial–West (55)
Basin and Range basin fill (131)
California Coastal Basin (18)
Central Valley (138)
Rio Grande (25)
Alluvial–Denver Basin (7)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (313)
Mississippi River Valley alluvial (5)
Surficial (30)
(34) (19) (25) (1) (5) (5) (35) (NA) (4) (81) (15) (2) (1) (41) (35) (8) (49) (37) (28) (11) (101) (94) (15) (42) (NA) (NA) (31) (12) (NA)
0.1 1.0 10 100 1,000 10,000 100,000
Manganese concentration, in micrograms per liter

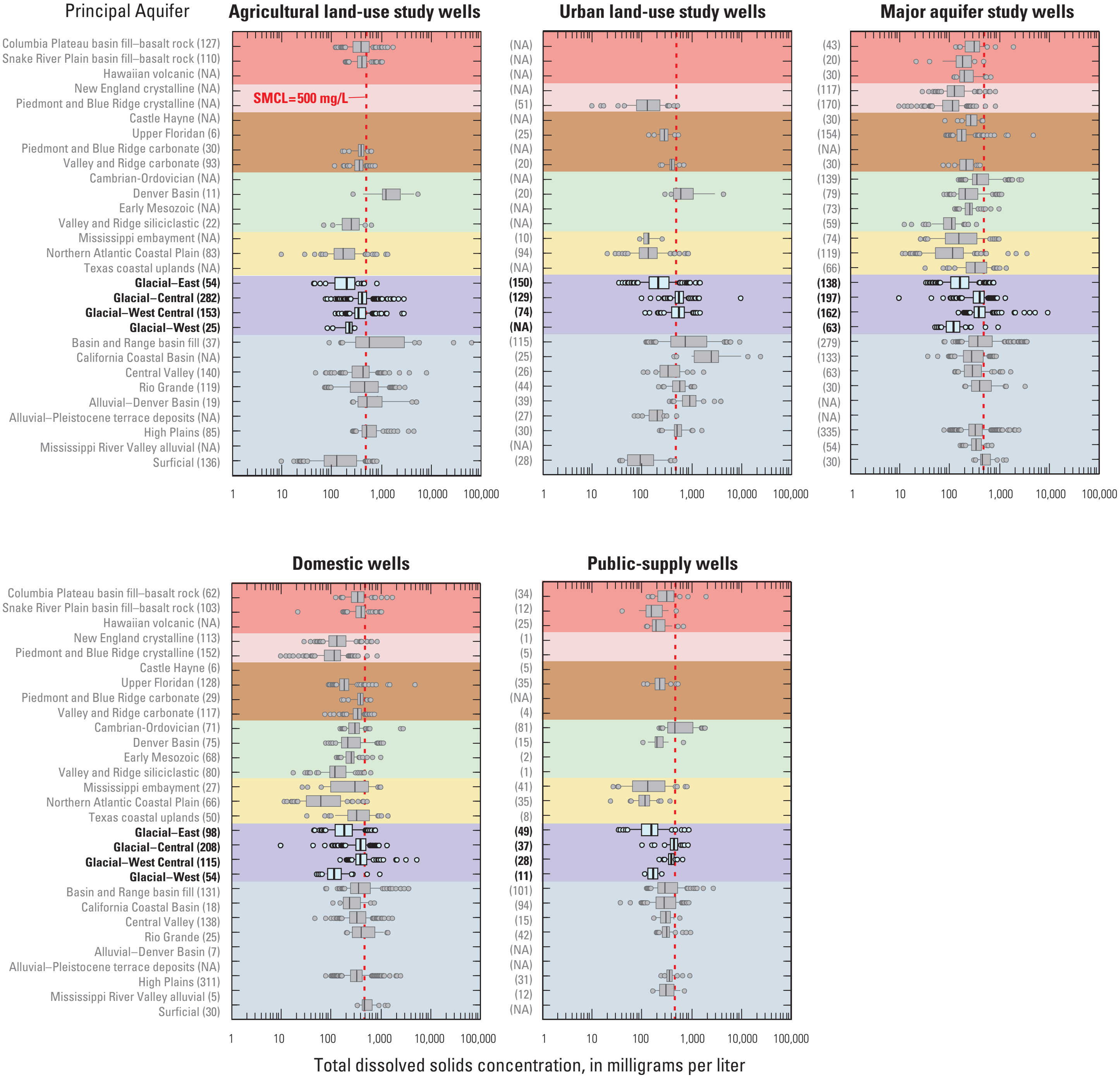
Nitrate plus nitrite (nitrate)

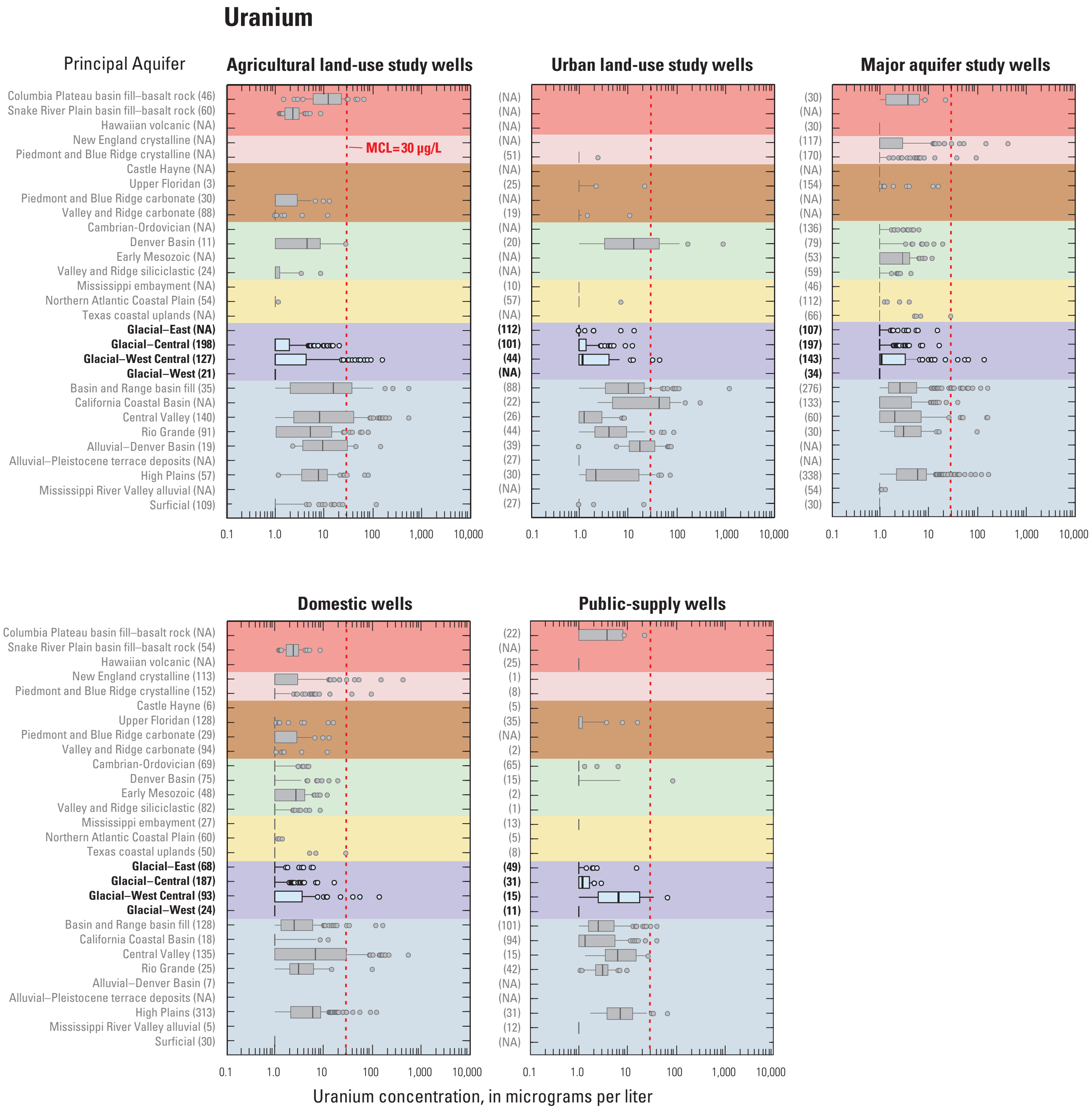


Radon


Principal Aquifer
Agricultural land-use study wells
Urban land-use study wells
Major aquifer study wells
Columbia Plateau basin fill–basalt rock (109)
Snake River Plain basin fill–basalt rock (81)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (NA)
Castle Hayne (NA)
Upper Floridan (4)
Piedmont and Blue Ridge carbonate (30)
Valley and Ridge carbonate (90)
Cambrian-Ordovician (NA)
Denver Basin (NA)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (21)
Mississippi embayment (NA)
Northern Atlantic Coastal Plain (30)
Texas coastal uplands (NA)
Glacial–East (11)
Glacial–Central (149)
Glacial–West Central (63)
Glacial–West (NA)
Basin and Range basin fill (35)
California Coastal Basin (NA)
Central Valley (83)
Rio Grande (47)
Alluvial–Denver Basin (NA)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (NA)
Mississippi River Valley alluvial (NA)
Surficial (29)
PMCL=
300 pCi/L
AMCL=
4,000 pCi/L
(NA) (NA) (NA) (NA) (21) (NA) (16) (NA) (18) (NA) (NA) (NA) (NA) (4) (1) (NA) (47) (92) (30) (NA) (89) (24) (NA) (22) (29) (22) (NA) (NA) (16)
(43) (77) (30) (112) (168) (30) (112) (NA) (30) (115) (59) (53) (59) (44) (90) (43) (137) (142) (80) (61) (239) (110) (62) (29) (NA) (NA) (327) (54) (30)
10 100 1,000 10,000 100,000 1,000,000
Domestic wells
Public-supply wells
Columbia Plateau basin fill–basalt rock (59)
Snake River Plain basin fill–basalt rock (115)
Hawaiian volcanic (NA)
New England crystalline (109)
Piedmont and Blue Ridge crystalline (150)
Castle Hayne (6)
Upper Floridan (88)
Piedmont and Blue Ridge carbonate (29)
Valley and Ridge carbonate (112)
Cambrian-Ordovician (47)
Denver Basin (55)
Early Mesozoic (48)
Valley and Ridge siliciclastic (79)
Mississippi embayment (17)
Northern Atlantic Coastal Plain (55)
Texas coastal uplands (40)
Glacial–East (97)
Glacial–Central (153)
Glacial–West Central (58)
Glacial–West (48)
Basin and Range basin fill (112)
California Coastal Basin (17)
Central Valley (111)
Rio Grande (24)
Alluvial–Denver Basin (6)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (307)
Mississippi River Valley alluvial (5)
Surficial (30)
(34) (13) (25) (1) (8) (5) (5) (NA) (4) (66) (3) (2) (1) (27) (15) (NA) (41) (20) (1) (10) (83) (77) (1) (5) (NA) (NA) (16) (12) (NA)
10 100 1,000 10,000 100,000 1,000,000
Radon concentration, in picocuries per liter

Total Dissolved Solids




Uranium
Principal Aquifer
Agricultural land-use study wells
Urban land-use study wells
Major aquifer study wells
Columbia Plateau basin fill–basalt rock (46)
Snake River Plain basin fill–basalt rock (60)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (NA)
Castle Hayne (NA)
Upper Floridan (3)
Piedmont and Blue Ridge carbonate (30)
Valley and Ridge carbonate (88)
Cambrian-Ordovician (NA)
Denver Basin (11)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (24)
Mississippi embayment (NA)
Northern Atlantic Coastal Plain (54)
Texas coastal uplands (NA)
Glacial–East (NA)
Glacial–Central (198)
Glacial–West Central (127)
Glacial–West (21)
Basin and Range basin fill (35)
California Coastal Basin (NA)
Central Valley (140)
Rio Grande (91)
Alluvial–Denver Basin (19)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (57)
Mississippi River Valley alluvial (NA)
Surficial (109)
MCL=30 µg/L
(NA) (NA) (NA) (NA) (51) (NA) (25) (NA) (19) (NA) (20) (NA) (NA) (10) (57) (NA) (112) (101) (44) (NA) (88) (22) (26) (44) (39) (27) (30) (NA) (27)
(30) (NA) (30) (117) (170) (NA) (154) (NA) (NA) (136) (79) (53) (59) (46) (112) (66) (107) (197) (143) (34) (276) (133) (60) (30) (NA) (NA) (338) (54) (30)
0.1 1.0 10 100 1,000 10,000
Domestic wells
Public-supply wells
Columbia Plateau basin fill–basalt rock (NA)
Snake River Plain basin fill–basalt rock (54)
Hawaiian volcanic (NA)
New England crystalline (113)
Piedmont and Blue Ridge crystalline (152)
Castle Hayne (6)
Upper Floridan (128)
Piedmont and Blue Ridge carbonate (29)
Valley and Ridge carbonate (94)
Cambrian-Ordovician (69)
Denver Basin (75)
Early Mesozoic (48)
Valley and Ridge siliciclastic (82)
Mississippi embayment (27)
Northern Atlantic Coastal Plain (60)
Texas coastal uplands (50)
Glacial–East (68)
Glacial–Central (187)
Glacial–West Central (93)
Glacial–West (24)
Basin and Range basin fill (128)
California Coastal Basin (18)
Central Valley (135)
Rio Grande (25)
Alluvial–Denver Basin (7)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (313)
Mississippi River Valley alluvial (5)
Surficial (30)
(22) (NA) (25) (1) (8) (5) (35) (NA) (2) (65) (15) (2) (1) (13) (5) (8) (49) (31) (15) (11) (101) (94) (15) (42) (NA) (NA) (31) (12) (NA)
0.1 1.0 10 100 1,000 10,000
Uranium concentration, in micrograms per liter

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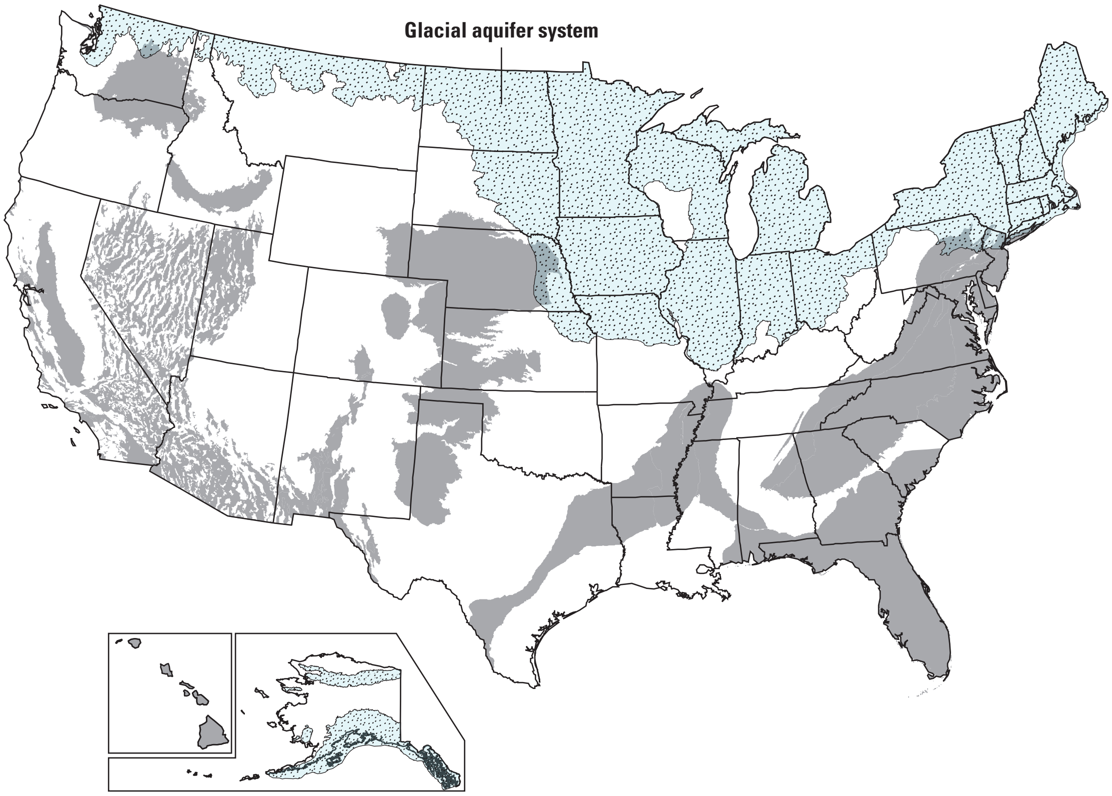

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