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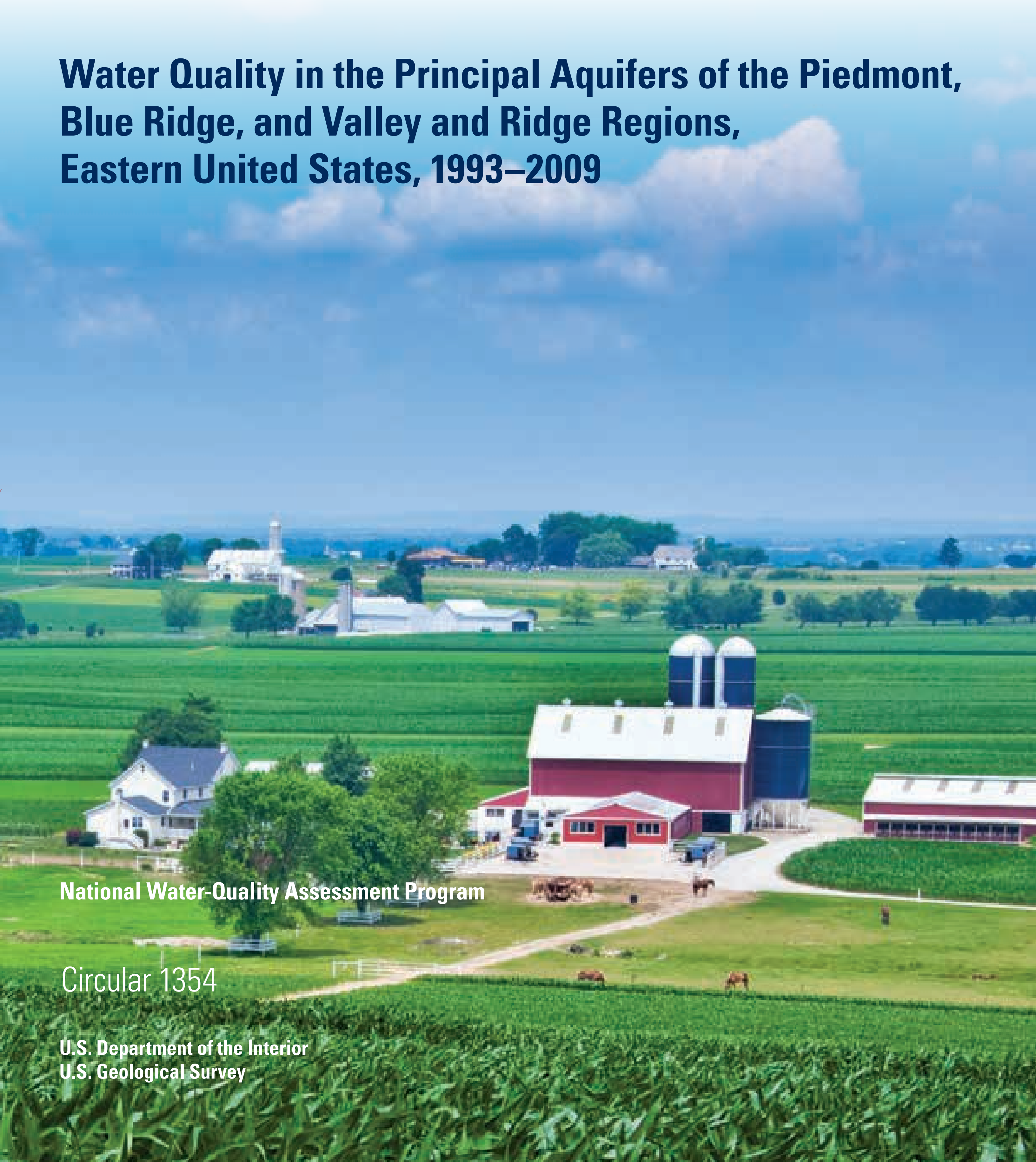
The Quality of Our Nation's Waters

Water Quality in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge Regions, Eastern United States, 1993–2009



National Water-Quality Assessment Program

Circular 1354

U.S. Department of the Interior
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By Bruce D. Lindsey, Tammy M. Zimmerman, Melinda J. Chapman,
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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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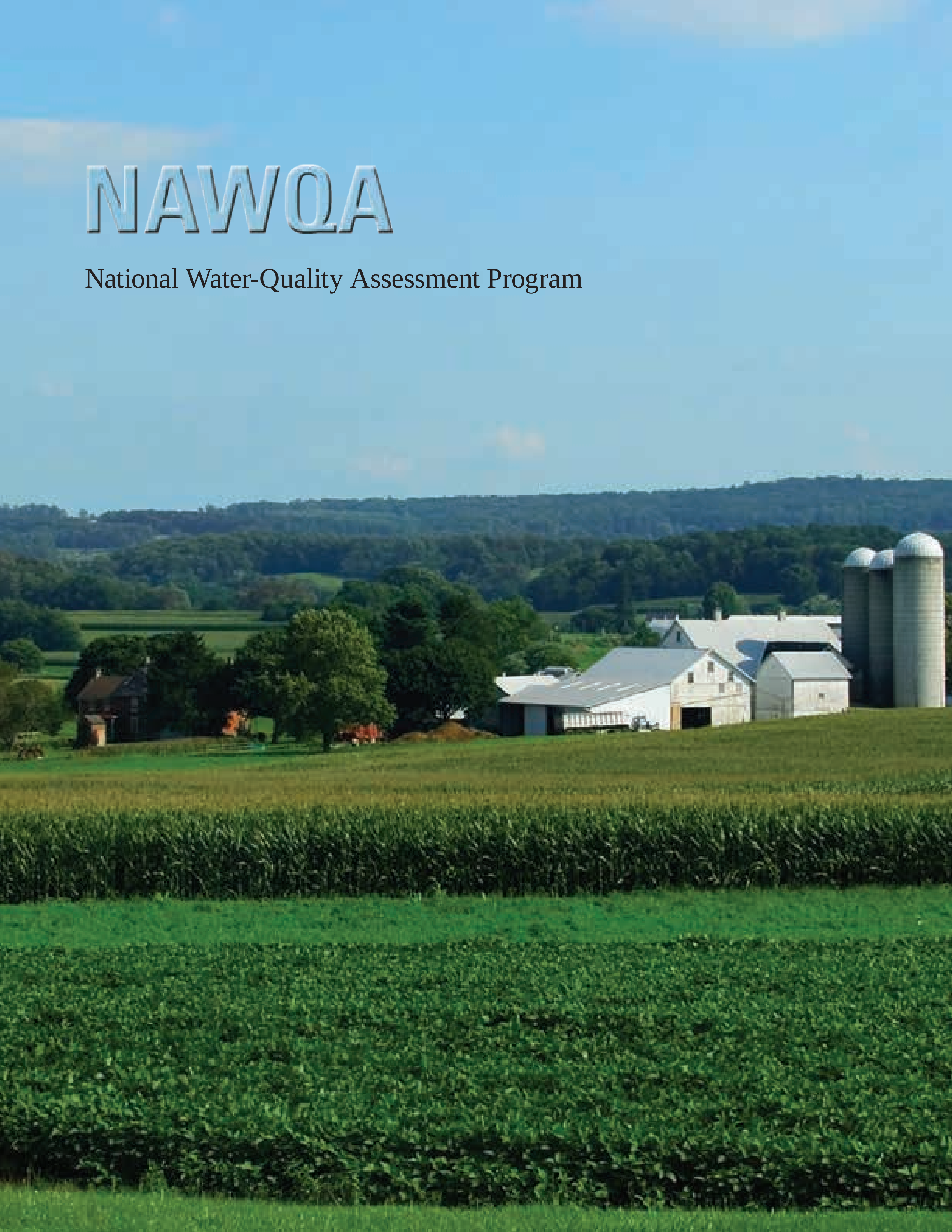
NAWQA

National Water-Quality Assessment Program



Foreword

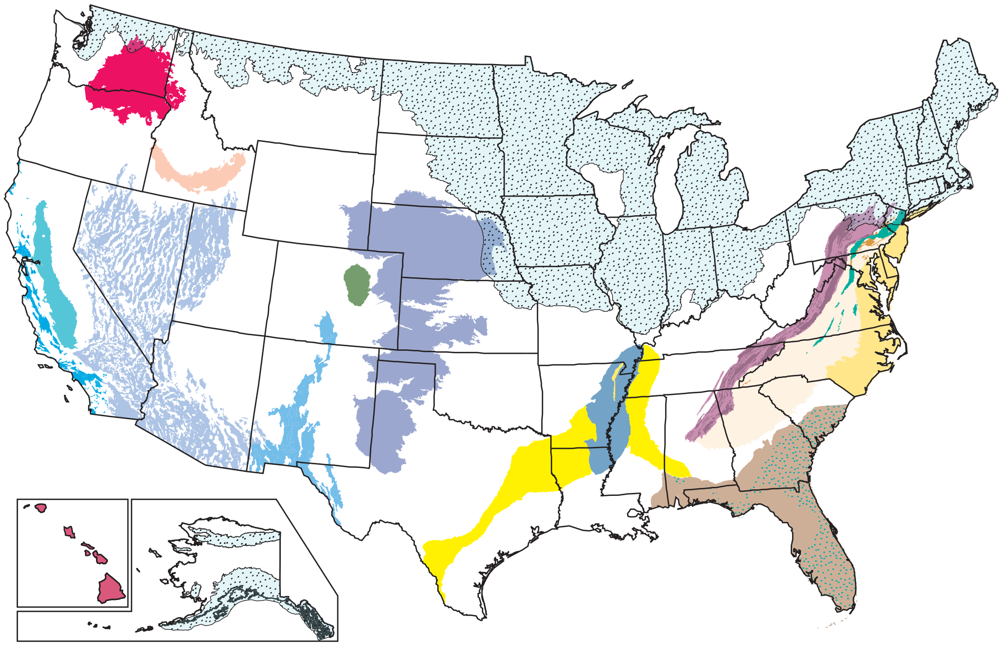
The United States has made major investments in assessing, managing, regulating, and conserving natural resources, such as water and a variety of ecosystems. Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources 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

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Southwest Principal Aquifers—Circular 1358

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🟧 Snake River Plain basin-fill and basaltic-rock aquifers

🟥 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 groundwater quality in five Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions: the Piedmont and Blue Ridge crystalline- and carbonate-rock aquifers, early Mesozoic basin (siliciclastic-rock) aquifers, and the Valley and Ridge carbonate- and siliciclastic-rock aquifers. This 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, or 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 the Piedmont, Blue Ridge, and Valley and Ridge regions are compared to conditions found elsewhere and to select 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, and the private sector. The information will be useful in addressing current issues, such as drinking-water quality, source-water protection, and monitoring and sampling strategies. This report will also 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 water in other areas across the region and the Nation.

Water-quality conditions in the Piedmont, Blue Ridge, and Valley and Ridge regions 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 in the following reports.

Factors Affecting Occurrence and Distribution of Selected Contaminants in Ground Water From Selected Areas in the Piedmont Aquifer System, Eastern United States, 1993–2003

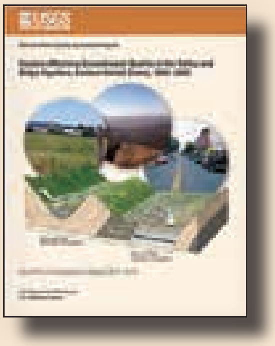
By Bruce D. Lindsey, William F. Falls, Matthew J. Ferrari, Tammy M. Zimmerman, Douglas A. Harned, Eric M. Sadorf, and Melinda J. Chapman

U.S. Geological Survey Scientific Investigations Report 2006–5104 (also available at *http://pubs.usgs.gov/sir/2006/5104/*)

Contributions of Phosphorus from Groundwater to Streams in the Piedmont, Blue Ridge, and Valley and Ridge Physiographic Provinces, Eastern United States

By Judith M. Denver, Charles A. Cravotta III, Scott W. Ator, and Bruce D. Lindsey

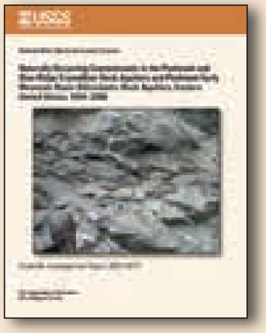
U.S. Geological Survey Scientific Investigations Report 2010–5176 (also available at *http://pubs.usgs.gov/sir/2010/5176/*)



Factors Affecting Groundwater Quality in the Valley and Ridge Aquifers, Eastern United States, 1993–2002

By Gregory C. Johnson, Tammy M. Zimmerman, Bruce D. Lindsey, and Eliza L. Gross

U.S. Geological Survey Scientific Investigations Report 2011–5115 (also available at *http://pubs.usgs.gov/sir/2011/5115/*)



Naturally Occurring Contaminants in the Piedmont and Blue Ridge Crystalline-Rock Aquifers and Piedmont Early Mesozoic Basin Siliciclastic-Rock Aquifers, Eastern United States, 1994–2008

By Melinda J. Chapman, Charles A. Cravotta III, Zoltan Szabo, and Bruce D. Lindsey

U.S. Geological Survey Scientific Investigations Report 2013–5072 (also available at *http://pubs.usgs.gov/sir/2013/5072/*)

Chapter 1: *Overview of Major Findings and Implications*

The Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions are a critical water resource, underlying an area with a population of more than 40 million people in 10 states. The suburban and rural population is large and growing rapidly and increasingly depends on groundwater as a source of water supply. The amount of water pumped from domestic (private) wells tapping these aquifers—more than 550 million gallons per day—is among the largest in the Nation. Some of these aquifers are among the most vulnerable in the Nation to contamination from chemicals with human-related or geologic sources. Untreated groundwater from nearly one-third of the drinking-water supplies sampled failed at least one test typically used by health officials to determine if water is safe to drink. The quality of groundwater in these aquifers also has ecological importance, as the aquifers are a major source of water and contaminants to streams and estuaries such as the Chesapeake Bay and the Albemarle-Pamlico Sound.

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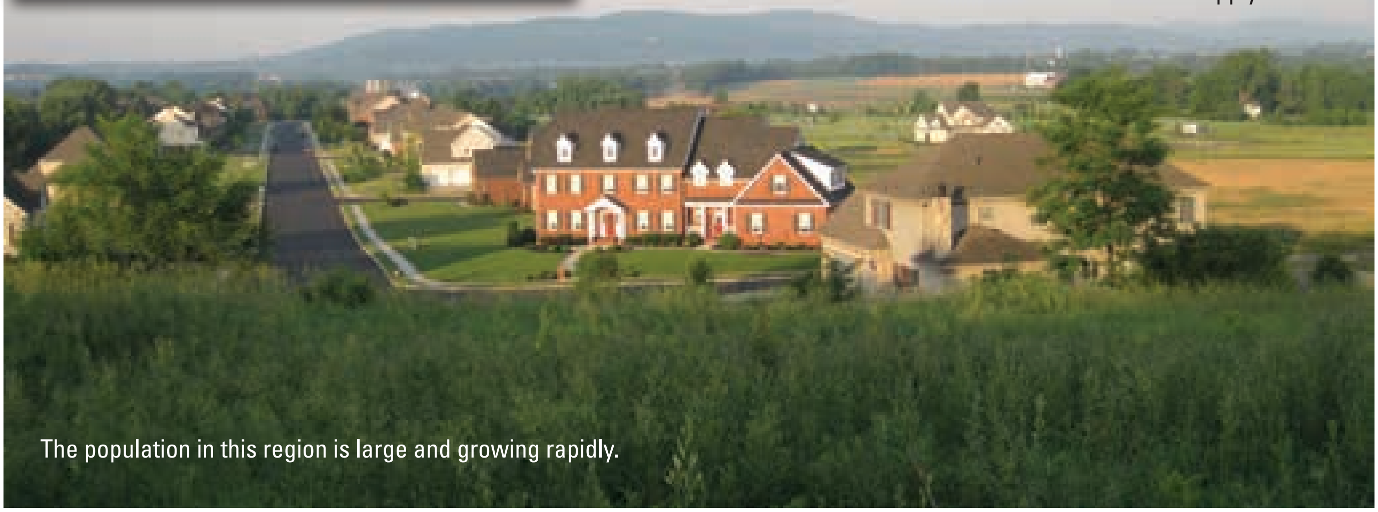
Photograph by Tammy Zimmerman, USGS

Groundwater is an important source of water for domestic supply.

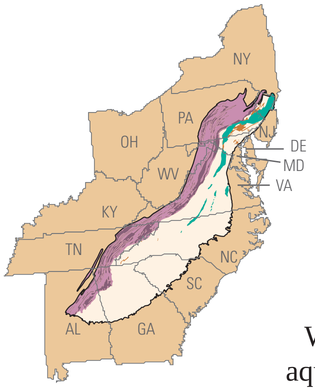


The population in this region is large and growing rapidly.

Photograph by Eliza Gross, USGS

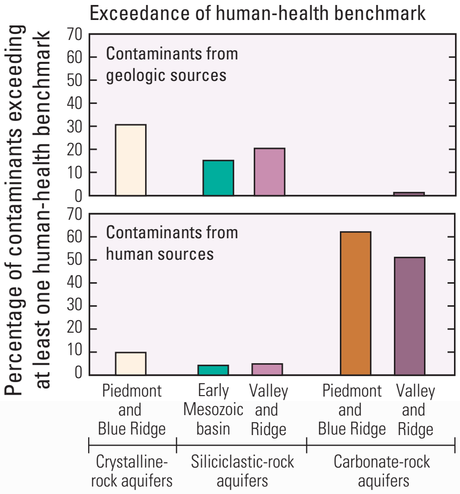
The aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions

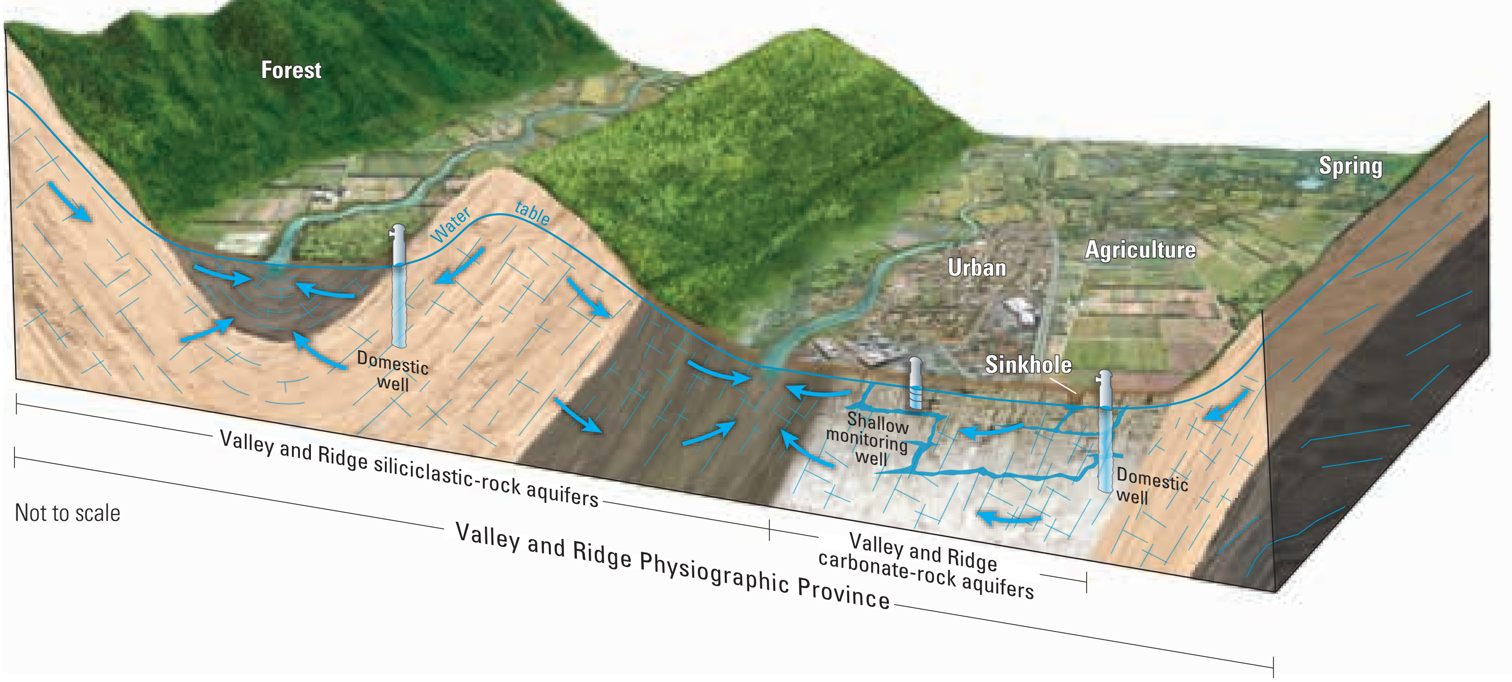
Valley and Ridge carbonate- and siliciclastic-rock aquifers, Piedmont and Blue Ridge carbonate- and



The aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions underlie an area with a population of more than 40 million people in 10 states. The suburban and rural population is large, growing rapidly, and increasingly dependent on groundwater as a source of supply, with more than 550 million gallons per day withdrawn from domestic wells for household use. Water from some of these aquifers does not meet human-health benchmarks for drinking water for contaminants with geologic or human sources.

Water from samples in crystalline- and siliciclastic-rock aquifers frequently exceeded standards for contaminants with geologic sources, and samples in carbonate-rock aquifers frequently exceeded standards for contaminants with human sources, most often nitrate and bacteria.





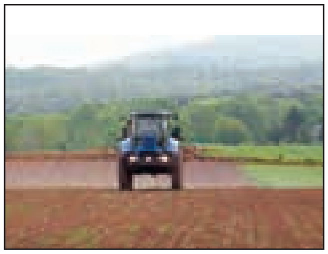
1 Many contaminants in groundwater have geologic sources, but geochemical conditions control whether or not those contaminants dissolve and move through groundwater

Water from the crystalline- and siliciclastic-rock aquifers frequently had concentrations of radon, manganese, and arsenic that exceeded human-health benchmarks. Concentrations of radon in nearly one of every four wells used as a source of drinking water in the crystalline-rock aquifers exceeded the proposed Alternative Maximum Contaminant Level (MCL) of 4,000 picocuries per liter (pCi/L). Concentrations of arsenic exceeded the drinking water standard of 10 micrograms per liter only under specific geochemical conditions. See chapter 6.

Photograph by Lester J. Williams, USGS

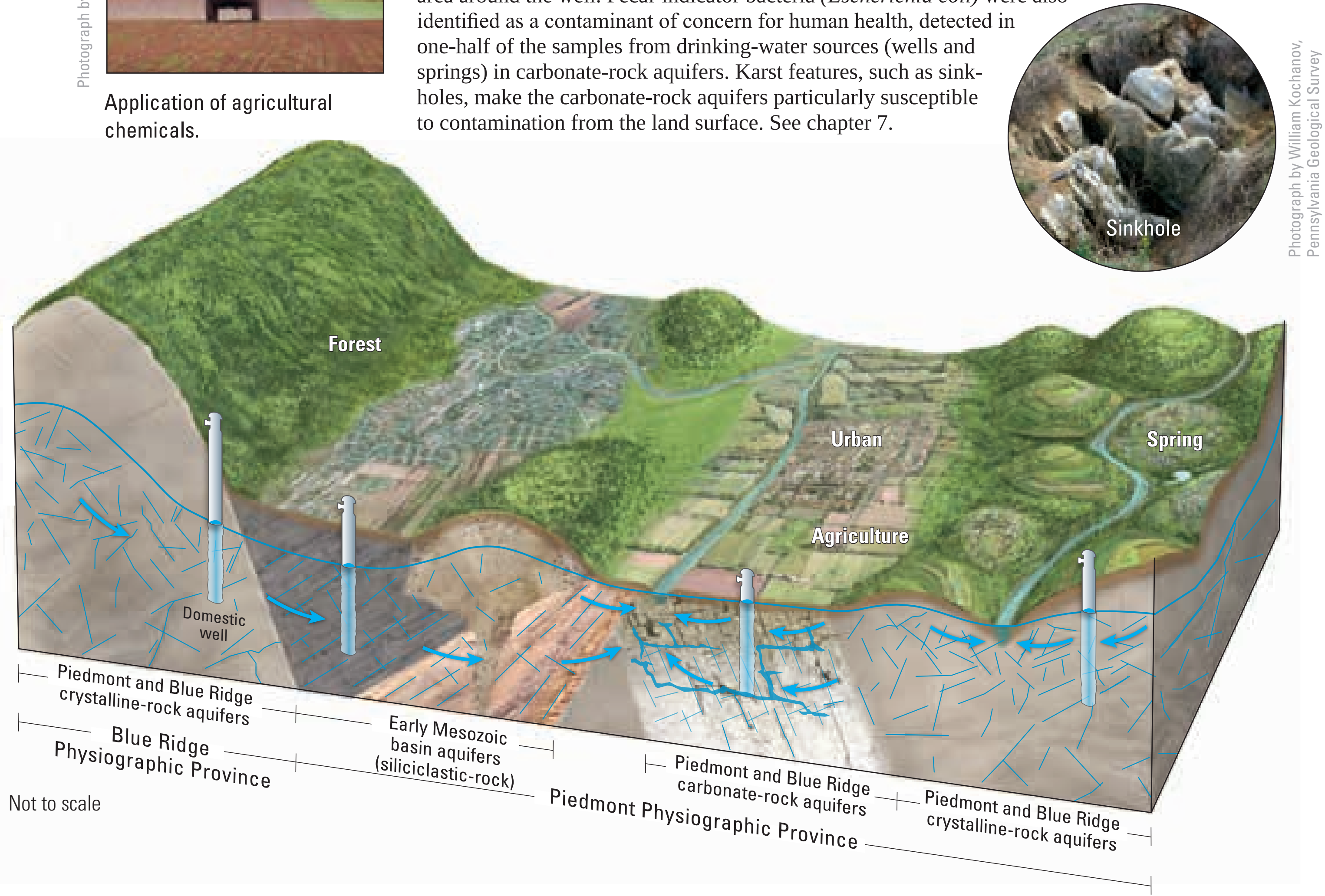
crystalline-rock aquifers, and Early Mesozoic basin aquifers

2 Concentrations of nitrate and bacteria—the main drinking-water contaminants with human sources—were high in carbonate-rock aquifers and frequently exceeded human-health benchmarks


Photograph by Connie Loper, USGS

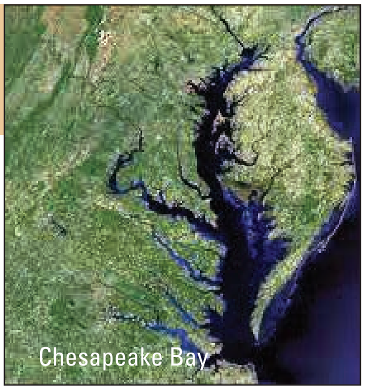
Application of agricultural chemicals.

Concentrations of nitrate from domestic wells in the carbonate-rock aquifers are the highest in the Nation for domestic water supplies, exceeding the Maximum Contaminant Level (MCL) of 10 milligrams per liter in water from one of every four wells or springs sampled, mainly in agricultural areas. Nitrate concentrations in water from wells in the crystalline-rock aquifers also frequently exceeded the nitrate MCL, where sources of nitrogen were high in the area around the well. Fecal-indicator bacteria *(Escherichia coli)* were also identified as a contaminant of concern for human health, detected in one-half of the samples from drinking-water sources (wells and springs) in carbonate-rock aquifers. Karst features, such as sinkholes, make the carbonate-rock aquifers particularly susceptible to contamination from the land surface. See chapter 7.



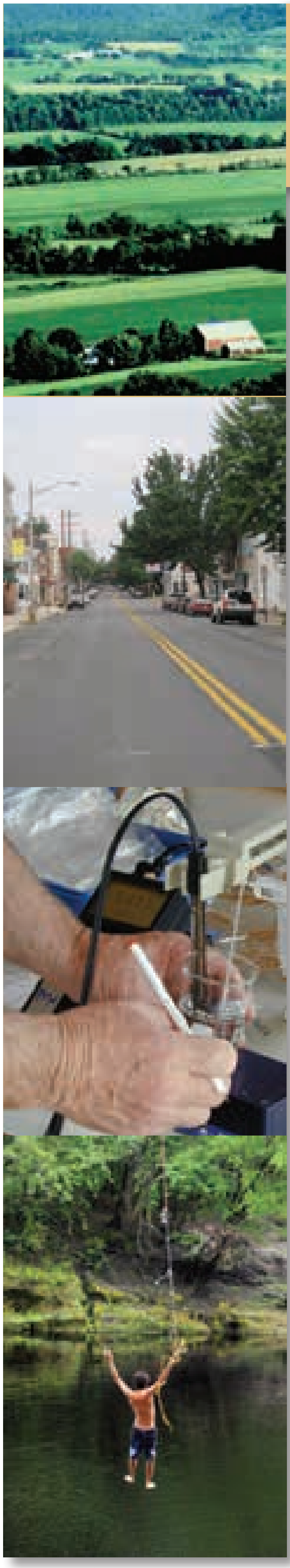
Not to scale

3 Large contributions of nitrate and phosphorus from groundwater to streams have a negative effect on ecological health of estuaries, such as the Chesapeake Bay and Albemarle-Pamlico Sound



About half of the nitrogen delivered by streams to the Chesapeake Bay originates from groundwater, with much of this coming from fertilizer and manure. Groundwater moves slowly; therefore, better management of nitrogen at the land surface may not result in improved stream-water quality for many years and in some cases several decades. In some areas, groundwater contains naturally occurring phosphorus from geologic sources at concentrations that exceed recommended in-stream criteria for phosphorus. Understanding how geologic sources deliver phosphorus to streams could contribute to the ongoing development of nutrient management strategies to limit transport of phosphorus to estuaries. See chapter 8.

Overview of Major Findings and



Photographs from top to bottom:
Albert Becher, USGS; Eliza Gross, USGS;
Joseph Ayotte, USGS; and Alan M. Cressler,
USGS

1 Bedrock geology controls where concentrations of radon, arsenic, and manganese in drinking water are potential human-health concerns

Crystalline rocks are the principal source of high concentrations of radon in groundwater in the Piedmont, Blue Ridge, and Valley and Ridge regions. Radon concentrations in water from nearly one of every four drinking-water wells sampled in the Piedmont and Blue Ridge crystalline-rock aquifers exceeded the limit of 4,000 picocuries per liter (pCi/L) proposed by the U.S. Environmental Protection Agency (USEPA) for public water suppliers,(1) one of the highest rates of exceedance in the Nation.(2, 3)

Siliciclastic rocks and their metamorphic (crystalline) equivalents are the principal source of arsenic and manganese in groundwater. Although concentrations of these trace elements were low in most parts of the study area, arsenic concentrations in groundwater exceeded the Maximum Contaminant Level (MCL) of 10 micrograms per liter (µg/L) set by the USEPA for public water supplies in localized areas of the Piedmont and Blue Ridge crystalline-rock and early Mesozoic basin aquifers (siliciclastic rocks). In these areas, geochemical conditions are such that arsenic is released from the rock into groundwater, and nearly 10 percent of the arsenic concentrations measured exceeded the MCL. Most of the exceedances of the human-health benchmark for manganese were in water from wells in the Valley and Ridge siliciclastic-rock aquifers, where concentrations in 15 percent of samples exceeded the limit of 300 µg/L, one of the highest rates of exceedance in the Nation.

Because geology plays such an important role in controlling where groundwater might contain contaminants from geologic sources at concentrations of potential concern for human health, information such as detailed geologic maps can help local water managers to predict where concentrations might exceed the MCL. Basic measures of water chemistry, such as pH and dissolved oxygen, also can help managers determine where testing for contaminants from geologic sources might be advisable. More than 7 million people in these regions rely on domestic wells for their drinking water, but routine testing of water from domestic wells is not required, and thus homeowners are responsible for the testing, maintenance, or treatment of the water from their domestic wells. The widespread detection of contaminants from geologic sources in domestic wells emphasizes the need for public education aimed at describing probable locations of areas where groundwater might be contaminated and informing the public of available testing and treatment options.

2 A combination of bedrock geology and human activities on the land surface controls where concentrations of bacteria and nitrate in drinking water are potential human-health concerns

Carbonate-rock aquifers are highly susceptible to contamination from human-related sources because they have features such as sinkholes and conduits that allow contaminants to move rapidly from the land surface into the aquifer. The carbonate-rock aquifers commonly are overlain by large flat areas well suited for agricultural and urban development. The human activities associated with these land uses are sources of many contaminants, including bacteria and nitrate. As a result, fecal-indicator bacteria (*Escherichia coli*) were detected in one-half of the drinking-water sources (wells and springs) sampled in the Piedmont and

Implications

Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers, and bacterial contamination was present in all of the aquifers. Concentrations of nitrate in domestic water sources in these same two carbonate-rock aquifers are the highest in the Nation, exceeding the USEPA MCL of 10 milligrams per liter as nitrogen (mg/L as N) in one of every four wells and springs sampled.

Crystalline-rock aquifers, although typically overlain by areas of less intense agricultural activity than the carbonate-rock aquifers, also are susceptible to contamination related to human activities. In areas where agricultural activity in areas overlying the crystalline-rock aquifers was greatest, the median concentration of nitrate in groundwater was 3 times higher than that in nonagricultural areas. Expansion of high-intensity agricultural activities, such as confined animal-feeding operations and increased acreage of corn for biofuels, in areas over both carbonate- and crystalline-rock aquifers is likely to result in higher concentrations of nitrate and bacteria in groundwater.

As agricultural land is converted to suburban development, homeowners and developers are likely to determine that the groundwater is contaminated with nitrate and bacteria associated with the previous use of the land. Continued public outreach and education can increase homeowners' awareness of the need for testing the water in domestic wells and the types of contaminants that are likely to be detected in a given area.

3 Groundwater is a source of nitrate and phosphorus to streams and coastal waters, such as the Chesapeake Bay and Albemarle-Pamlico Sound

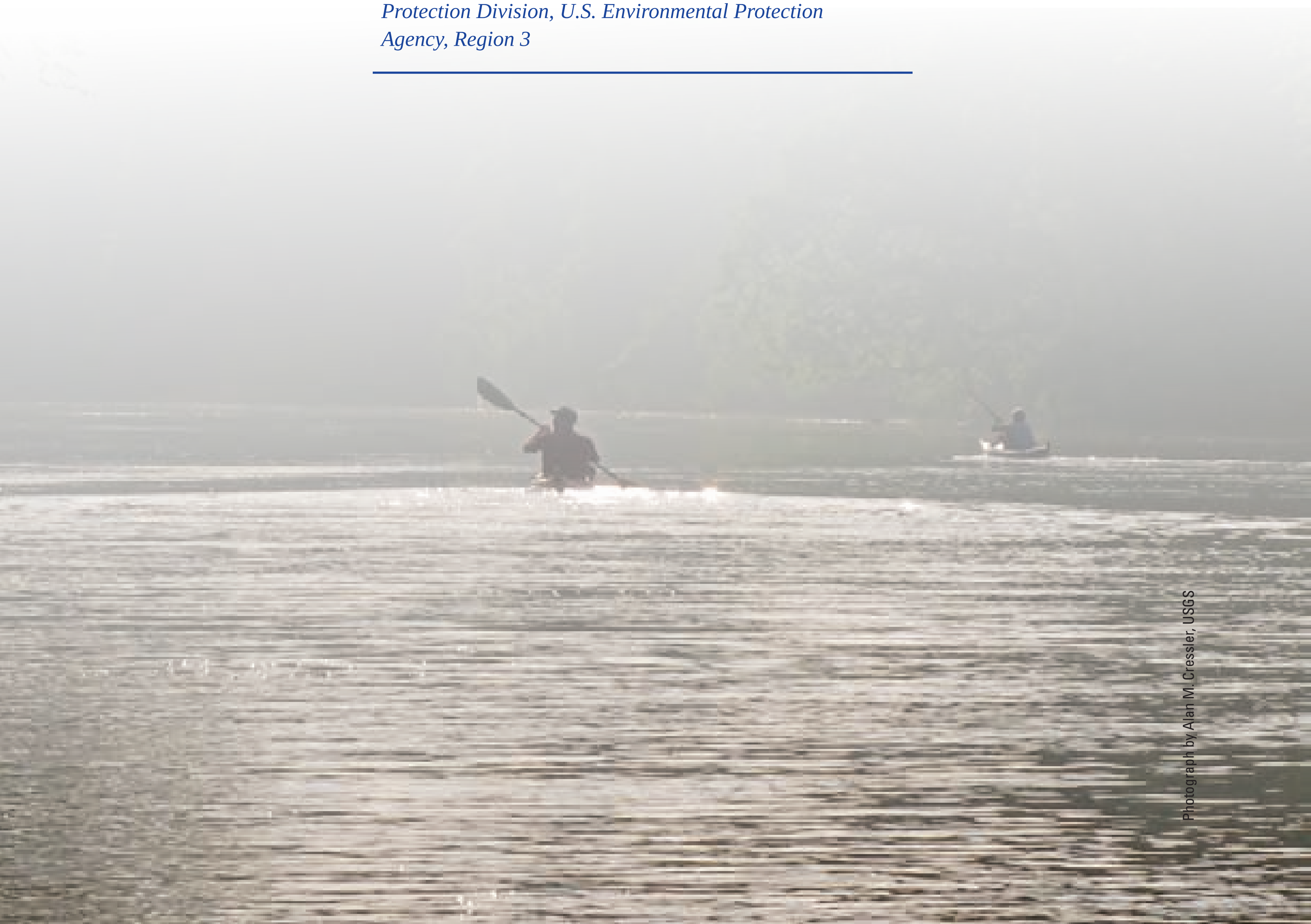
Nitrate and phosphorus both can be transported by groundwater to streams. Where groundwater contains dissolved oxygen, as is common in the carbonate-rock aquifers and some of the crystalline-rock aquifers, nitrate does not break down and moves through the aquifer with the groundwater. The source of most of the nitrate is fertilizer and manure. Phosphorus transport requires that the groundwater contain little or no dissolved oxygen or have a high pH; these conditions are more common in the siliciclastic-rock aquifers and some of the crystalline-rock aquifers. The source of the phosphorus is geologic: it comes from minerals in these aquifers.

About half of the nitrogen delivered by streams to the Chesapeake Bay originates from groundwater. The majority of the streams sampled had nitrate concentrations that exceeded the ecological criteria recommended by the USEPA.(4) Because groundwater moves slowly, decades might be needed for changes in management practices at the land surface to be reflected in the concentrations of nitrate delivered by groundwater to streams. Understanding both the amount of nitrogen delivered by groundwater to streams and the associated lag times is essential to developing realistic expectations for recovery of the water quality in surface-water bodies after implementation of practices aimed at reducing in-stream nitrogen concentrations.

More than 20 percent of the phosphorus in streams draining crystalline- and siliciclastic-rock aquifers is from groundwater. Nearly half of the streams sampled had concentrations of phosphorus that exceeded the ecological criteria recommended by the USEPA.(4) Understanding which streams receive substantial amounts of phosphorus from geologic sources will allow development of more effective strategies to limit transport of phosphorus to streams and estuaries, such as the Chesapeake Bay and the Albemarle-Pamlico Sound.

Photographs from top to bottom: Copyright istockphoto.com; Eliza Gross, USGS; the USGS Photo Library; Alan M. Cressler, USGS

> *"High quality water resources are vital to the health and environmental and economic sustainability of our communities. NAWQA studies help to inform the EPA's Water Protection Division to reduce threats to our water supplies today and to protect our groundwater resources for the future."*
>
> *Victoria Binetti, Associate Division Director, Water Protection Division, U.S. Environmental Protection Agency, Region 3*



Photograph by Alan M. Cressler, USGS

Chapter 2: *NAWQA Approach to Assessing Water Quality in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge Regions*

This chapter summarizes the study design used to investigate water quality in Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions.

The Piedmont, Blue Ridge, and Valley and Ridge regions cover a large and diverse geographic area. These three physiographic provinces are subdivided by bedrock type to form five Principal Aquifers in these regions, and thus these Principal Aquifers form a natural framework for a study of groundwater quality (table 2–1). Agricultural and urban land uses are human activities that influence groundwater quality and thus also are important considerations in study design. Groundwater studies therefore are grouped by Principal Aquifer and by land use. This grouping allows for a comprehensive assessment of water quality in the regions that addresses broad questions about the occurrence, fate, and transport of contaminants in aquifers and the resulting quality of the water that is used for human consumption or that discharges to nearby surface-water bodies.

Most groundwater samples were collected from domestic-supply wells in the Piedmont, Blue Ridge, and Valley and Ridge regions. Additionally, some groundwater samples were obtained from springs, monitoring wells, and public-supply wells.

Assessing Water Quality in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge Regions

Some studies focused on the effects of specific land uses—such as agricultural or urban—on the quality of groundwater, whereas others characterized the quality of groundwater used as a drinking-water supply.

How does one go about characterizing the groundwater over an area as large as the 10 states covered by the Piedmont, Blue Ridge, and Valley and Ridge regions, let alone the whole United States? The approach taken by the U.S. Geological Survey (USGS) NAWQA Program is to use regional 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. Each of the many studies of each Principal Aquifer focused on different information needs about groundwater quality and the natural and human-related factors that influence it (fig. 2–1; tables 2–1 and 2–2; appendix 1, table A–1). Groundwater studies were designed to answer the following questions: How does land use affect groundwater quality? How does water quality change as it moves through the aquifer? What is the quality of the drinking-water resource?

Each study sampled a group of 20 to 30 wells and, in some cases, springs. Some of these groundwater studies were designed to assess the quality of water in aquifers that are the most important present and future groundwater resources for drinking-water supply and included samples from randomly located domestic (private) and public-supply wells. Wells were chosen without targeting a specific land use, and land use was mixed in the areas around these wells (see sidebar, What types of wells were sampled, and how might the choice of sites affect water quality?, p. 12). Agricultural and urban land-use studies were designed to characterize and explain the quality of recently recharged groundwater (generally less than 10 years old)(5) in these land-use settings. The agricultural land-use studies sampled mostly domestic wells and thus determined the quality of drinking water in agricultural areas. The urban land-use studies sampled mostly shallow monitoring wells that were installed as part of the NAWQA Program. The results of the land-use studies were used 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 similar settings in the future. Land-use studies also can provide an indication of recent changes in water quality related to changes in chemical use.

This report assesses water quality in five Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions. These Principal Aquifers are defined by grouping or splitting the three physiographic provinces on the basis of three major bedrock types—crystalline, siliciclastic, or carbonate. Grouping the Piedmont and Blue Ridge Physiographic Provinces and then splitting by bedrock type defines the Piedmont and Blue Ridge crystalline-rock aquifers, the Piedmont and Blue Ridge carbonate-rock aquifers, and the early Mesozoic basin aquifers (mostly siliciclastic bedrock); the latter group of aquifers is the exception because it does not include the rock type and province in its name. Splitting the Valley and Ridge Physiographic Province by bedrock type defines the Valley and Ridge siliciclastic-rock aquifers and the Valley and Ridge carbonate-rock aquifers. The names are all plural—aquifers—because, rather than representing a single contiguous aquifer, they represent a number of disconnected aquifers with common characteristics such as bedrock and physiography.

The bedrock types of the Principal Aquifers have a substantial effect on water quality and were used to group the study results for analysis. Within the five Principal Aquifers, the results are grouped as those that characterize the quality of groundwater used as a drinking-water supply in areas with mixed land use, those that characterize the quality of groundwater used as a drinking-water supply in agricultural areas, and those that characterize the quality of shallow (recently recharged) groundwater in urban areas (table 2–1).

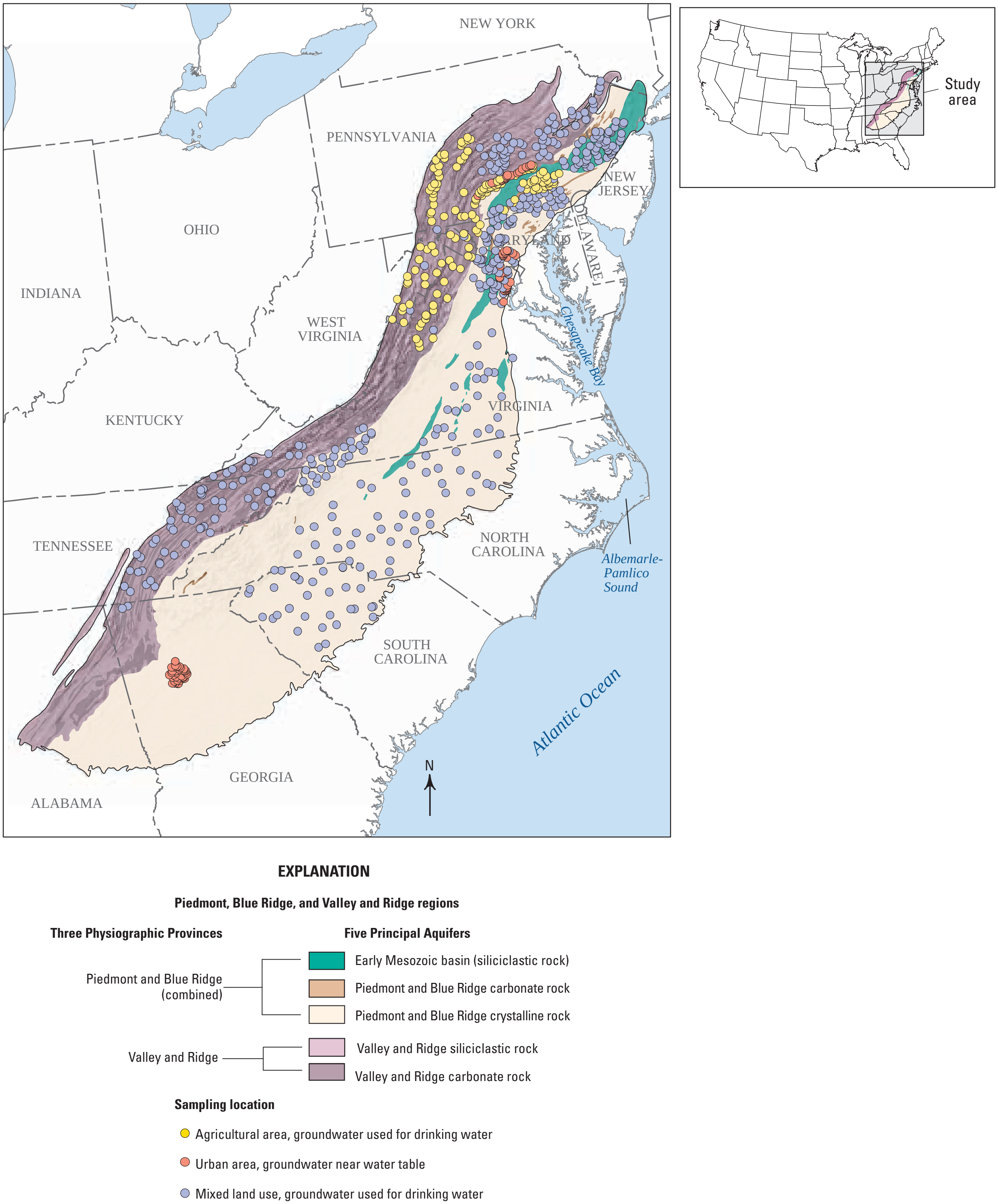


Figure 2–1. For this assessment, 642 wells and springs were sampled. Physiographic provinces and aquifer names established the framework for the study of this region. The sampling design focused on characterizing the quality of groundwater used for drinking water in areas with mixed land use, from domestic wells in areas of agricultural land use, and near the water table underlying urban areas.

Table 2–1. Characteristics of groundwater studies in the Piedmont, Blue Ridge, and Valley and Ridge regions.

Land and water use	Mixed land-use—Groundwater used for drinking water	Agricultural area—Groundwater used for drinking water	Urban area—Groundwater near water table
Objective of study	Assess quality of water in aquifers that are the most important present and future groundwater resources for drinking-water supply in mixed land-use areas	Assess quality of recently recharged water in aquifers used for drinking-water supply in agricultural land-use settings	Assess quality of recently recharged, shallow groundwater in urban land-use settings
Predominant use of water from sampling site	Domestic or public	Domestic	Unused monitoring well

Table 2–2. Numbers of sites by study grouping and Principal Aquifer.

[A single sample from each site was used to evaluate water quality. The suffix “a” indicates that the total number of sites includes springs]

	Number of sites sampled, by Principal Aquifer			
Name of aquifer	Mixed land use—Groundwater used for drinking water	Agricultural area—Groundwater used for drinking water	Urban area—Groundwater near water table	Total for aquifer
Piedmont and Blue Ridge crystalline-rock aquifers	178	24	70a	272
Early Mesozoic basin aquifers (Piedmont and Blue Ridge siliciclastic-rock)	74	0	0	74
Valley and Ridge siliciclastic-rock aquifers	62	25	0	87
Piedmont and Blue Ridge carbonate-rock aquifer	0	30	0	30
Valley and Ridge carbonate-rock aquifers	67a	92	20	179
	381	171	90	642

Aquifer (aq.ui.fer) —ăk'wə-fər

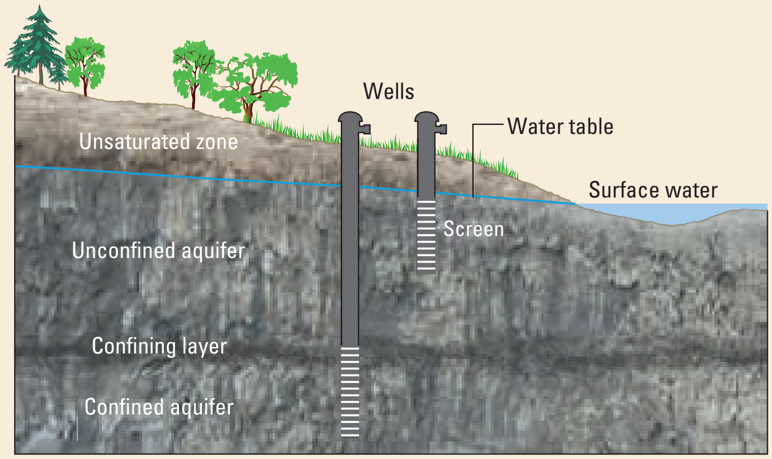
An underground layer of saturated permeable materials (rock, gravel, sand, or silt) that will yield a useful quantity of water to a well.

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.

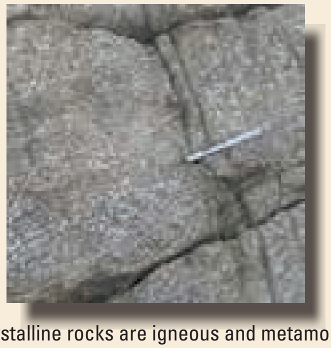
Wells in this report were completed in one of three types of bedrock, shown below. Water flows through the fractures in the bedrock and into the well.



Bedrock type and aquifer names

crystalline rock

Piedmont and Blue Ridge crystalline-rock aquifers



Crystalline rocks are igneous and metamorphic rocks that include granitic rocks (shown above) along with many other lithologic types.

siliciclastic rock

Early Mesozoic basin aquifers (mostly siliciclastic, some crystalline)

Valley and Ridge siliciclastic-rock aquifers

Siliciclastic rocks are sedimentary rocks that include shale and sandstone (shown above).

carbonate rock

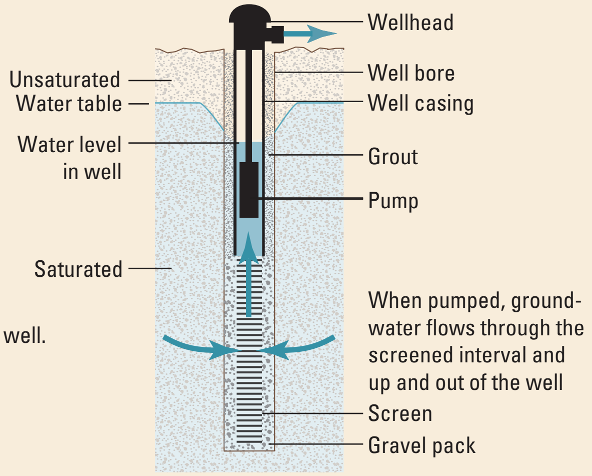
Piedmont and Blue Ridge carbonate-rock aquifers

Valley and Ridge carbonate-rock aquifers

Carbonate rocks include limestone (shown above) and dolomite.

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.



What types of sites were sampled, and how might the choice of sites affect water quality?

Two types of wells were sampled: drinking-water wells and monitoring wells. The drinking-water wells included domestic (private) wells and public-supply wells. Domestic wells usually 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. These wells commonly are installed in rural areas and so are more likely than public-supply wells to be vulnerable to contamination from agricultural chemicals. Public-supply wells pump water from deeper in the aquifer and commonly are installed in suburban and urban areas and so are more likely than domestic 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 wells and are operated for longer periods of time. As a result, public-supply wells pump much larger volumes of water than do domestic wells and thus draw in water from a much larger area. Therefore, public-supply wells are more vulnerable than domestic wells to manmade contamination from distant sources. If the amount of water withdrawn is large enough, a public-supply well can change the flow direction and velocity of the groundwater, which can, in turn, affect the groundwater geochemistry and the constituents contained within the groundwater. Routine testing of water from domestic wells is not required, and homeowners are responsible for testing, maintenance, or treatment of the water from their domestic well. Water from public-supply wells is required to be tested by the well operator on a routine basis to assure that the water provided to consumers meets Federal and State water-quality standards.

Monitoring wells sampled in the NAWQA groundwater studies were installed solely for assessing water quality. Monitoring wells are not pumped regularly—they are used for the measurement of water levels or occasionally the collection of water samples, but are not used for drinking water, irrigation, or other purposes.

Springs were sampled in some areas to represent shallow groundwater quality, and in other areas to represent groundwater used as a source of domestic or public supply. Springs, although often improved for human use, are natural discharge points for groundwater. The area contributing recharge to a spring can be very large, and in karst areas (see sidebar, Karst features make carbonate-rock aquifers highly susceptible to contamination, p. 29) might not reflect chemical characteristics of the land use immediately surrounding the spring. The volume of discharge from a spring is a general indicator of whether it represents recharge from a relatively small area or integrates water recharged over a larger area. Springs can be difficult to protect from surface contaminants such as bacteria.

Photograph by Eliza Gross, USGS

Photograph by Connie Loper, USGS

Groundwater-Quality Assessment Design

Water from 82 percent of the wells and springs in this study was a source of drinking water, and the depth ranges of wells generally were similar.

A major goal of the NAWQA Program was to assess the quality of water in aquifers that are the most important present and future groundwater resources used for drinking-water supply. Wells used for drinking water were sampled to assess this groundwater resource, and because no specific land use was targeted, these wells are in areas with a mix of land uses types. One sample was analyzed from each of 381 randomly selected wells and springs used in 16 different NAWQA studies—269 domestic wells, 36 public-supply wells, 41 other well types, and 35 springs (mixed land use, groundwater used for drinking-water supply; table 2–2). The water was sampled prior to any onsite treatment rather than at the tap, but in most cases households had no treatment system, so the quality of the water sampled and the quality of the water consumed by the homeowner were essentially the same. The wells are distributed across much of the area overlying the aquifer, but, because the wells are only in NAWQA groundwater-study areas, groundwater in some parts of the Piedmont, Blue Ridge, and Valley and Ridge regions is not represented (fig. 2–1). The type of well selected for each study may have an effect on the quality of water from those wells (appendix 2).

To assess the quality of recent groundwater recharge in areas of agricultural land use, groundwater samples were collected from 168 domestic wells, 2 stock wells, and 1 well supplying an institution (agricultural area, groundwater used for drinking-water supply; fig. 2–1; table 2–1). These agricultural land-use studies are unique in the NAWQA Program because, although monitoring wells typically were used by the NAWQA Program to assess recently recharged water, the relatively rapid movement of groundwater in this area allows samples from domestic wells to represent recently recharged water. Thus, the quality of water from these wells represents both recently recharged water and the resource used as a household drinking-water supply. The primary agricultural setting of the Piedmont, Blue Ridge, and Valley and Ridge regions is row crops, hay, and pasture, and most crops are grown without irrigation. Corn, a fertilizer- and pesticide-intensive crop, is the predominant crop. Concentrated animal-feeding operations for dairy cattle, hogs, and chickens are common.

To assess the quality of recent groundwater recharge in urban areas, 90 groundwater samples were collected from 50 shallow monitoring wells, 10 domestic wells, 11 other well types, and 19 springs (urban area, groundwater near water table; fig. 2–1; table 2–2). The urban land-use settings in the areas where samples were collected were similar to the settings where many Americans work and live—residential and commercial development either in established urban areas or recently developed suburbs. The suburbs are the most rapidly changing areas near the cities throughout the eastern United States, where land that previously was agricultural or forested is being converted to urban land uses. Wells usually were not available for sampling in this area, and so shallow monitoring wells were installed for this study. The domestic and other types of wells that were sampled most often were shallow, like the monitoring wells. Thus, the wells in the urban area most often tapped water that is just below the water table and not used directly as a drinking-water supply, but which is expected to move down into deeper parts of the aquifers that are used for drinking-water supply. The water quality of these samples is an indication of how the chemicals used in day-to-day life—pesticides, solvents, gasoline—might affect the quality of a future drinking-water resource.

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 186 constituents and properties measured for the Principal Aquifer assessments. 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(24) (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 51 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(48, 58, 59) (values used in this report were current as of February 2012; see *http://water.usgs.gov/nawqa/HBSL*). An HBSL was available for 72 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.(71)

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;(60) New Jersey Department of Environmental Protection(76)).

Screening-level assessments such as this one provide perspective on the potential significance of detected contaminants to human health and can help in planning future studies.(59) 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 Joseph Ayotte, USGS

Concentrations of constituents measured for this assessment were compared to human-health benchmarks.

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 focused 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 feasible. 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. 14). Low-level detections allow scientists to identify and evaluate emerging issues and to track contaminant levels over time.

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)	Iron and manganese
Radionuclides	Radon, 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
Trace elements (filtered)	Arsenic, boron, selenium
Radionuclides	Radium, alpha activity
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 the 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 Piedmont, Blue Ridge, and Valley and Ridge regions have diverse natural and manmade features, from pristine mountainous forested areas, to broad agricultural valleys, to large cities and sprawling suburbs. Unseen beneath the landscapes is a variety of types of bedrock. These bedrock types directly affect water quality, but also influence the landforms themselves and human activities on the surface. To evaluate groundwater resources of this region, it is essential to understand how both the natural features of the region and human activities on the land surface affect water quality.

This chapter summarizes background information for the Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions and provides the context for understanding findings about water quality in these Principal Aquifers. The chapter covers the environmental and hydrogeologic setting, including population, land use, and water use.

Photograph by Eliza Gross, USGS

Imagery from Pictometry™ International Corporation

Environmental Setting

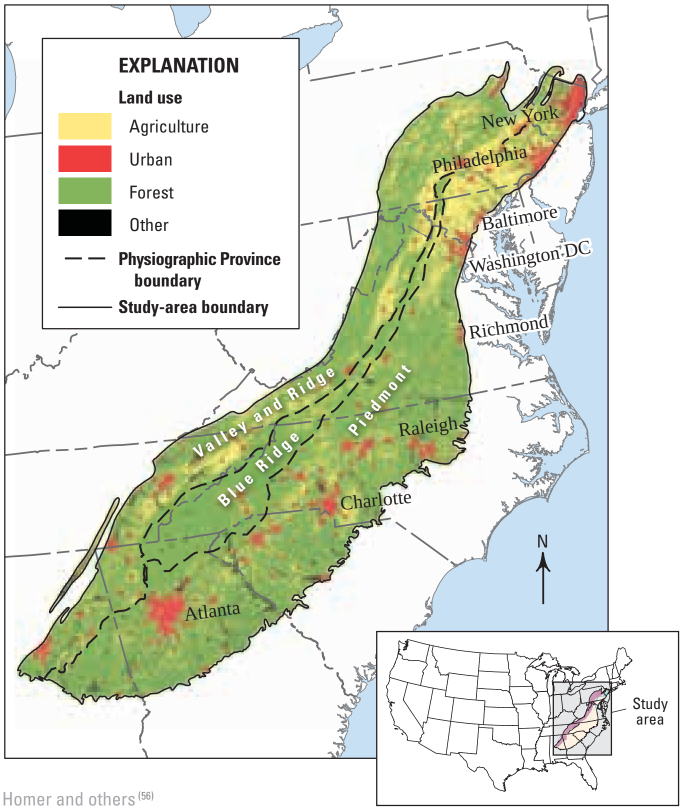
The Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions extend from Alabama northward to New York, covering 149,000 square miles. The five Principal Aquifers in this area(6) (fig. 2–1) generally correspond to the locations of the physiographic provinces with the same names, except that the early Mesozoic basin aquifers lie within the Piedmont Physiographic Province.(7)

The topography of the Piedmont generally reflects the underlying geology. Rolling hills and ridges are in areas underlain by the rocks most resistant to erosion, such as granite or sandstone. Flat lowlands are more common in areas underlain by more easily erodible rocks such as shale or carbonate rocks. The main topographic feature of the Blue Ridge is a long linear ridge that runs north and south and is underlain by crystalline rocks similar to those in the Piedmont. The topography of the Valley and Ridge also is characterized by long linear features—the valleys and ridges that give the province its name—and as in the Piedmont, the landforms reflect the underlying rocks. Relief ranges from about 4,000 feet in Virginia to nearly 1,000 feet in Alabama. Topography is important for groundwater quality because it affects the time taken and distance traveled by groundwater as it moves from the land surface through the aquifer, ultimately to discharge to streams.(8)

The climate of the region is humid and temperate, with average annual precipitation in the range of 40 to 60 inches. Precipitation is greater at higher elevations, and the temperatures are much warmer in the south than in the north. Recharge to the aquifers is highest in areas with the greatest precipitation and lowest temperatures.(8)

Land Use and Population Distribution Affect the Distribution of Potential Contaminants

The Piedmont, Blue Ridge, and Valley and Ridge regions are overlain by three predominant land uses. The land use overlying the largest area of all five aquifers combined is forest (fig. 3–1; table 3–1), and agricultural and urban land uses are the second and third largest land-use types. The distribution of these land-use types on the landscape affects water quality. For example, agricultural land uses are associated with sources of contaminants such as nutrients (9) and pesticides,(10) and urban land uses are associated with sources of contaminants such as pesticides and volatile organic compounds (VOCs). Large tracts of developed (agricultural or urban) land are more likely to have an adverse effect on water quality than areas where land is mostly undeveloped, such as forests.



Homer and others (56)

Figure 3–1. The most densely populated areas are in the Piedmont near New York, New York, Philadelphia, Pennsylvania, Baltimore, Maryland, Washington, DC, Charlotte, North Carolina, Raleigh, North Carolina, Richmond, Virginia, and Atlanta, Georgia. Population density is lower in more rural agricultural and forested areas in the Blue Ridge and the Valley and Ridge. Urban and agricultural land uses are potential sources of nitrate, pesticides, and volatile organic compounds in groundwater.

Table 3–1. The Piedmont, Blue Ridge, and Valley and Ridge regions in the early 2000s were predominantly forested.(56) Although agricultural and urban areas cover a smaller percentage of the land area than does forested land, contaminants associated with agricultural and urban practices, such as nitrate, pesticides, and volatile organic compounds, are important water-quality issues.

Principal Aquifer	Percentage of land use			
	Agricultural	Forested	Urban	Other
Piedmont and Blue Ridge crystalline-rock aquifers	19	71	6	4
Early Mesozoic basin aquifers	35	42	21	3
Valley and Ridge siliciclastic-rock aquifers	21	73	4	3
Piedmont and Blue Ridge carbonate-rock aquifers	52	29	16	2
Valley and Ridge carbonate-rock aquifers	37	53	7	3
All aquifers	22	68	7	3

Land use (fig. 3–1) and population are closely related. Most of the population in the study area resides in the part of the Piedmont that overlies the crystalline- and carbonate-rock aquifers—about 24 million in 2005 (fig. 3–2). Rapidly growing metropolitan and suburban areas around some large northeastern cities are in the Piedmont, although the cities themselves (Philadelphia, Baltimore, Richmond, and Washington, D.C.) are not. In the Southeast, large cities such as Atlanta, Charlotte, and Raleigh are completely within the Piedmont. Many of the suburban areas around these cities rely on groundwater, although large cities themselves use surface water as a source of supply. The population of the part of the Piedmont overlying the early Mesozoic basin aquifers is nearly 9 million, making this the most densely populated area overlying any of the five aquifers. The population of the Valley and Ridge (overlying both the carbonate- and siliciclastic-rock aquifers) is 5 million.(11)

The size of the rural population is important with respect to water use and water supply. Six of the 10 states with the largest rural populations in the Nation are in the Piedmont, Blue Ridge, and Valley and Ridge regions: Pennsylvania, North Carolina, Georgia, Tennessee, Alabama, and Virginia.(12) As a result, a large number of people living in areas of rural activities such as agriculture also rely on groundwater as a source of water for domestic supply.

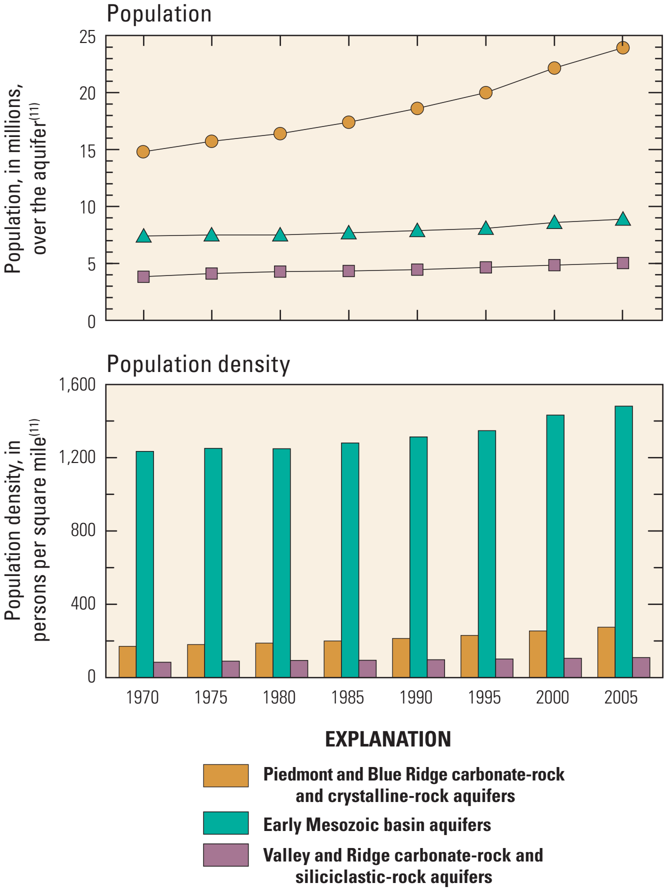


Figure 3–2. Total population and the rate of population growth are greatest in the area overlying the Piedmont and Blue Ridge crystalline- and carbonate-rock aquifers, whereas population density is greatest in the area overlying the early Mesozoic basin aquifers. Population growth creates an increasing demand for high-quality groundwater.

Water Use is Predominantly for Domestic and Public Supply

The total rate of water withdrawals from the five Principal Aquifers combined is 1.2 billion gallons per day, with about 1 billion gallons per day for domestic and public supply alone (fig. 3–3).(13) More people in these regions rely on groundwater for domestic supply than in the entire U.S. west of the Mississippi River.(14) The Piedmont and Blue Ridge crystalline- and carbonate-rock aquifers (combined) rank as the second highest in the Nation for domestic water-supply use, with the Valley and Ridge siliciclastic- and carbonate-rock aquifers (combined) and the early Mesozoic basin aquifers ranking seventh and ninth in the Nation, respectively. The early Mesozoic basin aquifers have lower total water-use volumes, but cover a smaller area with a higher population density; as a result, the groundwater resources in this area are critical for water supply. Water intended for domestic and public supply requires a high level of quality.

More than 7 million people in the Piedmont, Blue Ridge, and Valley and Ridge regions live in rural areas and rely on groundwater as a source of domestic supply (fig. 3–4). The States of Pennsylvania and North Carolina rank third and fourth in the Nation for the number of people that rely on domestic wells as a source of supply, and Virginia is among the top 10.(14) Routine testing of water from domestic wells is not required, and thus homeowners are responsible for testing, maintenance, and treatment of the water from their domestic well.

> *More people rely on groundwater for domestic supply in the Piedmont, Blue Ridge, and Valley and Ridge regions than in the entire United States west of the Mississippi River.*

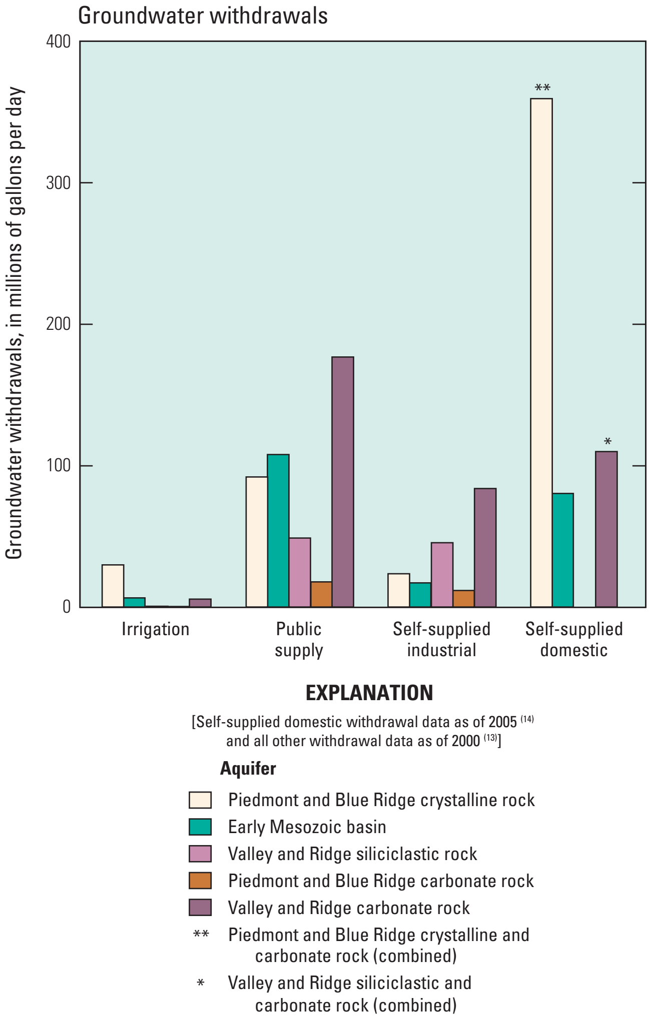
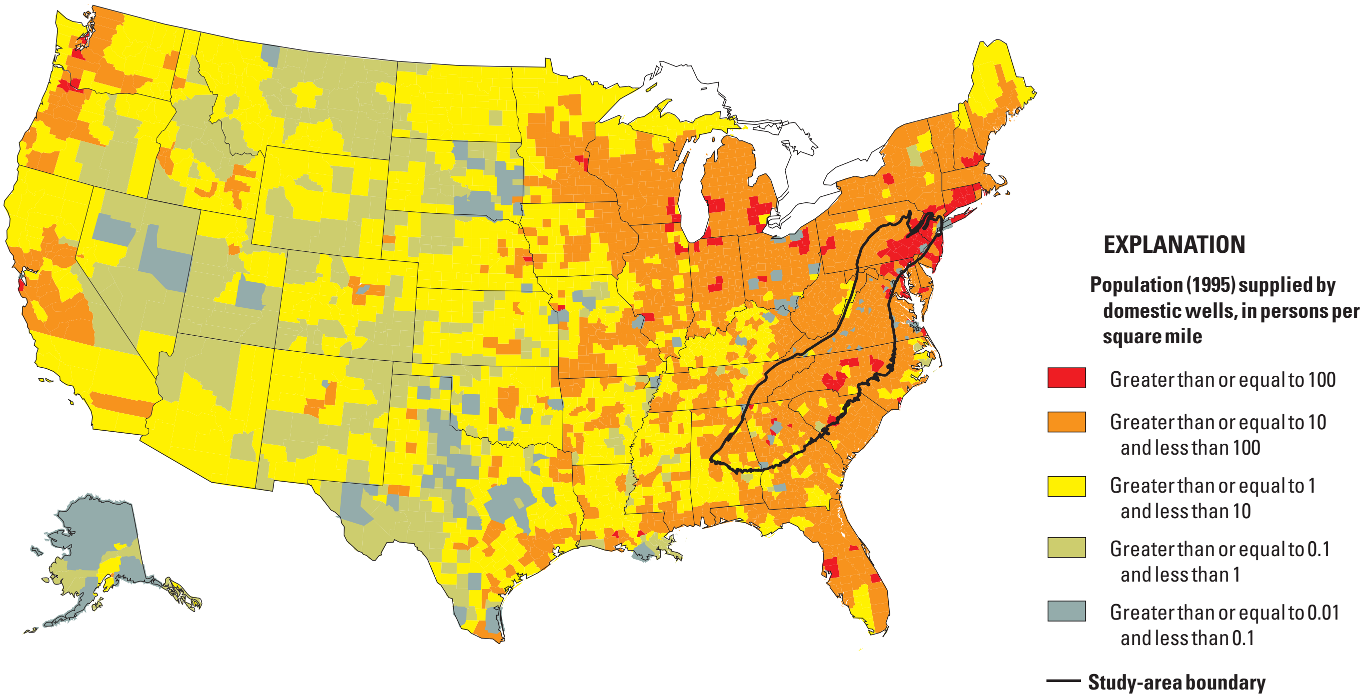


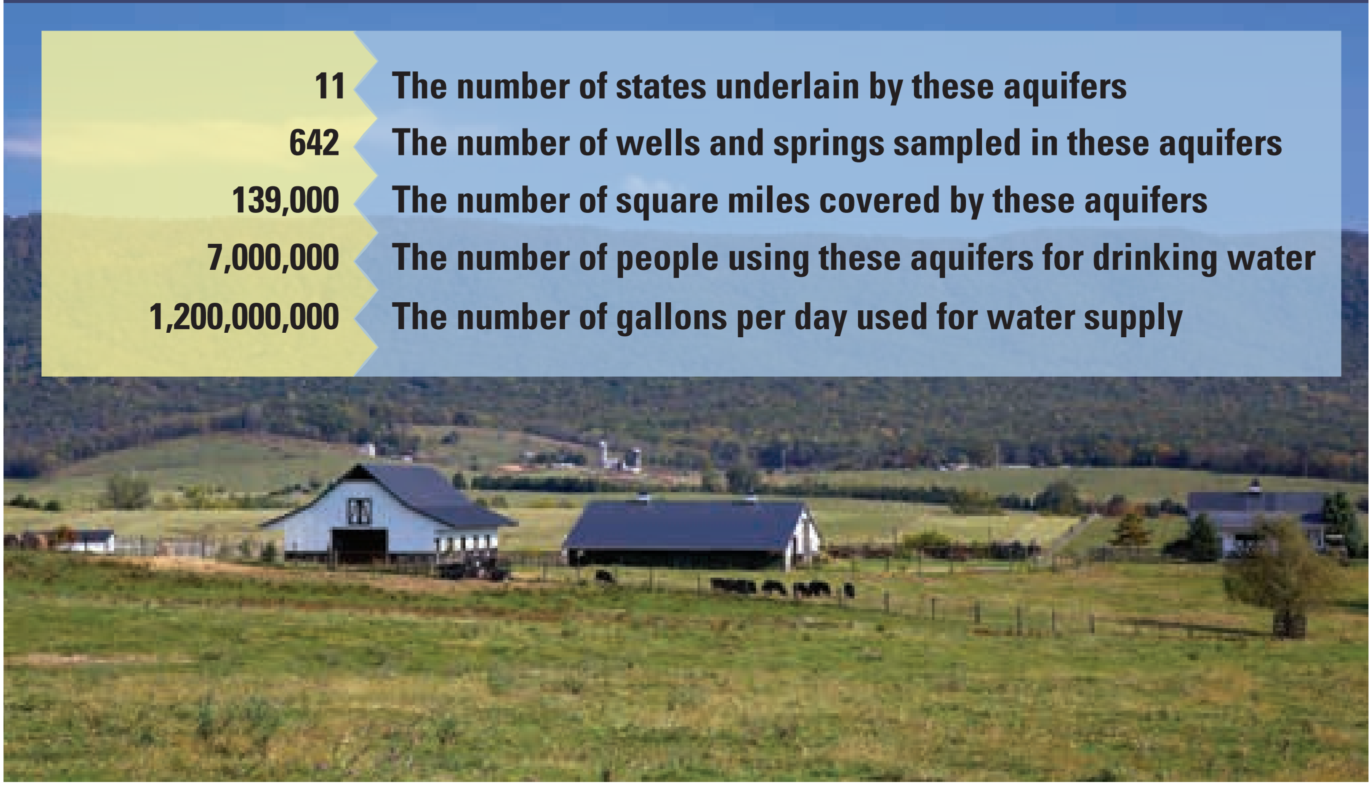
Figure 3–3. Public and domestic water supplies are the primary uses of groundwater from the Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions.(13, 14) Piedmont and Blue Ridge crystalline- and carbonate-rock aquifers (combined) rank as the second highest in the Nation for domestic water-supply use.



Modified from DeSimone[25]

Figure 3–4. The number of people per square mile who rely on domestic wells for a source of household supply is high in the Piedmont, Blue Ridge, and Valley and Ridge regions relative to other parts of the country. Routine testing of water from domestic wells is not required.

Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions at a glance



11	The number of states underlain by these aquifers
642	The number of wells and springs sampled in these aquifers
139,000	The number of square miles covered by these aquifers
7,000,000	The number of people using these aquifers for drinking water
1,200,000,000	The number of gallons per day used for water supply

Photograph by John H. Bowman

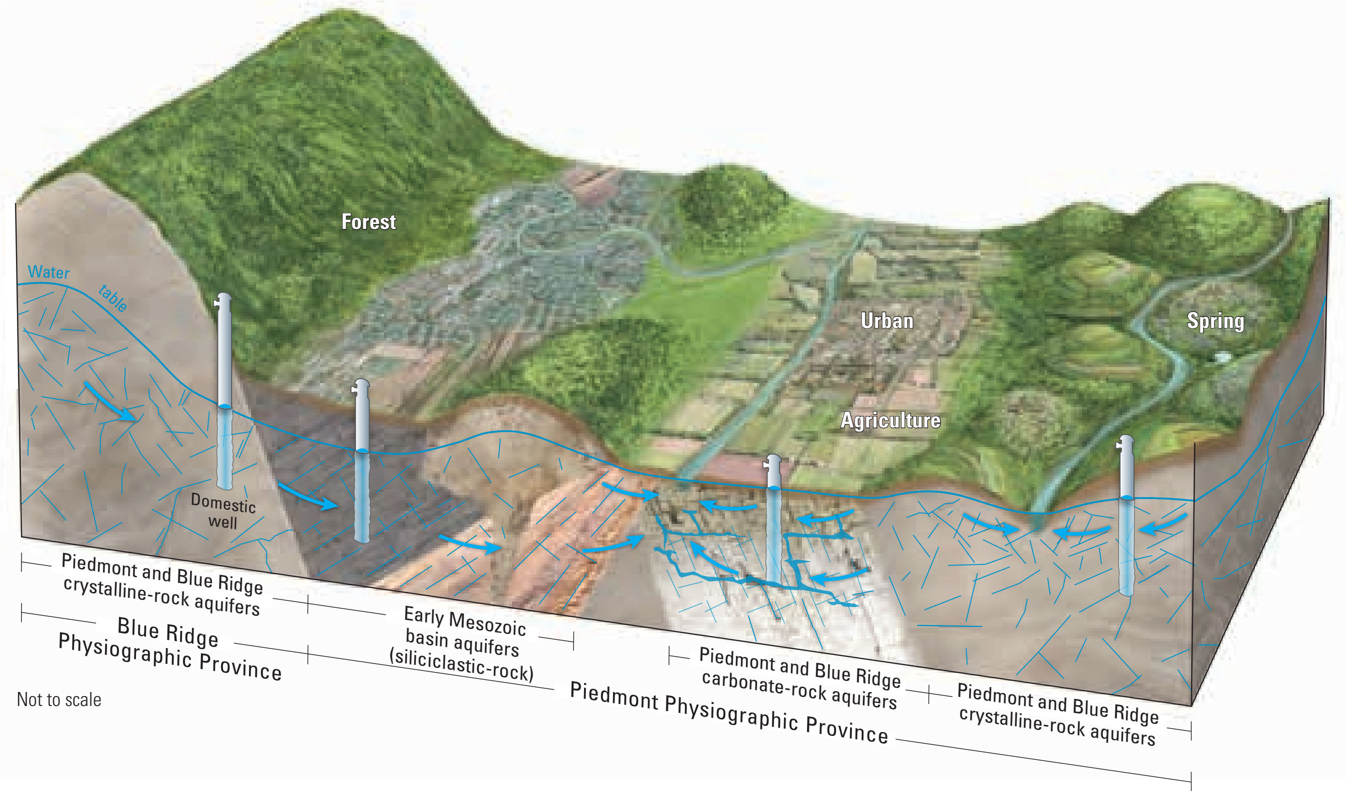


Figure 3–5. Areas with steep slopes, such as the Blue Ridge, are largely forested, whereas the flatter areas of the Piedmont are overlain by more agricultural and urban land. Groundwater flows through relatively small fractures in the Piedmont and Blue Ridge crystalline-rock aquifers and in the early Mesozoic basin aquifers. In the Piedmont and Blue Ridge carbonate-rock aquifers, however, water can enter the aquifer from the land surface through sinkholes and flow through enlarged fractures and conduits that develop in the carbonate rock. This hypothetical cross-section is based on the northern Piedmont. A cross-section of the southern Piedmont(67) illustrates an example of where the the carbonate-rock aquifers and early Mesozoic basin aquifers cover a small percentage of the overall area or are not present.

Hydrogeologic Setting Accounts for Many Differences in Water Quality

The ease with which water and contaminants move into and through an aquifer—called the intrinsic susceptibility—is influenced by aquifer properties, such as the size and connections of fractures in the bedrock, the amount and timing of recharge, and the time and distance over which the water is in contact with the aquifer. These characteristics vary by aquifer and bedrock type. In addition, bedrock type affects landforms (such as steep or flat terrain), which in turn affect recharge area and land use overlying the aquifers.

Characteristics of Aquifers in the Piedmont and Blue Ridge Physiographic Provinces

Piedmont and Blue Ridge Crystalline-Rock Aquifers

Groundwater in the Piedmont and Blue Ridge crystalline-rock aquifers moves through a network of well-connected fractures. In general, the water travels only a short distance before it discharges to the nearest stream (fig. 3–5); groundwater age—the time the water has spent in the aquifer—was less than 60 years in all of the wells in this area. In wells where groundwater ages were determined, about half of the ages were less than 20 years, and the other half of the ages were between 20 and 60 years (see chapter 4). Because of the short travel distances and young groundwater ages, human activities near a well are likely to have a substantial effect on the quality of water withdrawn from that well. Although much of the area overlying these aquifers is forested, a mix of urban and agricultural land that overlies some parts of the aquifers provides sources of human-related contaminants.

Piedmont and Blue Ridge Carbonate-Rock Aquifers

The Piedmont and Blue Ridge carbonate-rock aquifers are karst aquifers (see sidebar, Karst features make carbonate-rock aquifers highly susceptible to contamination, p. 29), which are more susceptible to contamination than are crystalline- or siliciclastic-rock aquifers. The term karst means that water moving through the aquifer has dissolved away

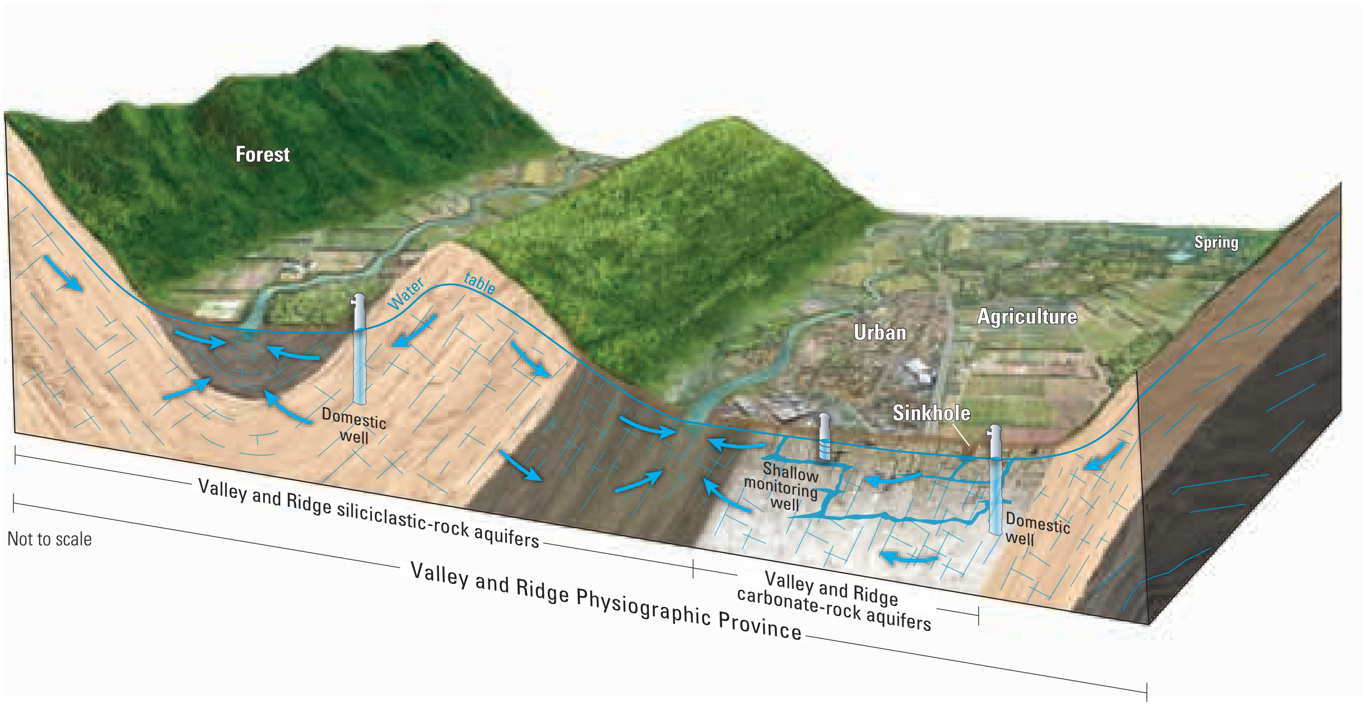


Figure 3–6. Land use overlying the Valley and Ridge siliciclastic-rock aquifers is a mix of forest and agriculture in the valleys and forest on the ridges. Water in the siliciclastic-rock aquifers flows through narrow fractures at slower rates than the rates of flow in the larger conduits of the carbonate-rock aquifers. A large percentage of the land in the areas overlying the Valley and Ridge carbonate-rock aquifers is used for agriculture. The largest urban centers overlie the Valley and Ridge carbonate-rock aquifers as well. The carbonate-rock aquifers have sinkholes, enlarged fractures, conduits, and other karst features that allow rapid transport of water and contaminants into and through the aquifers.

some of the rock, enlarging fractures in the bedrock into voids or conduits. Contaminants can move rapidly into and through these aquifers by way of the voids and conduits. No groundwater ages were determined for this aquifer, but it is similar to the Valley and Ridge carbonate-rock aquifers, in which about 75 percent of the wells had groundwater ages of less than 20 years and the other 25 percent between 20 and 60 years (see chapter 4). Unlike the other fractured-rock aquifers, the youngest groundwater ages are known to be on the order of a few days because of the rapid transport of water through the conduits in the bedrock. The land surface in this area is generally flat (fig. 3–5), increasing infiltration of water and contaminants. This area has the highest percentage of agricultural land use (52 percent) and the lowest percentage of forested land use (29 percent) of any of the aquifers, and agricultural chemicals are the main potential contaminants.

Early Mesozoic Basin Aquifers

The early Mesozoic basin aquifers mainly consist of siliciclastic rocks but also include minor amounts of crystalline rocks (fig. 3–5). Sandstone and shale are the major bedrock types. The terrain ranges from flat to hilly. This area has the highest percentage of urban land use (21 percent) compared to the other aquifers, giving these aquifers a greater potential source of urban contaminants. In wells where groundwater ages were determined, about half of the ages were less than 20 years, and the other half of the ages were between 20 and 60 years (see chapter 4). Areas in North Carolina known as the Durham-Sanford basins are siliciclastic-rock aquifers(8) that do not appear on figure 2–1, but these areas were not sampled as a part of the early Mesozoic basin aquifers.

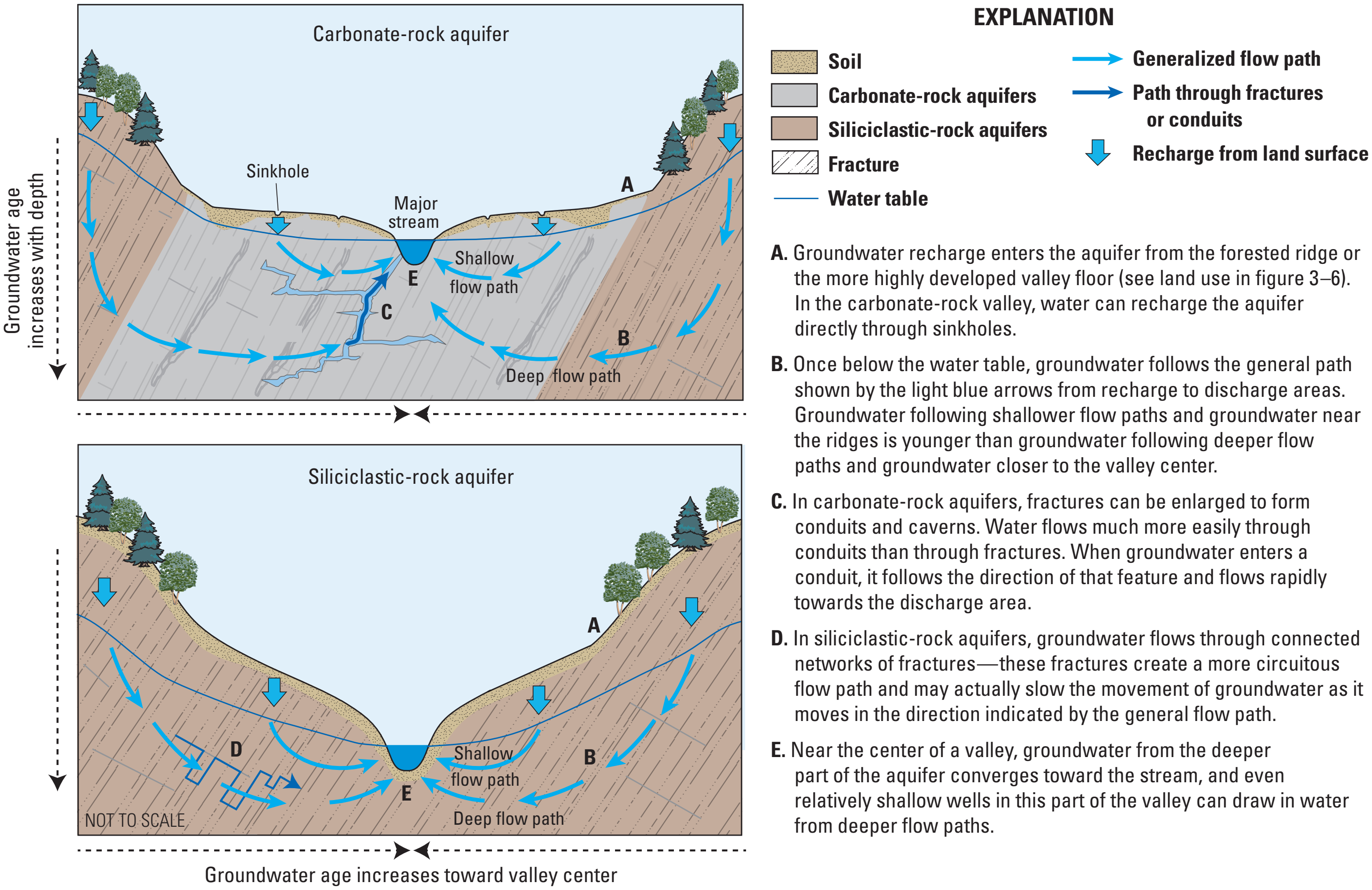
Characteristics of Aquifers in the Valley and Ridge Physiographic Province

Valley and Ridge Carbonate-Rock Aquifers

The Valley and Ridge carbonate-rock aquifers also are karst aquifers. The carbonate-rock aquifers typically are in a valley floor and are overlain by flat terrain. Groundwater generally flows from the adjacent ridges toward the valley center (figs. 3–6, 3–7), but because of the influence of geologic structures and karst conduits, the actual path followed by water is hard to predict. Water that moves through the fractures dissolves away some of the rock, enlarging the fractures into karst features such as sinkholes and conduits. In wells where groundwater ages were determined for the Valley and Ridge carbonate-rock aquifers, about 75 percent of the ages were less than 20 years, and the other 25 percent were between 20 and 60 years (see chapter 4). The youngest groundwater ages are known to be on the order of a few days because of the rapid transport of water through the conduits in the bedrock (see sidebar, Karst features make carbonate-rock aquifers highly susceptible to contamination, p. 29). A high percentage of the land overlying these aquifers is agricultural (37 percent), second only to the agricultural land overlying the Piedmont and Blue Ridge carbonate-rock aquifers, and provides a large potential source of agricultural chemicals.

Valley and Ridge Siliciclastic-Rock Aquifers

In the Valley and Ridge siliciclastic-rock aquifers, fractures are not enlarged by dissolution as they are in the carbonate-rock aquifers. The siliciclastic-rock aquifers therefore generally contain older water and are less susceptible to surface contamination than are the carbonate-rock aquifers. In wells where groundwater ages were determined, about two thirds of the ages were less than 20 years, and ages in the other third were between 20 and 60 years (see chapter 4). Sandstone is resistant to weathering and forms ridges that are nearly always forested. The valleys between the ridges typically are underlain by a more easily eroded bedrock type such as shale (figs. 3–6, 3–7). Among the five Principal Aquifers, the Valley and Ridge siliciclastic-rock aquifers are overlain by the highest percentage of forested land (73 percent) and thus have fewer potential sources of contaminants from human activities. The valleys underlain by siliciclastic bedrock are not as large or as flat as those underlain by carbonate bedrock, and so the intensity of agricultural activity (numbers of animals and density of cropland) overlying the siliciclastic-rock aquifers is lower than that overlying the carbonate-rock aquifers (fig. 3–7).



A. Groundwater recharge enters the aquifer from the forested ridge or the more highly developed valley floor (see land use in figure 3–6). In the carbonate-rock valley, water can recharge the aquifer directly through sinkholes.

B. Once below the water table, groundwater follows the general path shown by the light blue arrows from recharge to discharge areas. Groundwater following shallower flow paths and groundwater near the ridges is younger than groundwater following deeper flow paths and groundwater closer to the valley center.

C. In carbonate-rock aquifers, fractures can be enlarged to form conduits and caverns. Water flows much more easily through conduits than through fractures. When groundwater enters a conduit, it follows the direction of that feature and flows rapidly towards the discharge area.

D. In siliciclastic-rock aquifers, groundwater flows through connected networks of fractures—these fractures create a more circuitous flow path and may actually slow the movement of groundwater as it moves in the direction indicated by the general flow path.

E. Near the center of a valley, groundwater from the deeper part of the aquifer converges toward the stream, and even relatively shallow wells in this part of the valley can draw in water from deeper flow paths.

Figure 3–7. In carbonate-rock aquifers (top), recharge can enter the aquifer from both the siliciclastic-rock ridges and the carbonate-rock valley floor. Water recharged near the ridges is less likely to be affected by contamination from land-based sources because the ridges mostly are forested. In both types of aquifers in the Valley and Ridge, the position of a well along the groundwater-flow path affects the quality of water because water generally moves from a forested ridge toward a valley overlain by agriculture. As water approaches the discharge area (stream), flow paths from deeper parts of the aquifer, which are older and less likely to contain contaminants from human sources, begin to converge toward the stream, mixing with shallower water.(22)

Imagery from Pictometry™ International Corporation

Photograph by John H. Bowman

In the Piedmont, major land-use types are distributed evenly across the landscape, as opposed to the Valley and Ridge, where the land use follows a more structured, linear pattern. Ridges are mostly forested and agriculture is concentrated in the valley floors.

Aquifers, bedrock type, and lithologic groups in the Piedmont, Blue Ridge, and Valley and Ridge regions

In this report, each of the five Principal Aquifers is identified with a major bedrock type: crystalline, siliciclastic, or carbonate bedrock. The major bedrock types in each of these five Principal Aquifers can be further subdivided into different lithologic groups. For example, in the Piedmont and Blue Ridge crystalline-rock aquifers, five lithologic groups are identified. Groundwater quality can differ among the lithologic groups because of differences in mineral composition and geologic origin. For example, radon concentrations are much higher in the felsic igneous and metamorphosed sedimentary clastic lithologic group than in the mafic and ultramafic lithologic group because of differences in uranium content. Differences among lithologic groups are especially important for assessing contaminants from geologic sources. Subdividing the bedrock types into lithologic groups was found to be more useful for interpreting water quality in the Piedmont and Blue Ridge crystalline-rock aquifers and the early Mesozoic basin aquifers than in the other three Principal Aquifers. Geochemically important minerals may or may not be present in the vicinity of every well in a given lithologic group; therefore, the quality of water within a lithologic group may vary from well to well.

Bedrock type	**Crystalline-rock aquifers**	**Siliciclastic-rock aquifers**		**Carbonate-rock aquifers**	
Principal Aquifer The five Principal Aquifers consist of one of three bedrock types	Piedmont and Blue Ridge ■	Early Mesozoic basin ■	Valley and Ridge ■	Piedmont and Blue Ridge ■	Valley and Ridge ■
Lithologic group Lithologic groups are categories within a bedrock type (discussed only for the Piedmont and Blue Ridge crystalline and early Mesozoic aquifers in this report)	Felsic igneous and metamorphic Intermediate igneous and metamorphic Metamorphosed sedimentary clastic Quartz-rich metamorphic Mafic and ultramafic	Mafic and ultramafic (crystalline) Feldspar-rich sedimentary Clastic sedimentary Lacustrine sedimentary Quartz-rich sedimentary	Sandstone Shale	Limestone Dolomite Mixed limestone and dolomite	

Chapter 4: *Physical and Geochemical Processes Affect Groundwater Quality*

In these regions, landscape features control the flow of groundwater from the recharge areas on the ridges and hilltops to the discharge areas at streams and springs in low-lying areas. Furthermore, the differences in the bedrock types below the surface control important unseen processes, such as how easily water enters the aquifer and how long it takes for groundwater to move through the aquifer to a well or a discharge area. What minerals dissolve into the water, and what chemical transformations are contaminants likely to undergo during that journey? The physical and chemical characteristics of water vary among the five Principal Aquifers and therefore provide an important background for understanding the differences in water quality and answering these questions.

This chapter explains and discusses the natural physical and geochemical processes that affect the movement and quality of groundwater in the five Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions.

Photograph by Bruce Lindsey, USGS

The Physical Framework of the Aquifers Affects the Storage and Movement of Water

All five of the Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions are bedrock aquifers—water flows through and is withdrawn from fractures and other openings in the rock (see photograph to the right). Water flows from recharge areas toward lower parts of the landscape, where it discharges to springs or streams. Water travels slowly through these aquifers if fractures are small and poorly connected but travels faster if fractures are larger and well connected. Some water in carbonate-rock aquifers flows through fractures, but some water flows through the larger, well-connected voids (conduits) (see sidebar, Karst features make carbonate-rock aquifers highly susceptible to contamination, p. 29). Karst features greatly increase the rate of infiltration from the surface and movement of water and contaminants through the aquifer.

Photograph by William Burton, USGS

In fractured bedrock, water travels through the cracks and spaces between the rocks rather than through the rock itself. The water follows the direction of the fractures (blue arrows) rather than infiltrating straight down. The example above is a sedimentary rock with well-defined layers, typical of siliciclastic-rock aquifers in the Valley and Ridge and the early Mesozoic basin aquifers.

Most groundwater in these Principal Aquifers moves through networks of interconnected fractures.

Variations in Groundwater Age Affect Water Quality

Groundwater age is the time elapsed since the recharged water moved below the water table and became isolated from the atmosphere. The term “age” commonly is qualified with the word “apparent” to signify that the accuracy of the determined age depends on many variables; however, the term “groundwater age” is used in this report for simplicity. Groundwater age can affect the quality of water because the chemicals in use and released to the land surface have changed over time—for example, groundwater that recharged in the 1960s likely was exposed to different contaminants than groundwater that recharged in 1900 or 2000. In addition, concentrations of contaminants can be affected by groundwater age because older groundwater has had more time for human-related contaminants, such as organic chemicals and nitrate, to adhere to aquifer materials or to break down. On the other hand, older water has spent more time in contact with the aquifer rock, resulting in increased concentrations of constituents from geologic sources. For these reasons, an understanding of the distribution of groundwater ages in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions is helpful.

Groundwater in the carbonate-rock aquifers typically is younger than is groundwater in the crystalline- and siliciclastic-rock aquifers (fig. 4–1). Groundwater ages can be estimated by measuring compounds and radioactive substances that enter the ground with recharge and that travel with the groundwater to the sampling point. All of the groundwater measured in aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions was young (less than 60 years old) compared to groundwater in most aquifers of the Nation(15–20) because of abundant recharge and relatively short flow paths. In this report, groundwater ages are divided into two categories: less than 20 years and 20 to 60 years.

Young groundwater is likely to contain contaminants related to human activities, but old groundwater is likely to contain constituents from geologic sources.

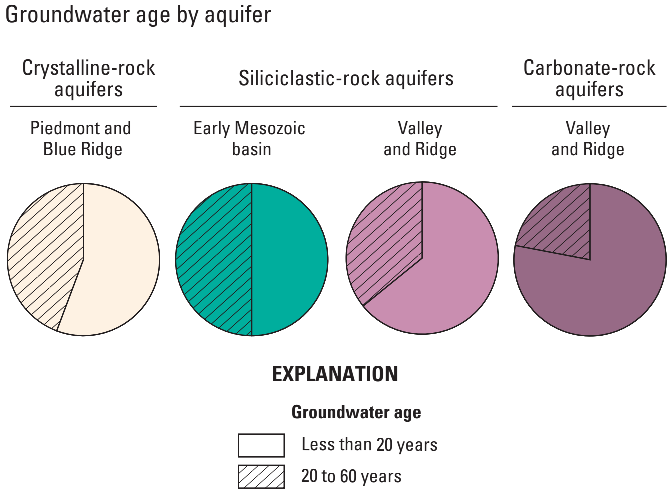


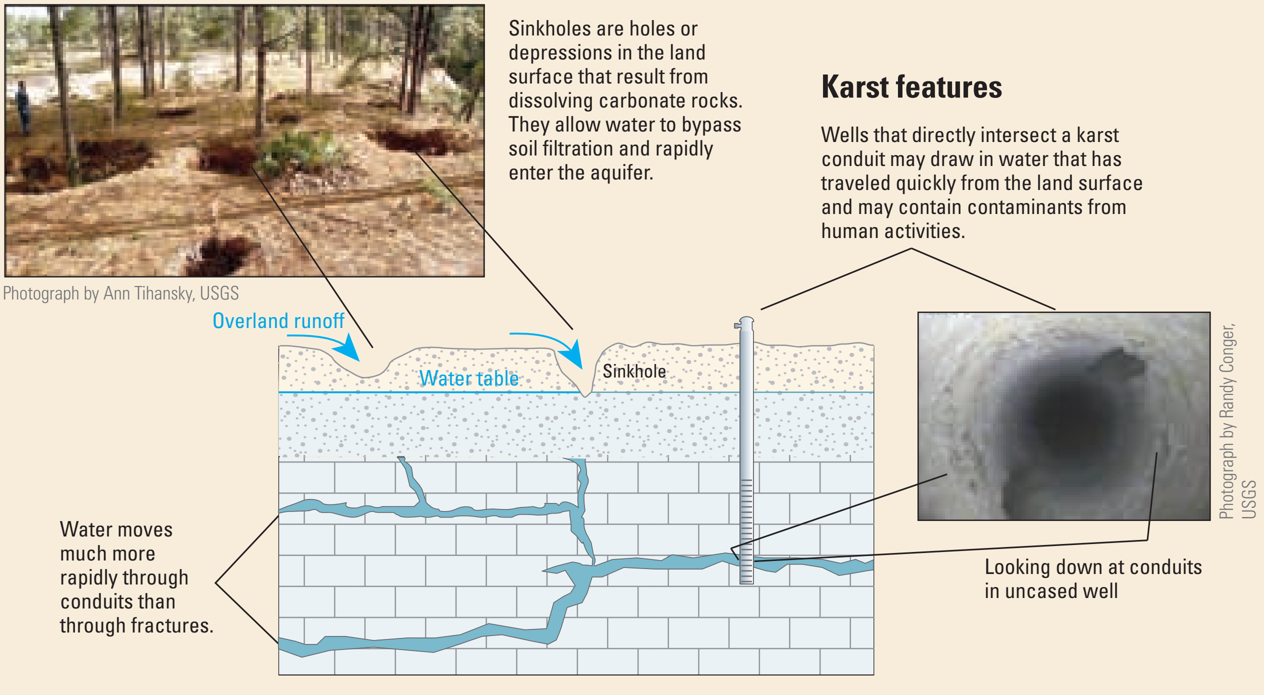
Figure 4–1. All of the groundwater in the Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions was young—60 years old or less—compared to groundwater in most aquifers of the Nation, but the percentage of samples from the Valley and Ridge carbonate-rock aquifers with groundwater ages of less than 20 years was larger than in the other aquifers. Groundwater with ages in the range of 0–20 years is more likely to contain human-related contaminants than is groundwater with ages in the range of 20–60 years because of the shorter available time for contaminants to break down and changes in chemical use over time.(15–20)

Karst features make carbonate rock aquifers highly susceptible to contamination

The Piedmont and Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers have unique features—referred to as karst features—that form when the rocks dissolve. Carbonate rocks, mainly limestone and dolomite, are much more soluble than most other bedrock types. Although carbonate rocks are fractured in a manner similar to the other fractured-bedrock aquifers, in karst systems the fractures become enlarged, and in some cases they are large enough to become caverns. Karst features include sinkholes, caverns, springs, and disappearing streams. Water can enter the aquifers directly through sinkholes and travel rapidly through cracks, fissures, and conduits. The karst features make the system highly susceptible to contamination (see photographs below); thus, if a contaminant source is present, contaminant levels in groundwater in areas with karst features can be higher than in areas where karst features do not exist. Moreover, predicting the movement of water and changes in concentration over time in an aquifer that includes karst features can be more challenging than in other aquifers.

The rapid transport of water through karst conduits in the carbonate-rock aquifer contributes to the younger ages of water in the carbonate-rock aquifers relative to that in the crystalline- and siliciclastic-rock aquifers (fig. 4–1). Some of the water in the carbonate-rock aquifers not only could have an age of less than 20 years—it could have traveled from the recharge area to the well or spring in a matter of days to weeks. Dye-tracing studies in these aquifers have shown that water can be transported from recharge areas to discharge areas miles away in days.(57) The ages shown in figure 4–1 likely pertain to the part of the carbonate-rock aquifer that is in the fractured rock without conduits, where flow tends to be slower than flow in conduits.

Karst conduits may allow turbulent flow that mixes air into the water and results in oxic conditions, which controls the degradation of some contaminants. Water samples from the carbonate-rock aquifers have higher concentrations of dissolved oxygen than the other aquifers. In carbonate-rock aquifers, areas with high and medium densities of sinkholes have higher concentrations of dissolved oxygen than areas with a low density of sinkholes. Thus, the presence of karst features helps explain both the young groundwater ages and the prevalence of oxic conditions in the carbonate-rock aquifers.



Karst features

Sinkholes are holes or depressions in the land surface that result from dissolving carbonate rocks. They allow water to bypass soil filtration and rapidly enter the aquifer.

Wells that directly intersect a karst conduit may draw in water that has traveled quickly from the land surface and may contain contaminants from human activities.

Water moves much more rapidly through conduits than through fractures.

Looking down at conduits in uncased well

Photograph by Ann Tihansky, USGS

Photograph by Randy Conger, USGS

Bedrock Type Affects General Properties of Water

Minerals that compose the three major bedrock types affect geochemical properties such as hardness and pH, which in turn affect the concentrations of other contaminants.

Minerals that compose the three major bedrock types affect the geochemical conditions in each of the aquifers, which in turn affect the transport of contaminants from both geologic and human sources. For example, the highly soluble calcite and dolomite minerals in carbonate-rock aquifers that lead to the development of karst features also lead to hard water, high dissolved solids concentrations, high alkalinity, and predominantly neutral (6.5–7.5) pH (fig. 4–2). Crystalline and siliciclastic rocks typically have less capacity than do carbonate rocks to neutralize acidic precipitation, resulting in lower pH. However, siliciclastic rocks in the early Mesozoic basin aquifers contain carbonate minerals in the natural cement between the sediment grains, and groundwater in these aquifers therefore is harder and has more neutral pH values than groundwater in the Valley and Ridge siliciclastic-rock aquifers (fig. 4–2). The pH and the concentrations of dissolved solids in groundwater affect the solubility and transport of many contaminants from geologic sources.

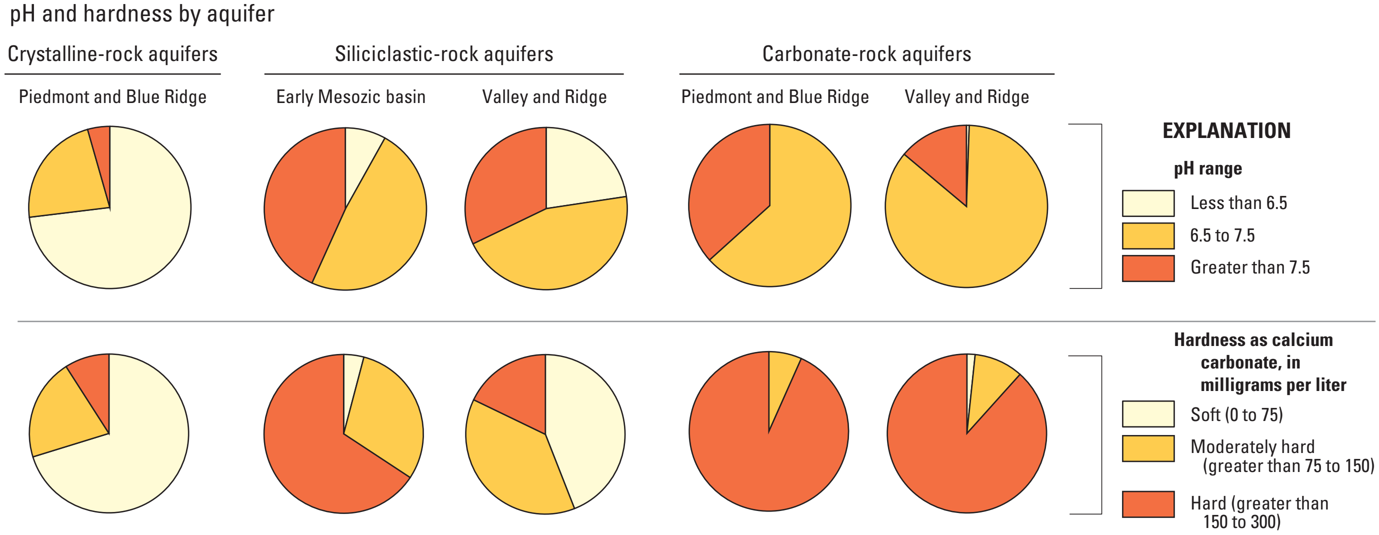
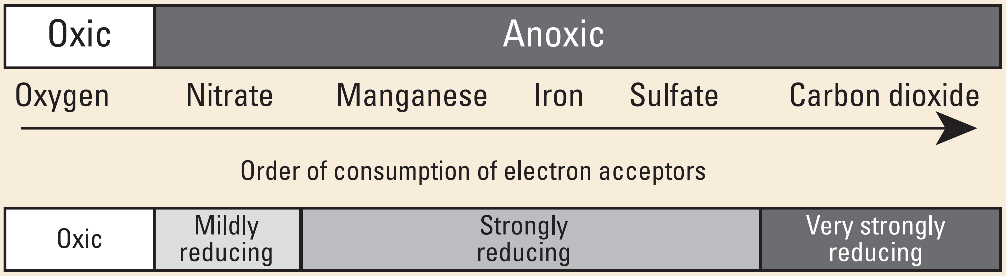


Figure 4–2. Low pH is a common characteristic of water from crystalline-rock aquifers, whereas hardness is a characteristic of water from the carbonate-rock aquifers and some parts of the siliciclastic-rock aquifers. Low pH and very low or high hardness can cause problems with the use of the water (see chapter 6), but these two basic geochemical properties also control concentrations of many other constituents.

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.

Reduction/Oxidation (Redox) Processes Affect Which Constituents are Detected in Groundwater

Redox processes (see sidebar, How do redox reactions work?, p. 31) affect the chemical quality of groundwater, and redox conditions vary among the Principal Aquifers (fig. 4–3). Redox processes can mobilize or immobilize trace elements from aquifer materials, contribute to the breakdown or preservation of human-related contaminants, and generate undesirable byproducts, such as dissolved iron, manganese, hydrogen sulfide, and methane.(21)

Older groundwater is more likely to be anoxic, but the onset of anoxic conditions differs among the aquifers. All of the water from wells that was less than 20 years old in the carbonate-rock aquifers was oxic, and a large percentage of the water older than 20 years was oxic as well. Thus, conditions in the carbonate-rock aquifers are favorable for the transport of contaminants that do not break down in oxic conditions, such as nitrate. In the crystalline- and siliciclastic-rock aquifers, water from a higher percentage of wells—even water with an age of less than 20 years—was anoxic or showed evidence of a mixture of anoxic and oxic waters (mixed redox source) (fig. 4–4). Concentrations of many contaminants from geologic sources, such as arsenic, iron, and manganese, are likely to be higher in older, anoxic water, such as in the crystalline- and siliciclastic-rock aquifers.

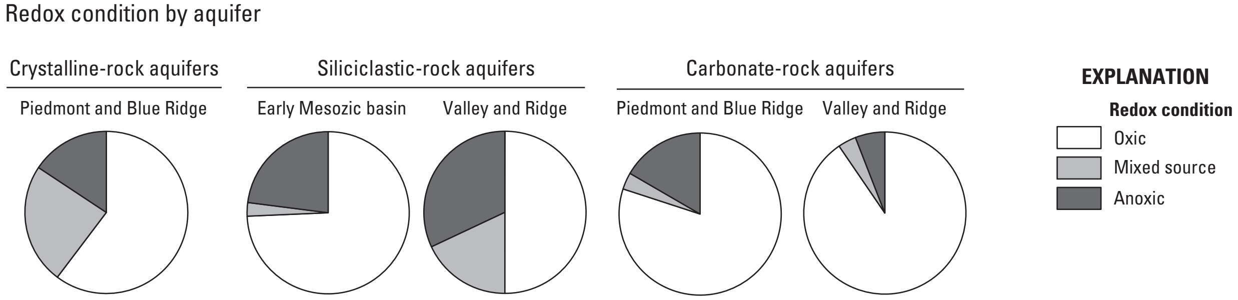


Figure 4–3. Redox conditions for as much as half of the water in the crystalline- and siliciclastic-rock aquifers were anoxic or mixed, whereas redox conditions in the carbonate-rock aquifers predominantly were oxic.

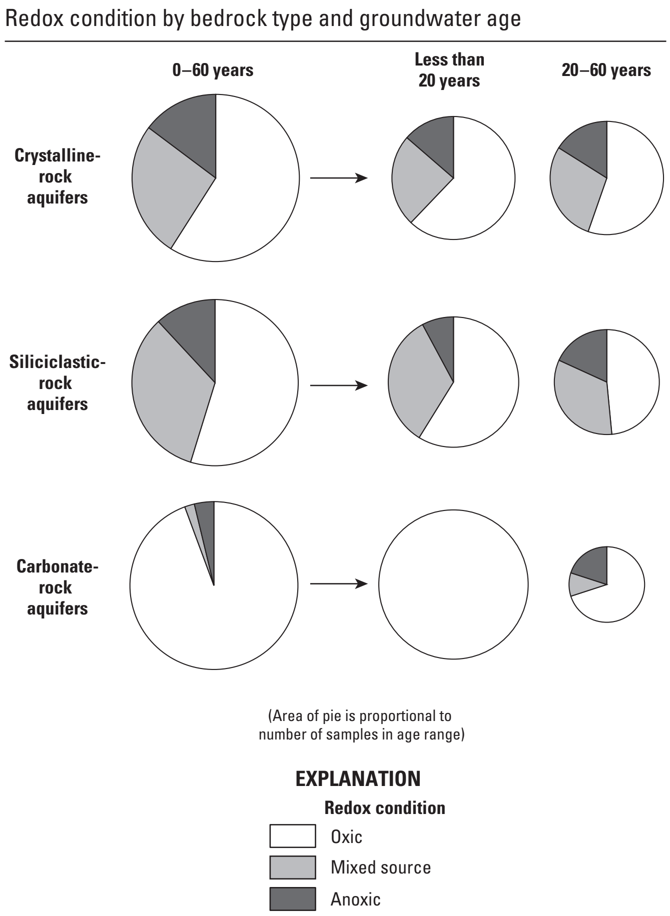
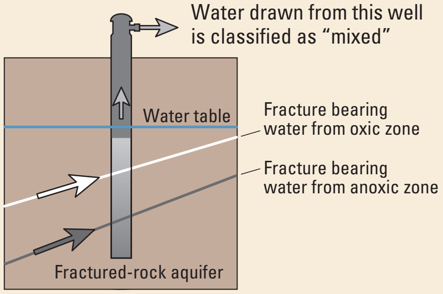


Figure 4–4. In all three types of aquifers, water with an age of less than 20 years was more likely to be oxic than water with an age of 20 years or more.(15–20) Nitrate and some other contaminants are less likely to break down in oxic water than in anoxic water. Trace elements like iron and manganese are more likely to be mobile in anoxic water.

Mixing of oxic and anoxic groundwater



A well may draw in water from parts of the aquifer that have different geochemical characteristics and may thus create a mixture that would not occur under normal conditions.

The Topographic Position of a Well on the Landscape Affects Water Quality

Chemical characteristics of groundwater can change as the water moves from the recharge area through the aquifer to a well or discharge area. In the Valley and Ridge aquifers, the relative location of the well on the landscape—its topographic position—is important because it indicates the position on the flow path and therefore groundwater age.(22) The topographic position is the location of the well with respect to the highest point in the watershed and the major stream draining the valley (fig. 4–5) and can indicate geochemical conditions. For example, the few wells in carbonate-rock aquifers with anoxic water were either near the ridge, where the water chemistry may have been affected by the nearby siliciclastic rocks, or in the low-lying valley centers, where the water is oldest. Oxic and anoxic water are found in all topographic positions in the siliciclastic-rock aquifers. Anoxic water was most common in low-lying areas, probably because older, anoxic water from deeper parts of the aquifers is moving into the shallower zones toward the groundwater-discharge areas.

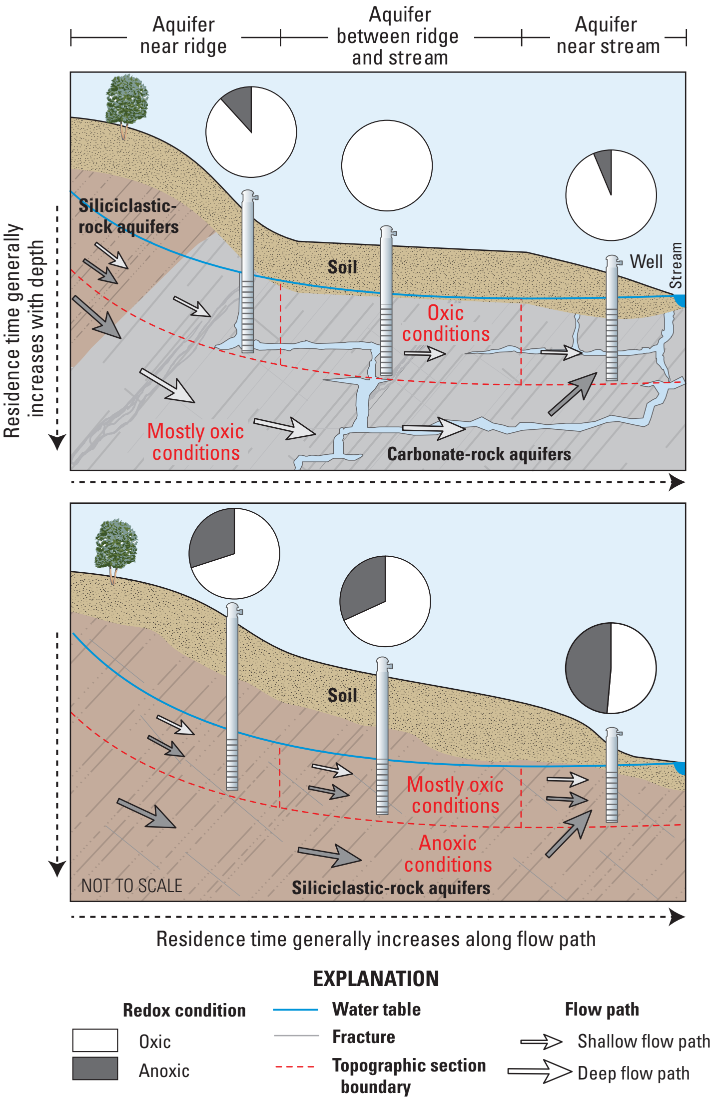


Figure 4–5. In the Valley and Ridge carbonate-rock aquifers, most groundwater samples were oxic regardless of the position on the flow path. In the Valley and Ridge siliciclastic-rock aquifers, a higher percentage of anoxic water in the center of the valley results from older groundwater converging into the shallower zone near the stream. Redox conditions control which contaminants are likely to be present.

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

Drinking water for public and domestic supply is the dominant use of groundwater in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions. Does the quality of groundwater support these uses? What constituents are present at concentrations that pose a potential human-health concern when groundwater is used as a source of drinking water? What constituents may adversely affect the use of the water? The chemical constituents of concern in these regions originate from geologic sources (radon, arsenic, and manganese) and also from human activities (nitrate and fecal-indicator bacteria).

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 Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions.

Imagery from Pictometry™ International Corporation

Twenty-eight percent of the sites that are used as a source of drinking water and were sampled for this assessment contained at least one contaminant at a concentration that exceeded its human-health benchmark (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 14). Of the 14 contaminants with concentrations that exceeded a human-health benchmark (table 5–1), 8 have a geologic source, and 17 percent of samples contained at least 1 of these 8 contaminants at a concentration exceeding its benchmark.

Table 5–1. Fourteen contaminants were found at concentrations greater than human-health benchmarks in samples from drinking-water wells whose concentrations exceeded their human-health benchmarks in at least one well.

[n, number of samples; *E. coli, Escherichia coli*; pCi/L, picocuries per liter; µg/L, micrograms per liter; mg/L, milligrams per liter; CFU/100 mL, colony-forming units per —, percentage exceeding one-tenth of human-health benchmark not evaluated]

Type of drinking-water contaminant	Contaminant name	Human-health benchmark			All drinking-water samples	
					Percentage exceeding	
		Value	Type	n	Human-health benchmark	One-tenth of human-health benchmark
Geologic sources	*Radon-222	300 pCi/L	Proposed MCL	478	83	—
		4,000 pCi/L	Proposed AMCL		11	—
	†Gross alpha activity	15 pCi/L	MCL	119	8.4	—
	Arsenic	10 µg/L	MCL	217	4.1	22
	Manganese	300 µg/L	HBSL	507	4.3	22
	ǂRadium-226 and radium-228	5 pCi/L	MCL	120	.83	—
	Uranium	30 µg/L	MCL	412	.49	13
	¶Antimony	6 µg/L	MCL	196	.51	1.5
	Strontium	4,000 µg/L	HBSL	206	.49	14
Human sources	Nitrate	10 mg/L	MCL	507	11	55
	Alpha HCH	0.006 µg/L	HBSL	441	.23	.23
	Dieldrin	0.002 µg/L	HBSL	522	1.3	1.5
	Acrylonitrile	0.06 µg/L	HBSL	259	.39	.39
	Trichloroethene (TCE)	5 µg/L	MCL	385	.26	1.3
	≈*Escherichia coli*	1 CFU/100 mL	MCL	234	24	—

* U.S. Environmental Protection Agency proposed AMCL and proposed MCL used for radon.

† The MCL for gross alpha excludes radon and uranium.

ǂ MCL is for the sum of Ra-226 and Ra-228.

¶ Although concentrations in some samples exceeded one-tenth of the benchmark, detection frequencies at one-tenth of the benchmark could not be fully determined because the detection limits for a large proportion of the samples were greater than one-tenth of the benchmark.

≈ Detection of a single *E. coli* colony is considered a violation of the drinking-water standard.

Four of the 8 are trace elements—arsenic, manganese, strontium, and antimony—and 4 are radionuclides—radon, gross alpha-particle activity, radium, and uranium. Concentrations of the other 6 contaminants that exceeded a human-health benchmark are related to human activities, and 23 percent of the samples—almost one-quarter—contained at least 1 of these contaminants at a concentration exceeding its human-health benchmark. These 6 contaminants are the bacterium *Escherichia coli* (*E. coli*), the nutrient nitrate, the pesticides dieldrin and alpha-HCH, and the VOCs trichloroethene and acrylonitrile.

in this study. These contaminants are derived from both human-related sources and geologic sources. This table lists the contaminants

100 milliliters; AMCL, Alternative Maximum Contaminant Level; MCL, Maximum Contaminant Level; HBSL, Health-Based Screening Level; n/a, not applicable;

Sources of contaminant in drinking water	**Potential health effects from exposure above the human-health benchmark**
Decay of radium-226, part of the uranium-238 decay series, in aquifer materials	Increased risk of lung cancer
Decay of radioactive elements, primarily uranium and radon, in aquifer materials	Increased risk of cancer
Aquifer materials, pesticide application in orchards, some industrial wastes	Skin damage, problems with circulatory system, increased risk of cancer
Aquifer materials, some industrial wastes	Neurological effects
Aquifer materials	Increased risk of cancer
Aquifer materials	Increased risk of cancer, kidney toxicity
Aquifer materials, discharge from petroleum refineries, fire retardants, ceramics, electronics, solder	Increase in blood cholesterol, decrease in blood sugar
Aquifer materials	Abnormal bone development
Fertilizer use, manure, sewage and septic-system effluent, aquifer materials	Infants below the age of 6 months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die; symptoms include shortness of breath and blue-baby syndrome
Hazardous waste sites, insecticide application	Increased risk of cancer
Insecticide	Liver and central nervous system problems, increased risk of cancer
Industrial discharges, leachate from chemical waste sites	Developmental, hematological, neurological, and reproductive effects, increased risk of cancer
Discharge from metal degreasing sites and factories	Liver problems, increased risk of cancer
Human sewage, animal manure	Gastrointestinal illness

Radon exceeded its proposed MCL(23) most frequently, with 83 percent of the sites sampled for radon exceeding the proposed MCL of 300 pCi/L; however, that frequency drops to 11 percent if the proposed Alternative Maximum Contaminant Level (AMCL)(23) of 4,000 pCi/L is considered. Following radon was *E. coli*, which exceeded its MCL in 25 percent of samples, and nitrate, which exceeded its MCL of 10 milligrams per liter as nitrogen (mg/L as N) in 11 percent of samples.

Exceedances of a human-health benchmark were unevenly distributed among the five Principal Aquifers, with clear differences based on aquifer bedrock type (fig. 5–1; table 5–2). Manganese and radon, contaminants from geologic sources, exceeded a benchmark most commonly in samples from the crystalline- and siliciclastic-rock aquifers, and contaminants from a human-related source exceeded a benchmark most commonly in samples from the carbonate-rock aquifers. The following chapters will explain how the sources and movement of the contaminants vary among the five Principal Aquifers, resulting in the observed patterns of occurrence and concentrations.

Only two wells in the carbonate-rock aquifers contained a constituent from a geologic source at a concentration that exceeded its human-health benchmark.

Some water-quality characteristics are not related to human health, but instead to the desirability of the groundwater to be used as a source of drinking water (table 5–3). The context for these characteristics, such as aesthetic issues (taste and odor), cosmetic issues (skin or tooth discoloration), or technical issues related to the effects of the water on plumbing (scale or corrosion), is provided by USEPA Secondary Maximum Contaminant Levels (SMCLs)(71) for public water supplies. Hardness does not have an SMCL, so concentrations were evaluated with respect to other USEPA guidelines. The reasons for the distribution of these contaminants, generally considered to be a nuisance rather than a hazard, are discussed in chapter 6.

Distributors of public-water supplies are required to reduce concentrations of contaminants to less than the MCL before distribution, sometimes at great expense.

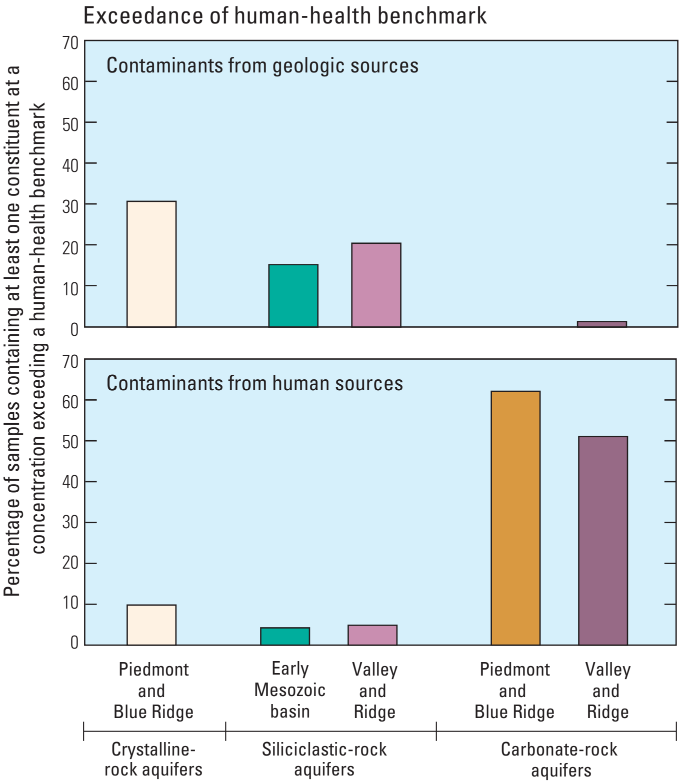


Figure 5–1. Patterns of contamination distinctly differed among the three major bedrock types. In the crystalline- and siliciclastic-rock aquifers, concentrations of contaminants from geologic sources—primarily manganese and radon—more commonly exceeded a human-health benchmark than did concentrations of contaminants associated with human activities. In contrast, in the carbonate-rock aquifers, exceedances of benchmarks for contaminants associated with human activities, such as nitrate and *Escherichia coli*, were among the highest in the Nation. Exceedances of benchmarks for contaminants from a geologic source were rare in the carbonate-rock aquifers; however, some of the natural constituents that exceeded standards in the crystalline- and (or) siliciclastic-rock aquifers—gross alpha-particle activity, radium, and arsenic—were not evaluated in most samples from the carbonate aquifers.

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.

Table 5–2. Contaminants whose concentrations in groundwater approached or exceeded human-health benchmarks varied by Principal Aquifer.

[n, number of samples; *E. coli*, *Escherichia coli*; pCi/L, picocuries per liter; µg/L, micrograms per liter; mg/L, milligrams per liter; CFU/100 mL, colony-forming units per

Source of drinking-water contaminant	Contaminant name	Human-health benchmark		Piedmont and Blue Ridge crystalline-rock aquifers		Early Mesozoic
		Value	Type	n	Percentage exceeding human-health benchmark	n
Geologic sources	*Radon	300 pCi/L	Proposed MCL	177	90	51
		4,000 pCi/L	Proposed AMCL		24	
	†Gross alpha activity	15 pCi/L	MCL	64	9.4	27
	Arsenic	10 µg/L	MCL	125	4.0	49
	Manganese	300 µg/L	HBSL	179	3.9	71
	ǂRadium	5 pCi/L	MCL	65	0	27
	Uranium	30 µg/L	MCL	179	1.1	51
	Antimony	6 µg/L	MCL	125	0.8	28
	Strontium	4,000 µg/L	HBSL	95	0	0
Human sources	Nitrate	10 mg/L	MCL	178	6.2	72
	Alpha HCH	0.006 µg/L	HBSL	113	0.88	71
	Dieldrin	0.002 µg/L	HBSL	194	0.52	71
	Acrylonitrile	0.06 µg/L	HBSL	137	0.73	49
	Trichloroethene (TCE)	5 µg/L	MCL	150	0	49
	¶*Escherichia coli*	1 CFU/100 mL	MCL	113	5.3	1
Percentage of sites where at least one contaminant exceeded benchmark					35	

* U.S. Environmental Protection Agency proposed AMCL and proposed MCL used for radon.

† The MCL for gross alpha excludes radon and uranium.

ǂ MCL is for combined radium—the sum of Ra-226 plus Ra-228.

¶ Detection of a single *E. coli* colony is considered a violation of the drinking-water standard.

100 milliliters; AMCL, Alternative Maximum Contaminant Level; MCL, Maximum Contaminant Level; HBSL, Health-Based Screening Level; n/a, not applicable]

basin aquifers	Valley and Ridge siliciclastic-rock aquifers		Piedmont and Blue Ridge carbonate-rock aquifers		Valley and Ridge carbonate-rock aquifers	
Percentage exceeding human-health benchmark	n	Percentage exceeding human-health benchmark	n	Percentage exceeding human-health benchmark	n	Percentage exceeding human-health benchmark
94	80	68	29	86	141	77
5.9		6.3		0		0
11	28	3.6	0	n/a	0	n/a
8.2	28	0	0	n/a	15	0
2.8	81	15	29	0	147	.7
3.7	28	0	0	n/a	0	n/a
0	83	0	29	0	70	0
0	28	0	0	n/a	15	0
n/a	28	0	0	n/a	83	1.2
0	82	3.7	29	62	146	18
0	82	0	29	0	146	0
2.8	82	0	29	3.5	146	2.1
0	28	0	0	n/a	45	0
2.0	57	0	29	0	100	0
0	28	3.6	0	n/a	92	54
19		25		62		52

Table 5–3. Seven constituents or physical properties were measured at concentrations that exceeded guidelines for aesthetic issues, such as taste or odor, or technical effects on plumbing, such as scaling or corrosion. These issues mostly are related to the natural characteristics of the water. The table lists any constituent whose concentration exceeded a guideline in at least one well.

[SMCL, Secondary Maximum Contaminant Level; MCL, Maximum Contaminant Level; TDS, total dissolved solids; n, number of samples; mg/L, milligrams per liter]

Constituent type	Constituent	Undesirable effect	Value of SMCL		All aquifers	Piedmont and Blue Ridge crystalline-rock aquifers	Early Mesozoic basin aquifers	Valley and Ridge siliciclastic-rock aquifers	Piedmont and Blue Ridge carbonate-rock aquifers	Valley and Ridge carbonate-rock aquifers
				n=	* 492	† 164	71	81	29	147
					Percentage of samples exceeding value					
Trace elements	Iron	Rusty color, sediment, taste, staining	0.3 mg/L		9.8	13	2.8	27	0	2.0
	Manganese	Staining, taste	0.05 mg/L		19	23	8.5	47	6.9	4.8
Major ions	Fluoride	Tooth discoloration	‡2 mg/L		0.2	0.6	0	0	0	0
	Sulfate	Salty taste	250 mg/L		0.4	0	2.8	0	0	0
Properties	TDS	Hardness, deposits, colored water, staining, salty taste	500mg/L		3.0	1.2	4.2	1.2	10	4.8
	Hardness	Encrustation, scale	¶150 mg/L		48	8.5	65	19	93	90
	pH	*Low pH*—bitter metallic taste, corrosion *High pH*—slippery feel, soda taste, deposits	≈6.5–8.5		30	68	8.3	22	0	.7

* n = 507 for manganese and 609 for hardness.

† n = 179 for manganese and 242 for hardness.

‡ Fluoride has an MCL of 4 mg/L, but it was never exceeded.

¶ Hardness does not have an SMCL; criteria are from U.S. Environmental Protection Agency(37).

≈ The pH in all samples that did not meet the criteria was less than 6.5 units with the exception of one sample from the Valley and Ridge siliciclastic-rock aquifers, in which the pH exceeded 8.5 units.

How Findings Compare With Those Across the Nation

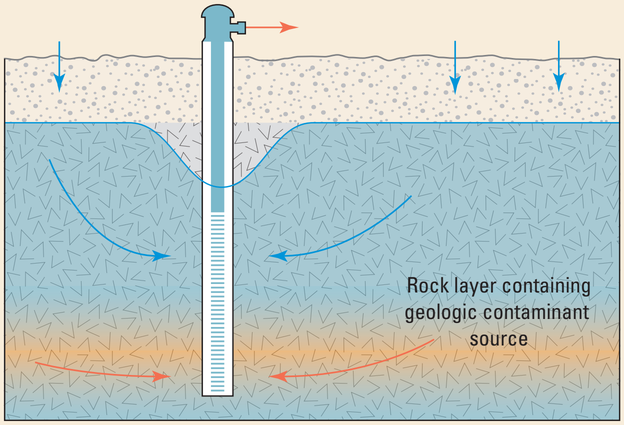
The percentage of drinking-water wells sampled in the Piedmont, Blue Ridge, and Valley and Ridge regions with at least one contaminant that exceeded its human-health benchmark (28 percent) was slightly higher than the percentage of domestic-supply wells (23 percent) or public-supply wells (22 percent) sampled across the Nation.(1, 25) These percentages are based on the proposed AMCL for radon of 4,000 pCi/L(23) and do not include bacteria, for consistency with national values. The percentage of wells used for drinking water in which *E. coli* was detected (25 percent) was much higher than the percentage of public- and domestic-supply wells sampled nationally in which the bacterium was detected (6 percent).(26) The Piedmont and Blue Ridge carbonate- and Valley and Ridge carbonate-rock aquifers ranked among the highest in the Nation for the percentage of samples with concentrations of nitrate that exceeded the MCL of 10 mg/L as N. The percentage of wells in the Piedmont and Blue Ridge crystalline-rock aquifers with exceedances of the proposed MCL and AMCL for radon also was high relative to the percentage of wells sampled nationally.

> *The Piedmont and Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers ranked among the highest in the Nation for the percentage of samples exceeding the nitrate MCL.*

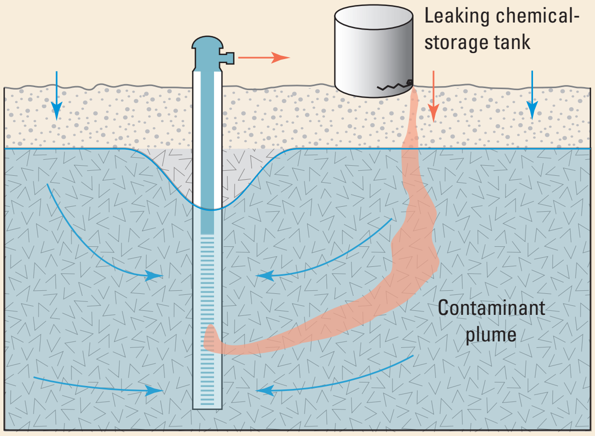
Sources of contaminants in groundwater

Contaminants measured in groundwater are either related to human activity at the land surface or a geologic source of the contaminant in the aquifer. Human-related sources can be from accidental spills at a single location—called a point source—or from a widespread source, such as fertilizers or pesticides that are used over a large area—called nonpoint sources. Geologic sources are materials in the aquifer that can be released into groundwater under certain geochemical conditions and also can be harmful to humans if ingested at high enough concentrations. Examples of contaminants from geologic sources include arsenic, uranium, and radon.

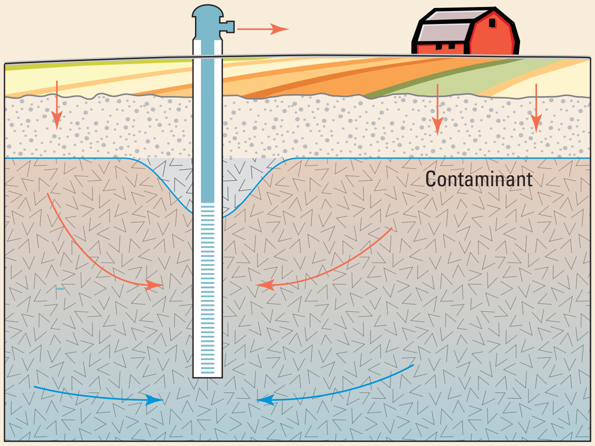
Geologic source



Human-related point source



Human-related nonpoint source



Modified from Eberts and others(7)

Cost of water treatment

Even when water is plentiful, it is not truly available for use unless the quality is acceptable for the intended use. Both water quality and availability are essential to maintaining water supply for municipal, domestic, agricultural, aquatic-life, and recreational use. Options to reduce or remove harmful constituents from water are available; they vary depending on the type of contaminant and the specifics of water-supply management, but can cost thousands of dollars per household.

Some options for domestic-well users and public-supply providers

- installing and maintaining household treatment devices;
- buying drinking water, either in bottles or from another supplier;
- blending water—diluting a contaminated source with water from an uncontaminated source;
- locating and developing a new uncontaminated source of drinking water; and
- building or upgrading and operating a treatment plant to remove contaminants.

Photograph by Bruce Lindsey, USGS

Example of domestic-well user's home water-treatment system.

Photograph from the Morrisons Cove Herald, used with permission

The nitrate removal plant in Martinsburg, Pennsylvania.

Public water suppliers are required to reduce contaminant concentrations to meet regulatory standards, sometimes at great expense

Groundwater is the major source for municipal water-supply systems in much of rural Pennsylvania. The water supply for Martinsburg, a south-central borough with a population of about 2,000 people, regularly has nitrate concentrations higher than the MCL of 10 mg/L. With no other water sources available, Martinsburg opened a water-treatment facility in 2011 to remove nitrate. The ion-exchange facility is the first of its type in Pennsylvania and cost $4.1 million, or more than $2,000 per person (Randy Stoltz, Martinsburg Municipal Authority, written commun., 2012). Nitrate contamination is also common in the surrounding areas.

A variety of point-of-use household water treatments are available

> *“My home system consists of a filter, a water softener, and an ultraviolet (UV) light system. I also have a reverse osmosis (RO) system serving the kitchen area. The filter, UV light, and RO systems treat for nitrate and bacteria and cost about $1,600. The UV light and RO filters are changed annually for about $200. The water softener is for extremely hard water, which was recently replaced for about $1,500 and costs about $100 a year for salt.”*
>
> *—Pennsylvania homeowner with domestic-supply well*

Chapter 6: *Constituents From Geologic Sources*

Constituents from geologic sources enter the groundwater at various depths beneath the land surface. The rocks that contain these constituents are not easily seen on the landscape, but the locations of these different rock types have been determined by geologic mapping and are used to determine the distribution of these constituents. Water samples from the crystalline-rock and siliciclastic-rock aquifers frequently contained one or more constituents from geologic sources at concentrations higher than their human-health benchmarks, but detections of these constituents were rare in samples from the carbonate-rock aquifers. The contaminants from geologic sources that most frequently exceeded human-health benchmarks were arsenic, manganese, and radon. A substantial percentage of samples from crystalline- and siliciclastic-rock aquifers also did not meet non-health-related guidelines for pH and manganese.

This chapter describes the sources of and factors that affect constituents from geologic sources in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions.

Why is it important to understand concentrations of contaminants from geologic sources?

Nationally, the trace elements arsenic and manganese and the radionuclides uranium, radon, and radium are among the contaminants from geologic sources that most frequently exceed human-health benchmarks.(1, 2) Domestic-well owners rarely test for these contaminants, but should be aware of their potential presence in groundwater and the health risks if their concentrations exceed human-health benchmarks. Millions of people in the Piedmont, Blue Ridge, and Valley and Ridge regions consume water from domestic wells that is not regulated or monitored in the same way as public water supplies and could be a source of exposure. A better understanding of the geochemical environments that are associated with high levels of contaminants allows water managers to focus on the most important problems in specific geographic areas. The trace-element and radionuclide concentration data collected for large-scale regional studies, such as this one, could be used to provide assistance to private-well owners in identifying where the potential human-health risks are highest and information for prioritization of private wells for sampling.

Lithology Controls Where Concentrations of Arsenic and Manganese in Groundwater Are Elevated

Arsenic is a trace element in aquifer materials and also in pesticides and industrial waste. Long-term exposure to arsenic in drinking water is related to elevated risks of cancer and skin damage.(27)

Groundwater in some parts of the Piedmont, Blue Ridge, and Valley and Ridge regions had concentrations of arsenic and manganese that exceeded human-health benchmarks. The areas with elevated concentrations of arsenic were in specific lithologic groups in the Piedmont and Blue Ridge crystalline-rock and early Mesozoic basin aquifers. Elevated concentrations of manganese were common in the Piedmont and Blue Ridge crystalline-rock, early Mesozoic basin, and Valley and Ridge siliciclastic-rock aquifers.

Four trace elements—arsenic, antimony, manganese, and strontium—were elevated (detected in one or more water samples at concentrations greater than their human-health benchmarks; table 5–1). Eight other trace elements—barium, copper, lead, selenium, molybdenum, nickel, thallium, and zinc—were detected at concentrations greater than one-tenth of their human-health benchmarks near levels that are of potential concern for human health. Concentrations of arsenic and manganese exceeded the human-health benchmarks much more frequently than did concentrations of antimony and strontium. For a complete listing of the detection frequencies of trace elements and radionuclides, see table A3–1.

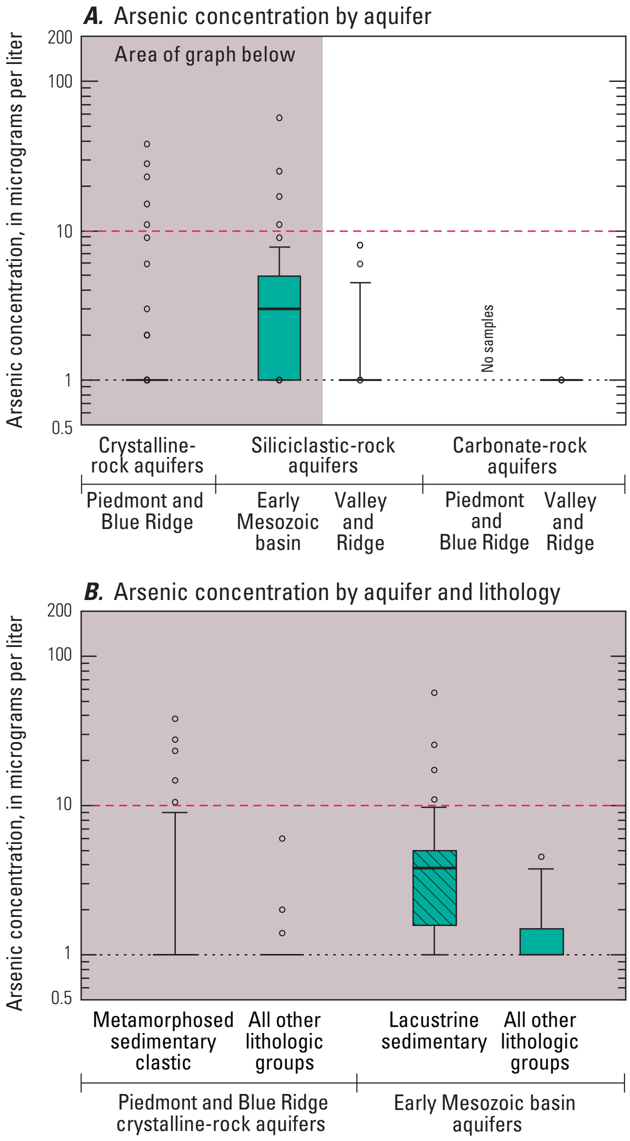
Arsenic Concentrations in Groundwater That Exceed Drinking-Water Standards Are Associated With Specific Lithologic Groups

Concentrations of arsenic exceeded the MCL of 10 µg/L in only 4 percent of all drinking-water wells sampled in the Piedmont, Blue Ridge, and Valley and Ridge regions (table 5–1), less frequently than the national rate for domestic wells (7 percent)(3) or public-supply wells (10 percent).(2) However, elevated arsenic concentrations in groundwater in the Piedmont, Blue Ridge, and Valley and Ridge regions have a predictable distribution geographically with respect to geochemical conditions. Concentrations of arsenic exceeded the MCL in 9 percent of drinking-water wells in two specific lithologic groups: the lacustrine sedimentary lithologic group in the early Mesozoic basin aquifers and the metamorphosed sedimentary clastic lithologic group in the Piedmont and Blue Ridge crystalline-rock aquifers (fig. 6–1; table 5–2; see sidebar, Aquifers, bedrock type, and lithologic groups in the Piedmont, Blue Ridge, and Valley and Ridge regions, p. 26). These lithologic groups are made up of fine-grained sedimentary rocks, such as mudstone, shale, siltstone, their metamorphic equivalents, and some metavolcanic rocks.(28)

Arsenic concentrations exceeded the MCL in groundwater associated with only two specific lithologic groups in two Principal Aquifers, indicating that a targeted approach to further testing for arsenic could be used.

Elevated arsenic concentrations were associated with high pH, providing a screening tool for further investigation of arsenic.

Lithology can vary greatly within a well bore, as shown by the dark and light rocks in the rock core. Because of its origin, the dark shale is likely to bear arsenic that could dissolve and contribute to arsenic found in a well. Although these lithologies may make up a small fraction of the rock, the arsenic may be released from the rock into the groundwater under specific geochemical conditions in concentrations high enough to be of potential human-health concern.



EXPLANATION

- - - - **USEPA Maximum Contaminant Level (MCL) for arsenic**

······ **Common assessment level for arsenic**

See sidebar, Boxplots, this page

Because of variations in reporting limits, a common assessment level of 1.0 microgram per liter is used to evaluate concentrations of arsenic. For a single compound or element, the common assessment level is typically set at the maximum level commonly used to report nondetections.

Figure 6–1. *A*, The highest concentrations of arsenic were measured in samples from the early Mesozoic basin aquifers. The early Mesozoic basin aquifers and the Piedmont and Blue Ridge crystalline-rock aquifers were the only aquifers in which arsenic concentrations exceeded the MCL of 10 micrograms per liter in one or more samples. *B*, Within those two Principal Aquifers, concentrations of arsenic exceeded the MCL only in samples from the metamorphosed sedimentary clastic lithologic group in the Piedmont and Blue Ridge crystalline-rock aquifers and the lacustrine sedimentary lithologic group in the early Mesozoic basin aquifers.

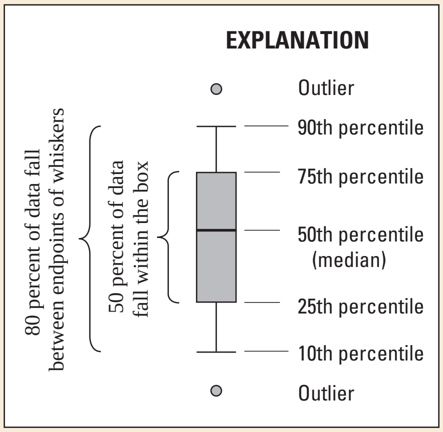
Boxplots

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 percentile are shown as individual points (outliers).



Arsenic is not released from rocks—even arsenic-rich rocks—into the groundwater except under specific geochemical conditions.(29–32) Although arsenic concentrations in groundwater in some settings are influenced by redox conditions, in these aquifers, pH exerts much more control over arsenic concentrations than redox conditions (fig. 6–2). The lithologic groups that had the highest concentrations of arsenic in groundwater (lacustrine sedimentary and metamorphosed sedimentary clastic) also had the highest pH values.

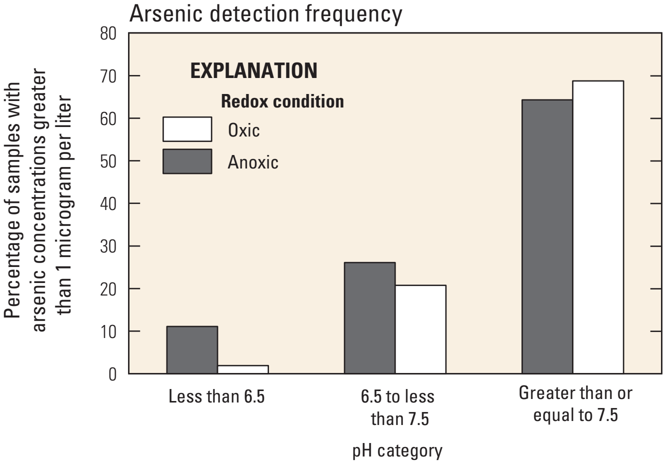


Figure 6–2. The highest arsenic concentrations are associated with high pH. The largest percentage of samples with a concentration of arsenic exceeding 1 microgram per liter was from waters with a pH greater than 7.5 regardless of whether the redox conditions were oxic or anoxic.

Although the health concerns for long-term exposure to arsenic in drinking water are well documented,(27) most homeowners with domestic-supply wells are unaware if their drinking-water supply contains arsenic unless they have specifically tested for it. Testing may be prudent,(33) especially if the water has high pH and is from one of the bedrock types or specific lithologic groups identified here as having high potential for elevated arsenic concentrations (fig. 6–3). Because of the considerable variation in the composition of rocks in these aquifers, however, arsenic concentrations also might be elevated in wells not in the areas highlighted on figure 6–3.

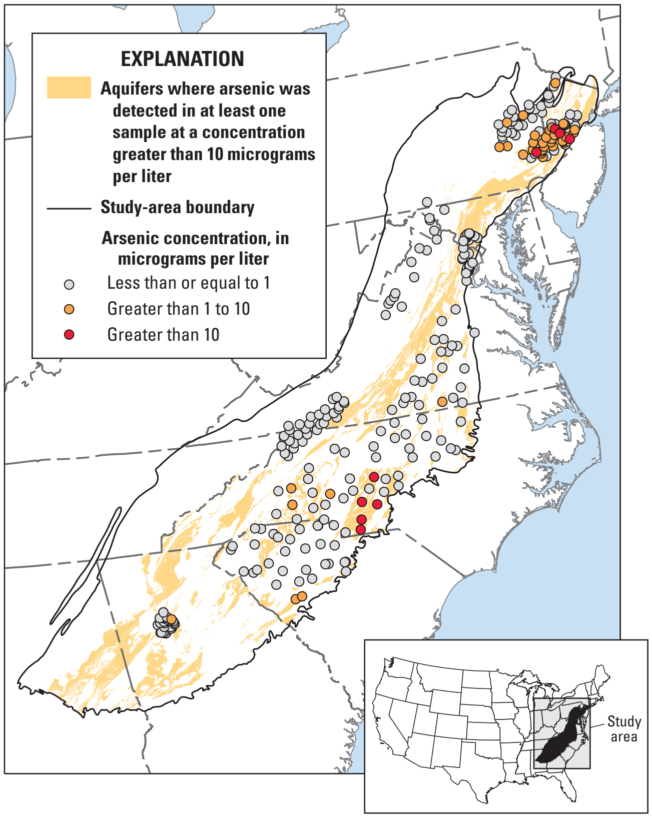


Figure 6–3. Nine percent of groundwater samples from both the metamorphosed sedimentary clastic and lacustrine sedimentary lithologic groups had concentrations of arsenic that exceeded the MCL of 10 micrograms per liter. Arsenic concentrations in about 90 percent of samples in the lacustrine sedimentary lithologic group exceeded 1 microgram per liter, whereas concentrations in only about 20 percent of the samples in the metamorphosed sedimentary clastic group exceeded this level. No wells in any other aquifers or in any other lithologic group had concentrations of arsenic that exceeded the MCL, and only 5 percent of the samples from those areas had concentrations that exceeded 1 microgram per liter. Identification of these lithologic groups can be used to target sampling efforts to those areas most likely to have elevated concentrations of arsenic.

Manganese Concentrations Exceed Human-Health Benchmarks Most Frequently in Wells in the Valley and Ridge Siliciclastic-Rock Aquifers

Overall, only 4 percent of the samples from drinking-water wells contained manganese at a concentration greater than the human-health benchmark of 300 µg/L (table 5–1). The highest concentrations of manganese were in samples from drinking-water wells in the Valley and Ridge siliciclastic-rock aquifers (fig. 6–4), where 15 percent of wells had manganese concentrations that exceeded the benchmark. In contrast, concentrations exceeded the human-health benchmark in only a single sample from the carbonate-rock aquifers (table 5–2). In addition to posing concerns for human health, manganese also is considered a nuisance constituent in groundwater because it stains plumbing fixtures (see nuisance contaminants in chapter 6).

Manganese concentrations in groundwater tend to be elevated in areas where the bedrock contains manganese and geochemical conditions in the aquifer are such that manganese is released from the rock into the groundwater. High concentrations of manganese were related to anoxic redox conditions and, to a lesser extent, to low pH(35) (fig. 6–5), which are more common in the Valley and Ridge siliciclastic-rock aquifers (figs. 4–2, 4–3) and the Piedmont and Blue Ridge crystalline-rock aquifers than in the other three aquifers. Measures of redox condition and pH, however, typically are not available to homeowners, but because the SMCL of 50 µg/L is lower than the human-health benchmark of 300 µg/L, visual signs such as staining could be an indication of elevated concentrations of manganese. However, manganese can be at high enough concentrations to be a potential health concern without any visible evidence; thus testing is the best alternative for those who live in areas that tend to have high manganese concentrations.

25
Mn
55

Manganese is a trace element in aquifer materials and some industrial wastes. Manganese has a human-health benchmark, established because of neurological effects, of 300 µg/L.(58, 59)

Most of the concentrations of manganese exceeding the human-health benchmark were in the Valley and Ridge siliciclastic-rock aquifers and were associated with low pH and anoxic conditions.

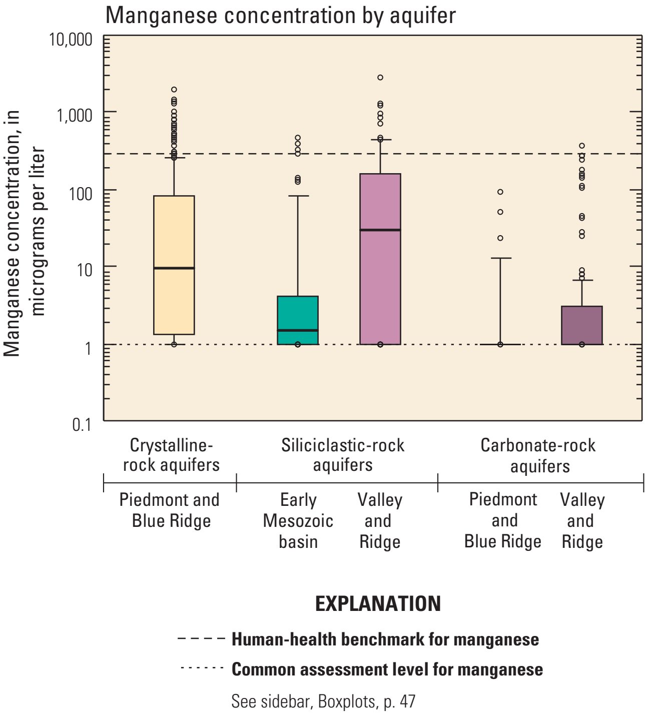


Figure 6–4. Manganese concentrations were highest in samples from the Valley and Ridge siliciclastic-rock aquifers, where 15 percent of the samples exceeded the human-health benchmark of 300 micrograms per liter. Manganese concentrations were lowest in the carbonate-rock aquifers, where they exceeded the benchmark in only a single sample.

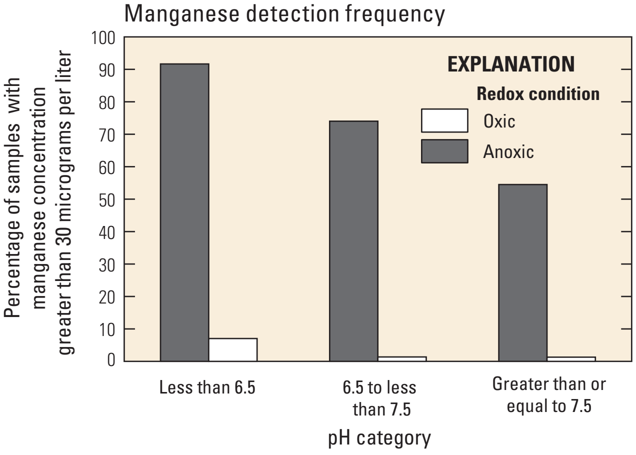


Figure 6–5. Manganese is released from manganese-bearing minerals when groundwater is anoxic and has low pH. Anoxic conditions have a greater effect on manganese concentration than does pH. More than 90 percent of samples that were anoxic and had a pH of less than 6.5 contained manganese at a concentration exceeding 30 micrograms per liter (one-tenth of the human-health benchmark).

Radon Concentrations Frequently Exceeded Proposed Drinking-Water Standards, and Other Radionuclides Exceeded Standards in a Few Cases

Uranium is the parent of many other radioactive elements (see sidebar, Radioactive decay, p. 51)—its radioactive decay produces other radionuclides. Although present in trace amounts in many types of bedrock, uranium is present in higher amounts in some bedrock types, including the felsic crystalline rocks that are found in parts of the Piedmont and Blue Ridge crystalline-rock aquifers. Uranium, radium, and radon have different geochemical characteristics and are transported by groundwater in different ways; for this reason, groundwater from areas underlain by rocks with high uranium content does not always have high concentrations of other radionuclides.

86
Rn
222

Groundwater in the Piedmont, Blue Ridge, and Valley and Ridge regions routinely had concentrations of radon that exceeded both the 300 pCi/L proposed MCL and the 4,000 pCi/L proposed AMCL.(23) The highest concentrations of radon were in water from wells in the Piedmont and Blue Ridge crystalline-rock aquifers, and especially in specific lithologic groups in these aquifers.

Uranium Concentrations Exceed Human-Health Benchmarks in a Few Wells and Locations of High Concentrations Are Related to Geology

Concentrations of uranium exceeded the MCL of 30 µg/L in fewer than 1 percent of the drinking-water wells sampled (table 5–1). Although the two samples with the highest concentrations of uranium were from the Piedmont and Blue Ridge crystalline-rock aquifers, the median uranium concentration was highest for samples from the early Mesozoic basin aquifers, followed by those from the Piedmont and Blue Ridge carbonate-rock aquifers (fig. 6–6).

Uranium concentrations are greater than 3 µg/L most commonly in groundwater that has a pH greater than 7.5 (fig. 6–7).(28) The sedimentary-rock aquifers of the early Mesozoic basin and the Piedmont and Blue Ridge carbonate-rock aquifers have both the highest percentage of wells with high pH (fig. 4–2) and the highest concentrations of uranium (fig. 6–6). The highest median uranium concentrations were in areas where source rocks had moderate to high uranium content and pH greater than 7.5.(28) In contrast, in the Piedmont and Blue Ridge crystalline-rock aquifers, although uranium-bearing minerals are abundant, uranium concentrations in water generally were low, likely because of the low pH of these waters. This result indicates the critical role of groundwater geochemistry for controlling uranium in groundwater regardless of the uranium content of the surrounding bedrock.

Concentrations of uranium in groundwater were low where pH was low, even in the presence of uranium-rich rocks.

92
U
238

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


Photographs by Bruce Lindsey, USGS

Felsic rocks, such as granite (far left), generally are uranium-rich because of the presence of uranium in the mineral feldspar, a light-colored mineral that is a component of felsic rocks. Where uranium is abundant, other radionuclides also can be present. Mafic rocks, such as diabase (on the right), contain much less feldspar and thus much less uranium, so mafic rocks are less likely to be sources of radionuclides.

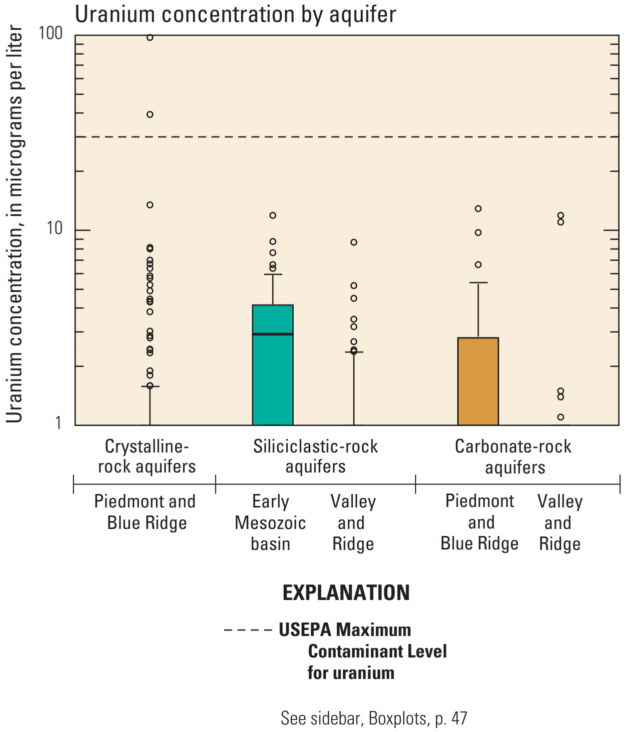


Figure 6–6. The median concentration of uranium was higher in the early Mesozoic basin aquifers than in the other four Principal Aquifers. High pH in the early Mesozoic basin aquifers allows uranium to be released from uranium-rich rocks of the aquifer into the groundwater.

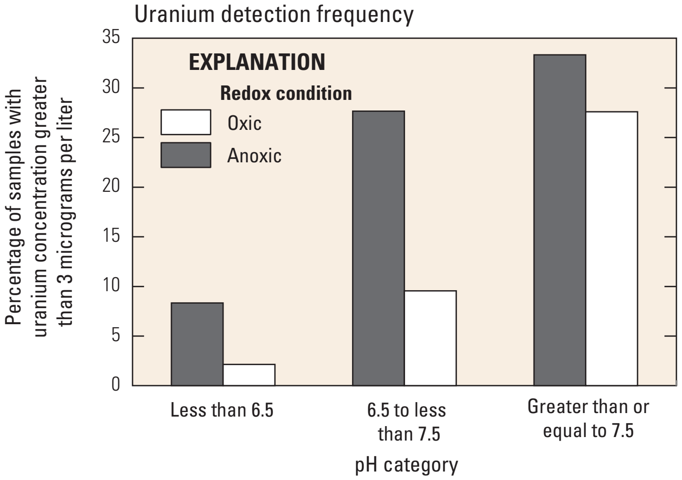


Figure 6–7. Uranium concentrations greater than 3 micrograms per liter (one-tenth of the MCL) were more common where samples were anoxic and pH was high.

Radioactive decay

Two of the radionuclides of concern, radium-226 and radon-222, are products of the radioactive decay of uranium-238. The other radionuclide of concern, radium-228, is a product of the radioactive decay of thorium-232. The USEPA MCL for radium is for the combined total of radium-226 and radium-228. In this report, uranium-238 is referred to as uranium; radon-222 is referred to as radon; and the combined concentration of radium-226 and radium-228 is referred to as radium concentration.

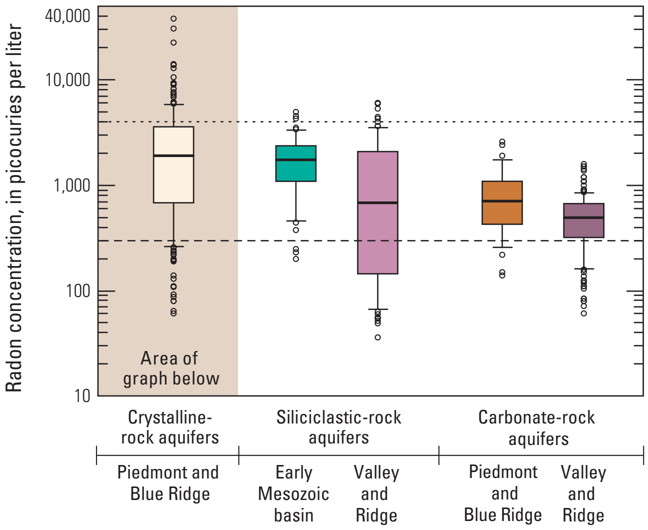
Radon Exceeds the Proposed Alternative Maximum Contaminant Level in About One of Every Four Wells Sampled in the Crystalline-Rock Aquifers

Radon (radon-222) is a water-soluble, radioactive gas that originates from the radioactive decay of radium-226, part of the uranium-238 decay series; thus the source of radon in groundwater is aquifer materials. Radon in drinking water is associated with lung cancer and stomach cancer.

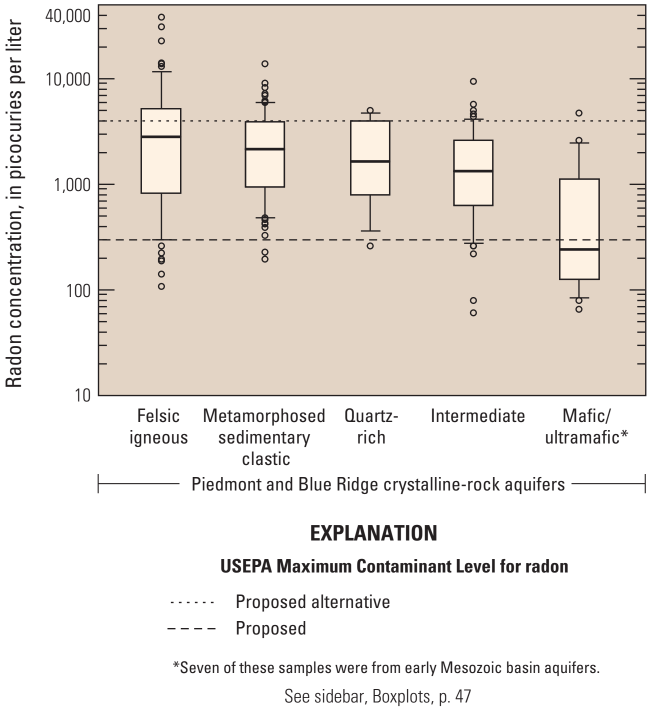
Concentrations of radon in 83 percent of the wells sampled exceeded the proposed MCL of 300 pCi/L, and 11 percent exceeded the proposed AMCL of 4,000 pCi/L for radon (table 5–1).[(23)] In the Piedmont and Blue Ridge crystalline-rock aquifers, one in every four samples contained radon at a concentration exceeding the higher of the two proposed MCLs (4,000 pCi/L) (fig. 6–8*A*).

High radon concentrations were very closely linked to bedrock type. Although median radon concentrations were greater than the proposed MCL of 300 pCi/L in water samples from all five Principal Aquifers (fig. 6–8*A*), concentrations in some samples exceeded the proposed AMCL of 4,000 pCi/L only in the Piedmont and Blue Ridge crystalline-rock aquifers, the early Mesozoic basin aquifers, and the Valley and Ridge siliciclastic-rock aquifers. The geographic distribution of the aquifers where radon exceeded 4,000 pCi/L includes a large percentage of the Piedmont, Blue Ridge, and Valley and Ridge regions (fig. 6–9.) Variations in lithology also affected the pattern of concentrations within individual aquifers. Within the Piedmont and Blue Ridge crystalline-rock aquifers, the mafic lithologic group had notably lower concentrations of radon relative to the other lithologic groups in that aquifer (fig. 6–8*B*).

A. Radon concentration by aquifer



B. Radon concentration by lithology



*Seven of these samples were from early Mesozoic basin aquifers.

See sidebar, Boxplots, p. 47

Figure 6–8. *A*, The median concentration of radon in groundwater samples from each of the five Principal Aquifers exceeded the proposed MCL of 300 picocuries per liter. Concentrations in one or more samples from the crystalline-rock aquifers and siliciclastic-rock aquifers exceeded the proposed AMCL of 4,000 picocuries per liter. *B*, Radon concentrations in groundwater samples from the Piedmont and Blue Ridge crystalline-rock aquifers and the early Mesozoic basin aquifers are related to lithologic group. In the lithologic groups from left to right, the rocks generally contain less uranium, and thus there is less radon in the groundwater.

Radon concentrations that exceeded the proposed AMCL of 4,000 pCi/L were measured in samples from wells across large areas of the Piedmont, Blue Ridge, and Valley and Ridge regions, and concentrations greater than 300 pCi/L were likely to be measured almost anywhere throughout this area (fig. 6–9). The widespread distribution of elevated concentrations of radon indicates the importance of continued public education and outreach, particularly because both air and water affect an individual's exposure to radon (see sidebar, Radon risk from water, this page).

Radon concentrations were most likely to be elevated in groundwater in the crystalline-rock aquifers.

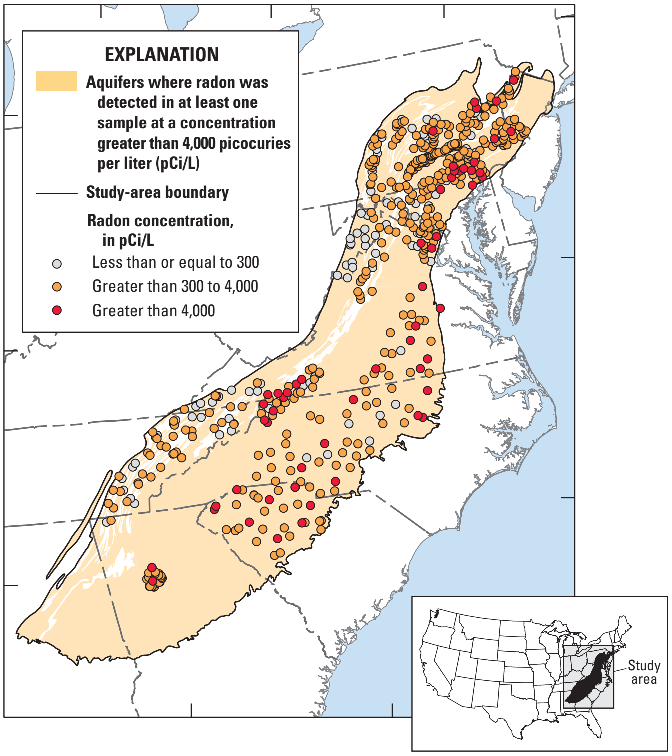
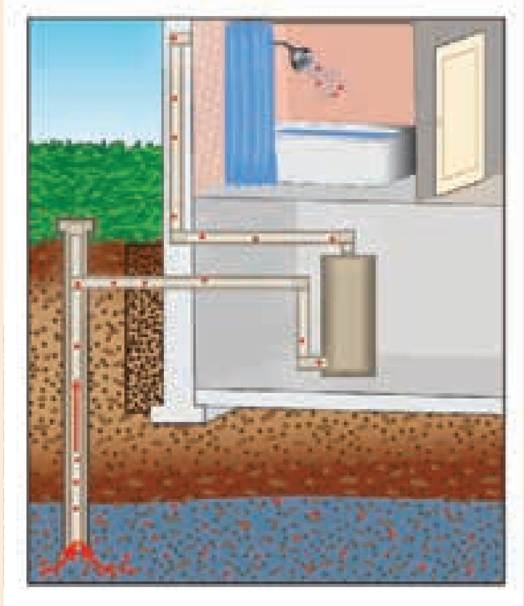


Figure 6–9. Wells with radon concentrations that exceeded the proposed AMCL of 4,000 picocuries per liter of radon were distributed across a large geographic area.

Radon risk from water

Radon is a naturally occurring radioactive gas and is part of the decay series of uranium, an element that is found in trace amounts in many aquifer sediments and rocks. Radon is soluble in water and was detected in samples of groundwater from all wells in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge Region. USEPA classifies radon as a human carcinogen,(49) and people who are exposed to radon, mostly in the air but also through drinking water, have an increased risk of getting cancer over their lifetime, especially lung cancer.(61) Health effects from radon in drinking water are primarily through inhalation, after the gas is released from solution—for example, in the shower. Radon gas (represented by red dots) dissolved in groundwater can be pumped from a well and then contained within household pipes. Once the water is aerated through a faucet and released into the air, the radon can be inhaled when people are close to showerheads or drinking directly from faucets.

In 1999, the USEPA proposed two regulatory levels for radon in drinking water. The higher level, the AMCL of 4,000 pCi/L, would apply to public water systems or states that have programs to reduce radon risks from all sources. The lower level, the MCL of 300 pCi/L, would apply to systems or states that do not have such programs in place.(23) Both proposed MCLs are used as human-health benchmarks in this circular, but are not yet formal regulatory benchmarks. For more information on radon and how to test for it, see *http://www.epa.gov/radon/index.html*.



Modified from Otten and others(75)

Radon gas (represented by red dots) dissolved in groundwater can be pumped from a well and then contained within household pipes. Once the water is aerated through a faucet and released into the air, the radon can be inhaled when people are close to showerheads or drinking directly from faucets.

Radium Exceeds Drinking Water Standards Only in Unique Geologic Areas

88
Ra
226

Radium is an element that results from the radioactive decay of uranium in aquifer materials. Elevated concentrations of radium, like radon, in drinking water are associated with an increased risk of cancer.

Only a single sample contained radium at a concentration that exceeded the MCL for radium (greater than 5 pCi/L for radium-226 and radium-228 combined; table 5–1). This sample was from a well in the early Mesozoic basin aquifers (table 5–2). The two siliciclastic-rock aquifers (Valley and Ridge siliciclastic-rock aquifers and early Mesozoic basin aquifers) had higher median concentrations of radium than did the Piedmont and Blue Ridge crystalline-rock aquifers. No samples from the Valley and Ridge carbonate-rock or Piedmont and Blue Ridge carbonate-rock aquifers were analyzed for radium.

Anoxic conditions and low pH favor the release of radium from minerals into groundwater.(36) Consequently, concentrations of radium exceeded 1 pCi/L more frequently in samples with anoxic or mixed redox conditions than in oxic samples. Of the samples in which the radium concentration exceeded 1 pCi/L, 85 percent had anoxic or mixed redox conditions or a pH value less than 6.5. For oxic samples, radium exceeded 1 pCi/L most frequently when pH values were less than 5.5.

High Concentrations of Nuisance Constituents and Properties in Groundwater Affect its Desirability for Use

Water from the carbonate-rock aquifers generally is hard, whereas water from the crystalline-rock aquifers has low pH and is corrosive.

Groundwater in many parts of the Piedmont, Blue Ridge, and Valley and Ridge regions did not meet recommended levels for nuisance constituents and properties. Where these constituents and properties, such as hardness and pH, are high or low, water treatment may be needed to improve the taste or odor or to prevent effects on plumbing, such as corrosion or encrustation. Groundwater in the Piedmont and Valley and Ridge carbonate-rock aquifers commonly is very hard. Groundwater in the Piedmont and Blue Ridge crystalline-rock aquifers commonly is soft and corrosive. Concentrations of dissolved iron and manganese are elevated primarily in groundwater from crystalline- and siliciclastic-rock aquifers.

Secondary Maximum Contaminant Levels (SMCLs)

SMCLs are referred to as guidelines, because they are not enforceable and do not relate to human health. Instead, they are intended to prevent scaling; staining of fixtures and laundry; corrosion of plumbing; undesirable taste, odor, and color; or other undesirable characteristics. Hardness does not have an SMCL but is included with the SMCLs because of its potential negative effect on water use.

Photograph by William Warner

Low pH can lead to corrosion, damaging pipes and eventually causing leaks.

Differences in the mineralogy of the five Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions affect the general chemistry of the water. Aquifer minerals such as calcite and dolomite that dissolve readily result in groundwater with high alkalinity and stable, near-neutral pH (6.5 to 7.5), whereas less soluble silicate minerals generally lead to groundwater with lower alkalinity and lower, less stable pH values. Dissolved minerals and the pH of the water can adversely affect use of the water (see sidebar, Secondary Maximum Contaminant Levels (SMCLs), p. 54).

Low pH and soft water can lead to corrosion, damaging pipes and eventually causing leaks. Hard water can cause scaling and clogging of plumbing (encrustation), but soft water with low pH can corrode pipes. Water was hard (calcium carbonate equivalent 150 to 300 mg/L) or very hard (calcium carbonate equivalent greater than 300 mg/L)(37) in about one-half of the drinking-water wells sampled, mostly in the carbonate-rock aquifers. About one-third of the samples were soft (calcium carbonate equivalent 0 to 75 mg/L) and had pH values less than the recommended pH of 6.5—the majority of these were from the Piedmont and Blue Ridge crystalline-rock aquifers. More than 90 percent of the wells in the two carbonate-rock aquifers and 65 percent of the wells in the early Mesozoic basin aquifers had hard water (fig. 4–2; table 5–3). Calcite and dolomite in the rocks of these aquifers dissolves easily and leads to groundwater with high concentrations of calcium and magnesium, which are the main components of water hardness. Although high hardness is not a major problem in the crystalline-rock aquifers, low pH levels and very soft water there can cause corrosion of plumbing (table 5–3).

Elevated concentrations of iron and manganese can cause staining of plumbing fixtures and laundry and can cause drinking water to have an unpleasant taste. Concentrations of iron exceeded the SMCL in 10 percent of the drinking-water samples from all aquifers, and manganese concentrations exceeded the SMCL in 19 percent of the drinking-water samples from all aquifers. Iron and manganese concentrations most commonly exceeded SMCLs in water from the Valley and Ridge siliciclastic-rock aquifers (table 5–3), where groundwater was more likely to be anoxic (fig. 4–3) and have low to moderate pH (fig. 4–2; table 5–3). Iron and manganese exceeded the SMCLs in nearly a quarter of the samples from the Piedmont and Blue Ridge crystalline-rock aquifers. Geochemical conditions typical of carbonate-rock aquifers, such as neutral pH and oxic conditions, lead to low concentrations of iron and manganese in the water. Substantial costs are associated with onsite treatment for low pH, hardness, or metals such as iron and manganese. Homeowners choosing not to treat their water face potential costs from corroded pipes (low pH), clogged plumbing fixtures (hard water), additional costs for detergents (hard water), or stained laundry (iron and manganese).

Elevated concentrations of iron and manganese in wells in the Valley and Ridge siliciclastic-rock aquifers can cause water to have an unpleasant taste and to stain laundry and plumbing fixtures.

Photograph courtesy of Culligan

Concentrations of Contaminants From Geologic Sources Are Controlled by Source, pH, and Redox Conditions

Concentrations of all five of the contaminants from geologic sources that were the focus of this study—arsenic, manganese, radon, uranium, and radium—are controlled by some combination of the minerals in the rock, pH, and redox conditions. In general, radon concentrations greater than 300 pCi/L in groundwater were common in all of the aquifers, but concentrations greater than 4,000 pCi/L were found only in areas with uranium-rich rocks (table 6–1). Elevated concentrations of manganese in groundwater are associated with more anoxic conditions, with pH being a potential secondary contributing factor. Elevated concentrations of arsenic and uranium in groundwater both are associated with elevated pH, with arsenic- or uranium-rich source rocks being a secondary factor (table 6–1). Elevated concentrations of radium in groundwater follow the same pattern as manganese, with elevated concentrations being associated with more anoxic conditions, and pH being a potential secondary contributing factor. These patterns of concentrations are different from those that would be anticipated based solely on abundance of source materials in the rock, illustrating the dominance of geochemical controls.

Table 6–1. Factors controlling concentrations of constituents from geologic sources in the groundwater of the Piedmont, Blue Ridge, and Valley and Ridge regions.

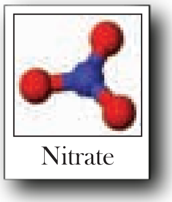
Constituent	Factors that favor elevated constituent concentrations
Radon	Uranium-rich aquifer rocks
Manganese	Manganese-rich aquifer rocks, low pH, low dissolved oxygen concentrations
Arsenic	Arsenic-rich aquifer rocks, high pH
Uranium	Uranium-rich aquifer rocks and high pH
Radium	Uranium-rich aquifer rocks, high pH, low dissolved oxygen concentrations

Chapter 7: *Contaminants Associated With Human Activities*

Human activities bring about changes that are visible on the land surface, such as fields and pastures, residential developments, small towns, and large cities. Each of these changes brings sources of potential contaminants to groundwater. In the Piedmont, Blue Ridge, and Valley and Ridge regions, a number of contaminants that are associated with human activities were detected in groundwater, and some were detected at concentrations of potential concern for human health. Samples from the two carbonate-rock Principal Aquifers frequently contained contaminants associated with human sources at concentrations higher than human-health benchmarks, but very few samples from the crystalline-rock and siliciclastic-rock aquifers exceeded these benchmarks. Bacteria and nitrate were the contaminants that most frequently exceeded their benchmarks. Pesticides and VOCs, although frequently detected, rarely were measured at concentrations exceeding human-health benchmarks.

This chapter describes the sources and factors that affect human-related contaminants in the Principal Aquifers in the Piedmont, Blue Ridge, and Valley and Ridge regions.

Photograph by Bruce Lindsey, USGS



Sources of nitrate include fertilizer, animal manure, and human sewage. Excess nitrate in drinking water is associated with adverse human-health effects, including methemoglobinemia, which can cause death in infants.(38)

Nitrate Exceeds Drinking-Water Standards in Carbonate-Rock Aquifers With Intensive Agricultural Activity

In the Piedmont and Blue Ridge and the Valley and Ridge carbonate-rock aquifers, concentrations of nitrate in more than 25 percent of samples from drinking-water wells exceeded the MCL of 10 mg/L as N. In contrast, in the Valley and Ridge siliciclastic-rock aquifers, early Mesozoic basin aquifers, and Piedmont and Blue Ridge crystalline-rock aquifers, the nitrate MCL was exceeded in fewer than 4 percent of samples. Bedrock type, land use, and redox conditions affect the concentrations of nitrate.

Nitrate Concentrations Are Highest in the Carbonate-Rock Aquifers

Nitrate concentrations in groundwater in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions exceeded the MCL of 10 mg/L for nitrate in 11 percent of the samples, but the distribution of high nitrate concentrations among the five aquifers was dissimilar (fig. 7–1*A*). Concentrations in the carbonate-rock aquifers were among the highest in the Nation (table A–4),(39) in sharp contrast to concentrations in the Piedmont and Blue Ridge crystalline-rock aquifers, the early Mesozoic basin aquifers, and the Valley and Ridge siliciclastic-rock aquifers, where the rate of exceedance of the MCL for nitrate for domestic wells was similar to that for the rest of the Nation.(9) The wide range in nitrate concentrations results from differences in aquifer susceptibility and sources of nitrogen.

Nitrogen Sources, Including Agriculture And Other Human Activities, Affect Nitrate Concentrations

Differences in sources of nitrogen ranged widely among the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions and account for many of the observed differences in nitrate concentrations in groundwater. Nitrate concentrations in groundwater were highest in areas affected by human activities on the land surface, such as agricultural and urban land use that create major sources of nitrogen (fig. 7–1*B*). Estimates of the annual mass of nitrogen applied in the area surrounding each site, including nitrogen from manure, chemical fertilizer, and atmospheric deposition, also can help to explain the variability in nitrate concentrations measured. Manure and chemical fertilizer were the primary sources of nitrogen in most areas and usually were directly related to high nitrate concentrations (fig. 7–2).(40)

Water from 25 percent of the wells and springs used as sources of drinking water in the two carbonate-rock Principal Aquifers exceeded the MCL for nitrate, the highest rate of exceedance among Principal Aquifers assessed in the Nation.

Groundwater from agricultural areas in the Piedmont and Blue Ridge carbonate-rock aquifers (fig. 7–1*B*) ranked as having the highest median nitrate concentrations of any of the agricultural areas sampled in the Nation (11 mg/L) (appendix A–4). In this area, 52 percent of the total area overlying the Principal Aquifer is agricultural land, and the number of pounds per square mile of nitrogen applied to the area surrounding wells in this area ranks among the highest in the Nation (fig. 7–2). Lancaster County, Pennsylvania, which overlies the Piedmont and Blue Ridge carbonate-rock aquifers and part of the Piedmont and Blue Ridge crystalline-rock aquifers, was ranked as the county with the highest application rate of nitrogen produced from manure from confined animal-feeding operations in the Nation in 1982, 1987, and 1992.(40) The samples from this area were predominantly from domestic-supply wells, so the results represent the drinking-water supply as well as recently recharged groundwater in agricultural areas.

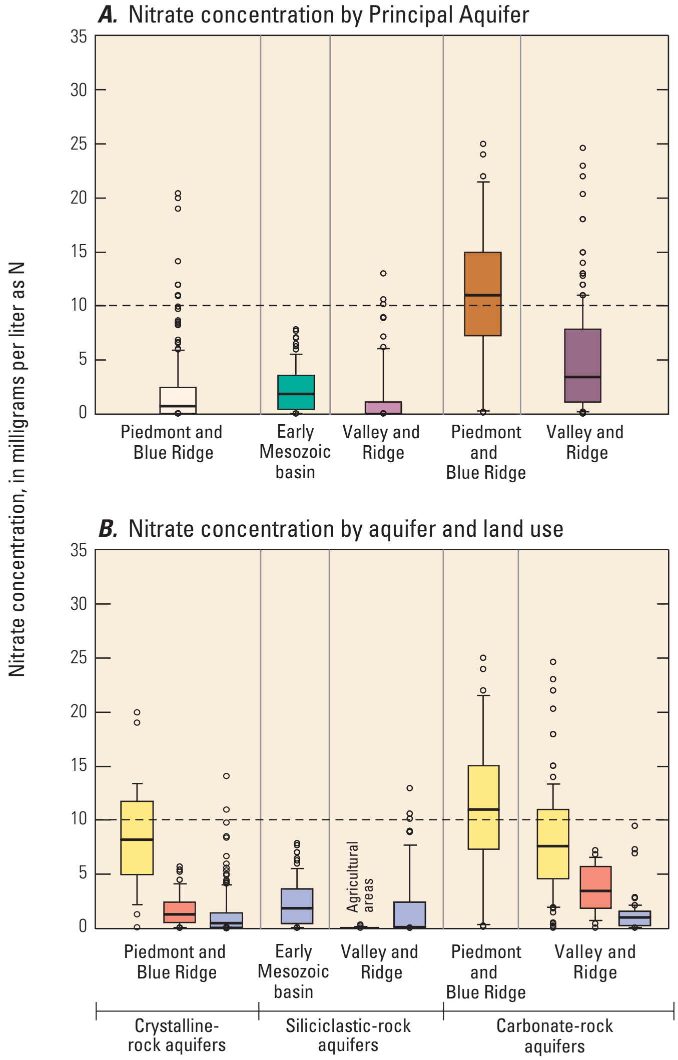


Figure 7–1. *A*, Nitrate concentrations were highest in the Piedmont and Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers. *B*, The combination of agricultural land use and carbonate or crystalline bedrock resulted in higher concentrations of nitrate in groundwater than did other aquifer and land-use combinations.

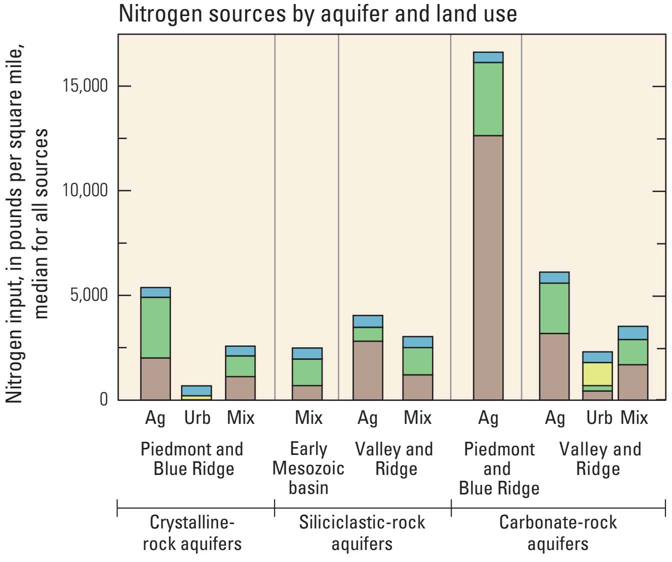


Figure 7–2. The Piedmont and Blue Ridge carbonate-rock aquifers underlie an area with some of the highest nitrogen inputs in the Nation, mainly as a result of manure application from animal-feeding operations.[40] The agricultural areas overlying other aquifers also have high inputs of nitrogen.

The wells sampled in an agricultural area in the Piedmont and Blue Ridge crystalline-rock aquifers also had high concentrations of nitrate (fig. 7–1*B*). Many of these samples were collected in Lancaster County, Pennsylvania. These wells are also domestic-supply wells, and although they are not plotted separately in appendix 4 (they are grouped with the domestic wells), the median concentrations of nitrate are among the highest in the Nation. Although this area makes up a fairly small part of the Piedmont and Blue Ridge crystalline-rock aquifers, these results demonstrate that, like the carbonate-rock aquifers, the crystalline-rock aquifers are vulnerable to nitrate contamination when nitrogen sources, such as fertilizer and manure, are present.

Redox Processes, Groundwater Age, and Karst Features Affect Transport and Fate of Nitrate

Although nitrogen sources help to explain concentrations of nitrate in groundwater, other factors play a critical role as well. Where an aquifer does not have conditions that favor nitrate persistence or transport, concentrations in groundwater may be low, even if large nitrogen sources are present.

Nitrate is most likely to degrade in the siliciclastic-rock aquifers, because of relatively old groundwater ages and anoxic conditions.

Whether or not nitrate remains in groundwater is controlled by denitrification, a process that reduces nitrate to harmless nitrogen gas (see sidebar, How do redox reactions work?, p. 31). Denitrification can take place in anoxic conditions but not in oxic conditions (see chapter 4). Nitrate in the carbonate-rock aquifers is least likely to be removed by denitrification, because these aquifers have the most oxic water (fig. 4–3). In contrast, many of the samples in the Valley and Ridge siliciclastic-rock aquifers had anoxic water (fig. 4–3), and the effects of denitrification are evident. The agricultural area of the Valley and Ridge siliciclastic-rock aquifers had the fourth highest inputs of nitrogen among the 10 aquifer land-use groupings (fig. 7–2), but samples from wells in these areas had the lowest median nitrate concentration of any of these groups (fig. 7–3). If wells with similar nitrogen inputs are compared, wells with oxic water had nitrate concentrations that were much higher than did wells with anoxic water (fig. 7–3). Although nitrate was more likely to become degraded in some aquifers than others, any individual well with oxic conditions and large nitrogen sources is likely to have high nitrate concentrations, regardless of the aquifer.

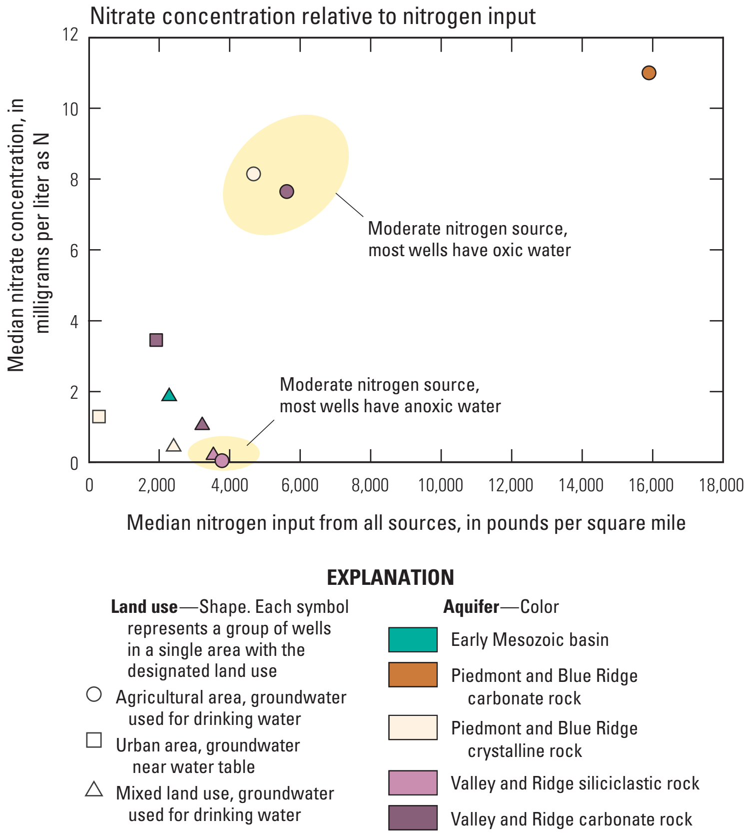


Figure 7–3. Nitrogen inputs and redox conditions together control concentrations of nitrate. Wells in areas with moderate inputs of nitrogen and oxic conditions had higher median nitrate concentrations than did wells in areas with moderate inputs of nitrogen and anoxic conditions. Median nitrate concentrations in the areas with anoxic groundwater were 20 to 100 times lower than those in areas with similar inputs of nitrogen and oxic groundwater. The nitrogen source is a circular area with a 1,640-foot radius around each well.(40)

Karst features in the carbonate aquifers provide a pathway for contaminants to enter the aquifer and contribute to oxic conditions that prevent nitrate from being removed by denitrification in the aquifer.

Groundwater age is related to nitrate concentrations because older water was recharged when nitrogen application rates were lower than at present and thus should contain lower concentrations of nitrate than water that recharged more recently. Also, reducing conditions that favor denitrification may take several years to develop. Because denitrification can substantially affect concentrations of nitrate, older water may have lower concentrations of nitrate than younger water, even if the initial nitrate concentrations were the same.

One of the reasons that the carbonate-rock aquifers are susceptible to nitrate contamination is that they have high-permeability karst features, such as sinkholes and conduits, which allow contaminants from the surface to easily enter the aquifer and to rapidly move through them (see sidebar, Karst features make carbonate-rock aquifers highly susceptible to contamination, p. 29). As a consequence, much of the water that reaches a well is very young. In addition, the presence of sinkholes favors oxic conditions,(41) making denitrification unlikely. The combination of direct infiltration of contaminants into the aquifer, rapid movement through the aquifer, and oxic conditions within the aquifer, coupled with large nitrogen inputs, explains the high nitrate concentrations in samples from the carbonate-rock aquifers.

Photograph by William Kochanov, Pennsylvania Geological Survey

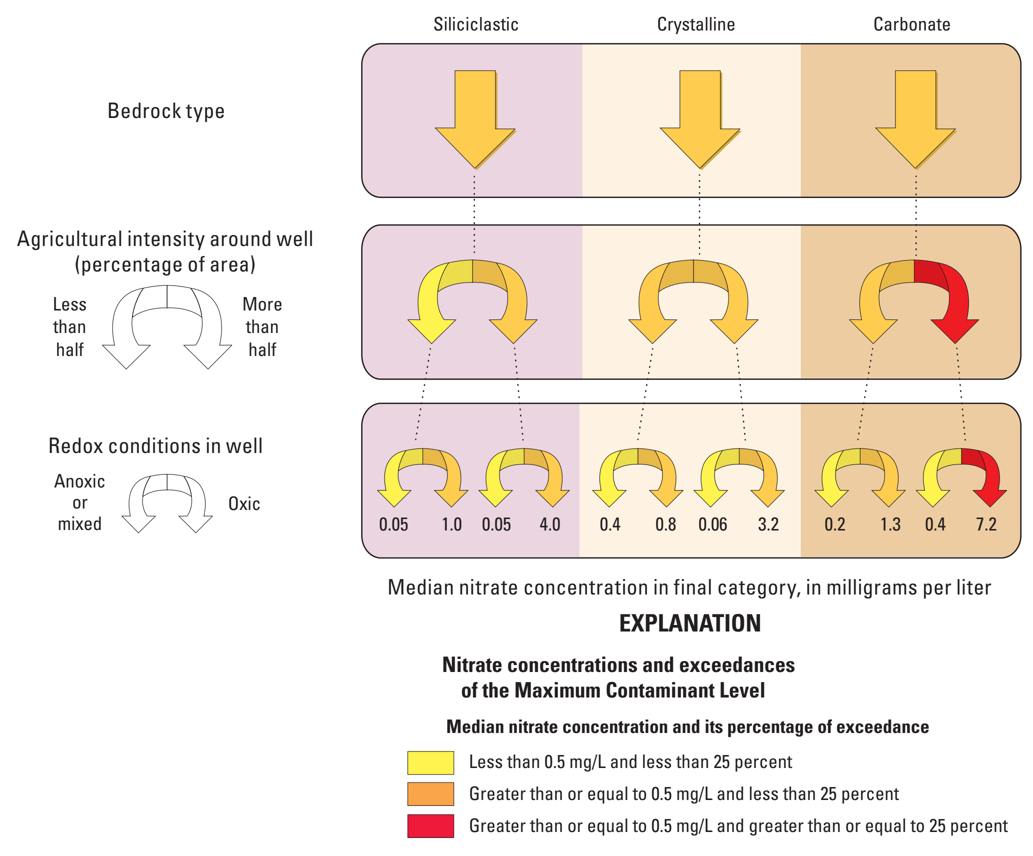
Photograph by Eliza Gross, USGS

Photograph by Eliza Gross, USGS

Weathered rocks that make up the carbonate-rock aquifer are exposed at the surface and provide direct pathways for water and contaminants to enter the aquifer without the filtering effects of soils. Voids, or enlarged holes in carbonate rocks, such as the ones shown here, are common in the aquifer. Water moves rapidly through these voids and remains oxygenated.

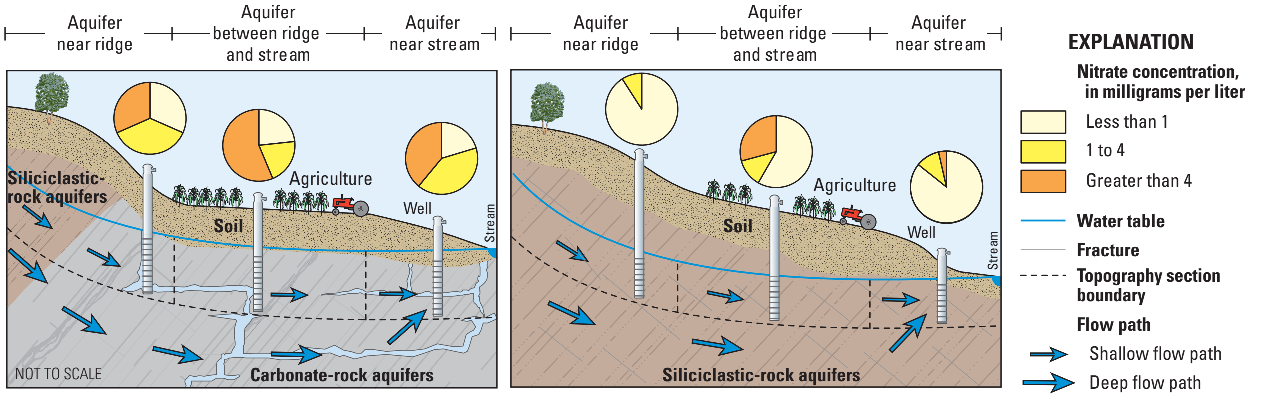
Bedrock type and agricultural land use are important, but ultimately redox conditions control nitrate concentrations

The interaction of bedrock, land use, and redox conditions control concentrations of nitrate in groundwater. Nitrate concentrations were higher in samples from the carbonate-rock aquifers than in samples from the siliciclastic-rock or crystalline-rock aquifers, and the areas with more agricultural land had higher nitrate concentrations than areas with less agricultural land. Within every bedrock-type and land-use category, the subsets of samples with oxic conditions had higher nitrate concentrations than the corresponding samples with anoxic or mixed redox conditions, and, within each bedrock type, the median nitrate concentration for the low agricultural land-use/oxic category was higher than for the high agricultural land-use/anoxic category. In the first category, inputs of nitrogen are low, but oxic conditions allow nitrate to persist, whereas in the second category, higher inputs of nitrogen are present, but anoxic or mixed redox conditions cause nitrate to be transformed into harmless nitrogen gas. No groups with anoxic or mixed redox conditions had median concentrations of nitrate that were greater than 0.5 mg/L, regardless of bedrock type or land use. These results illustrate that anoxic conditions result in low nitrate concentrations even where aquifers are highly susceptible and inputs of nitrogen are large.



In the Valley and Ridge region, the topographic position on the landscape affects nitrate concentrations

Nitrate concentrations are related to the topographic position of the well on the landscape in the Valley and Ridge region.[22] In the area close to the ridge, groundwater is oxic, making denitrification unlikely, but nitrate concentrations are low because few nitrogen sources are associated with the forested land use overlying that part of the aquifer. Midway between the ridge and stream, the nitrate concentrations are higher because the water is oxic, and agricultural activity provides nitrogen sources. Concentrations in groundwater close to the stream are lower, despite the high percentage of agricultural land overlying this area. Several reasons for this finding are possible. Shallow wells in this area may draw in water from the oldest end of a shallow flow path or a deep flow path converging toward the stream with even older water. Because the water at this point on the flow path is oldest, denitrification might have removed more of the original nitrate. Older water is also most likely to have recharged when nitrogen inputs at the land surface were lower (fig. 4–5). Understanding this potential spatial distribution of nitrate concentrations across a valley could be useful for choosing a source of water supply in these areas. This relation between nitrate concentration and topography applies to both the carbonate-rock and siliciclastic-rock aquifers of the Valley and Ridge region, although nitrate concentrations are higher in the carbonate-rock aquifers.



What Do High Concentrations of Nitrate Mean for Drinking-Water Availability?

Homeowners with high concentrations of nitrate in their domestic wells have three alternatives: potential human-health problems, treatment, or obtaining alternative sources of domestic supply (see sidebar, Cost of water treatment, p. 44). Which alternative is chosen depends on awareness, financial resources, and personal preferences of the homeowner. Domestic-well owners who are unaware of the issue or unable to afford treatment systems could be consuming contaminated water. The USGS did not assess public water systems in those areas of the carbonate-rock aquifers that had the highest levels of nitrate, but numerous public-supply systems in this aquifer have had to make costly upgrades for nitrate treatment. In Pennsylvania, fewer than 2 percent of approximately 18,000 public drinking-water systems that use groundwater as their source need a permanent nitrate-removal system, but most of those that do are concentrated in five counties that are underlain by carbonate-rock aquifers. The number of systems in those five counties using permanent nitrate treatment increased 13 percent between 2009 and 2012.

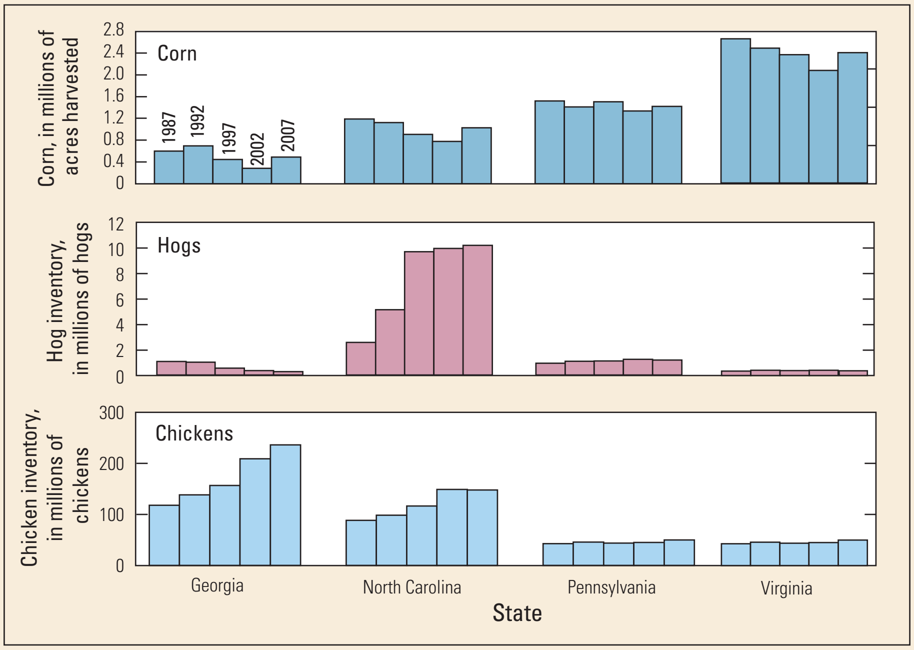
If nitrogen inputs increase substantially in areas overlying the carbonate-rock or crystalline-rock aquifers, concentrations of nitrate in groundwater could increase at some time in the future. For example, if the number of concentrated animal-feeding operations or the number of acres in corn production increases in areas overlying these susceptible aquifers, increases in nitrate concentrations in groundwater should be expected.

Imagery from Pictometry™ International Corporation

Concentrated animal-feeding operations produce large amounts of manure, which is stored in lagoons, as shown here, until it is used to fertilize crops. Areas with large sources of nitrogen from animal manure had the highest median nitrate concentrations.

Nitrogen sources are changing over time

Activities that affect nitrogen inputs are increasing in some states within the study area. Corn acreage began to trend downward in the late 1990s, but then increased in Georgia, North Carolina, Pennsylvania, and Virginia from 2002 to 2007, possibly from increased corn acreage for ethanol production. North Carolina had a large and increasing inventory of hogs during this time period. North Carolina is the state with the largest number of hogs in the study area and in 2007 ranked second in the Nation in hog production.(72–74) During 1987–2007, the number of hogs quadrupled, but the number of hog farms decreased by half because of the concentration of more animals onto a small number of very large operations. Georgia similarly had a continuing increase in the number of chickens and in 2007 had the largest number of broilers in the Nation. The general implication is that agricultural activity related to high concentrations of nitrate is increasing. As of 2012, only a single well network in these five Principal Aquifers has been sampled for trends in nitrate concentrations, and no statistically significant changes in nitrate concentrations were found.(62) The samples were from Pennsylvania and Virginia, however, where the rates of chicken and hog production are relatively steady. No samples for the determination of nitrate trends in well water were collected in networks in North Carolina or Georgia, where potential sources are increasing.



Bacteria Were Detected in Many Wells

In the Piedmont, Blue Ridge, and Valley and Ridge regions, total coliform bacteria were detected in all samples from springs and nearly 60 percent of samples from wells. *E. coli*, an indicator of fecal contamination, was detected in 91 percent of samples from springs and 17 percent of samples from wells. Although detections were frequent in all aquifers and settings, the carbonate-rock aquifers had a higher frequency of detection for *E. coli* and total coliform, as did areas overlain by agricultural land use.

Total coliform bacteria were detected in more than half of the wells sampled, regardless of aquifer, indicating that wells in fractured bedrock also are vulnerable to microbial contamination. Total coliform bacteria and *E. coli* were detected most frequently in wells in the Valley and Ridge carbonate-rock aquifers (fig. 7–4). Sinkholes, fractures, and rapid flow of water are typical of carbonate aquifers and make these aquifers vulnerable to bacterial contamination.

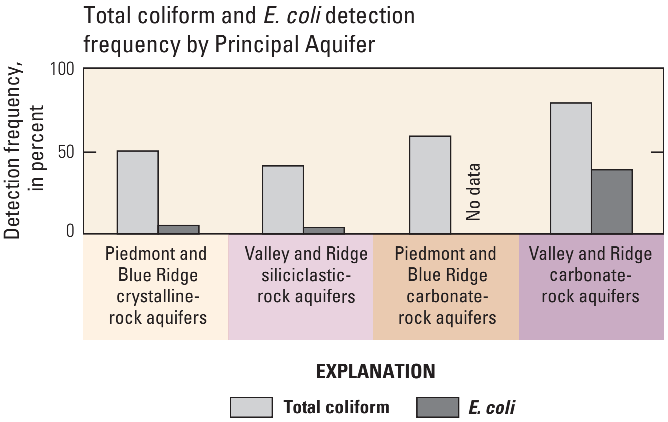


Figure 7–4. Total coliform bacteria were detected in nearly half of the wells in the sampled aquifers, indicating a potential pathway exists for microbial pathogens to contaminate water supplies. *Escherichia coli* (*E. coli*), an indicator of fecal contamination, was detected in nearly half of the wells sampled in the Valley and Ridge carbonate-rock aquifers. Most of the wells sampled were domestic-supply wells; domestic-well owners are responsible for monitoring and treating their household water supply. Springs were not included in the aquifer analysis.

Bacteria

Total coliform and E. coli *are found in the feces of warm-blooded animals; total coliform are also present in soils. Total coliform bacteria are typically not harmful, but they are used as a screening tool to signal the possible presence of other microbial contaminants.* E. coli *does not always cause illness but is an indicator of direct fecal contamination. Some strains of* E. coli *can cause gastrointestinal illness and even more serious health effects.*

One in four of the drinking-water sources (wells and springs) analyzed for bacteria showed evidence of fecal contamination, indicating a potential human-health concern.

Animal Manure and Human Sewage Are Sources of Bacteria

Sources of bacteria vary by land use.(42) Both total coliform and *E. coli* were detected more frequently in wells in agricultural areas than in wells surrounded by other land-use types (fig. 7–5), likely because of the high density of livestock and manure application in agricultural areas. In some cases, bacteria were detected in a well in an undeveloped area far from intensive livestock operations—in these cases, an onsite septic system or wildlife could have been the source of the bacteria.

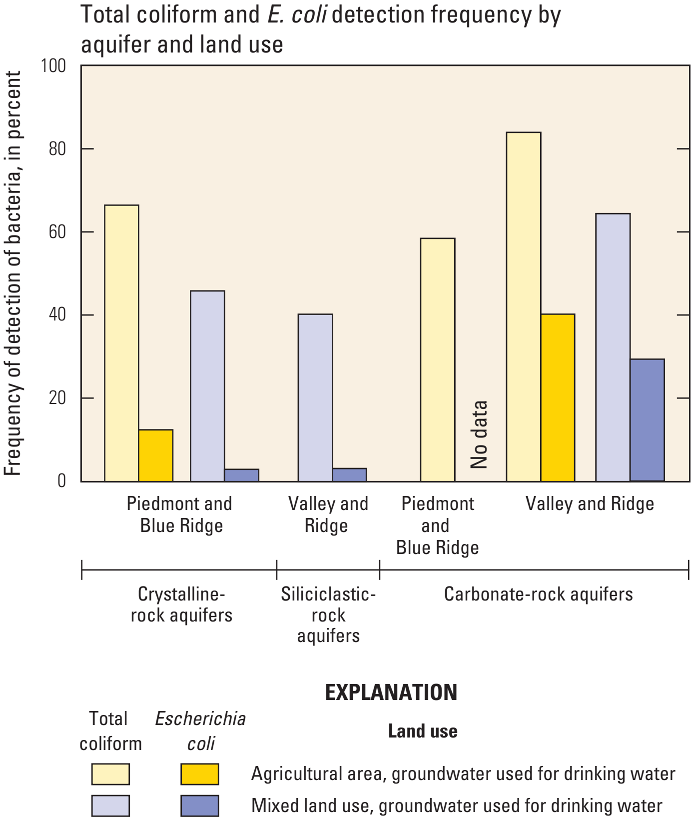
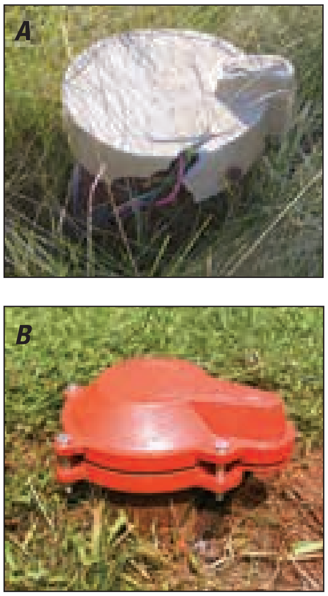


Figure 7–5. Total coliform and *Escherichia coli* were detected most commonly in samples from wells surrounded by agricultural land, likely because of manure application in these areas. The relatively high detection frequency of total coliform in all of the land-use areas likely is related to its presence in soils and other nonfecal environments.

Photograph by Tim McCabe, U.S. Department of Agriculture

Animal manure applied as a fertilizer is related to the highest nitrate concentrations and also introduces total coliform bacteria and *Escherichia coli* to the environment.



Photographs by Bruce Lindsey, USGS

A loose-fitting or poorly maintained well cap, such as *A*, the cracked cap in this picture, may not prevent bacteria from entering a well. *B*, A sanitary seal has a rubber gasket that tightly seals the casing when properly installed. This seal prevents dirt and insects from entering a well through the top of the casing and has been shown to reduce the frequency of detections of bacteria in wells.

Karst Features and Well-Construction Practices Affect the Transport and Survival of Bacteria

The presence of karst features helps explain why bacteria were detected more frequently in wells in carbonate-rock aquifers than in wells in other bedrock types (fig. 7–4). Furthermore, total coliform and *E. coli* were detected much more frequently in samples from springs—a typical karst feature—than in samples from wells (fig. 7–6). Springs typically flow out of large fractures that allow rapid transport of bacteria without any filtration.

Total coliform bacteria were detected in all, and *E. coli* was detected in nearly all, of the 23 springs sampled, which are used for drinking-water supply. Drinking water that contains *E. coli*, a common indicator of fecal contamination, could be a risk to human health. Springs can have short, shallow flow paths and are not protected from bacterial sources at the land surface. Although wells typically have a casing that prevents surface runoff from entering the well, both wells and springs in the carbonate-rock aquifers are highly vulnerable to fecal contamination.

Well-construction characteristics are important factors that affect concentrations of bacteria, particularly *E. coli*.(43) A loose-fitting well cap allows dirt and insects to get underneath and fall into the well. Sanitary well caps minimize the detection frequency of bacterial contamination.(43) Lack of a cement-grout seal can allow water and bacteria to travel down the annular space outside of the casing and into the well (see sidebar, Anatomy of a well, p. 11). Wells with cement-grout seals had a lower detection frequency of bacteria than did wells in which soil was used to fill the annular space.(44)

Implications of Fecal Contamination of Water Supplies

Human consumption of bacteria-laden water from domestic-supply wells probably is common and is likely to cause a number of unreported illnesses.(45) Education focused on homeowner awareness of the benefits of maintaining well integrity, regular water testing, and treating water from the domestic-supply well could reduce exposure to bacteria from drinking water. In some cases, even those who are aware of bacterial contamination of their domestic-water supply choose to drink the water because of the high cost of permanent point-of-use treatment or purchasing bottled water. Pathogenic viruses that cause illness—not just indicator organisms—are present in some samples of water drawn from wells tapping the Piedmont and Blue Ridge crystalline-rock aquifers, the Valley and Ridge carbonate-rock aquifers, and the Valley and Ridge siliciclastic-rock aquifers.(46)

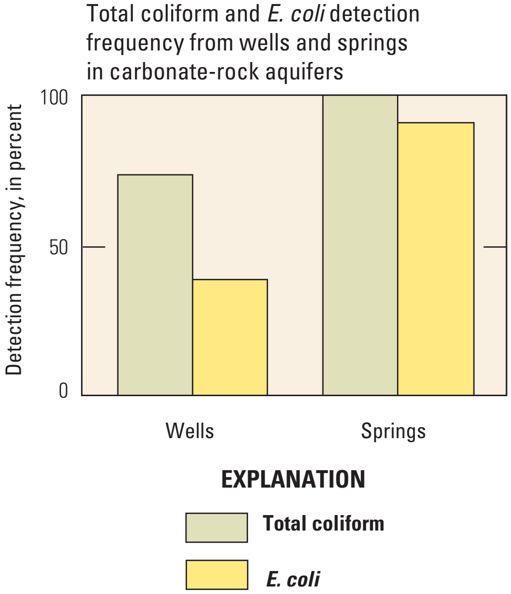


Figure 7–6. Total coliform bacteria were detected in all, and *Escherichia coli* (*E. coli*) was detected in nearly all, of the 23 springs sampled, which are used for drinking-water supply. Drinking water that contains *E. coli*, a common indicator of fecal contamination, could be a risk to human health.

Pesticides Were Detected Frequently but in Most Cases at Low Concentrations

At least one pesticide was detected in 55 percent of samples, and multiple pesticide compounds were commonly detected in a single sample. Median atrazine concentrations in domestic wells in the Piedmont and Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers were higher than those measured in domestic wells nationally. However, only 2 of the 47 pesticides analyzed—dieldrin and alpha-HCH—were measured at concentrations that exceeded their human-health benchmarks—and these exceedances were found in samples from fewer than 2 percent of sites used as sources of drinking water.

Thirty-five of the 47 pesticide compounds measured were detected in at least one sample, and at least one pesticide was detected in 55 percent of samples. The most frequently detected pesticides were atrazine, deethylatrazine, metolachlor, simazine, prometon, tebuthiuron, and dieldrin. Of the 47 pesticides analyzed, only dieldrin and alpha-HCH were measured at concentrations that exceeded their human-health benchmarks in samples of drinking water. The concentration of dieldrin exceeded its human-health benchmark in water samples from 1.3 percent of sites, and alpha-HCH exceeded its human-health benchmark in water samples from 0.2 percent of sites used as drinking water. Pesticides at concentrations greater than one-tenth of a human-health benchmark are approaching levels of potential concern for human health.(48) Atrazine exceeded 0.3 µg/L, one-tenth of its MCL of 3.0 µg/L, in 7 percent of samples collected from sites used as sources of drinking water. The pesticides cyanazine, simazine, and alachlor also were detected at concentrations greater than one-tenth of their respective human-health benchmarks in some wells (see appendix 3, table A3–2).

Pesticides

Pesticides include herbicides, insecticides, and fumigants. Pesticides analyzed for this study include compounds that can cause cancer(47) or other adverse health effects.(24)

Only two pesticide compounds were measured at concentrations that exceeded their human-health benchmarks and that occurred in fewer than 2 percent of the wells sampled.

Photograph by Connie Loper, USGS

Bedrock Type and Land Use Affect the Occurrence and Distribution of Pesticides

Pesticides were detected in more than 90 percent of samples of groundwater from carbonate-rock aquifers in areas overlain by urban or agricultural land use.

The frequency of detection of at least one pesticide was greater in samples from the agricultural and urban areas in carbonate- and crystalline-rock aquifers than in samples from the other combinations of Principal Aquifer and land use (fig. 7–7). Detection frequencies in those areas were among the highest in the Nation. Almost all of the samples with concentrations exceeding one-tenth of any pesticide benchmark were collected from wells in carbonate-rock aquifers overlain by agricultural land use.

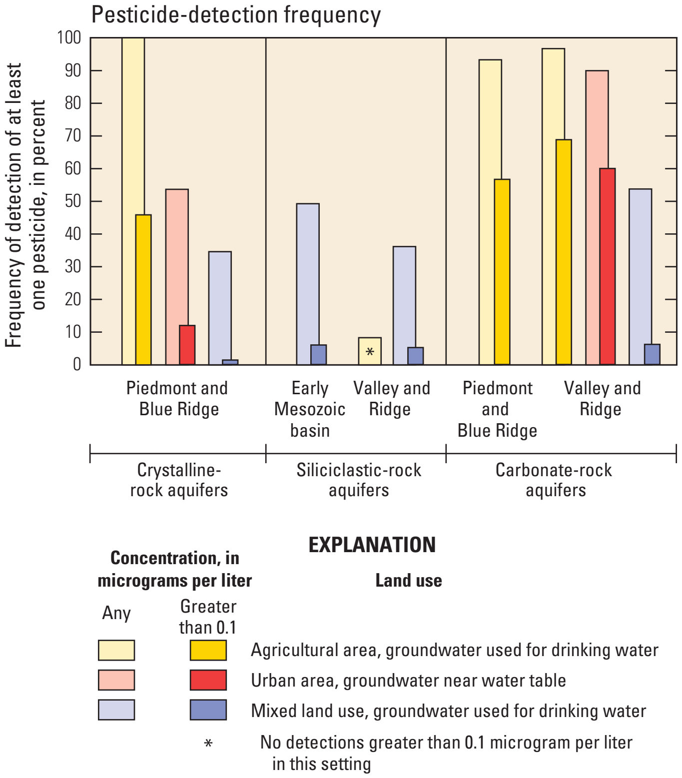


Figure 7–7. Pesticides were detected most frequently in samples from carbonate- and crystalline-rock aquifers in areas overlain by agricultural or urban land use. Detection frequencies in these areas are among the highest in the Nation.

Assessment levels

Pesticide occurrence is evaluated at two assessment levels: detections at any concentration without regard to differences in reporting levels among pesticides, and detections at a concentration greater than 0.1 µg/L. The second option is called a common assessment level, and it facilitates comparison of detection frequencies among compounds with different reporting levels.

Mixtures of pesticides (two or more pesticides detected in the same sample) also were detected more frequently in the carbonate-rock aquifers than in crystalline- and siliciclastic-rock aquifers (fig. 7–8). In fact, mixtures of pesticides in the Piedmont and Blue Ridge and Valley and Ridge carbonate-rock aquifers were much more prevalent than in aquifers nationwide with five or more pesticides detected in more than 40 percent of wells in agricultural areas and more than 80 percent of the wells in urban areas. In contrast, the frequency of detection of mixtures in crystalline- and siliciclastic-rock aquifers was nearly identical to that seen nationally, with the exception of the crystalline-rock aquifers in areas of agricultural land use. In all of the bedrock types, mixtures were usually detected more frequently in water from sites in agricultural and urban land-use settings than in water from sites used as a drinking-water supply in areas of mixed land use. Human-health benchmarks are not available for most mixtures of pesticides, but the detection of multiple pesticide compounds in drinking-water wells is a potential health concern, even at concentrations below human-health benchmarks. The reason is that the health effects of mixed compounds may be different from the health effects of each compound in isolation, and these interactions are not well understood.(2)

Detections of multiple pesticides in a well were much more common in the carbonate-rock aquifers than in the crystalline- and siliciclastic-rock aquifers or in other aquifers nationally.

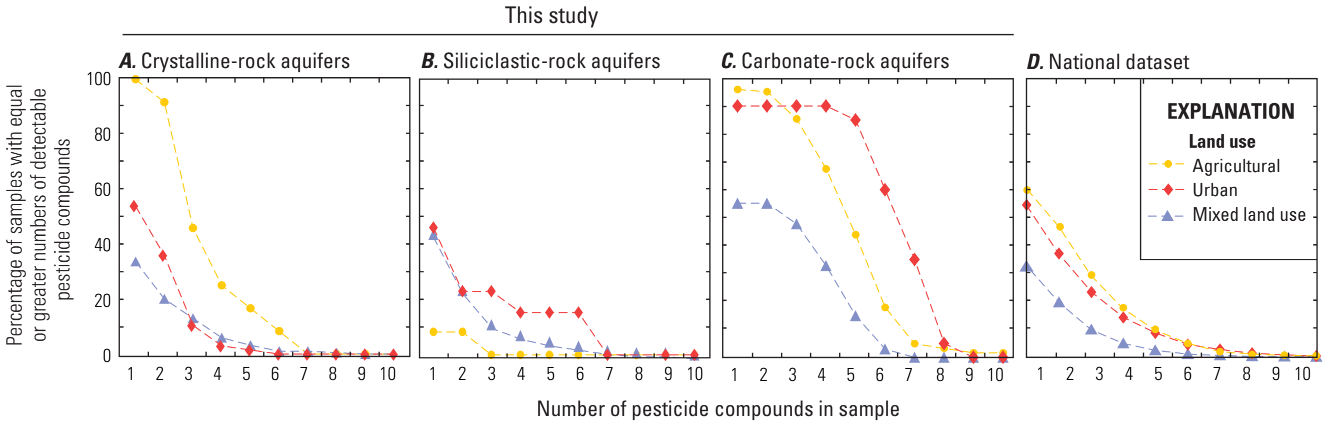


Figure 7–8. Mixtures of pesticides (two or more pesticides in the same sample) were more common in samples from the carbonate-rock aquifers *(C)* than in samples from crystalline- and siliciclastic-rock aquifers *(A, B)*. With the exception of mixtures in the crystalline-rock aquifers in areas of agricultural land use, the pattern of pesticide mixtures in crystalline- and siliciclastic-rock aquifers *(A, B)* was similar to that reflected in data for the entire Nation *(D)*.(10)

Sources of Pesticides Are Related to Land Use and Affect Which Pesticides Are Detected

Most pesticides are manmade chemicals, and their presence in the environment is the direct result of human activities in the agricultural, industrial, commercial, and home and garden environments.(10) Undeveloped areas such as forests include little or no direct pesticide sources, and pesticides were rarely detected in samples collected in those areas. Atrazine and metolachlor are agricultural pesticides with high application rates in the Piedmont, Blue Ridge, and Valley and Ridge regions (appendix 5). Detection frequencies of these two herbicides and deethylatrazine (a degradation product of atrazine) were higher in areas with more agricultural land use (fig. 7–9). Higher concentrations of dieldrin, a pesticide that was used in urban areas and is now banned, were detected in areas with a larger percentage of urban land surrounding a well.(8, 22) Simazine, prometon, and tebuthiuron are general-use herbicides that have both agricultural and urban uses—these pesticides were detected most frequently in samples from urban areas in the carbonate-rock aquifers. Pesticides with highest use—atrazine and metolachlor—were among the most frequently detected pesticides in domestic and public-supply wells (fig. 7–10).

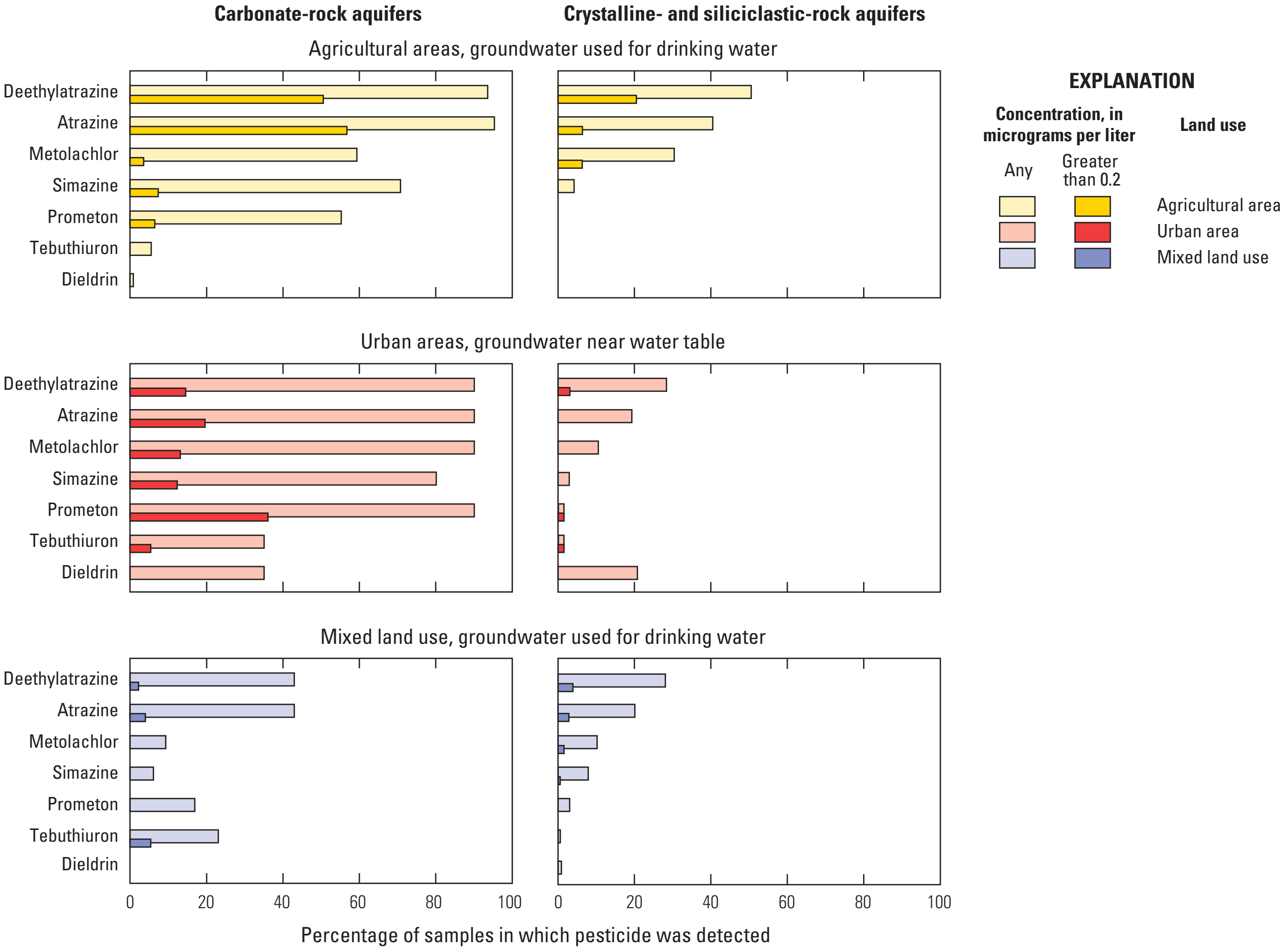


Figure 7–9. Pesticides were detected most frequently in samples of groundwater in the carbonate-rock aquifers in areas overlain by agricultural and urban land use. Detection frequencies for metolachlor, simazine, and prometon in urban networks in the carbonate-rock aquifers equaled or exceeded the detection frequency in agricultural networks. The agricultural-use herbicides deethylatrazine, atrazine, and metolachlor also had high detection frequencies in wells from the crystalline-rock aquifers overlain by agricultural land use. These pesticides were not detected in the siliciclastic-rock aquifers overlain by agricultural land use.

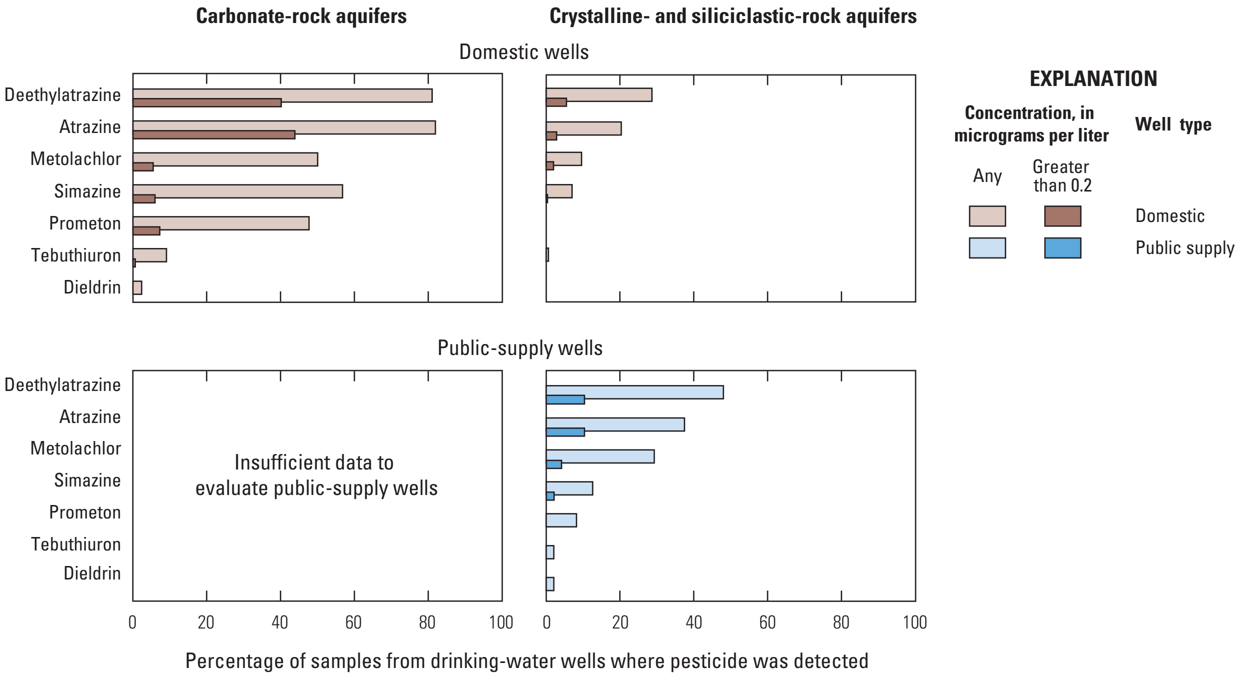


Figure 7–10. All seven of the most frequently detected pesticides were detected most often in samples of groundwater from domestic wells in the carbonate-rock aquifers. Many of these domestic wells are also in agricultural areas. Comparisons show that detection frequencies in public-supply wells in crystalline-rock aquifers are greater than in domestic wells in that same aquifer; however, other comparisons to public-supply wells are not possible because of the lack of samples.

Photograph by Kevin Breen, USGS

Chemical Properties of Pesticides Affect Their Transport and Persistence

The combination of use and physical and chemical properties influences the likelihood of the detection of a pesticide in groundwater. Two aspects of pesticide chemistry of particular importance are resistance to degradation—often call “persistence”—and the pesticide’s affinity for attaching, or adsorbing, to the surfaces of soil particles. Persistent pesticides remain in the environment in their original form for long periods and hence have the potential to be transported once they are released in the environment. A persistent pesticide that does not adsorb to soil has a high potential to move down to and with the groundwater and likely will be detected more frequently than a nonpersistent pesticide that adsorbs to soil.

Metolachor and atrazine have high and nearly identical application rates in this area (appendix 5), and neither is likely to adsorb to soil particles, but metolachor was detected about half as often as atrazine, likely because metolachor breaks down more rapidly. Chlorpyrifos has a moderately high application rate (appendix 5), but is almost never detected (appendix 3, table A3–2) because it adsorbs to particles and breaks down quickly. Dieldrin was banned several years before these samples were collected and moves very slowly in groundwater because it readily adsorbs to particle surfaces but is still detected because it breaks down very slowly.

Atrazine Concentration is Related to Topographic Position

The relations among the combined effects of sources, transport, fate, and frequency of detection of pesticides in the environment are illustrated by atrazine concentrations in the Valley and Ridge carbonate-rock aquifers. In the topographic position nearest the ridge, atrazine concentrations in groundwater increase from the ridge toward the valley. The ridge is mostly forested, and the increase in concentrations likely results from the increasing intensity of agricultural activity and pesticide use toward the valley (fig. 7–11). In the middle topographic section, concentrations do not change substantially. In the area near the stream, however, concentrations of atrazine decrease, despite high percentages of urban and agricultural land use in the valley center. This decrease could be the result of dilution, as deeper flow paths with old, low-atrazine water converge with shallower flow paths toward the discharge point. A sample with a larger proportion of old water is likely to have lower concentrations of pesticides because the older water was recharged during a time when usage was lower, and any atrazine that might have been present may have been degraded.

Pesticides Detected in Drinking-Water Wells and Springs Rarely Exceeded Human-Health Benchmarks

The likelihood of a pesticide concentration exceeding a human-health benchmark in a public-supply well or domestic well is low on the basis of the results of this assessment. Only about 2 percent of the wells sampled had a pesticide concentration that exceeded its benchmark. Furthermore, the pesticide that most frequently exceeded its benchmark was dieldrin, which is no longer used. The prevalence of mixtures of pesticides in groundwater could be important if new information about the human-health effects of mixtures becomes available. However, the frequent detection of pesticides indicates that manmade chemicals can be transported to and through all five aquifers. The awareness that these aquifers are susceptible to contamination from manmade chemicals is important when future aquifer-protection efforts and the need for continued monitoring are considered as chemical-use patterns evolve.

> *The likelihood that a concentration of a pesticide in groundwater used as a source of drinking water will exceed a human-health benchmark is very low.*

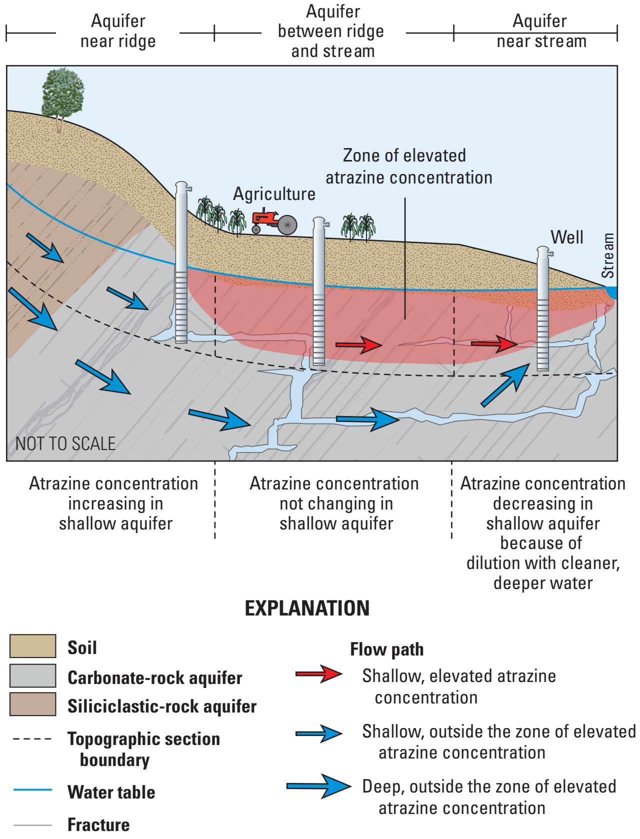
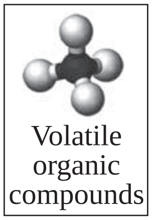


Figure 7–11. Concentrations of atrazine in groundwater are related to the topographic position on the landscape in the Valley and Ridge carbonate-rock aquifers.(22) Across the three topographic positions within the shallow aquifer, atrazine concentrations tended to increase as groundwater moved away from the ridge, remained stable between the ridge and the stream, and decreased as groundwater approached the stream. This pattern is attributed to increases in sources of atrazine along the valley floor and degradation of atrazine along the flow path and (or) dilution with older water less affected by atrazine use.

Volatile Organic Compounds Were Frequently Detected in Samples of Groundwater From Urban Areas



Volatile organic compounds are in gasoline, solvents, and other household, commercial, and industrial chemicals. VOCs analyzed for this study include compounds that can cause cancer(47) or other adverse health effects.(24)

VOCs were frequently detected in wells in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions, but concentrations generally were below human-health benchmarks. Almost 30 percent of the samples from wells had at least one VOC detected at a common assessment level of 0.2 µg/L or greater, with chloroform and methyl *tert*-butyl ether (MTBE) having the highest detection frequency. Detection frequency of VOCs was highest in urban areas. Only one well used as a source of drinking water had a concentration of a VOC (trichloroethene) that exceeded an MCL, and another well had a concentration that exceeded the human-health benchmark for acrylonitrile.

Of the 86 VOCs analyzed, only trichloroethene and acrylonitrile had concentrations that exceeded human-health benchmarks (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 14)(48, 49) in samples collected from sources of drinking water. A single sample from a domestic-supply well in the early Mesozoic basin aquifers contained trichloroethene (TCE) at a concentration that exceeded its MCL, and a sample of raw water (before treatment) from a public-supply well in the Piedmont and Blue Ridge crystalline-rock aquifers contained acrylonitrile at a concentration that exceeded its human-health benchmark. Eight other VOCs—1,2-dichloroethane, 1,2-dichloropropane, benzene, carbon tetrachloride, methylene chloride, naphthalene, tetrachloroethene (PCE), and trichloromethane (chloroform)—were detected at concentrations that were greater than one-tenth of their respective human-health benchmarks in samples from sources of drinking water (appendix 3, table A3–3 lists all VOCs analyzed and their detection frequencies).

Of the 86 VOCs analyzed, 54 were detected in at least one sample. MTBE was the most frequently detected VOC in drinking-water supply wells, followed by chloroform, 1,1,1-trichloroethane, PCE, and TCE (appendix 3, table A3–3). The frequency of detection of chloroform at concentrations of greater than 0.2 µg/L in domestic-supply wells in all of the aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions (7 percent; fig. 7–12) was only slightly higher than the national rate of (5 percent).(50) Public-supply wells in the crystalline-rock aquifers, however, had detection frequencies of chloroform (19 percent; fig. 7–12) that were almost twice as high as the national rate (11 percent).(50) High pumping rates in public-supply wells capture water recharged from a larger area than domestic-supply wells, increasing the probability of drawing water from an area affected by a leak or spill of VOCs. The public-supply wells in the crystalline-rock aquifers are in densely populated areas, where there are many potential sources of VOCs. These factors can increase the detection frequency of VOCs in public-supply wells.(2) Unlike the other human-related contaminants—nitrate and pesticides—differences in detection frequencies of VOCs among domestic wells in carbonate and crystalline-rock and siliciclastic-rock aquifers at a common assessment level of 0.2 µg/L were negligible.

Although concentrations of VOCs were well below human-health benchmarks, detections of VOCs in samples from about one-third of the wells indicated a general susceptibility to contamination by VOCs.

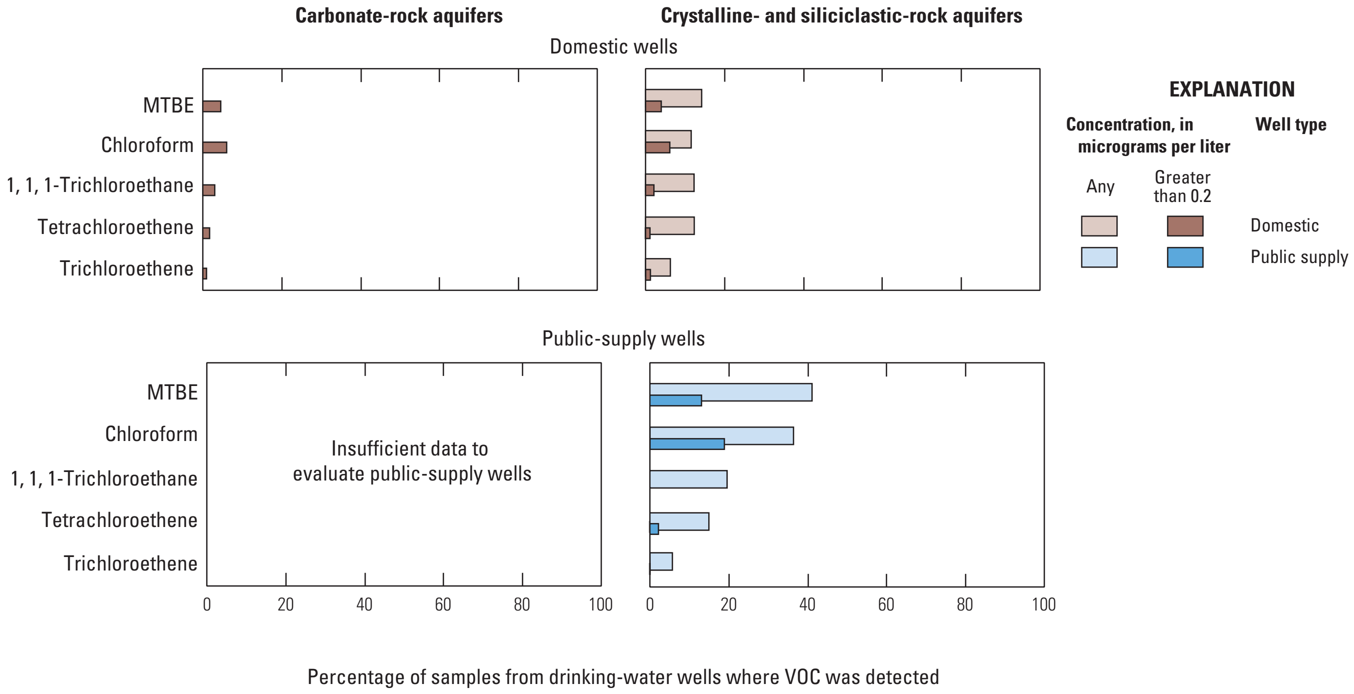


Figure 7–12. The highest detection frequencies of the most frequently occurring VOCs were in public-supply wells in the crystalline rock aquifers, but public-supply wells were not evaluated in the other aquifers. These wells tend to be in more urban areas, and high pumping rates in these wells draw in water from a large area. Comparisons show very low detection frequencies in the carbonate bedrock and the other bedrock types and similar patterns of detection frequencies. Domestic wells in all of the aquifers tended to be near forested or agricultural areas, where potential VOC sources are few.

Photograph copyright istockphoto.com

Volatile Organic Compounds Are Associated Primarily With Urban Land Use and Densely Populated Areas

Detection frequencies of VOCs were highly variable by land-use category, ranging from 75 percent in groundwater from urban areas of the carbonate-rock aquifers to as low as 4 percent in groundwater from agricultural areas of the Valley and Ridge carbonate-rock aquifers (fig. 7–13). The higher frequency of detection for VOCs in urban groundwater than in other land-use types is consistent with the greater abundance of potential sources of VOCs in urban areas. The majority of the detections in urban areas were in shallow monitoring wells not used as sources of drinking water. The pattern of detection frequencies for MTBE, chloroform, 1,1,1-trichloroethane, tetrachloroethene, and trichloroethene with respect to land use (fig. 7–14) was similar to the overall detection pattern for VOCs (fig. 7–13), with all five being detected more frequently in wells in urban areas than in wells in areas with agricultural land use or drinking-water-supply wells in areas of mixed land use.

> *Because VOC detections are related to urban land use, areas that are densely populated but rely on groundwater for domestic supply are at the greatest risk of exposure to VOCs.*

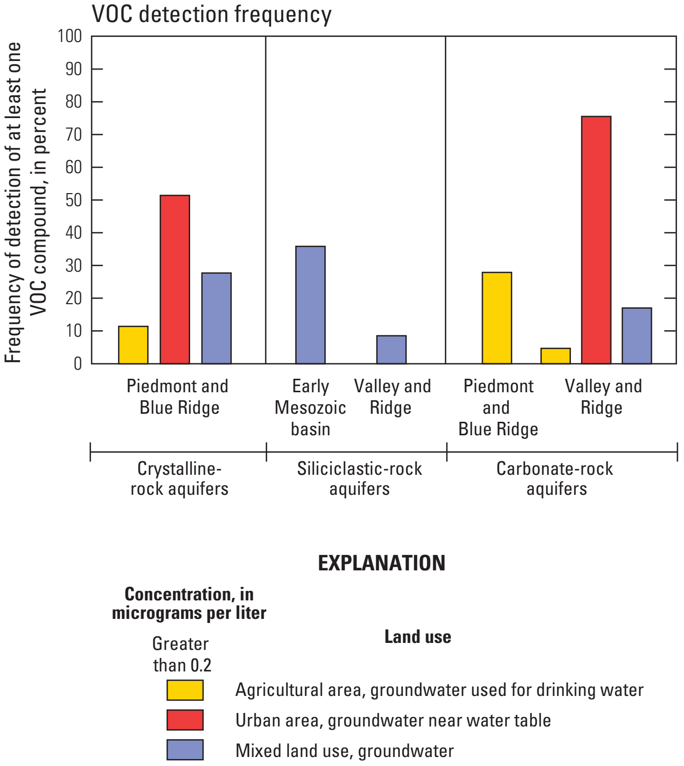


Figure 7–13. VOCs were detected most commonly in wells in urban areas overlying the carbonate-rock aquifers. This detection frequency is consistent with the greater abundance of potential sources of VOCs in urban areas. The differences among bedrock types, however, were not as large as for other contaminants related to human activities, such as pesticides and nitrate.

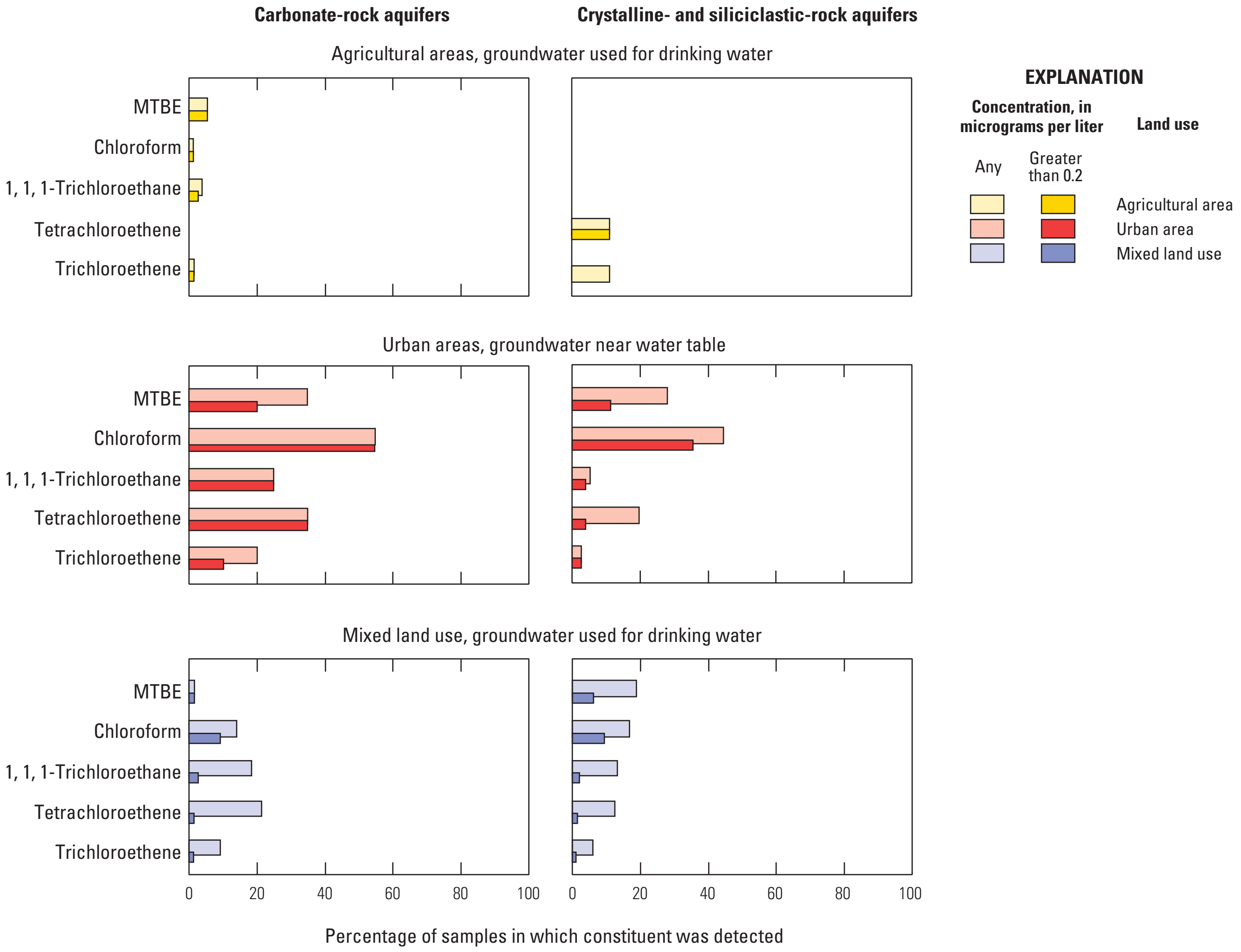


Figure 7–14. Differences among detection frequencies for the five most frequently detected VOCs follow the same pattern as the overall detection frequencies. Detections were rare in agricultural areas and most frequent in urban areas, and detection frequencies were highest in the urban areas underlain by carbonate bedrock. In areas of mixed land use, detection frequencies did not vary greatly among the three aquifer bedrock types.

The frequency of detection of VOCs in groundwater is highest in the most densely populated portions of the study area (fig. 7–15). Wells in urban areas and the densely populated early Mesozoic basin area had higher detection frequencies of at least one VOC than did wells in more rural areas with lower population densities but highly susceptible carbonate lithologies. This result is consistent with the increase in potential VOC sources as population density increases. Sources of the VOCs analyzed include gasoline, disinfection byproducts (created from chlorination of water or wastewater), solvents, and organic synthesis compounds. These VOCs enter the environment from leaking storage tanks and accidental spills, which are more common in urbanized areas than in agricultural or rural areas. Products that go down household drains may also contain VOCs; therefore, septic systems and leaking sewer lines also could be a source of VOCs to groundwater. Densely populated areas often use public water supplies, which would be required to test and treat for VOCs if concentrations were above MCLs. Homeowners in areas that are densely populated but that continue to use domestic-supply wells would be most likely to encounter high concentrations of VOCs.

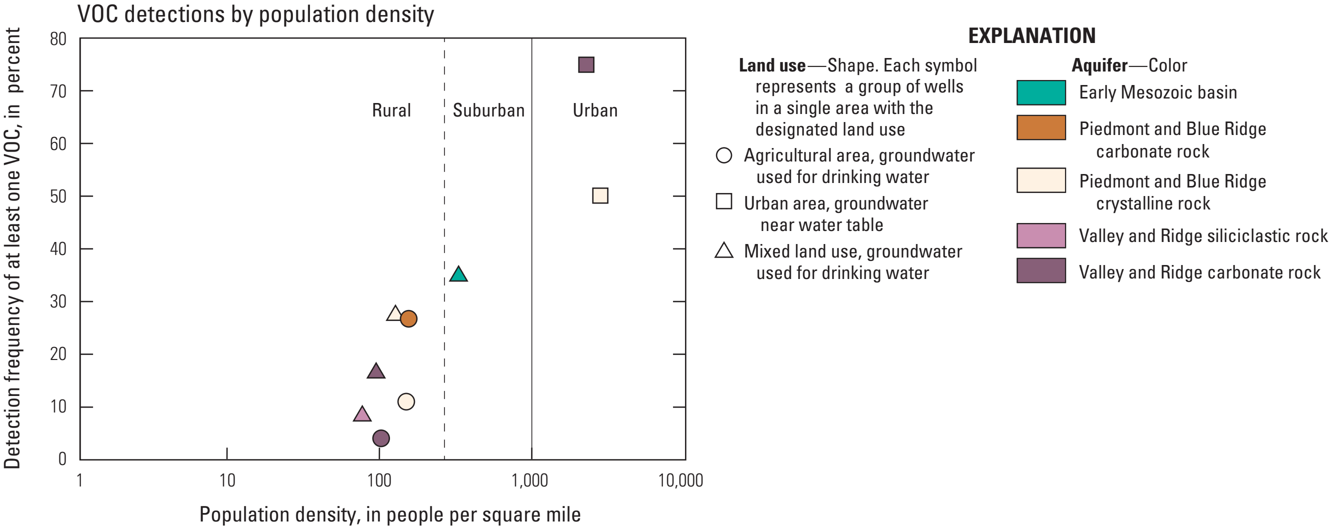


Figure 7–15. As population density[(40)] increases from rural to suburban to urban areas, the frequency of detection of at least one volatile organic compound increases from less than 10 percent to more than 75 percent.

MTBE and chloroform accounted for nearly 40 percent of all of the detections of VOCs. Both MTBE and chloroform are highly soluble, degrade relatively slowly in both oxic and anoxic groundwater,(51) and are widely used. MTBE was used from the late 1980s until about 2006 to increase the octane rating of gasoline, and its presence in groundwater likely is the result of leaking storage tanks or other inadvertent releases. Use of MTBE has recently been banned in many states as a result of its widespread presence in groundwater; however, its use was common during the sampling period for the studies summarized in this report.(50) Chloroform has some industrial uses, but it also is a byproduct that is formed when water is disinfected with chlorine, one of the most common procedures used at water-treatment plants. Chlorinated tap water used for irrigation or leaking sewer lines therefore could be a source of chloroform to groundwater. The characteristics of these chemicals coupled with their pervasive sources account for their high detection frequency in groundwater.

Chloroform and MTBE accounted for nearly 40 percent of the detections of VOCs.

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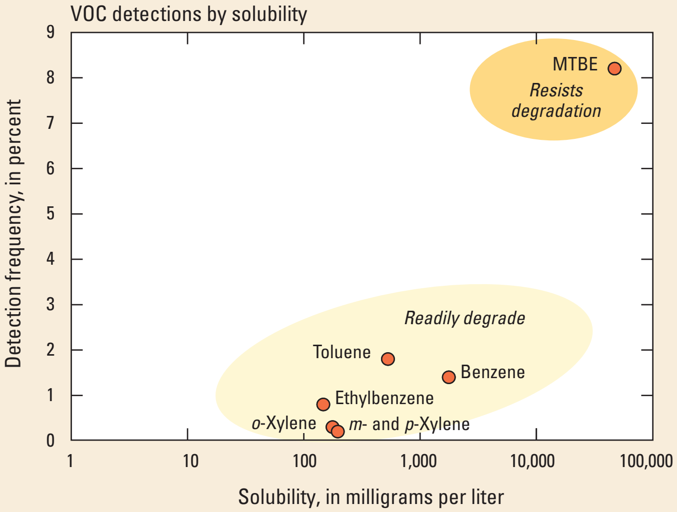
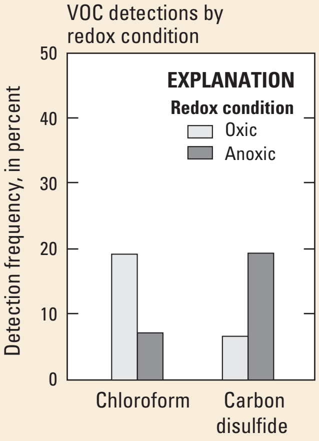
Properties of individual VOCs and geochemical conditions in the aquifers affect transport and persistence

Although VOCs were detected most commonly in urban areas with abundant potential sources (fig. 7–13), the properties of each compound also affect whether they are transported with groundwater, in turn affecting the patterns of VOCs that are detected. Properties that affect transport of VOCs in groundwater include solubility, density, and degradation characteristics. The gasoline additive MTBE (methyl *tert*-butyl ether) and benzene, toluene, ethylbenzene, and xylene (known as BTEX compounds), also found in gasoline, provide a good example of how differences in chemical properties affect VOC occurrence. The sources of these compounds are similar, since all would be present in a leak or spill of gasoline, but the extent to which they dissolve in water and how rapidly they break down are very different. The gasoline additive MTBE dissolves readily(63) and resists degradation,(50) and it was detected much more frequently in groundwater than were the BTEX compounds, which are less soluble(64, 65) and degrade more readily.(50) Therefore both the amount of a VOC released to the environment and its chemical characteristics affect whether or not it is detected and at what concentration.

Degradation characteristics of individual VOCs affect their occurrence in groundwater, but degradation also depends on conditions in the aquifer. For example, chloroform is more persistent in oxic groundwater, and carbon disulfide is more persistent in anoxic groundwater—these characteristics are reflected in the frequencies at which they are detected. Thus, if sources are similar, detection frequencies of other VOCs in water samples will tend to be higher when redox processes in the aquifer favor the persistence of that compound and lower when redox processes favor degradation of that compound.(50)





Chapter 8: *Can Discharge of Nutrients From Groundwater Impair the Health of Streams and Estuaries?*

Streamflow in the Piedmont, Blue Ridge, and Valley and Ridge regions is sustained by groundwater discharge, but groundwater discharge can contribute nitrate and phosphorus to the streams in concentrations that affect their ecological health. About 50 percent of the nitrogen in streams in this area comes from groundwater. More than 20 percent of the phosphorus in streams overlying crystalline-rock and siliciclastic-rock aquifers is from groundwater and originates from geologic sources.

This chapter describes the transport of nitrogen and phosphorus from groundwater to surface-water bodies in the Piedmont, Blue Ridge, and Valley and Ridge regions.

Between periods of rainfall, streamflow is sustained by discharge of groundwater from the aquifer. Contaminants in the aquifer discharge to the stream, providing a large proportion of the total contaminant load in the stream.

Photograph by Eliza Gross, USGS

Carbonate-rock aquifers delivered the highest loads of nitrate to streams.

Nitrogen and phosphorus are essential nutrients for plant growth; however, when these nutrients are overabundant in surface water, harmful algae can bloom, causing problems such as depletion of oxygen in the water and production of toxins, subsequently harming bay grasses, fish, crabs, and oysters. Groundwater discharge (see sidebar, Groundwater discharge sustains baseflow, this page) contributes nitrogen and phosphorus to streams and to estuaries downstream, such as the Chesapeake Bay(52) and the Albemarle Sound. The Chesapeake Bay is typical of estuaries in the Piedmont, Blue Ridge, and Valley and Ridge regions: groundwater discharge accounts for about half of the stream water flowing into the Bay. A substantial amount of the nitrogen and phosphorus reaching the Bay is delivered by groundwater discharge as well. The largest effort ever undertaken by the USEPA to reduce contamination in a watershed was recently established for the Chesapeake Bay.(53)

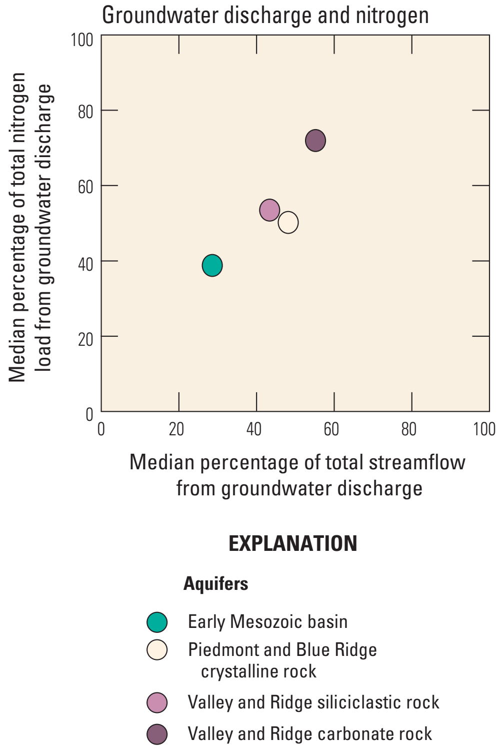


Figure 8–1. Nitrogen load in streams is related to the amount of streamflow that comes from groundwater discharge.

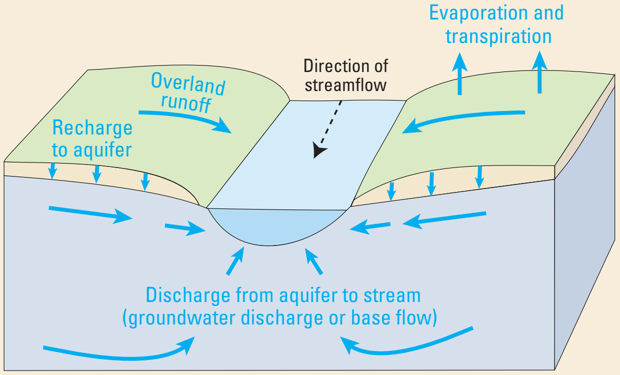
Groundwater discharge accounts for about 30 to 55 percent of the water flowing in streams—this groundwater contribution to streamflow is called base flow. About 40 to 70 percent of the nitrogen load in streams in the Piedmont, Blue Ridge, and Valley and Ridge regions is from base flow (fig. 8–1).(54) Carbonate-rock aquifers deliver the highest percentage of flow and the highest loads of nitrate to streams, and the early Mesozoic basin aquifers deliver the lowest. The close connection, both chemically and physically, between the aquifer and the streams is reflected in the similar concentrations of nitrate in samples collected from wells and from stream base flow (fig. 8–2).(54) Three factors contribute to the high loads of nitrate contributed by the carbonate-rock aquifers: the ratio of base flow to total streamflow is higher because overland runoff is less; inputs of nitrogen to the groundwater are higher; and the groundwater commonly is oxic, so denitrification is less likely in streams that receive discharge from these aquifers (fig. 8–3). In contrast, in the areas overlying the other aquifers, the proportion of overland runoff is larger, the percentage of agricultural land use is lower, and anoxic conditions leading to denitrification are more common than in the carbonate-rock aquifers. These factors contribute to low nitrogen loads in base flow.

Concentrations of nitrate in stream base flow generally mirror concentrations of nitrate in groundwater discharging to those streams. The majority of the streams contained nitrate at concentrations that exceeded the USEPA recommended ecological criterion.(4)

Groundwater discharge contributed 30 to 55 percent of flow and 40 to 70 percent of the nitrogen load to streams. Concentrations of nitrate exceeded the levels recommended by the U.S. Environmental Protection Agency for protection of aquatic life and stream health (recommended ecological criterion) in the majority of the streams sampled.

Groundwater discharge sustains streamflow

In the water cycle, precipitation can run overland into streams, evaporate, transpire, or infiltrate into the aquifer. Water that infiltrates into the aquifer may be extracted by wells or eventually discharge to streams. This discharge of groundwater to streams sustains streamflow between periods of rainfall and is known as base flow. As groundwater travels from recharge to discharge, contaminants can move with the water and eventually discharge to the stream with the water at the end of the flow path (modified from Winter and others, fig. 8(66)).



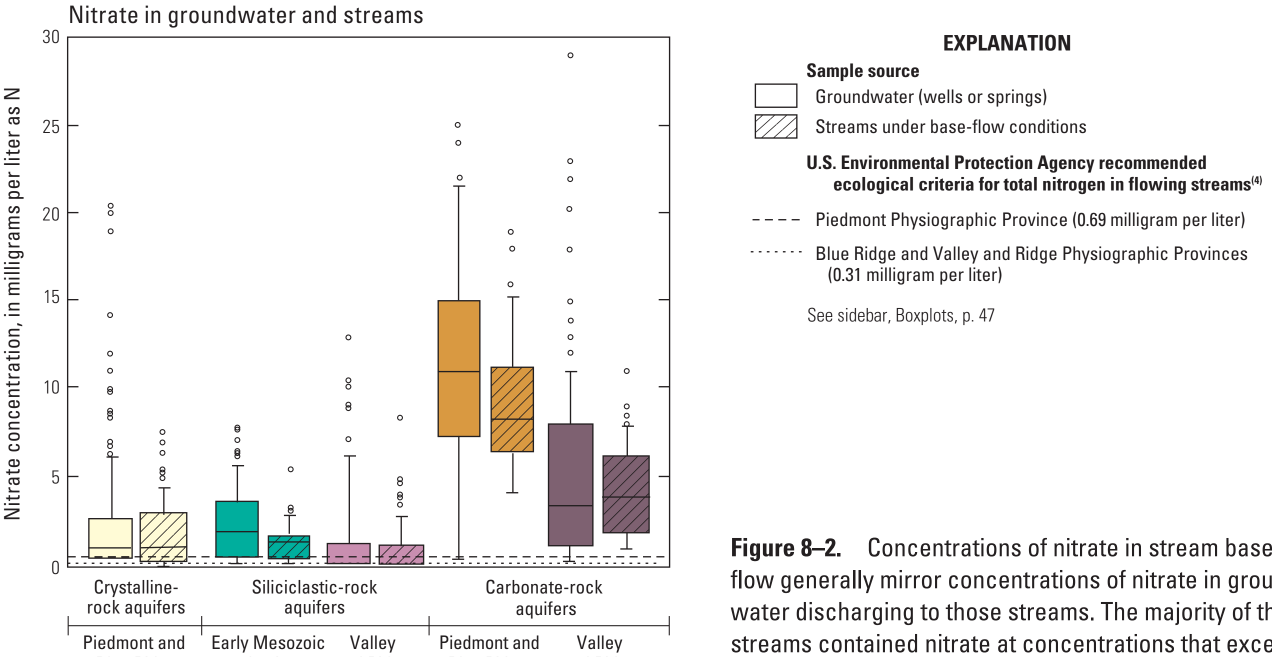


Figure 8–2. Concentrations of nitrate in stream base flow generally mirror concentrations of nitrate in groundwater discharging to those streams. The majority of the streams contained nitrate at concentrations that exceeded the U.S. Environmental Protection Agency recommended ecological criterion.[4]

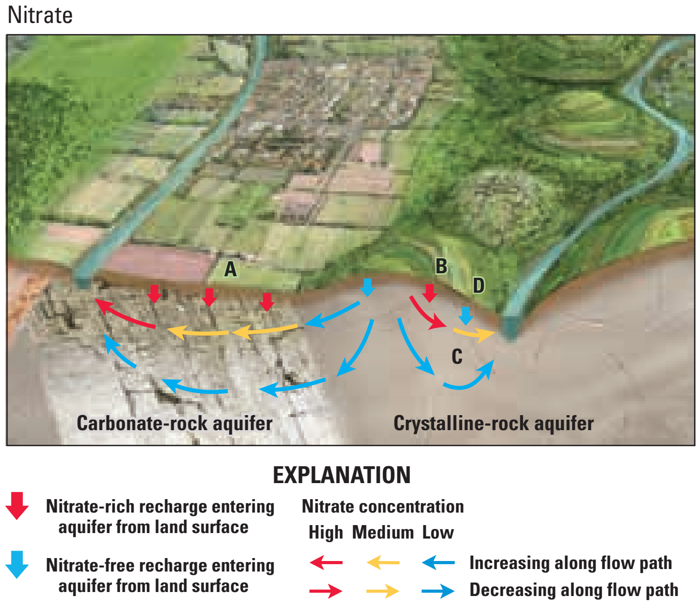


Figure 8–3. A, Large nitrogen sources provide nitrate to recharge to carbonate-rock aquifers, where oxic conditions allow the nitrate to move through the aquifer to the stream without denitrification. B, Nitrate enters the aquifers from sources above the crystalline-rock (and other) aquifers, C, but concentrations are likely to be lower by the time they reach the stream because of denitrification along the flow path or D, because of dilution from water recharging through undeveloped areas.

Concentration and load are related measures of nutrient levels in streams

Concentration—Concentration is the mass of a constituent per volume of water, such as milligrams per liter. The concentration is important because it determines the potential ecological effects of the nutrients at the place and time the sample is collected. The USEPA-recommended criteria for nutrients in streams[4] are given as concentrations. These recommended criteria represent the maximum level of a contaminant necessary to protect designated uses of rivers and streams—such as protection of aquatic life and recreation.

Load—Load is the total mass of a contaminant transported in a stream or river, calculated by multiplying the concentration of the contaminant by the flow rate. It is given as a mass for a specified time period, in units such as tons per year. Loads are important for evaluating the potential ecological effects of nutrients on receiving water bodies downstream and over longer time periods. Regulatory limits on nutrient loads are site specific.

Groundwater Can Contribute a Large Amount of Phosphorus to Streams

Concentrations of dissolved phosphorus exceeded recommended ecological criteria for total phosphorus in streams in 42 percent of stream base-flow samples.

Elevated concentrations of phosphorus are a concern for stream ecology in the region—the recommended ecological criteria for total phosphorus in streams (see sidebar, Concentration and load are related measures of nutrient levels in streams, p. 85) were exceeded in 42 percent of stream base-flow samples and 29 percent of groundwater samples. Groundwater discharge to streams contributes about 20 percent of the phosphorus load measured in stream base flow.(55)

Concentrations of phosphorus in groundwater are controlled by the type of rock that makes up the aquifer. Median phosphorus concentrations in samples from the crystalline-rock and siliciclastic-rock aquifers—0.02 mg/L—were twice as high as those from the carbonate-rock aquifers because some of the minerals that make up the crystalline and siliciclastic rocks contain phosphorus (fig. 8–4). Geochemical conditions such low alkalinity, low calcium concentrations, and anoxic conditions allow phosphorus to be dissolved from minerals in the crystalline-rock and siliciclastic-rock aquifers and to be transported with the groundwater (fig. 8–5). Potential geologic contributions of phosphorus to groundwater and streams from these aquifers are important watershed-management considerations.

Minerals in the carbonate-rock aquifers contain little phosphorus. In addition, geochemical conditions in the carbonate-rock aquifers are such that any phosphorus that enters the aquifer in recharge is likely to precipitate or adsorb to mineral surfaces as the groundwater moves along flow paths (fig. 8–5). As a result, concentrations of dissolved phosphorus in groundwater samples from the carbonate-rock aquifers were very low—more than 75 percent of the samples from the carbonate-rock aquifers had phosphorus concentrations less than the reporting limit of 0.01 mg/L (fig. 8–4). Despite very low concentrations of phosphorus in carbonate-rock aquifers, dissolved phosphorus concentrations in stream base flow commonly were at least twice as high as in groundwater (median concentration 0.02 mg/L) in areas underlain by carbonate-rock aquifers (fig. 8–4). It is unknown why concentrations are higher in stream base flow than in groundwater samples, but evidently the source of the dissolved phosphorus in base flow or geochemical conditions at groundwater discharge locations are different from those of the groundwater that was sampled.

Concentrations of dissolved phosphorus in groundwater samples from the carbonate-rock aquifers were very low—more than 75 percent of the samples from the carbonate-rock aquifers had phosphorus concentrations less than the laboratory reporting limit of 0.01 mg/L.

Potential geologic contributions of phosphorus to groundwater and streams are an important watershed-management consideration.

Phosphorus: essential nutrient but quantity is key

Phosphorus is an important nutrient but, like nitrogen, it can cause problems in surface-water bodies when concentrations are too high. The total amount of phosphorus in a sample of stream water can include substantial amounts of particle-bound phosphorus, particulate organic phosphorus, and dissolved phosphorus; however, the predominant form of phosphorus in groundwater is dissolved phosphorus. For this reason, in this discussion, the term “phosphorus” is used to refer to sources and loads, but the term “dissolved phosphorus” is used to refer to measured concentrations.

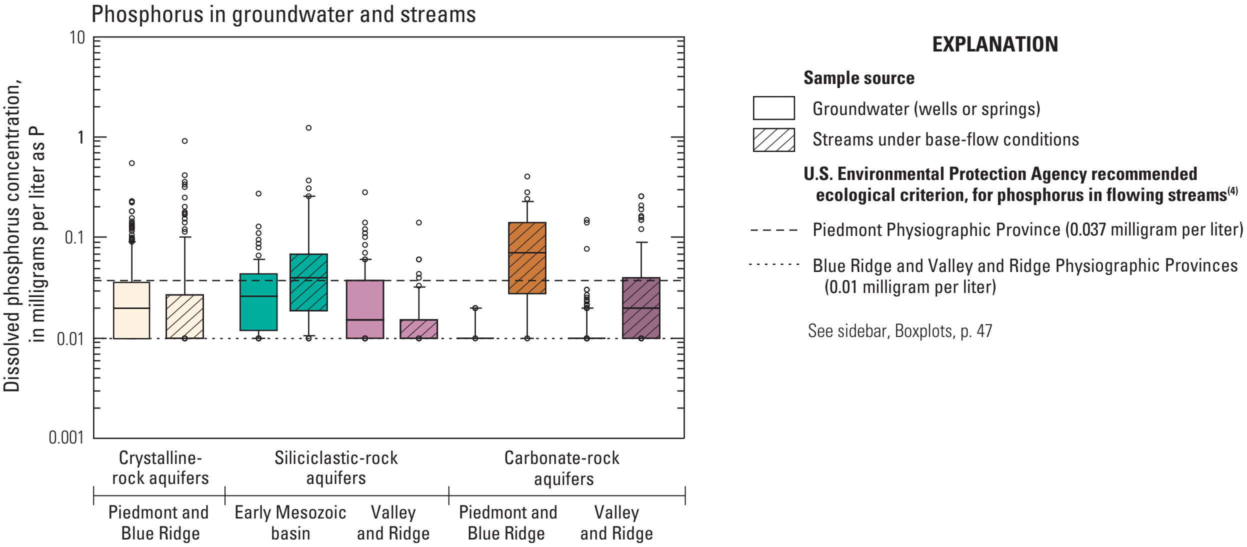


Figure 8–4. Dissolved phosphorus concentrations were higher in samples of groundwater from crystalline-rock and siliciclastic-rock aquifers than in samples from carbonate-rock aquifers. Consequently, contributions of dissolved phosphorus in crystalline-rock and siliciclastic-rock aquifers from geologic sources to stream base flow may be a substantial fraction of the total amount of phosphorus in streams. In contrast, the relatively low dissolved phosphorus concentrations in groundwater in carbonate-rock aquifers cannot explain the high concentrations in base flow in streams in these areas.

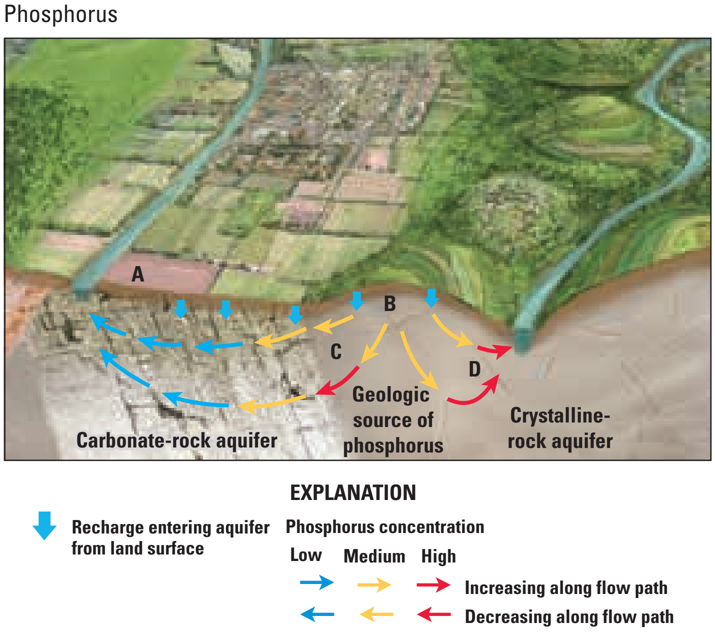


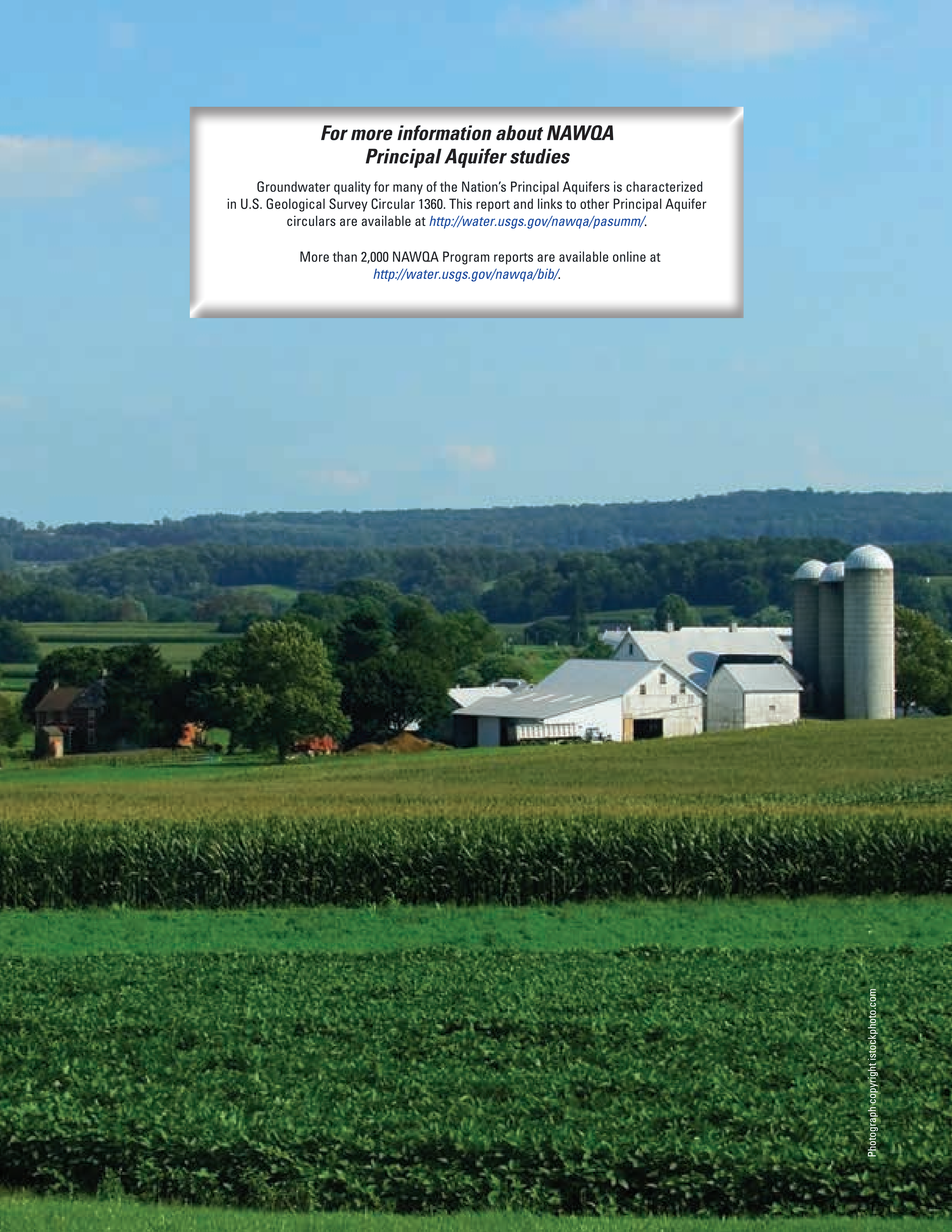
Figure 8–5. A, Phosphorus rarely infiltrates through soils to groundwater, regardless of land use. B, In aquifers with a geologic source of phosphorus, groundwater dissolves the phosphorus from the rock. C, Phosphorus moving with groundwater into the carbonate-rock aquifers precipitates or is adsorbed. D, Water travels long distances in the crystalline-rock aquifer with increases in phosphorus concentration along the flow path because of the geologic source of phosphorus.

Dissolved phosphorus concentrations were higher in samples of groundwater from crystalline-rock and siliciclastic-rock aquifers than in samples from carbonate-rock aquifers. Consequently, contributions of dissolved phosphorus in crystalline-rock and siliciclastic-rock aquifers from geologic sources to stream base flow may be a substantial fraction of the total amount of phosphorus in streams. In contrast, the relatively low dissolved phosphorus concentrations in groundwater in carbonate-rock aquifers cannot explain the high concentrations in base flow in streams in these areas.

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/*.



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Glossary

A

adsorb/adsorption Process in which ions or molecules dissolved in groundwater become attached to the surfaces of solid materials, such as sediment or rock particles in aquifers, either temporarily or permanently.

Alternative Maximum Contaminant Level (AMCL) The higher of two proposed U.S. Environmental Protection Agency regulatory levels for radon in drinking water. The higher level, the AMCL of 4,000 pCi/L, would apply to public water systems or states that have programs to reduce radon risks from all sources. The lower level of 300 pCi/L would apply to systems or states that do not have such programs in place. Both proposed MCLs are used as human-health benchmarks in this circular, but are not yet formal regulatory benchmarks.

anoxic Having 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 significant quantities of water to wells and springs.

B

base flow Streamflow coming from groundwater seepage into a stream or river. Base flow is the continual contribution of groundwater to streams and rivers and is an important source of streamflow between rainstorms.

bedrock/bedrock type General term for consolidated (solid) rock that underlies soils or other unconsolidated material. In this report bedrock type refers to carbonate, crystalline, or siliciclastic bedrock.

C

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

conduit/conduit flow Groundwater flow through pipe-like or channel-like openings in the rock. Conduits control the direction of water flow and greatly increase the speed at which water travels through the aquifer.

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 Circular, any manmade compound at any concentration, or any naturally occurring constituent measured at a concentration exceeding its human-health benchmark.

crystalline bedrock/crystalline-rock aquifer
Rocks (igneous or metamorphic) consisting wholly of crystals or fragments of crystals. Granite and schist are examples of crystalline rocks.

D

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

denitrification The bacterial reduction of dissolved nitrate to nitrogen gas. It is the most important way that 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, for example, from a spring, from a 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.

F

felsic A term applied to igneous rocks, such as granite, that contain abundant light-colored minerals such as feldspar and quartz. Also, a term applied to those minerals as a group.

G

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

groundwater age *See* apparent groundwater age.

groundwater flow path The route or pathway followed by water flowing through the hydrologic system. Usually refers to subsurface (groundwater) flow.

groundwater residence time The average amount of time it takes for groundwater to move from the point where it enters the aquifer to a specific point of discharge, such as a well or stream.

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 ground-water samples can be compared; and (3) is consistent with USEPA Office of Water methodologies.

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 drunk to lower the concentration of the contaminant below the benchmark.

I

igneous rocks Rocks that solidified from molten or partly molten material. Granite is an example of an igneous rock.

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

K

karst Surface and subsurface terrane that is formed on and in soluble rocks, such as limestone and gypsum, primarily by dissolution and collapse and that is characterized by sinkholes, caves, and underground drainage.

karst aquifer A body of soluble rock that conducts water principally via a connected network of tributary conduits formed by the dissolution of the rock, which drains a groundwater basin and discharges to at least one perennial spring.

L

land-use study A study by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program used 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/lithologic group The physical character of a rock on the basis of color, structure, mineralogical composition, grain size, and other characteristics. As used in this report, it is a subdivision of the major bedrock types.

M

mafic A term applied to igneous rocks, such as basalt, that contain abundant dark-colored minerals with a high percentage of magnesium and iron. Also, a term applied to those minerals as a group.

major-aquifer studies A study by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program that involves sampling of water at 20 to 30 domestic and (or) public-supply wells that withdraw water from major aquifers. The major aquifer studies represent a mix of land uses and target water that is used for drinking-water supply.

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.

metamorphic rocks 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.

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

nonpoint source A contaminant source that is not a discrete point, such as a pipe, ditch, or tunnel. Areas of fertilizer and pesticide applications, atmospheric deposition, and stormwater runoff are examples of sources of nonpoint contamination.

O

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

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.

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.

point source A stationary location or fixed facility from which contaminants are discharged, for example, a pipe, ditch, ship, ore pit, or factory smokestack.

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, water that is added.

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.

S

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.

siliciclastic bedrock/siliciclastic-rock aquifer Rocks formed by the compaction and cementation of quartz-rich mineral grains. Sandstone and shale are examples of siliciclastic rocks.

sinkhole Any closed depression in soil or bedrock formed by the erosion and transport of earth material from below the land surface, which has a closed topographic contour and drains to the subsurface. Typically occurs in karst terrane.

susceptibility *See* definition for intrinsic susceptibility.

T

tritium unit (TU) A measure of the concentration of tritium (^{3}H), equal to one ^{3}H atom in 1,018 atoms of hydrogen (H), or 3.24 picocuries per liter.

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 byproducts of chlorine disinfection.

vulnerable/vulnerability The tendency or likelihood for contaminants to reach a specified position in the ground-water system after introduction at some location above the uppermost aquifer. The vulnerability of a groundwater resource to contamination depends both on its intrinsic susceptibility and on the locations and types of geologic sources of contamination and contamination associated with human activities, locations of wells, and 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 1–6

Appendix 1. NAWQA Cycle 1 groundwater sampling networks in the Piedmont, Blue

[Water-use abbreviations: DOM, domestic supply; PUB, public supply; ODW, other drinking-water supply (commercial, institutional); OTH, other (stock,irrigation, fire, dewatering,
urban land use; urban, greater than 25 percent urban land use and less than 25 percent agricultural land use; undeveloped, less than 25 percent agricultural and less than 5 percent urban

Names used by the NAWQA Program			Network description used in this report
Network name	Study unit name	Network type	
			Early Mesozoic basin
potosus2	Potomac River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
delrsus1	Delaware River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
linjsus3	Long Island and New Jersey Coastal Drainages	Major-aquifer study	Mixed land uses, groundwater used for drinking water
			Piedmont and Blue Ridge
lsuslusag1	Lower Susquehanna River Basin	Land-use study	Agricultural areas, groundwater used for drinking water
			Piedmont and Blue Ridge
acfblusur1	Apalachicola-Chatahoochee-Flint River Basin	Land-use study	Urban areas, groundwater near water table
acfblusur2	Apalachicola-Chatahoochee-Flint River Basin	Land-use study	Urban areas, groundwater near water table
albesus8	Albemarle-Pamlico Drainage Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
kanasus2	Kanawa-New River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
*lsussus2	Lower Susquehanna River Basin	Major-aquifer study	Agricultural areas, groundwater used for drinking water Mixed land uses, groundwater used for drinking water
podldwgs1	Potomac River Basin	Source-water quality assessment	Mixed land uses, groundwater used for drinking water
podllusrc1	Potomac River Basin	Land-use study	Urban areas, groundwater near water table
podlreffo2	Potomac River Basin	Reference network	Mixed land uses, groundwater used for drinking water
potosus1	Potomac River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
santdwgs1	Santee River Basin and Coastal Drainages	Source-water quality assessment	Mixed land uses, groundwater used for drinking water
santsus3	Santee River Basin and Coastal Drainages	Major-aquifer study	Mixed land uses, groundwater used for drinking water
			Valley and Ridge
lsuslusag2	Lower Susquehanna River Basin	Land-use study	Agricultural areas, groundwater used for drinking water
lsuslusag3	Lower Susquehanna River Basin	Land-use study	Agricultural areas, groundwater used for drinking water
luslusur1	Lower Susquehanna River Basin	Land-use study	Urban areas, groundwater near water table
potolusag1	Potomac River Basin	Land-use study	Agricultural areas, groundwater used for drinking water
podlreffo1	Potomac River Basin	Reference network	Mixed land uses, groundwater used for drinking water
utenspr1	Upper Tennessee River Basin	Spring study	Mixed land uses, groundwater used for drinking water
utensus1	Upper Tennessee River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
			Valley and Ridge
delrsus2	Delaware River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
lsussus1	Lower Susquehanna River Basin	Major-aquifer study	Mixed land uses, groundwater used for drinking water
†potolusag2	Potomac River Basin	Land-use study	Agricultural areas, groundwater used for drinking water
potolusfo1	Potomac River Basin	Land-use study	Mixed land uses, groundwater used for drinking water

* This network was sampled as a single network but regrouped on the basis of land use for this analysis.

† One well from the potolusag2 network was in the Valley and Ridge carbonate-rock aquifers and was grouped with that aquifer for analysis.

Ridge, and Valley and Ridge Principal Aquifers.

industrial); UN, unused monitoring well or spring; land-use definitions for 1,640-ft radius around well: agriculture, greater than 50 percent agricultural land use and less than 5 percent land use; mixed, any site not meeting the other three definitions]

What data were collected and why	Number of sites sampled	Water use of sites (listed in descending order)	Aquifer bedrock type	Sampling period	Predominant land use (listed in descending order)
aquifers					
Assess the quality of water in major aquifer	23	DOM, ODW	Siliciclastic, crystalline	1994	Agriculture, mixed
Assess the quality of water in major aquifer	30	DOM, UN, PUB, ODW	Siliciclastic	1999	Agriculture, mixed, urban
Assess the quality of water in major aquifer	21	DOM	Siliciclastic, crystalline	1998	Agriculture, mixed, urban
carbonate-rock aquifers					
Describe effects of agricultural land use on shallow groundwater	30	DOM, OTH	Carbonate	1993	Agriculture
crystalline-rock aquifers					
Describe effects of urban land use on shallow groundwater	21	DOM, UN, OTH	Crystalline	1994–95	Urban
Describe effects of urban land use on shallow groundwater	19	SPRINGS-UNUSED	Crystalline	1994–95	Urban
Assess the quality of water in major aquifer	55	DOM, ODW, UN	Crystalline	2007	Mixed
Assess the quality of water in major aquifer	30	DOM, ODW, PUB, UN	Crystalline	1997	Mixed, agriculture, undeveloped
Describe effects of agricultural land use on shallow groundwater	24	DOM	Crystalline	1994	Agriculture
Assess the quality of water in major aquifer	6	DOM	Crystalline	1994	Forested
Assess the quality of source water used by community water systems dependent on groundwater sources for public supply	15	PUB	Crystalline	2003	Mixed, agriculture
Describe effects of urban land use on shallow groundwater	30	UN	Crystalline	2003	Urban, mixed
Describe background conditions for water quality near podllusrc1 network	2	UN	Crystalline	2003–05	Undeveloped
Assess the quality of water in major aquifer	25	DOM, ODW, UN	Crystalline	1994	Agriculture, urban, mixed
Assess the quality of source water used by community water systems dependent on groundwater sources for public supply	15	PUB	Crystalline	2008	Undeveloped, mixed
Assess the quality of water in major aquifer	30	DOM, ODW	Crystalline	1998	Undeveloped, mixed
carbonate-rock aquifers					
Describe effects of agricultural land use on shallow groundwater	30	DOM, ODW	Carbonate	1994	Agriculture
Describe effects of agricultural land use on shallow groundwater	30	DOM, OTH	Carbonate	1995	Agriculture
Describe effects of urban land use on shallow groundwater	20	DOM, UN, ODW, OTH	Carbonate	1995	Urban, mixed
Describe effects of agricultural land use on shallow groundwater	32	DOM	Carbonate	1993 and 2002	Agriculture, mixed
Describe background conditions for water quality near potolusag1 network	2	UN	Carbonate	2002	Undeveloped
Assess the quality of water in major aquifer through sampling of springs	35	SPRINGS-DOM, UN, PUB	Carbonate	1997	Mixed, undeveloped, agriculture
Assess the quality of water in major aquifer	30	DOM, ODW, UN, OTH	Carbonate	1998–99	Mixed, undeveloped, agriculture
siliciclastic-rock aquifers					
Assess the quality of water in major aquifer	30	DOM, PUB, ODW, UN	Siliciclastic	2000	Agriculture, urban, mixed
Assess the quality of water in major aquifer	29	DOM	Siliciclastic	1993	Agriculture, undeveloped
Describe effects of agricultural land use on shallow groundwater	25	DOM	Siliciclastic	1995	Agriculture, mixed
Describe effects of forested land use on shallow groundwater	3	DOM, ODW	Siliciclastic	1995	Undeveloped

Appendix 2. 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 sample 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-flow path (*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 of mixed land use.
- Vulnerability studies are designed to assess the vulnerability of water delivered by public-supply wells to contamination from geologic and manmade sources. 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 are designed to determine the detection frequency and concentrations of unregulated manmade chemicals in groundwater from public-supply wells that serve large numbers of people (*http://water.usgs.gov/nawqa/swqa/*).
- Results of these studies were reinforced by placing the areas for some of the studies within the boundaries of larger studies. For example, the recharge areas for flow-path studies were placed 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 placed within the boundaries of the major aquifer studies to provide information on how the quality of recharge affects the quality 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 assessment.

Appendix 3.

Water-quality properties and constituents measured and a summary of data for Circular 1354, including laboratory reporting levels and human-health benchmarks for drinking water, are presented only online in PDF form. The tab-delimited data also are available for download at *http://pubs.usgs.gov/circ/1354/*.

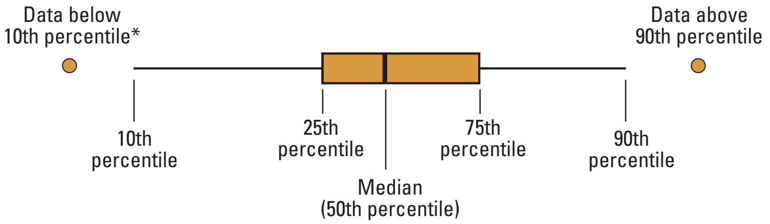
Appendix 4. The Piedmont, Blue Ridge, and Valley and Ridge Regions Principal Aquifers in a national context.

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/*.(78)

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

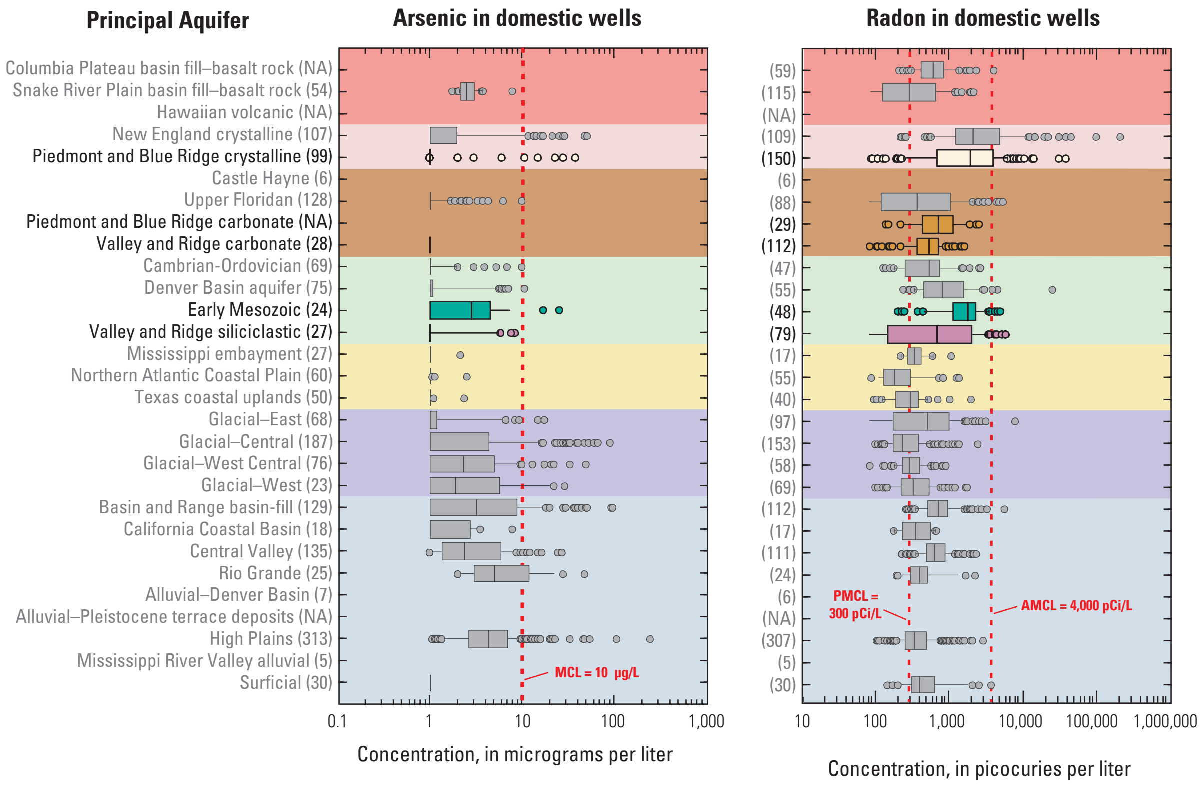


Figure A4–1. Concentrations of arsenic and radon in Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions in a national context.

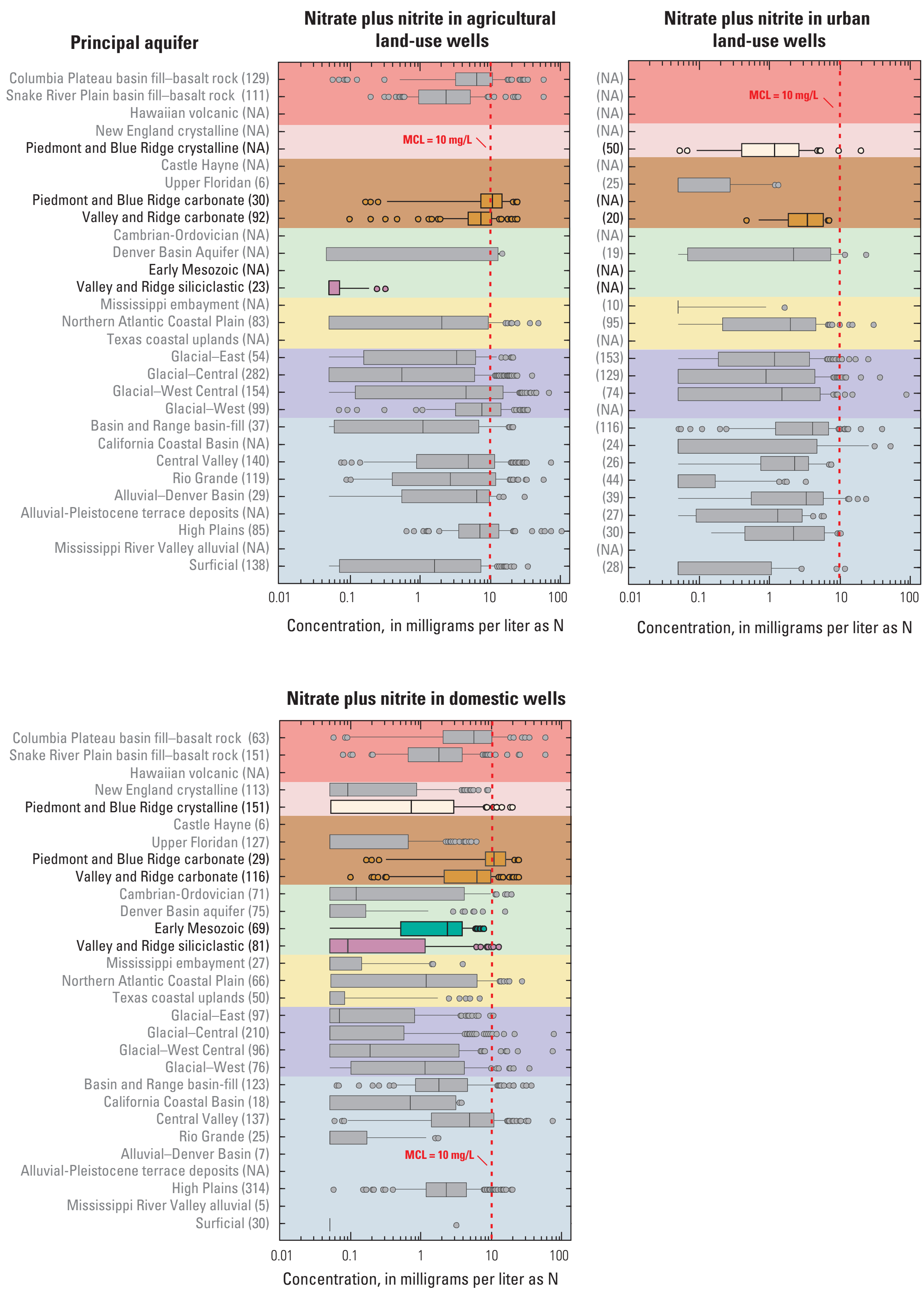


Figure A4–2. Concentrations of nitrate plus nitrite in Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions in a national context

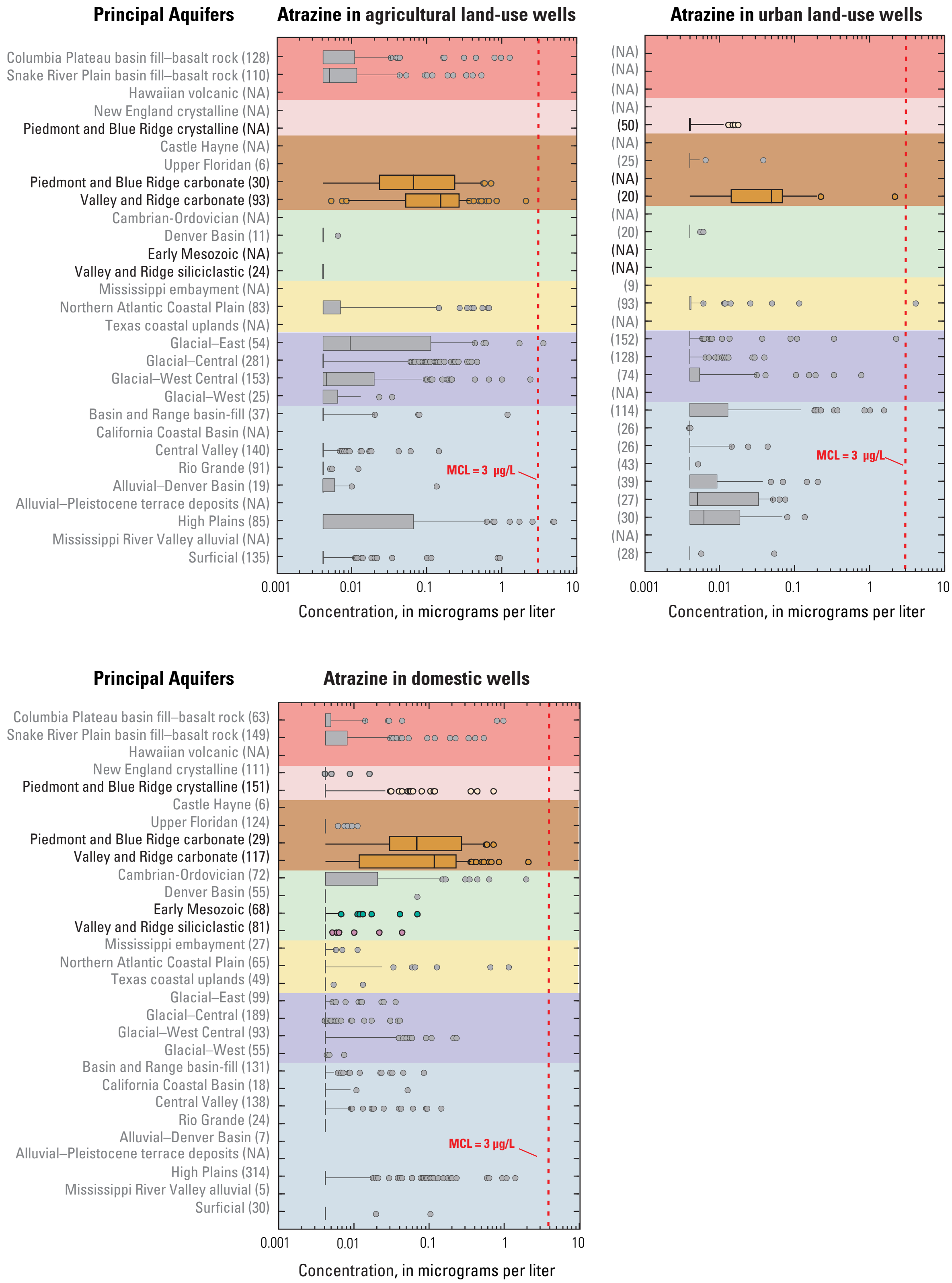


Figure A4–3. Concentrations of atrazine in Principal Aquifers of the of the Piedmont, Blue Ridge, and Valley and Ridge regions in a national context.

Appendix A5–1. Median estimated pesticide application rates in 1,640-foot radius around wells in the Piedmont, Blue Ridge, and Valley and Ridge

[Purple shading indicates the compound analyzed for this study as one of the 47 pesticides considered in this report; turquoise shading indicates the compound analyzed as one around wells in the entire Piedmont, Blue Ridge, and Valley and Ridge regions(40)]

Pesticide name	Piedmont, Blue Ridge, and Valley and Ridge regions	Piedmont and Blue Ridge crystalline-rock aquifers			Early Mesozoic Basin aquifers
		Agricultural area, groundwater used for drinking water	Urban area, groundwater near water table	Mixed land use, groundwater used for drinking water	Mixed land use, groundwater used for drinking water
Atrazine	2.81935	18.1027	0	0.9209	5.8796
Metolachlor	2.18153	26.2701	0	0.5686	6.4269
2-4-D	1.45619	1.91145	0.00335	1.47692	1.04367
Alachlor	0.87990	3.13786	0	0.37758	1.58316
Chlorpyrifos	0.67702	2.1948	0.00026	0.424	0.46811
Glyphosate	0.62834	1.57021	0.00038	0.21434	0.93554
Pendimethalin	0.51646	10.9862	0	0.2215	0.6156
Methyl-bromide (VOC schedule)	0.47826	2.8023	0	0.3003	0.5172
Simazine	0.41200	1.49714	0.00008	0.13081	0.71509
Sulfur	0.34645	3.84947	0.00048	0.1098	1.07934
Oil	0.34238	1.51694	0.00192	0.11876	0.53809
Mancozeb	0.27749	1.25224	0.00038	0.16105	0.26724
Captan	0.25585	1.50632	0.00099	0.07442	0.54124
Terbufos	0.17474	0.39616	0	0.14621	0.22473
*Cyanazine	0.17371	1.24328	0	0.05712	0.59418
Chloropicrin	0.11990	0.6797	0	0.07243	0.12439
Chlorothalonil	0.11990	0.87618	0	0.03823	0.79568
Azinphos-methyl	0.07423	0.35149	0.00003	0.01106	0.13877
Ziram	0.06903	0.32945	0	0.04093	0.12563
Carbaryl	0.06850	0.13701	0.00084	0.04324	0.07456
Metiram	0.06003	0.5899	0.00023	0.02528	0.08324
Dimethoate	0.05397	0.27783	0	0.01506	0.04119
Methomyl	0.04762	0.21909	0	0.02454	0.14396
Linuron	0.04250	0.25095	0	0.00928	0.07275
Methyl-parathion	0.03743	0.20274	0.00007	0.03596	0.04985
Maneb	0.01464	0.09038	0	0.00233	0.08081
Acephate	0.01165	0.10206	0	0.00706	0.02394
Bentazon	0.00958	0.03886	0	0.01896	0.01092
Maleic-hydrazide	0.00390	0.0446	0	0.00203	0.00117
Ethalfluralin	0.00108	0.01133	0	0.0008	0.00004

*The sale and use of Cyanazine was prohibited after September 30, 2002.

regions, in kilograms, in 1997.

of the 86 volatile organic compounds considered in this report. Pesticides are sorted in descending order of the mass of active ingredient applied in the 1,640-foot radius

Valley and Ridge siliciclastic-rock aquifers		Piedmont and Blue Ridge carbonate-rock aquifers	Valley and Ridge carbonate-rock aquifers		
Agricultural area, groundwater used for drinking water	Mixed land use, groundwater used for drinking water	Agricultural area, groundwater used for drinking water	Agricultural area, groundwater used for drinking water	Urban area, groundwater near water table	Mixed land use, groundwater used for drinking water
1.5856	10.4065	35.2294	19.2818	2.3225	0.7701
1.9519	13.0461	38.3035	22.4624	2.7737	0.2593
1.595	1.24741	2.45768	2.1197	0.22432	0.40262
0.56449	1.91987	5.43722	3.28255	0.37547	0.11135
0.67373	1.23229	5.28276	2.77033	0.28954	0.40395
3.03327	0.8351	2.11997	1.49684	0.16219	0.13244
0.0298	5.5499	20.5867	10.2396	1.3458	0.1917
0	1.6084	10.2111	1.1718	0.1715	0.0115
0.53557	0.7506	2.2998	1.6861	0.17145	0.10222
0.04527	0.60604	1.48427	1.30771	0.15191	0.00159
0.16157	0.82877	0.75578	3.41969	0.18212	0.24109
0.02683	0.73017	2.01281	1.27056	0.08146	0.34223
0.03866	0.73545	0.88334	2.87422	0.17198	0.04703
0.06705	0.24368	0.78097	0.46239	0.04984	0.01306
0.00098	0.76464	2.44832	1.24968	0.15667	0.01799
0	0.42363	2.62315	0.28331	0.04360	0.00222
0	0.43761	2.05981	0.44488	0.06475	0.02243
0.01133	0.16579	0.20357	0.61046	0.035	0.03504
0.04163	0.18866	0.18992	0.77434	0.0388	0.02069
0.0017	0.06184	0.15629	0.11727	0.01079	0.54896
0.04928	0.27555	0.29705	1.70989	0.07641	0
0.13847	0.27813	0.83292	0.58679	0.05841	0.00127
0.00561	0.10352	0.20858	0.26032	0.01974	0.01867
0.0115	0.11491	0.25138	0.16935	0.02721	0
0.01992	0.10107	0.15638	0.31087	0.01883	0.00193
0	0.04218	0.23947	0.05041	0.00633	0.01309
0	0.01217	1.31522	0.01169	0.00273	0.40517
0.00181	0.00555	0.05546	0.02303	0.0014	0.0029
0	0.01357	1.8552	0.00834	0.00208	0.60776
0	0.00470	0.04164	0.0056	0.00121	0

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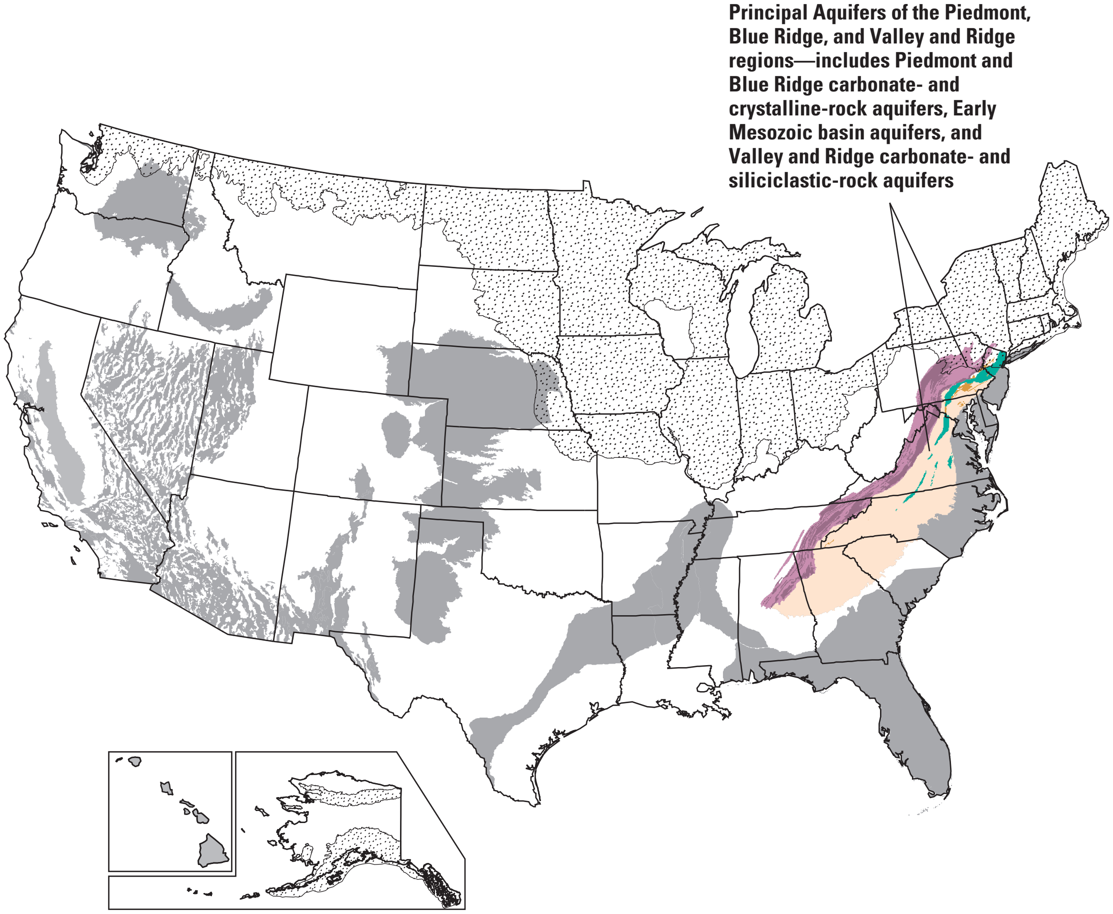

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