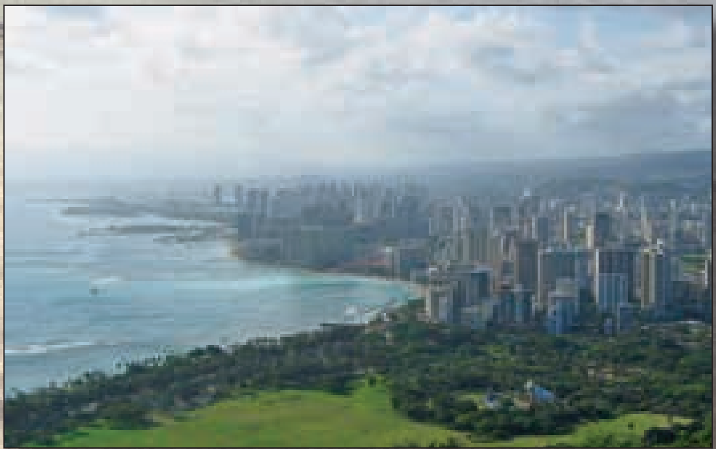
science for a changing world

The Quality of Our Nation's Waters

Groundwater Quality in the Columbia Plateau and Snake River Plain Basin-Fill and Basaltic-Rock Aquifers and the Hawaiian Volcanic-Rock Aquifers, Washington, Idaho, and Hawaii, 1993–2005



National Water-Quality Assessment Program

Circular 1359

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

Cover photographs.

Background: Wheat harvest on the Palouse hills of the Columbia Plateau, Washington (United States Department of Agriculture, Agricultural Research Service).

Foreground, left: Aerial photograph of a dairy in the Snake River Plain, Idaho (copyright Kestrel Aerial Services, Inc., ©www.kestrelaerial.com, used with permission).

Foreground, right: Looking north at Honolulu, Hawaii, from the top of Diamondhead (Michael G. Rupert, U.S. Geological Survey).

The Quality of Our Nation's Waters

Groundwater Quality in the Columbia Plateau and Snake River Plain Basin-Fill and Basaltic-Rock Aquifers and the Hawaiian Volcanic-Rock Aquifers, Washington, Idaho, and Hawaii, 1993–2005

By Michael G. Rupert, Charles D. Hunt, Jr., Kenneth D. Skinner, Lonna M. Frans, and Barbara J. Mahler

National Water-Quality Assessment Program

Circular 1359

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2014

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit *http://www.usgs.gov* or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit *http://www.usgs.gov/pubprod*

To order this and other USGS information products, visit *http://store.usgs.gov*

Suggested citation:
Rupert, M.G., Hunt, C.D., Jr., Skinner, K.D., Frans, L.M., and Mahler, B.J., 2014, The quality of our Nation's waters—Groundwater quality in the Columbia Plateau and Snake River Plain basin-fill and basaltic-rock aquifers and the Hawaiian volcanic-rock aquifers, Washington, Idaho, and Hawaii, 1993–2005: U.S. Geological Survey Circular 1359, 88 p., *http://dx.doi.org/10.3133/cir1359*.

Library of Congress Cataloging-in-Publication Data

Rupert, Michael G., 1959-
The quality of our nation's waters---groundwater quality in the Columbia Plateau and Snake River Plain basin-fill and basaltic-rock aquifers and the Hawaiian volcanic-rock aquifers, Washington, Idaho, and Hawaii, 1993--2005 / by Michael G. Rupert, Charles D. Hunt, Jr., Kenneth D. Skinner, Lonna M. Frans, and Barbara J. Mahler.
pages cm. -- (Circular / U.S. Geological Survey ; 1359)
Includes bibliographical references.
ISBN 978-1-4113-3757-2
1. Water quality--Columbia Plateau. 2. Water quality--Idaho--Snake River Plain Aquifer. 3. Water quality--Washington (State) 4. Water quality--Hawaii. 5. Groundwater--Quality--Columbia Plateau. 6. Groundwater--Quality--Idaho--Snake River Plain Aquifer. 7. Groundwater--Quality--Washington (State) 8. Groundwater--Quality--Hawaii. I. Hunt, Charles D. II. Skinner, K. D. (Kenneth D.) III. Frans, Lonna M. IV. Mahler, B. J. (Barbara June), 1959- V. Geological Survey (U.S.) VI. Title. VII. Series: U.S. Geological Survey circular; 1359.
TD223.7.R87 2014
628.1'1409797--dc23

2014001749

ISSN 1067-084X (print)
ISSN 2330-5703 (online)
ISBN 978-1-4113-3757-2

NAWQA

National Water-Quality Assessment Program

"The NAWQA study results provide Hawaii with an important database describing the status of water quality in aquifers on Oahu. Many of Oahu's groundwaters have been subject to only limited monitoring in the past, so these data will represent a baseline to which results from future studies can be compared. Reports on chemical contaminants in aquifers are particularly useful because these data are expensive to obtain and thus rarely collected. Similar data sets from the other Hawaiian islands are sorely needed."

—Dr. June Harrigan, Hawaii Department of Health, Environmental Planning Office

Photograph by Michael G. Rupert, USGS

Foreword

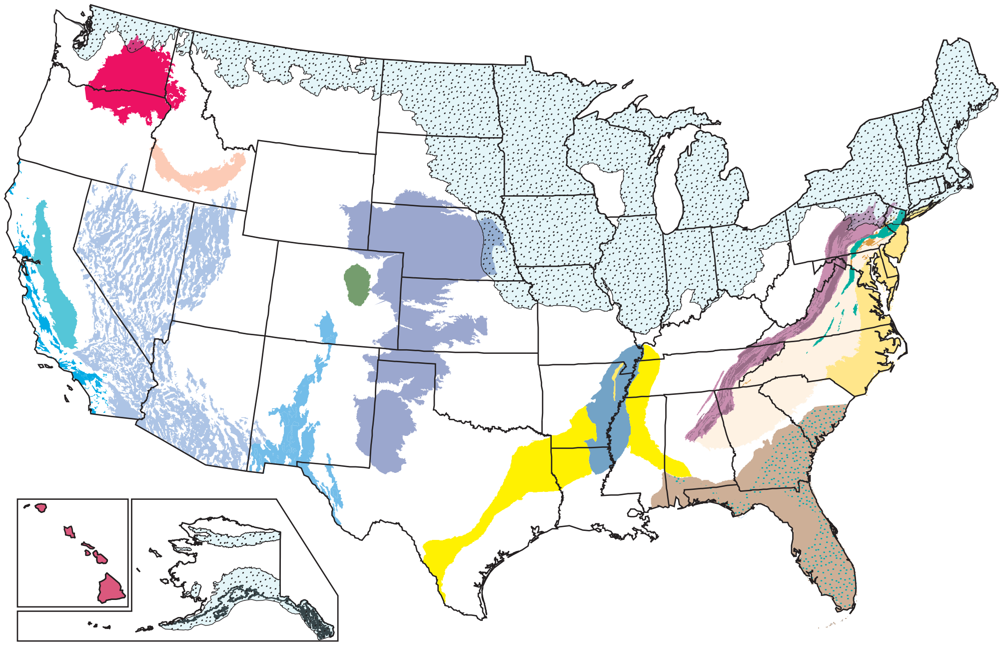
The United States has made major investments in assessing, managing, regulating, and conserving natural resources, such as water and a variety of ecosystems. Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources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

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

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

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

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



Principal Aquifers and Water-Quality Summary Reports

National summary of groundwater quality in Principal Aquifers—Circular 1360

- **High Plains aquifer system**—Circular 1337
- **Glacial aquifer system**—Circular 1352
- **Northern Atlantic Coastal Plain surficial aquifer system**—Circular 1353

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

- Piedmont and Blue Ridge carbonate-rock aquifers
- Piedmont and Blue Ridge crystalline-rock aquifers
- Valley and Ridge siliciclastic-rock aquifers
- Valley and Ridge carbonate-rock aquifers
- Early Mesozoic basin aquifers

- **Upper Floridan aquifer and overlying surficial aquifers**—Circular 1355
- **Mississippi embayment–Texas coastal uplands aquifer system**—Circular 1356
  - Mississippi River Valley alluvial aquifer
- **Denver Basin aquifer system**—Circular 1357

Southwest Principal Aquifers—Circular 1358

- California Coastal Basin aquifers
- Central Valley aquifer system
- Basin and Range basin-fill aquifers
- Rio Grande aquifer system

Western Volcanics—Circular 1359

- Hawaiian volcanic-rock aquifers
- Snake River Plain basin-fill and basaltic-rock aquifers
- Columbia Plateau basin-fill and basaltic-rock aquifers

Contents

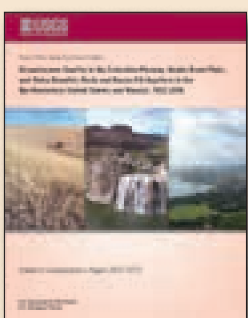
Introduction to This Report

This report contains the major findings of a regional assessment of groundwater quality in three areas: the Columbia Plateau in Washington, the Snake River Plain in Idaho, and the island of Oahu, Hawaii. It is one of a series of reports by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program that present major findings for Principal Aquifers, other aquifers, and major river basins across the Nation. In these reports, water quality is discussed in terms of local, State, regional, and national issues. Conditions in the Columbia Plateau, the Snake River Plain, and Oahu are compared to conditions found elsewhere and to selected national benchmarks, such as those for drinking-water quality.

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

Water-quality conditions in the Columbia Plateau, the Snake River Plain, and Oahu 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 the groundwater quality in the Columbia Plateau and Snake River Plain basin-fill and basaltic-rock aquifers and Hawaiian volcanic-rock aquifers are discussed in the following reports:

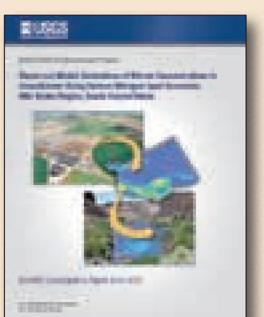


Groundwater Quality in the Columbia Plateau, Snake River Plain, and Oahu Basaltic-Rock and Basin-Fill Aquifers in the Northwestern United States and Hawaii, 1992–2010

U.S. Geological Survey Scientific Investigations Report 2012–5123

By Lonna M. Frans, Michael G. Rupert, Charles D. Hunt, Jr., and Kenneth D. Skinner

(Also available at *http://pubs.usgs.gov/sir/2012/5123/*)

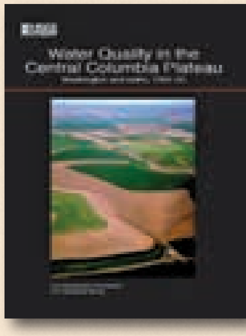


Numerical Model Simulations of Nitrate Concentrations in Groundwater Using Various Nitrogen Input Scenarios, Mid-Snake Region, South-Central Idaho

U.S. Geological Survey Scientific Investigations Report 2012–5237

By Kenneth D. Skinner and Michael G. Rupert

(Also available at *http://pubs.usgs.gov/sir/2012/5237/*)

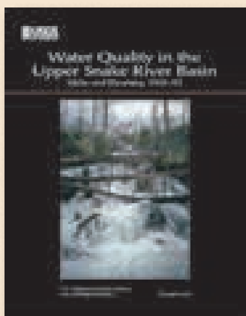


Water Quality in the Central Columbia Plateau, Washington and Idaho, 1992–95

U.S. Geological Survey Circular 1144

By Alex K. Williamson, Mark D. Munn, Sarah J. Ryker, Richard J. Wagner, James C. Ebbert, and Ann M. Vanderpool

(Also available at *http://pubs.usgs.gov/circ/circ1144/*)



Water Quality in the Upper Snake River Basin, Idaho and Wyoming, 1992–95

U.S. Geological Survey Circular 1160

By G.M. Clark, T.R. Maret, M.G. Rupert, M.A. Maupin, W.H. Low, and D.S. Ott

(Also available at *http://pubs.usgs.gov/circ/circ1160/*)

Water Quality on the Island of Oahu, Hawaii, 1999–2001

U.S. Geological Survey Circular 1239

By Stephen S. Anthony, Charles D. Hunt, Jr., Anne M.D. Brasher, Lisa D. Miller, and Michael S. Tomlinson

(Also available at *http://pubs.usgs.gov/circ/2004/1239/*)

Chapter 1: *Overview of Major Findings and Implications*

Residents of the Columbia Plateau, the Snake River Plain, and the island of Oahu depend on groundwater as their primary source of drinking water. Although the depth to the water table can be several hundred feet, the groundwater is vulnerable to contamination because the permeable sediments and rocks in these areas allow contaminants to move readily down to the water table. Intense agricultural activities overlie groundwater used for drinking-water supply and these activities are increasing in some areas. For example, the number of dairy cattle in the Snake River Plain of Idaho increased fivefold between 1987 and 2007, an increase that is roughly equivalent in terms of nitrogen production to a population growth of more than 4 million people. Nitrogen and other contaminants associated with such agricultural activities can adversely affect groundwater quality. In Hawaii, which is often thought of as a pristine tropical environment, past use of agricultural chemicals to control insect pests has led to persistent groundwater contamination in some areas.

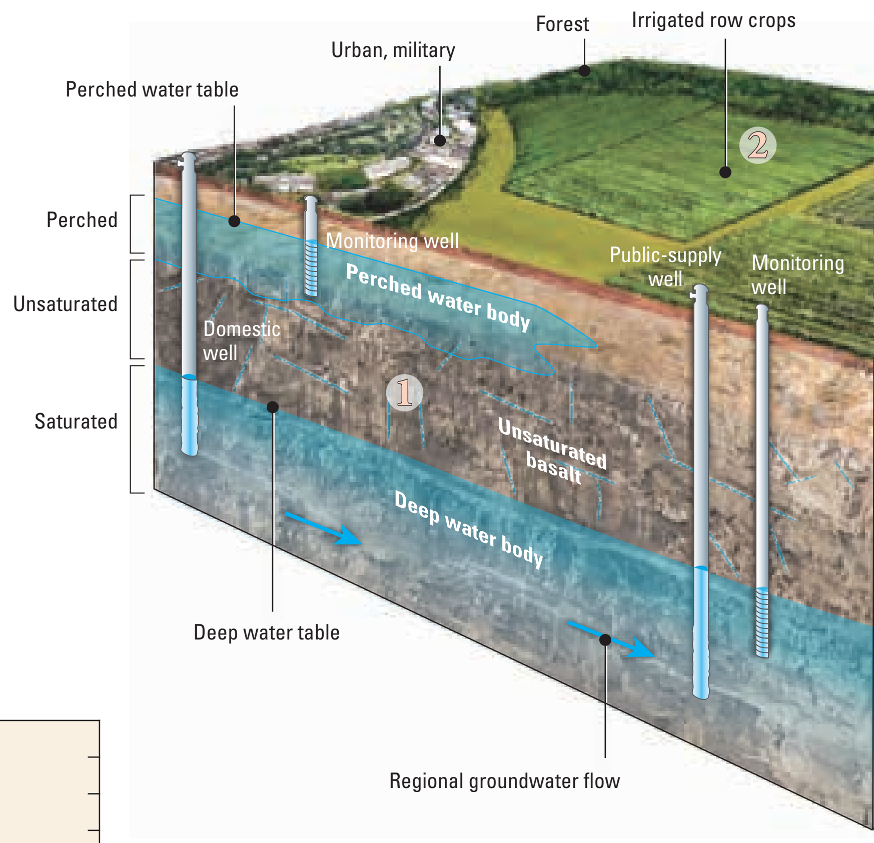
Groundwater has become an increasingly important source for agricultural and domestic water needs.

Overview of Major Findings of Groundwater Quality for the Columbia and the Hawaiian Volcanic-Rock Aquifers

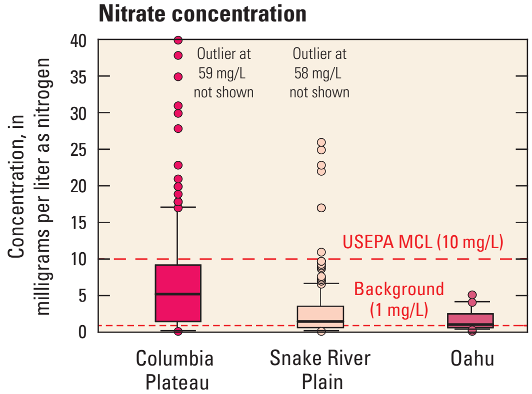
The Columbia Plateau, Snake River Plain, and Hawaii are large volcanic areas in the western United States and mid-Pacific ocean that contain extensive regional aquifers of a hard, gray, volcanic rock called basalt. Residents of the Columbia Plateau, the Snake River Plain, and the island of Oahu depend on groundwater as their primary source of drinking water. Although the depth to the water table can be several hundred feet, the groundwater is highly vulnerable to contamination because the permeable sediments and rocks allow contaminants to move readily down to the water table. Intense agricultural and urban activities occur above the drinking-water supply and are increasing in some areas. Contaminants such as nitrate, pesticides, and volatile organic compounds, associated with agricultural and urban activities, have adversely affected groundwater quality.

1 The Columbia Plateau, Snake River Plain, and Oahu aquifers are vulnerable to contaminants related to human activities despite depths to groundwater that are among the greatest in the Nation

Although depth to the water table can be many hundreds of feet, the permeable geologic materials overlying the aquifers allow many contaminants to move readily from the land surface to the water table. For example, nitrate concentrations were above the drinking-water standard (U.S. Environmental Protection Agency Maximum Contaminant Level, USEPA MCL) of 10 milligrams per liter (mg/L) as nitrogen in water from 20 percent of wells sampled in the Columbia Plateau, and 4 percent of wells sampled in the Snake River Plain. One or more pesticide compounds were detected in water from half of the wells sampled in all three areas combined, though most concentrations were below human-health benchmarks.



Groundwater in the Columbia Plateau had higher nitrate concentrations than did groundwater in the Snake River Plain or on Oahu.

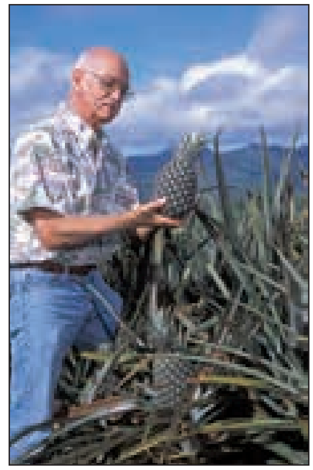


See sidebar, Boxplots, p. 41

Plateau and Snake River Plain Basin-Fill and Basaltic-Rock Aquifers

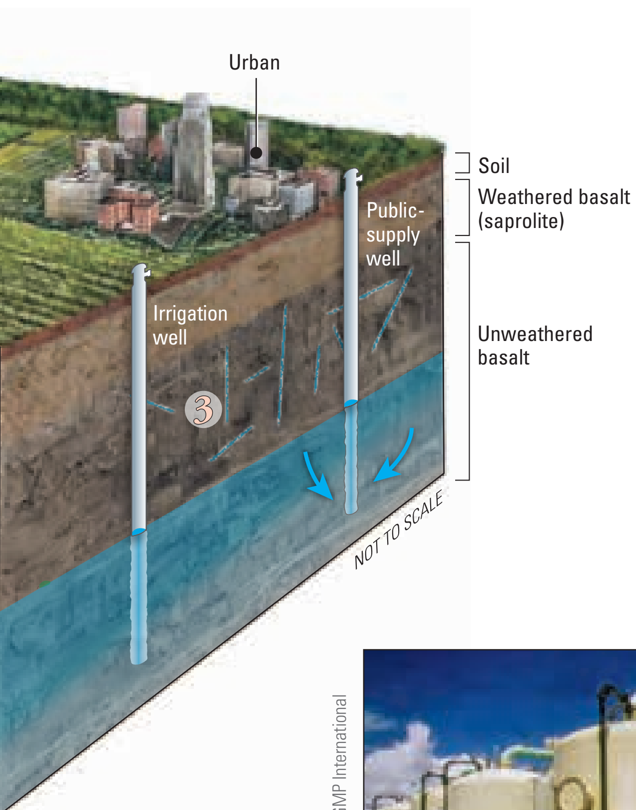
2 Chemicals that have been banned for over 30 years are still a potential human-health concern in groundwater

Several soil fumigants and the pesticide dieldrin were banned more than 30 years ago, yet have been detected at concentrations exceeding human-health benchmarks in some groundwater samples. Chemicals that are no longer in use but are persistent in the environment are termed "legacy contaminants." These chemicals do not readily break down in groundwater, and several decades (or longer) are required to flush the chemicals through the aquifers. Exceedances of human-health benchmarks occurred most frequently on Oahu, where concentrations of one or more soil fumigants exceeded Hawaii MCLs in water from 13 percent of public-supply wells sampled, and concentrations of dieldrin exceeded the human-health benchmark in water from 10 percent of public-supply wells sampled. Tracking changes in concentrations of legacy contaminants could require decades of groundwater monitoring.



Photograph by Peggy Greb, USDA ARS

Soil fumigants are used in pineapple cultivation.



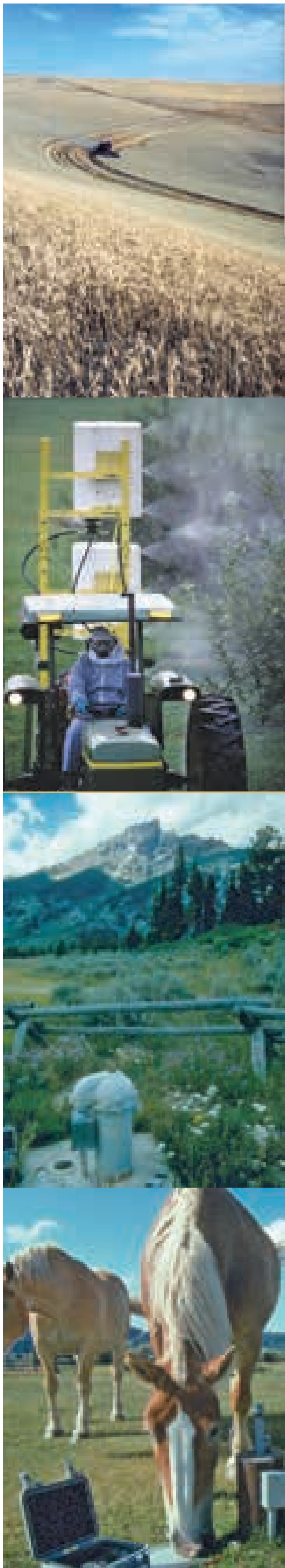
3 Although the aquifers of the Columbia Plateau, Snake River Plain, and Oahu are composed of similar geologic materials (basalt), contamination issues vary among the aquifers because of differing geochemical conditions and differing land and chemical uses

Contaminants from geologic sources and nitrate were more commonly detected in groundwater sampled in the Columbia Plateau and Snake River Plain than on Oahu. For example, elevated concentrations of radon, arsenic, molybdenum, and manganese were detected in water from some wells in the Columbia Plateau and Snake River Plain, but not in wells on Oahu, because the aquifer materials and geochemical conditions on Oahu do not promote mobilization of these constituents in groundwater.

Contaminants related to human activities—soil fumigants and solvents—were detected more frequently on Oahu than in the Columbia Plateau and Snake River Plain. At least one soil fumigant or solvent was detected in water from more than half of the wells sampled on Oahu. These contaminants are present in groundwater on Oahu because of past intensive application of soil fumigants to control insect pests in a tropical climate and releases of solvents in military and urban lands. The discovery of soil fumigant and solvent contamination on Oahu in the 1980s led to well closures and installation of costly water-treatment facilities.

Photograph courtesy of GMP International

Water-treatment systems are required to remove soil fumigants from drinking water on Oahu.



Photographs from top to bottom: USDA ARS; Keith Weller, USDA ARS; Michael G. Rupert, USGS; Michael G. Rupert, USGS

Overview of Major Findings of
and Snake River Plain Basin-Fill and Basaltic-Rock

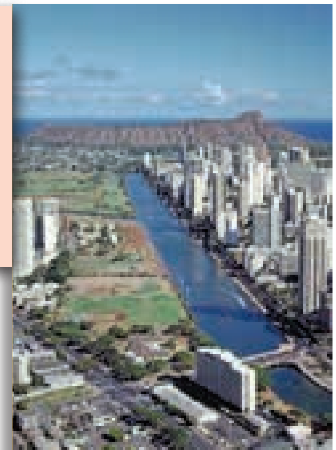
1 The Columbia Plateau, Snake River Plain, and Oahu aquifers are vulnerable to contaminants related to human activities despite depths to groundwater that are among the greatest in the Nation.

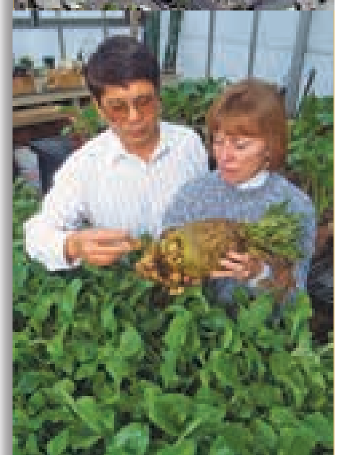
Nitrite plus nitrate as nitrogen (nitrate) and pesticides were widely detected in groundwater samples from the Columbia Plateau and the Snake River Plain aquifers. Although depth to the water table can be many hundreds of feet, the permeable geologic materials overlying the aquifers allow contaminants to move readily from the land surface to the water table. Human activities associated with intensive agriculture in areas that rely on aquifers for drinking water are a source of numerous contaminants, including nitrate and pesticides. For example, nitrate concentrations were above the U.S. Environmental Protection Agency Maximum Contaminant Level of 10 milligrams per liter in water from 20 percent of wells sampled in the Columbia Plateau, and 4 percent of wells sampled in the Snake River Plain. One or more pesticide compounds were detected in water from half of the wells sampled in the three areas combined, though most concentrations were below human-health benchmarks. The widespread occurrence of pesticides and elevated concentrations of nitrate demonstrates the vulnerability of the aquifers to contamination and indicates that comprehensive groundwater protection strategies are warranted to help assure those concentrations do not exceed human-health benchmarks in the future.

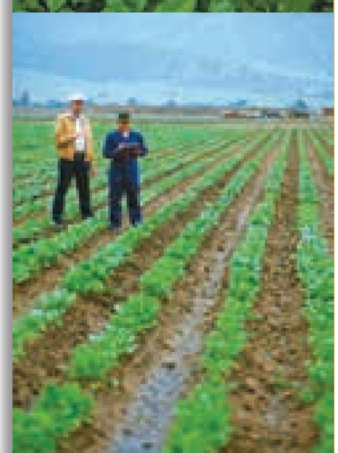
2 Chemicals that have been banned for over 30 years are still a potential human-health concern in groundwater.

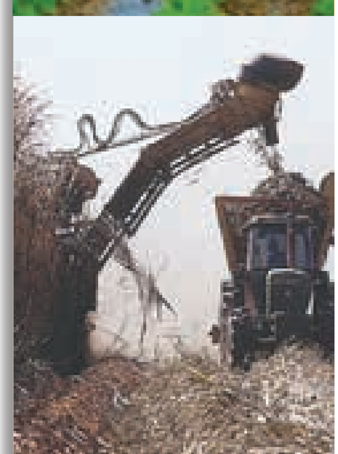
Chemicals that are no longer in use but are persistent in the environment are termed “legacy contaminants.” These chemicals include several soil fumigants and the pesticide dieldrin, which were banned more than 30 years ago, yet have been detected at concentrations exceeding human-health benchmarks in some groundwater samples. Exceedances of human-health benchmarks occurred most frequently on Oahu, where concentrations of one or more soil fumigants exceeded Hawaii Maximum Contaminant Levels in water from 13 percent of public-supply wells sampled, and concentrations of dieldrin exceeded the human-health benchmark in water from 10 percent of public-supply wells sampled. Soil fumigants also exceeded human-health benchmarks in groundwater samples from the Columbia Plateau and Snake River Plain, but in only a few wells. These chemicals do not readily break down in groundwater, and several decades (or longer) are required to flush the chemicals through the aquifers. For these reasons, current land use may not be a good indicator of existing groundwater quality because contamination from former land use and chemical applications may be present. As an example, if existing agricultural land is converted to residential use, homeowners and developers could encounter groundwater contaminated with agricultural legacy contaminants. This was the case on Oahu, where public-supply wells drilled in former agricultural lands tapped groundwater contaminated by fumigants, requiring installation of expensive treatment systems. Tracking changes in concentrations of legacy contaminants could require decades of groundwater monitoring.

Groundwater Quality for the Columbia Plateau Aquifers and the Hawaiian Volcanic-Rock Aquifers









3 *Although the aquifers of the Columbia Plateau, Snake River Plain, and Oahu are composed of similar geologic materials (basalt), contamination issues vary among the aquifers because of differing geochemical conditions and differing land and chemical uses.*

Contaminants from geologic sources and nitrate were more commonly detected in groundwater sampled in the Columbia Plateau and Snake River Plain than on Oahu, but contaminants related to human activities were more commonly detected in groundwater on Oahu. For example, elevated concentrations of radon, arsenic, molybdenum, and manganese were detected in water from some wells in the Columbia Plateau and Snake River Plain, but not in wells on Oahu, because the aquifer materials and geochemical conditions on Oahu do not promote mobilization of these constituents in groundwater. Groundwater in the Columbia Plateau and Snake River Plain had much higher concentrations of nitrate than did groundwater on Oahu—nitrate concentrations in Columbia Plateau water samples were about 5 times higher than in samples from Oahu. Nitrate concentrations in groundwater in the Snake River Plain are rising, reflecting a near doubling of nitrogen input from nitrogen fertilizer and cattle manure between 1987 and 2007. Computer modeling forecasts that, if nitrogen inputs remain at current (2008) levels, nitrate concentrations in Snake River Plain groundwater will continue to increase for at least 50 years; therefore, agricultural management practices that decrease nitrogen application will be all the more important in the coming decades. Continued public outreach and education can increase homeowners' awareness of the need for domestic-well testing and of the water-treatment options available.

Soil fumigants and solvents, contaminants related to human activities, were detected much less frequently in the Columbia Plateau and Snake River Plain than on Oahu. The image of Oahu is that of a pristine tropical environment, but groundwater in many areas of the island is contaminated with soil fumigants and solvents, in some cases at concentrations of concern for human health. At least one soil fumigant or solvent was detected in water from more than half of the wells sampled on Oahu. These contaminants are present in groundwater on Oahu because of past intensive application of soil fumigants to control insect pests in a tropical climate and releases of solvents in military and urban lands. Discovery of soil fumigant and solvent contamination on Oahu in the 1980s led to well closures and installation of costly water-treatment facilities. Wellhead protection programs can minimize future groundwater contamination related to human activities, but the decades-long persistence of contaminants from former chemical releases and application may continue to place a financial burden on society in the form of water-treatment costs.

Photographs from top to bottom: Doug Peebles, Douglas Peebles Photography; Scott Bauer, USDA ARS; Scott Bauer, USDA ARS; David Nance, USDA ARS

Taggart Creek, in the Jackson valley study area, near Grand Teton National Park, Wyoming. Creeks such as this provide important recharge to groundwater.

Photograph by Michael G. Rupert, USGS

Chapter 2: *NAWQA Approach to Assessing Groundwater Quality*

How does one go about characterizing the groundwater encompassing an area as large as that covered by the Columbia Plateau, Snake River Plain, and Oahu aquifers, let alone the entire United States? The approach taken by the USGS is to use different types of groundwater studies 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? Groundwater studies are the building blocks of NAWQA's water-quality assessments of Principal Aquifers. Using a nationally consistent approach allows comparison between the many regions of the United States (see sidebar, Understanding study results, p. 9).

This chapter summarizes the study design used to investigate water quality in the Columbia Plateau, Snake River Plain, and Oahu aquifers.

Photograph by Michael G. Rupert, USGS

As part of the NAWQA Program, water samples were collected from domestic, public-supply, monitoring, irrigation, and stock wells in a variety of settings. Here, horses graze next to a domestic well in the Jackson valley study area, Wyoming.

Characterizing Groundwater Quality: The NAWQA Approach

Three types of studies were conducted in each Principal Aquifer, each with a different focus on information needs about groundwater quality and the natural and human-related factors that influence it. Groundwater studies designed to broadly assess water-quality conditions of the groundwater resource in relatively large areas were conducted to sample networks of existing domestic (private) and public-supply wells—these studies, called major aquifer studies or study unit surveys, involved sampling wells in areas with a mix of land uses (see appendix 1). Groundwater studies designed to characterize and explain the quality of recently recharged groundwater (generally less than 10 years old[(1)]) underlying agricultural and urban land were conducted to sample networks of domestic wells and shallow monitoring wells that were installed as part of the NAWQA Program—these studies are called land-use studies. Land-use studies were done in agricultural areas of the Columbia Plateau and Snake River Plain but not on Oahu. Urban areas were not studied in any of the three study areas. Groundwater studies that focused on areas of the aquifers where particular contaminants were expected to be higher than in other areas were conducted to sample domestic and monitoring wells—these studies are called special studies. Special studies were done in the Columbia Plateau and on Oahu but not in the Snake River Plain. The area sampled by the special studies was within the area sampled by the studies in agricultural lands, which in turn was within the area sampled in mixed land uses, providing a multiscale approach to understanding groundwater quality (fig. 2–1).

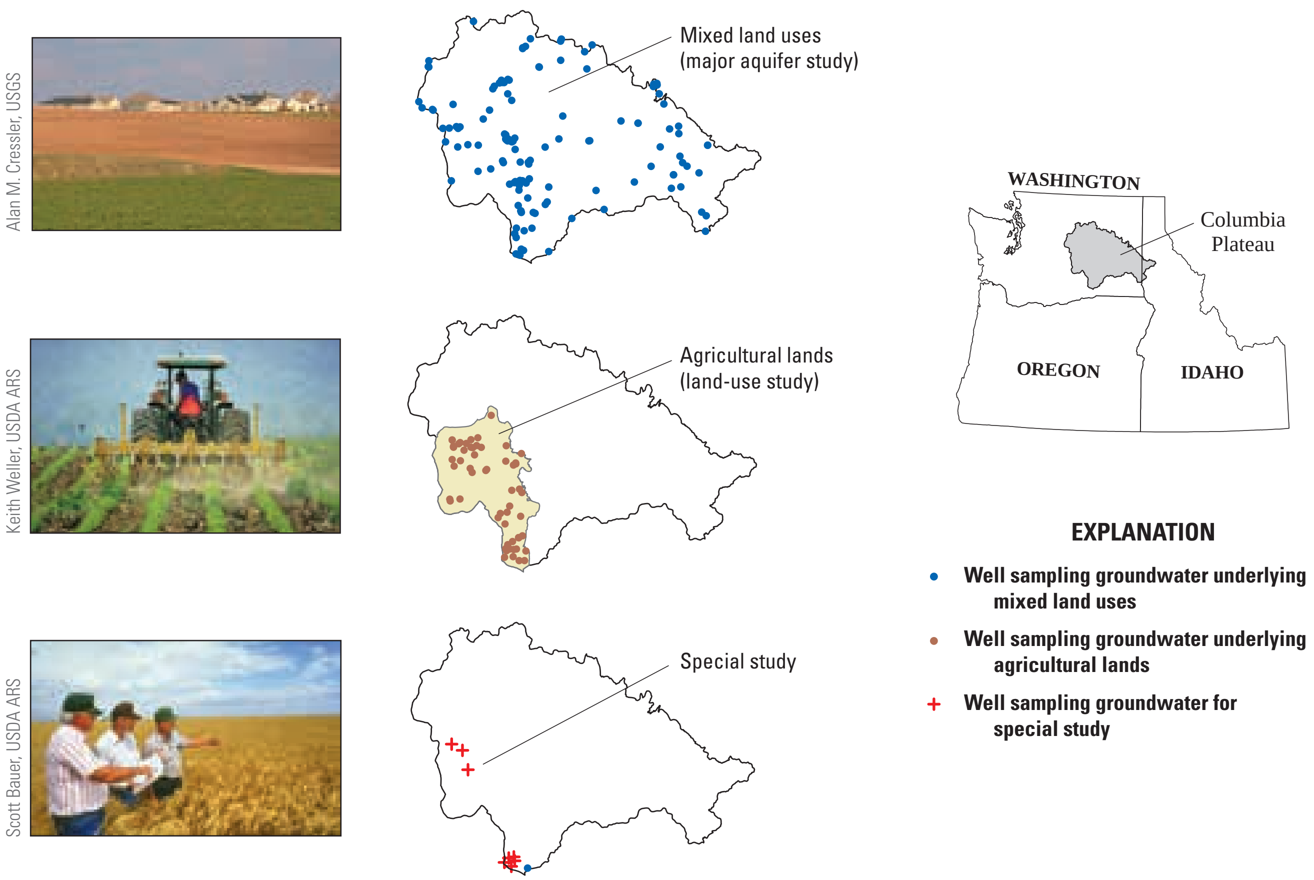


Figure 2–1. The NAWQA approach in the Columbia Plateau and Snake River Plain and on Oahu used three types of groundwater studies (studies in areas of mixed land uses, studies in agricultural lands, and special studies) to assess groundwater-quality conditions at regional and local scales. The area sampled by the special studies was within the area sampled by the studies in agricultural lands, which in turn was within the area sampled by the studies in mixed land uses. Shown here is an example of the approach used in the Columbia Plateau.

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. 10) prior to any treatment. They represent the quality of the groundwater resource but not necessarily the quality of tap water.
- The focus of the assessments is the condition of the total resource, including groundwater in a wide range of hydrologic and land-use settings across the Nation, rather than conditions at specific sites with known water-quality concerns.
- The assessments are guided by a nationally consistent study design, and all assessments use the same methods of sampling and analysis. Findings apply to water quality of a particular aquifer but also contribute to the larger picture of how and why water quality varies regionally and nationally. This consistent approach helps to determine if a water-quality issue is isolated or widespread. (See *http://water.usgs.gov/nawqa/about.html* for more information.)
- The assessments focus on aquifers used for water supply or on shallow groundwater that underlies an area with a particular type of land use. The wells sampled were selected to represent typical conditions in these aquifers. Because the wells are located only in NAWQA groundwater study areas, the samples may not be representative of all groundwater throughout the Principal Aquifers.
- Analytical methods used by USGS chemists for assessments of water quality in Principal Aquifers are designed to measure constituents at as low a concentration as possible (see appendix 2). 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. 36). Low-level detections allow scientists to identify and evaluate emerging issues and to track contaminant levels over time.

Is there a difference in the quality of water produced by domestic, public-supply, and monitoring wells?

The sampling results from domestic, public-supply, and monitoring wells were combined to provide a general overview of the quality of groundwater in the Columbia Plateau and Snake River Plain and on Oahu. But is there a difference in the quality of water produced by these three types of wells?

Domestic wells usually are shallower than public-supply wells; therefore, domestic wells pump water that is nearer to sources of manmade contaminants, such as fertilizers and pesticides, applied at the land surface. On the other hand, because public-supply wells pump water from deeper in the aquifer, they might be more likely to have higher concentrations of constituents from geologic sources, because deeper water generally has been in contact with the aquifer rock for a longer period of time. In addition to being deeper, public-supply wells have larger pumps and longer screened intervals than do domestic wells, and are pumped for longer periods of time. As a result, public-supply wells pump much larger volumes of water than do domestic wells, and so have much larger capture zones. Thus, public-supply wells are more vulnerable than are domestic wells to manmade contamination from distant sources. If the amount of water withdrawn is large enough, it can change the flow direction and velocity of the groundwater, which can, in turn, affect the groundwater chemistry and the constituents contained therein.

Domestic wells tend to be located in rural areas, so they are more likely to be vulnerable to contamination from agricultural chemicals, whereas public-supply wells, which tend to be located in suburban and urban areas, are more vulnerable to contamination from chemicals associated with urban activities.

Routine testing of water from domestic wells is not required and homeowners are responsible for the testing, maintenance, or treatment of the water from their domestic well. Water that is provided to consumers from public-supply wells is required to be tested on a routine basis to help assure that the water meets Federal and State water-quality standards.

Finally, some groundwater samples were collected from monitoring wells. Monitoring wells, which typically do not have permanent pumps installed, are used for measuring water levels or occasionally collecting water samples with portable pumps, but are not used for drinking water, irrigation, or other purposes. Monitoring wells were installed by NAWQA to sample groundwater near the water table, so monitoring wells are shallower than domestic or public-supply wells located in the same areas.

For more information on the quality of groundwater from domestic wells sampled in many areas of the Nation, please see DeSimone and others.[(2)] For more information on water from public-supply wells sampled in many areas of the Nation, please see Toccalino and Hopple.[(3)]

Aquifer (aq.ui.fer)—äkwefer

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

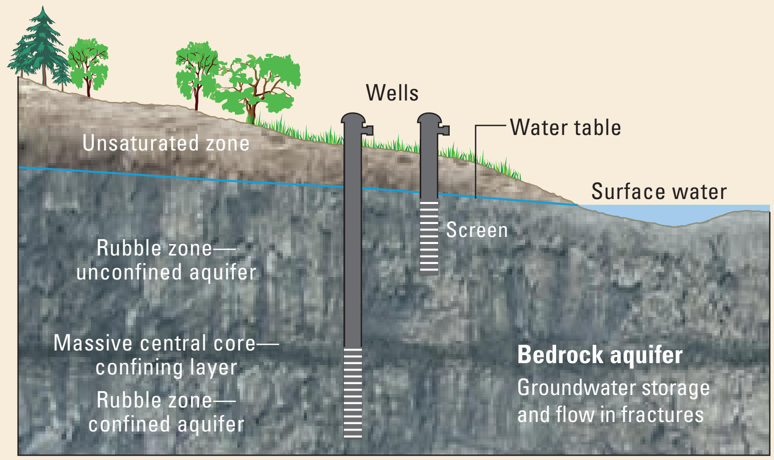
The **unsaturated zone** is the area below the land surface and above an aquifer. In addition to soil, rocks, and air, it contains water from the land surface (such as rain) that is slowly moving downward to the water table of the aquifer.

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

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

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

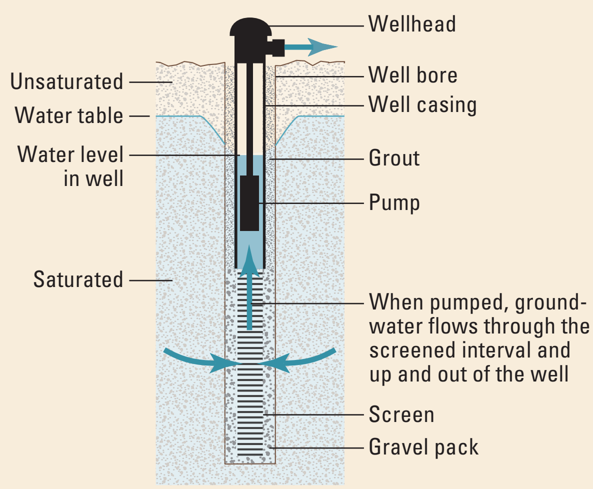
The pressure within a confined aquifer can be greater than that in the overlying unconfined aquifer if the source of the water in the confined aquifer is at a higher elevation than the unconfined aquifer. In that case, water in a well in a confined aquifer will rise to a higher level than that in the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



Sedimentary aquifer
Groundwater storage and flow between grains of sediment

Anatomy of a well

A well is really just 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, allowing 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 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.



Assessing Water Quality in the Columbia Plateau, Snake River Plain, and Oahu Aquifers

To provide a broad assessment of groundwater-quality conditions in areas with mixed land uses across a large geographic area, one sample was collected from each of 285 randomly selected,[(4)] existing domestic and public-supply wells located in the three study areas (figs. 2–2, 2–3, 2–4; table 2–1). Samples were analyzed for major and trace inorganic constituents, nutrients, pesticides, and volatile organic compounds (VOC) (see sidebar, NAWQA assessments use a wide range of geochemical data and site information, p. 14). Samples were collected from the basalt aquifers of the Columbia Plateau, the Snake River Plain, and Oahu (appendix 1) and from major alluvial aquifers of the Snake River Plain. In the Columbia Plateau and on Oahu, most samples were collected from public-supply wells, so the results provide valuable insight into the quality of public drinking-water resources. In the Snake River Plain, most samples were collected from domestic wells, so the results provide insight on the quality of private drinking-water resources. To assess whether groundwater quality is changing in areas of mixed land use in the Columbia Plateau, 43 wells were resampled about 10 years later (table A1–1).

To assess the quality of groundwater underlying agricultural land, one sample was collected from each of 233 randomly selected wells in the Columbia Plateau and Snake River Plain (table 2–1). Groundwater studies in agricultural areas were designed to evaluate how a single crop type, irrigation regime, or other key characteristic affects water quality (table A1–1). In the Quincy-Pasco, Washington, area of the Columbia Plateau, samples of groundwater underlying two types of agricultural land—irrigated row crops and orchards—were collected. Further, for each of the two land-use types, groundwater was collected at two depths: Shallow groundwater near the water table was sampled from monitoring wells that withdraw groundwater from the basin-fill sediments, and deeper groundwater was sampled from domestic wells that withdraw groundwater from a mixture of basin-fill sediments and basalt rock (fig. 2–2). In the Palouse, Washington, area of the Columbia Plateau, groundwater underlying dryland grains was sampled. Two types of wells also were sampled in the Palouse area—shallow monitoring wells that withdraw groundwater in wind-blown silt (loess) sediments, and domestic wells that withdraw deeper groundwater from the underlying basalt aquifer. In the Snake River Plain, samples of groundwater underlying irrigated row crops were collected in four areas. In three of those areas, the wells tap the basalt aquifer, and in one area, the wells tap a local sedimentary aquifer overlying the basalt aquifer (fig. 2–3). Monitoring wells in the Quincy-Pasco and Palouse areas of the Columbia Plateau, and domestic wells in the A&B, Idaho, and Jerome/Gooding, Idaho, areas of the Snake River Plain (fig. A1–2; table A1–1), were resampled about 10 years later to assess whether the groundwater quality had changed. No studies of groundwater quality underlying agricultural lands were conducted on Oahu.

In the Columbia Plateau, a special study was conducted to investigate the occurrence of soil fumigants in an area with a history of fumigant contamination (table A1–1). For this study, samples collected from a network of domestic wells were analyzed using laboratory methods that can detect 1,2-dibromoethane (ethylene dibromide, EDB) and 1,2-dibromo-3-chloropropane (DBCP) at concentrations much lower than those typically reported. On Oahu, a special study involved the use of monitoring wells to evaluate contamination in a zone of groundwater near the water table (called the irrigation-recharge layer). The irrigation-recharge layer overlies the groundwater sampled from the public-supply wells on Oahu.

Table 2–1. Summary of NAWQA groundwater studies in the Columbia Plateau and Snake River Plain and on Oahu discussed in this report. Appendix 1 describes the groundwater studies in greater detail.

[—, not studied]

Groundwater study area	Number of wells sampled (and median well depth) in groundwater studies				
	Agricultural lands		Mixed land uses		
	Groundwater near water table tapped by monitoring wells	Deeper groundwater tapped by domestic wells	Groundwater near water table tapped by monitoring wells	Deeper groundwater tapped by domestic wells	Deeper groundwater tapped by public-supply wells
Columbia Plateau	51 (36 feet)	77 (134 feet)	—	—	139 (185 feet)
Snake River Plain	—	105 (190 feet)	—	101 (182 feet)	—
Oahu	—	—	15 (693 feet)	—	30 (512 feet)

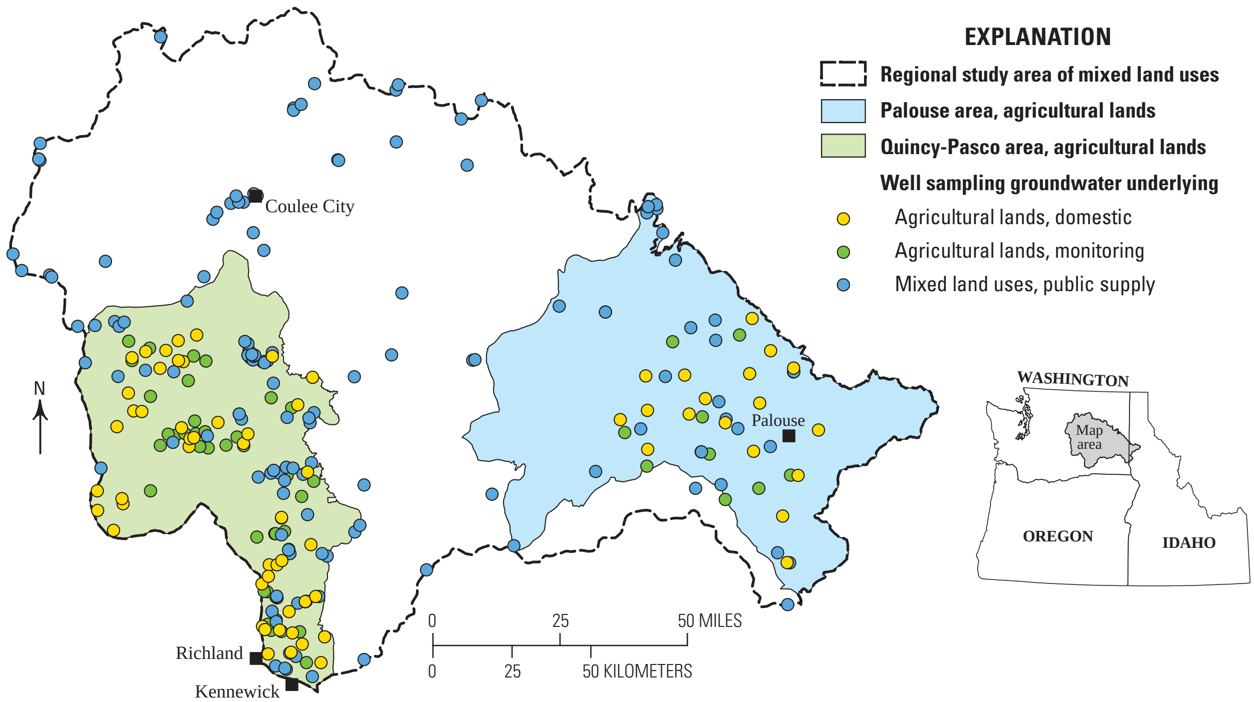


Figure 2–2. In the Columbia Plateau, 267 wells were sampled to assess groundwater quality in a variety of land-use settings—51 monitoring wells in agricultural lands, 77 domestic wells in agricultural lands, and 139 public-supply wells in areas of mixed land uses. Appendix 1 describes the Columbia Plateau study area in greater detail.

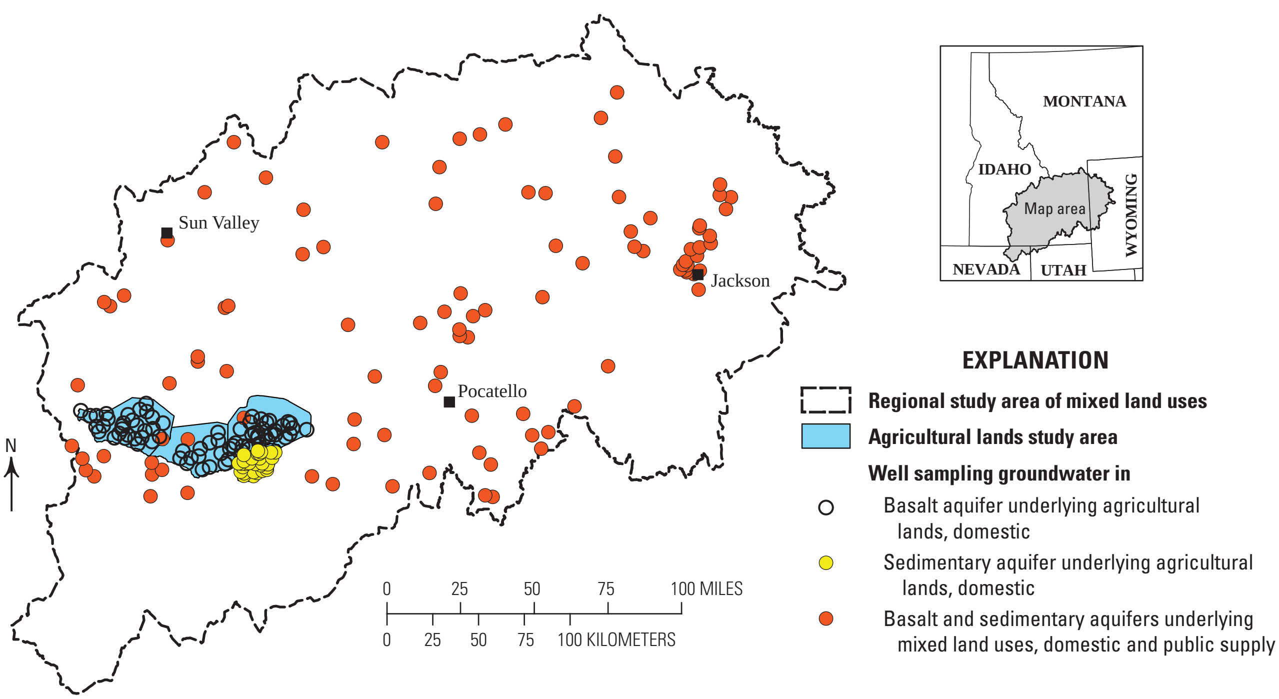


Figure 2–3. In the Snake River Plain, 105 wells in agricultural lands and 101 wells in areas of mixed land uses were sampled to evaluate groundwater quality across the study area. Appendix 1 describes the Snake River Plain study area in greater detail.

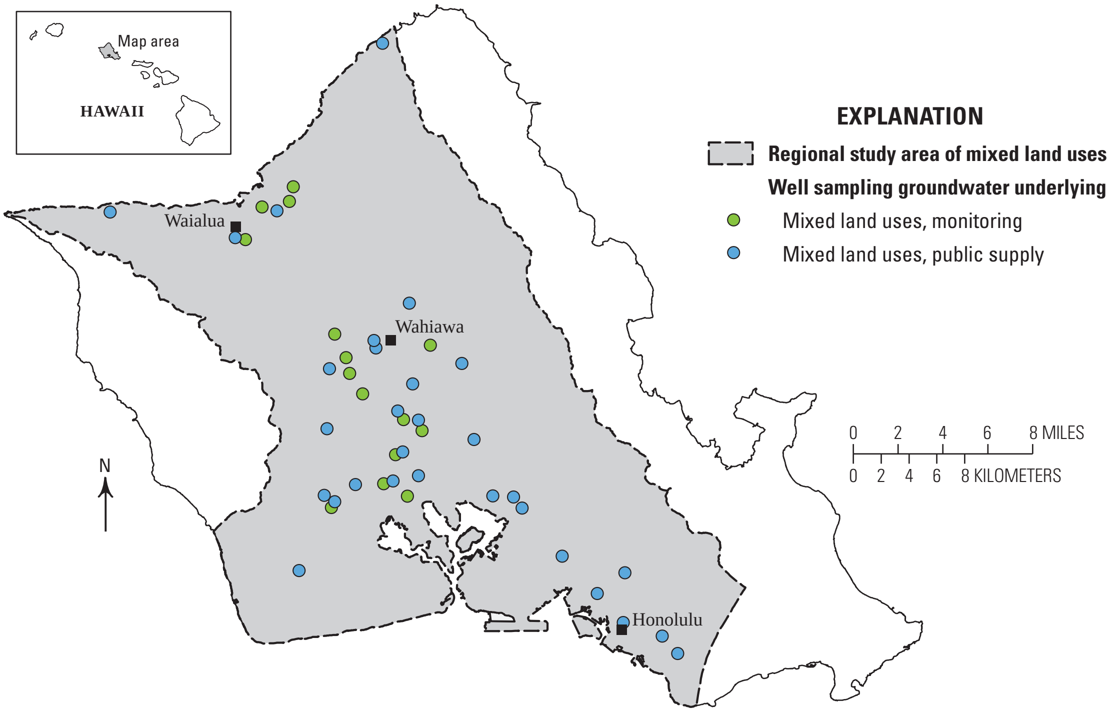


Figure 2–4. Fifteen monitoring wells and 30 public-supply wells were sampled on Oahu to evaluate groundwater quality underlying areas of mixed land uses. Appendix 1 describes the Oahu study area in greater detail.

Photograph by Scott Bauer, USDA ARS

Sugar beets are an important row crop in the Snake River Plain. NAWQA studies in the Snake River Plain were designed to evaluate the effects of irrigated row-crop agriculture on groundwater quality.

Photograph by Keith Weller, USDA ARS

This air-curtain orchard sprayer uses multiple cross flow fans to disperse pesticide to apple trees. Under some conditions, the smooth, gentle flow of air can substantially reduce spray drift. Groundwater underlying orchards was sampled in the Quincy-Pasco, Washington, area of the Columbia Plateau to investigate the occurrence of nitrate and pesticides.

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

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

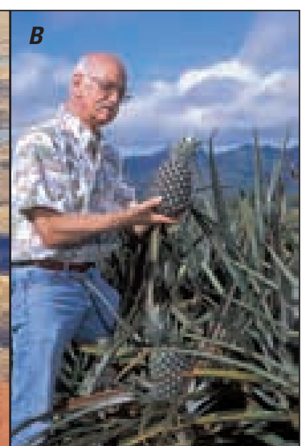
Chemists at the USGS National Water Quality Laboratory analyze groundwater samples using an array of sophisticated techniques.

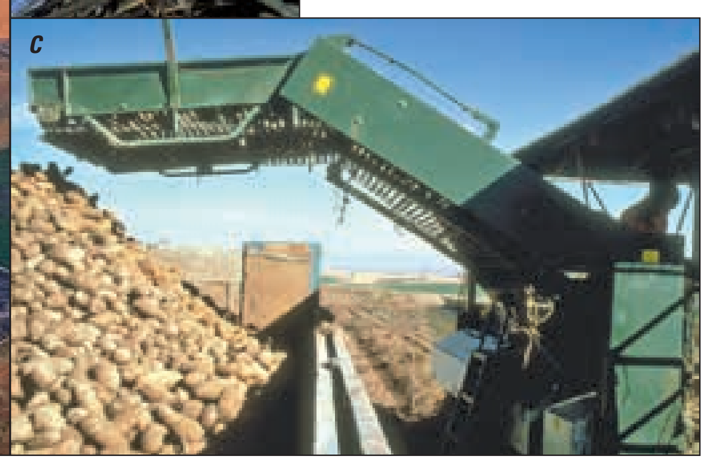
Additional information (often called “ancillary information”) about the well and surrounding environment complements the chemical data measured. This additional information often is key to making sense of the chemical data. For example, the information might be used to determine that shallow groundwater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

Chapter 3: *Environmental and Hydrogeologic Setting*

There are striking similarities—and differences—among the Columbia Plateau, Snake River Plain, and Oahu aquifers. All three areas contain extensive regional aquifers of a hard, gray, volcanic rock called basalt, which sets these three Principal Aquifers apart from all others in the United States. Although the aquifer materials are similar among the three areas, differences in agricultural practices and climate affect the hydrogeologic systems and groundwater quality of the areas. Much of the land in the Columbia Plateau and Snake River Plain is arid desert; without irrigation, agriculture would not be possible. In contrast, the tropical climate on Oahu allows crops such as pineapple and sugarcane to be grown. The differences between irrigation methods and types of crops grown in the three areas affect the amount of groundwater recharge and the types of chemicals transported to the groundwater along with the recharge.

This chapter summarizes background information for the Columbia Plateau, Snake River Plain, and Oahu aquifers, 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.





A, Irrigation has allowed the Columbia Plateau to become some of the most productive agricultural areas in the United States. *B*, Pineapple cultivation on Oahu uses drip irrigation to reduce the harmful effects of root damage from nematodes and to reduce moisture stress to the plants during dry periods. *C*, The popular Idaho potato could not be grown in the Snake River Plain without extensive irrigation systems.

Photographs by *A*, Doug Wilson, USDA ARS; *B*, Peggy Greb, USDA ARS; *C*, ©1976 by W.H. Mullins and published with permission

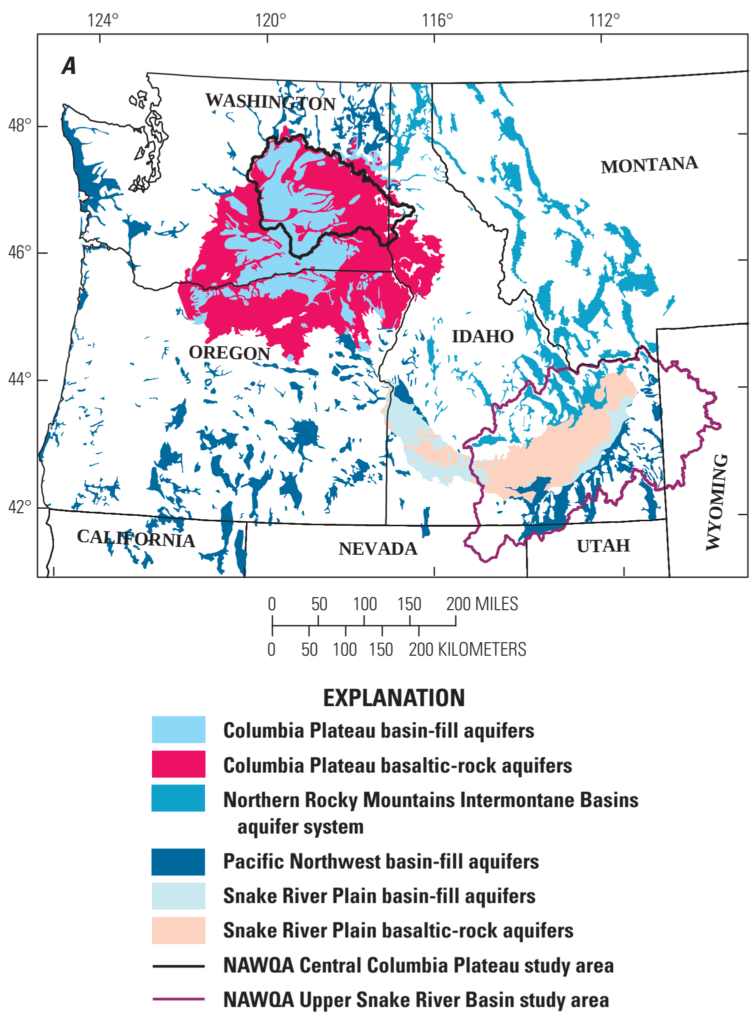
Environmental Setting

The Columbia Plateau, the Snake River Plain, and the Hawaiian Islands are large volcanic areas in the western United States and mid-Pacific Ocean, respectively (fig. 3–1). Each area contains extensive regional aquifers of a hard, gray, volcanic rock called basalt. The Columbia Plateau aquifers encompass 50,600 square miles in parts of Washington, Oregon, and Idaho. The Snake River Plain aquifers encompass 15,600 square miles across southern Idaho and a small sliver of eastern Oregon. The aquifers underlying the Hawaiian Islands encompass only 6,446 square miles. For additional details about the environmental setting, geology and groundwater hydrology in these three areas, refer to the USGS Ground Water Atlas of the United States.(5)

Two Principal Aquifers in the Columbia Plateau drainage basin are included in this assessment: the Columbia Plateau basin-fill aquifers and the Columbia Plateau basaltic-rock aquifers (fig. 3–1; appendix 1).(5) The basaltic-rock aquifers are overlain by the basin-fill aquifers, which are composed of unconsolidated and semiconsolidated sand and gravel. For brevity, hereafter in this report, this study area will be referred to as the Columbia Plateau.

In the Snake River Plain, the primary focus of study was the Snake River Plain basaltic-rock aquifers in the Upper Snake River Basin, which encompasses the Eastern Snake River Plain and surrounding tributary valleys (fig. 3–1; appendix 1). Four Principal Aquifers are located in the Upper Snake River Basin: the Northern Rocky Mountains Intermontane Basins aquifer system, the Pacific Northwest basin-fill aquifers, the Snake River Plain basin-fill aquifers, and the Snake River Plain basaltic-rock aquifers.(5) Groundwater samples were collected from all four Principal Aquifers, but most samples were collected from the Snake River Plain basaltic-rock aquifers. For brevity, hereafter in this report, the Upper Snake River Basin will be referred to as the Snake River Plain study area.

In Hawaii, groundwater quality was assessed on the island of Oahu (fig. 3–1). The most important aquifers are composed of volcanic rocks. Consolidated sedimentary deposits, which are principally coralline limestone, form productive aquifers in lowlands and nearshore areas, but generally contain brackish water or saltwater.(5) The sedimentary aquifers were not sampled because they are not important drinking-water resources.



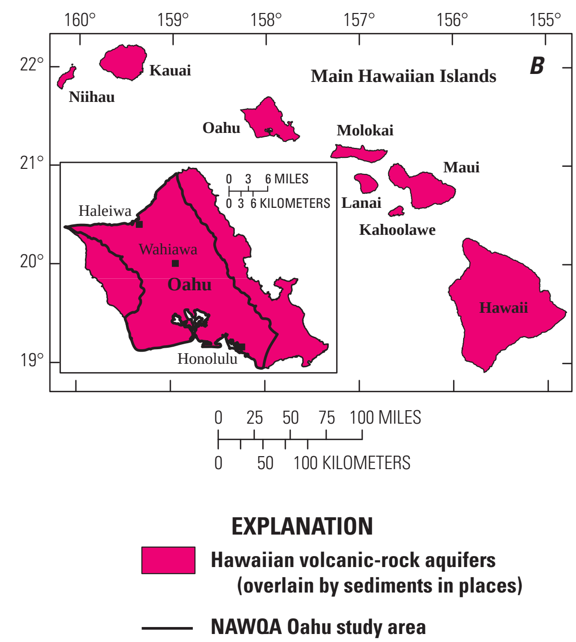


Figure 3–1. *A*, The Columbia Plateau and Snake River Plain in the western United States are underlain by extensive aquifers of sediments and basalt. *B*, The Hawaiian Islands are underlain by volcanic-rock aquifers (mostly basalt). Groundwater was sampled only on the island of Oahu (inset).

The Columbia Plateau, Snake River Plain, and Oahu aquifers at a glance.....

Photograph by USDA ARS

The Columbia Plateau

160	Percent increase in population since 1970
821,000	The number of people living in the area in 2005
Less than 15 inches	Mean annual precipitation
810 million gallons per day	Groundwater used for irrigation
223 million gallons per day	Groundwater used for public supply
33 million gallons per day	Groundwater used by domestic wells
30 to 300 feet thick	Average thickness of individual basalt flows
Nitrate	The most commonly detected contaminant above the USEPA MCL
20	Percent of wells with nitrate concentrations above the USEPA MCL

Photograph copyright Kestrel Aerial Services, Inc., ©www.kestrelaerial.com, used with permission

The Snake River Plain

225	Percent increase in population since 1970
491,000	The number of people living in the area in 2005
Less than 15 inches	Mean annual precipitation
2,900 million gallons per day	Groundwater used for irrigation
150 million gallons per day	Groundwater used for public supply
34 million gallons per day	Groundwater used by domestic wells
20 to 100 feet thick	Average thickness of individual basalt flows
Nitrate	The most commonly detected contaminant above the USEPA MCL
4	Percent of wells with nitrate concentrations above the USEPA MCL

Photograph by Michael G. Rupert, USGS

Oahu, Hawaii

140	Percent increase in population since 1970
902,000	The number of people living in the area in 2005
70 inches	Mean annual precipitation
171 million gallons per day	Groundwater used for irrigation
243 million gallons per day	Groundwater used for public supply
12 million gallons per day	Groundwater used by domestic wells
3 to 30 feet thick	Average thickness of individual basalt flows
Soil fumigants	The most commonly detected contaminants above the Hawaii or USEPA MCLs
0	Percent of wells with nitrate concentrations above the USEPA MCL

There is a large difference in climate among the three study areas, which, in turn, affects the amount of groundwater recharge and the movement of contaminants to the groundwater. The temperature range in the Columbia Plateau and Snake River Plain is extreme—low temperatures during the winter are below freezing and high temperatures during the summer exceed 100 degrees Fahrenheit (°F). Climate in the lower elevations of the Columbia Plateau and Snake River Plain is dry, with mean annual precipitation less than 15 inches over large areas and less than 8 inches in some places. Because the climate is so dry, most crops must be irrigated, although dryland (non-irrigated) crops such as winter and spring wheat can be grown in some of the wetter areas. Very little groundwater recharge occurs in the non-irrigated areas, but recharge from excess irrigation water can occur in irrigated areas, potentially transporting nitrite plus nitrate as nitrogen (nitrate) and pesticides with it. Precipitation in adjacent mountains and tributary valleys can be 45 to 60 inches or more;[6, 7] runoff from these mountainous regions provides surface-water irrigation waters and groundwater recharge to lower elevation areas.

In contrast, Oahu has a subtropical climate. Temperatures are mild and vary little. August is the warmest month of the year, with a mean temperature of 80.5 °F, and the coolest month is February, with a mean temperature of 72 °F.[8] Precipitation on Oahu varies greatly with elevation and exposure to prevailing easterly trade winds—from less than 25 inches per year near Honolulu to more than 275 inches in the surrounding mountains, one of the wettest places in the United States.[9] Rainfall varies dramatically over short horizontal distances; in some places, this variation can be as much as 80 inches over a horizontal distance of just 1 mile.

The climate can affect the types of contaminants that leach to the groundwater. For example, the climates in the Columbia Plateau and Snake River Plain are similar, and similar row crops are grown in both areas, so the types of pesticides used are similar (with the exception of pesticides used on specialty crops such as orchards in the Columbia Plateau or sugar beets in the Snake River Plain). The climate on Oahu and the crops grown (such as pineapple) are different from the Columbia Plateau or the Snake River Plain, so many of the pesticides used are different. The pesticide application rates are sometimes high on Oahu because of the difficulty in controlling insects and weeds in a tropical climate.

Population

A growing population increases the demand for good-quality drinking water. Population is increasing in all three areas—from 1970 to 2005, the population increased by 160 percent in the Columbia Plateau, by 225 percent in the Snake River Plain, and by 140 percent on Oahu (fig. 3–2). The population in the Columbia Plateau (821,000 in 2005) is widely distributed across rural farming communities and urban centers. The most densely populated urban area is also the most densely cultivated area—the southwest part of the Columbia Plateau near the tri-city area of Pasco-Richland-Kennewick (fig. 3–3). Because of the dense population, this area has the greatest nitrogen input and pesticide use. Similar to the Columbia Plateau, the population in the Snake River Plain (491,000 in 2005) is distributed among rural farming communities and urban centers such as Twin Falls, Pocatello, and Idaho Falls (fig. 3–4). Most of the urban communities are clustered near the Snake River or along its flood plain, and rural communities are scattered in tributary valleys and farther from the Snake River. The urban communities are adjacent to the most productive agricultural lands, so groundwater resources that provide drinking water for urban residents may be affected by agricultural activities on the surrounding lands. Although more people live in the Columbia Plateau than in the Snake River Plain, the population density is roughly the same. Oahu is the most populous (902,000 in 2005), most densely populated, and most urbanized of the three areas. Most of the population is concentrated in urban Honolulu and nearby suburban communities on southern Oahu (fig. 3–5). The population density on Oahu is about 100 times greater than that in the Columbia Plateau and Snake River Plain.

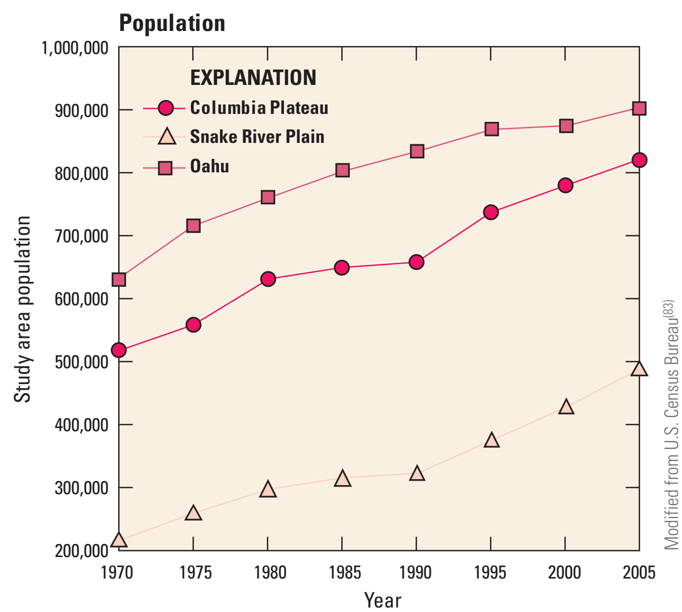


Figure 3–2. The number of people living in the Columbia Plateau and Snake River Plain and on Oahu has increased steadily since 1970. As population grows, so does the demand for good-quality drinking water.

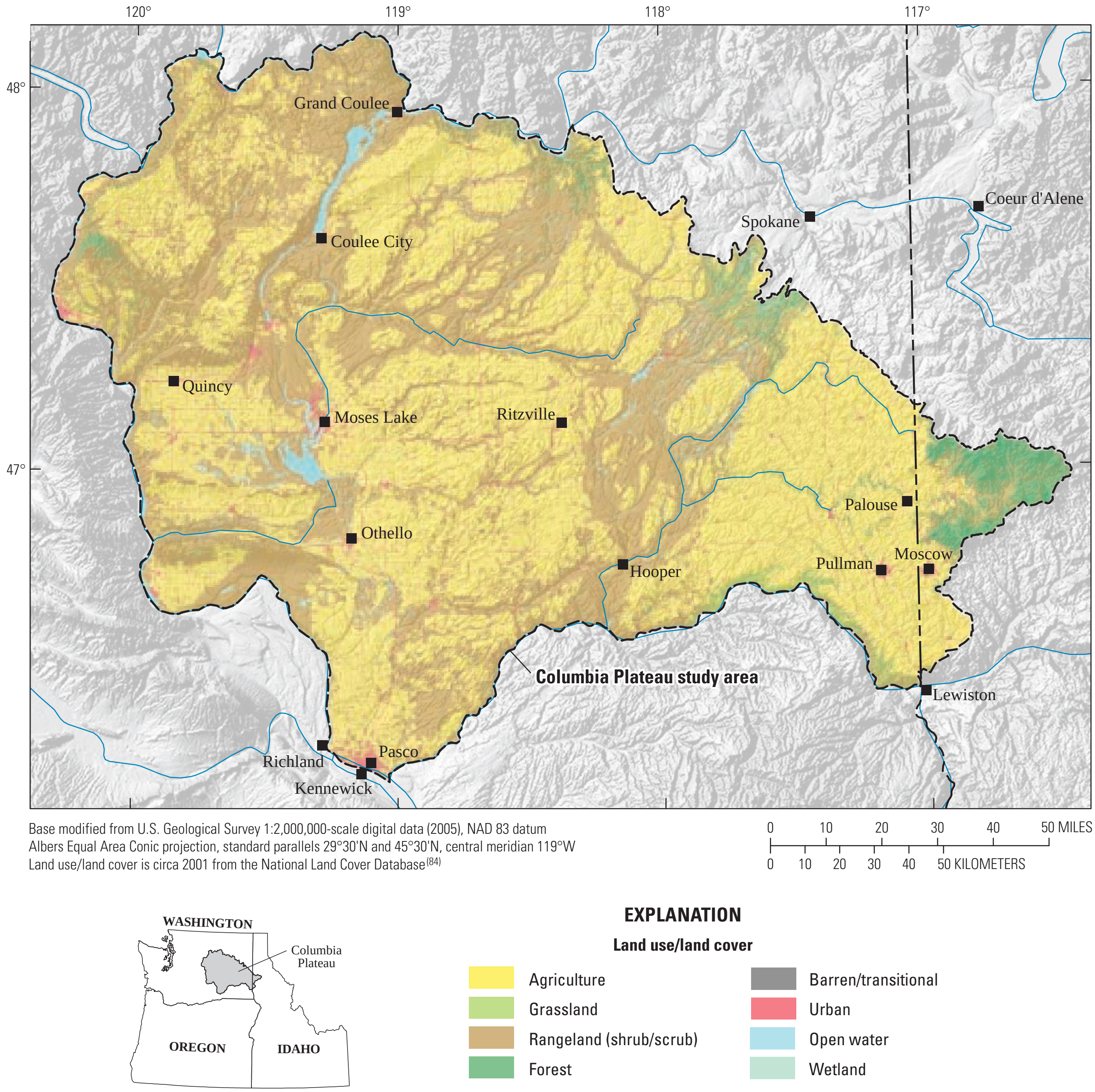


Figure 3–3. Land use is predominantly agricultural (yellow) in the Columbia Plateau.

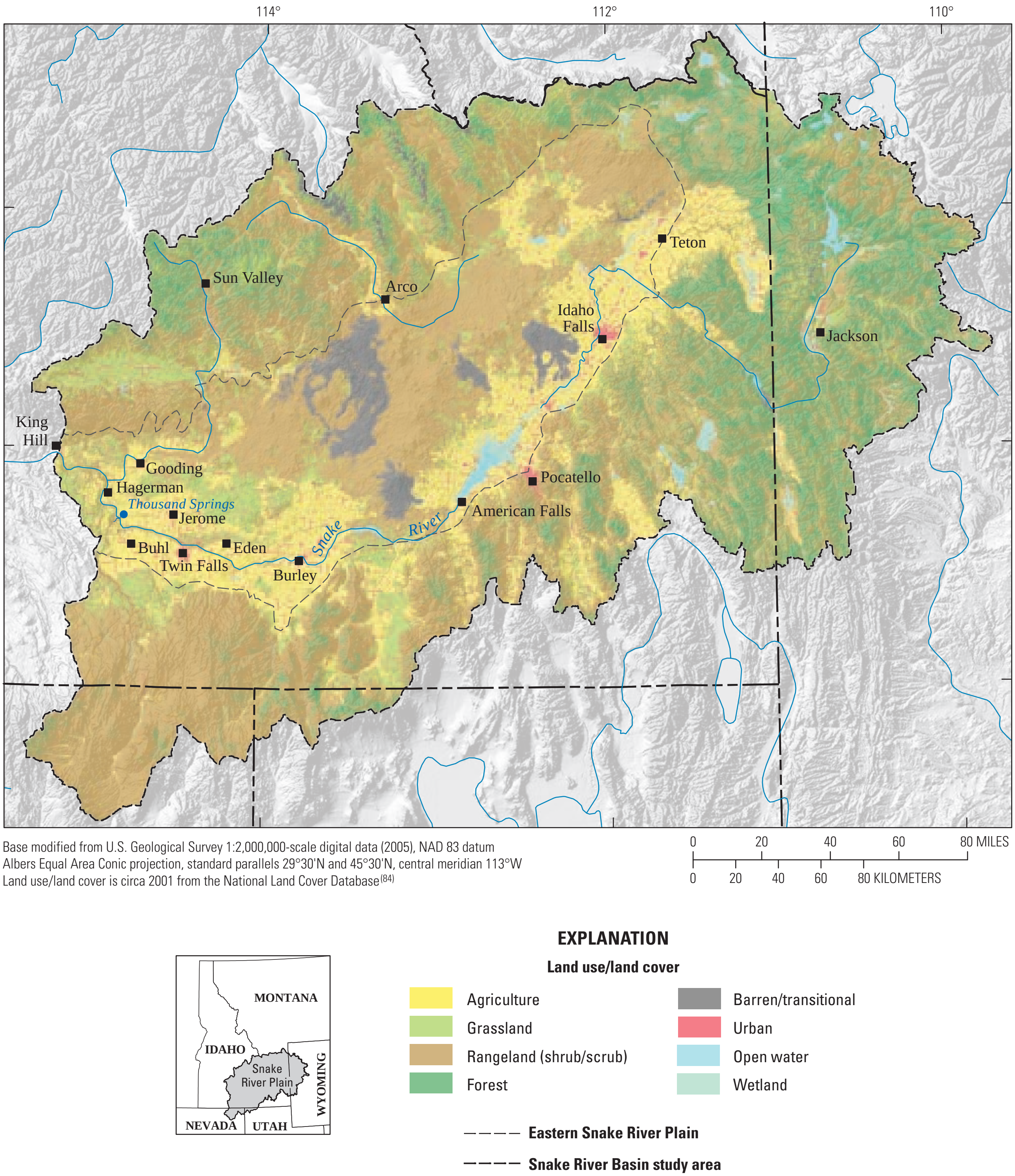


Figure 3–4. Agricultural land use is extensive in the central part of the Snake River Plain and the tributary valleys south and east of the plain. Rangeland and forested lands also make up a large percentage of the land use in the Snake River Plain. Agricultural land use has the greatest potential to adversely affect groundwater quality.

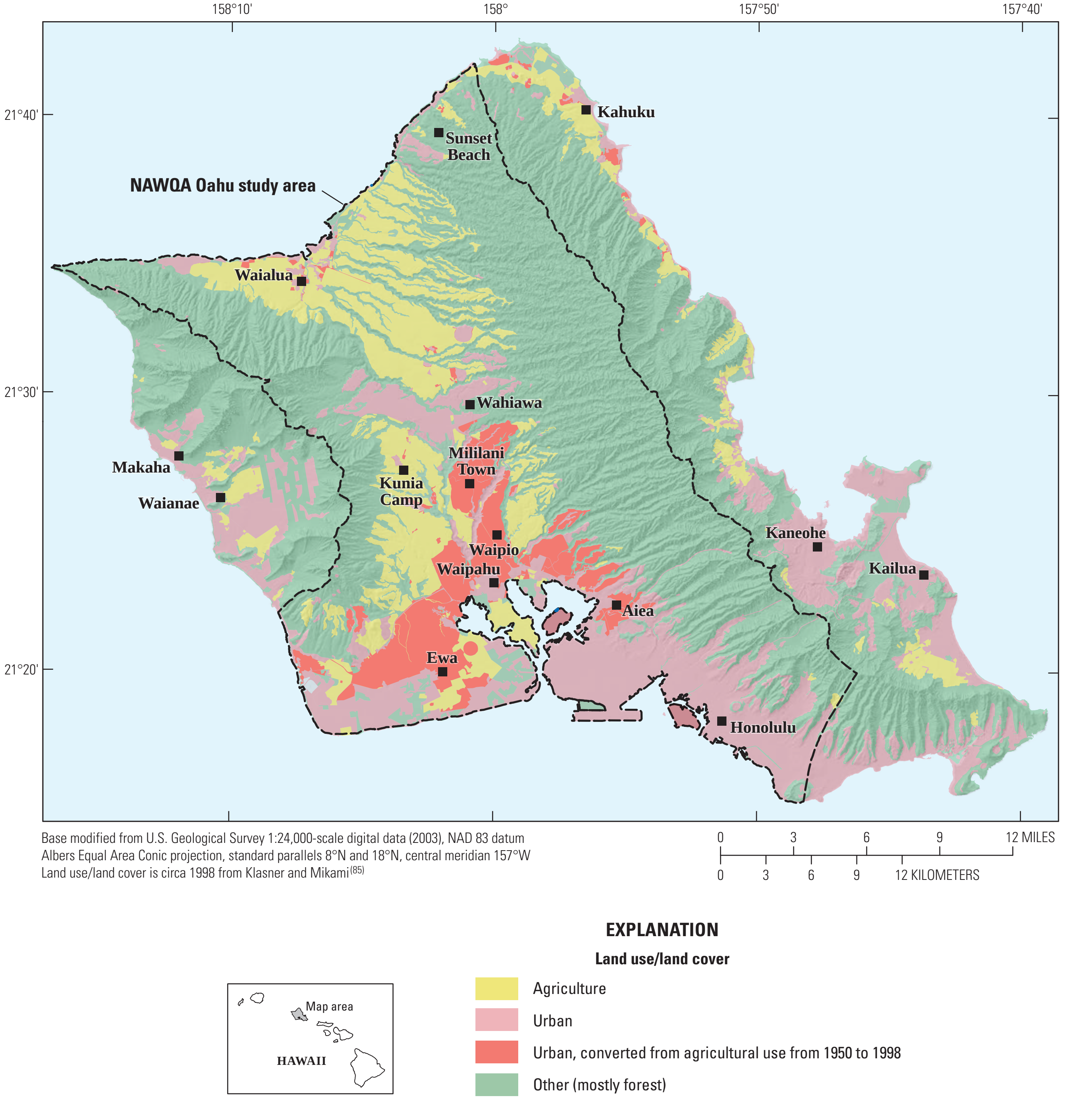


Figure 3–5. Agricultural land use extends over much of central Oahu, but many historically agricultural lands have been converted to urban land use.

Land Use and Water Use

Land use in the three study areas is diverse (figs. 3–3 to 3–5). Principal crops in the Columbia Plateau and Snake River Plain are row crops such as alfalfa, cereal grains (barley, oats, and wheat), potatoes, and corn. The Columbia Plateau also has orchards (primarily apples and cherries) and vineyards. Sugar beets are an important crop in the Snake River Plain. Agriculture on Oahu was dominated historically by sugarcane and pineapple, but sugarcane was phased out in 1996, leaving pineapple, orchards, and vegetables. The total number of cultivated acres has remained fairly constant in the Columbia Plateau and Snake River Plain, but has decreased on Oahu in recent decades, as former agricultural lands in central and southwest Oahu have been converted to suburban and light commercial use since the 1960s.

Of the various land uses in the three study areas, urban and agricultural land use have the greatest potential to adversely affect groundwater quality. The quality of groundwater underlying urban land can be affected by chemical leaks and spills, leachate from landfills, pesticide and fertilizer use, and wastewater disposal. The quality of groundwater underlying agricultural land can be affected by leaching of fertilizer, manure, and pesticides applied at the land surface. Crop rotation, tillage practices, and irrigation practices can affect groundwater quality by either promoting or reducing the leaching of contaminants to the groundwater.

The high crop productivity in the Columbia Plateau and Snake River Plain is possible only through irrigation. Crop irrigation is the dominant use of surface and groundwater in these areas (fig. 3–6). Some of this irrigation water is applied to fields in excess of what is needed by plants, so the excess water infiltrates down to the water table, potentially carrying nitrate and pesticides with it. Although domestic wells provide drinking water for a substantial part of the population in the Columbia Plateau and Snake River Plain, the actual amount of water pumped by a domestic well is small, so the overall water use by domestic wells is small. On Oahu, public water supply is the largest use of groundwater, but groundwater use for irrigation also is substantial.

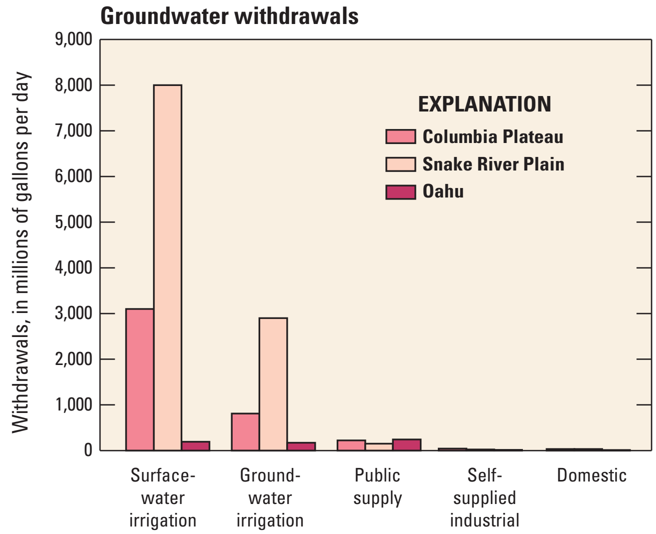


Figure 3–6. Crop irrigation is the dominant use of groundwater in the Columbia Plateau and Snake River Plain, but public supply is the dominant use of groundwater on Oahu. Maintaining good groundwater quality is essential to providing water for drinking, for livestock, and for the agricultural food-processing industry.

Photograph by Charles D. Hunt, Jr., USGS

The Snake River Plain basalt-rock aquifer supplies large volumes of groundwater from great depths for irrigation. Here, a single well is producing over 1,000 gallons of groundwater each minute to irrigate the surrounding fields. There are over 100 of these irrigation wells in the A&B area of the Snake River Plain (fig. A1–2), where groundwater is pumped and applied to crops, and then excess irrigation water is recharged back to the groundwater. This cycle causes dissolved constituents, such as salts and nitrate, to become more concentrated.

Photograph by Michael G. Rupert, USGS

Extensive irrigation canal systems divert water from the Snake River and distribute it across the Snake River Plain to irrigate fields. The Northside Canal, shown here, is located near Milner dam, where the entire flow from the Snake River is diverted for irrigation. Recharge from irrigation water has the potential to carry nitrate and pesticides to the groundwater in the Snake River Plain aquifers.

Hydrogeologic Setting

The largest and most productive aquifers in the Columbia Plateau and the Snake River Plain are composed of basalt, and each area is overlain by smaller sedimentary aquifers. On Oahu, there is one primary basaltic-rock aquifer. Movement of groundwater is primarily through fractures, voids, and conduits in the basaltic rocks and through intergranular pores in the sediments, where present.

The physical characteristics of the basalt aquifers allow groundwater and contaminants to flow quickly through the aquifers. Individual basalt flows have three zones: (1) a top layer of rock fragments (known as flow-top breccia in the Columbia Plateau and Snake River Plain and as rubble or “aa clinker” on Oahu), (2) a hard, dense, massive core, and (3) a basal layer of rock fragments (rubble) (fig. 3–7). The top and bottom layers are composed of rubble because the outer parts of the lava flows cooled quickly and crumbled apart; the middle layer is hard and dense because it cooled more slowly. Most of the groundwater and contaminants flow through the rubble zones. Much less groundwater flows through the massive central core because it is much less fractured; in the Columbia Plateau these middle layers are so thick and dense that they can act as confining layers, inhibiting groundwater and contaminant movement. Contaminants that reach the water table in basalt aquifers can migrate great distances because the rubble zones can allow large amounts groundwater to flow rapidly. Basalt does not react with most contaminants, such as nitrate or pesticides, so contaminants can persist for long periods and be transported for long distances.

Although the Columbia Plateau, Snake River Plain, and Oahu share a common rock type (basalt), the thickness and geometry of the basalt layers differ because of the environments in which the rocks were deposited and the ways in which the basalts erupted from the volcanoes. These differences, in turn, affect groundwater flow and the movement of contaminants. Columbia River and Snake River basalts erupted within large subsiding basins that contained major rivers and lakes. As a result, these aquifers contain sequences of basaltic rocks (from the volcanic eruptions) interlayered with sedimentary deposits (from the rivers and lakes). The sedimentary deposits are less permeable than the rubble zones in the basalt, so they limit the vertical movement of groundwater and contaminants. Oahu basalts erupted on a dome-shaped island instead of in a large subsiding basin, and sedimentary deposits within the basalt flows are much less prevalent than in the Columbia Plateau or Snake River Plain.

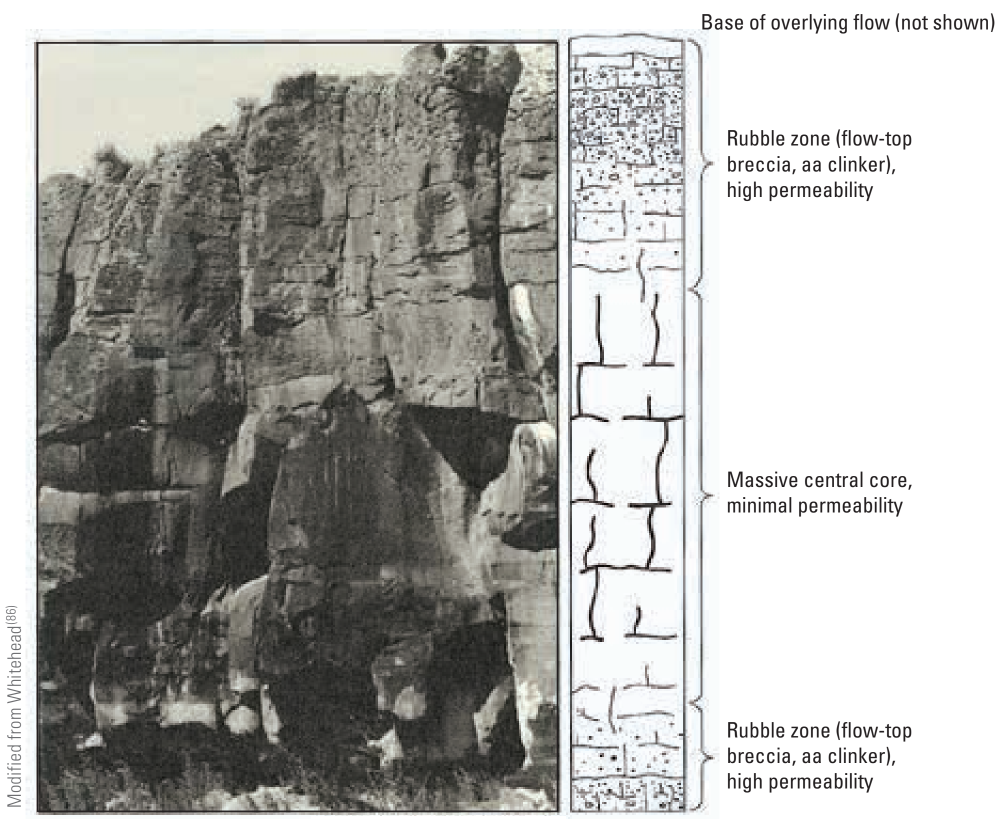
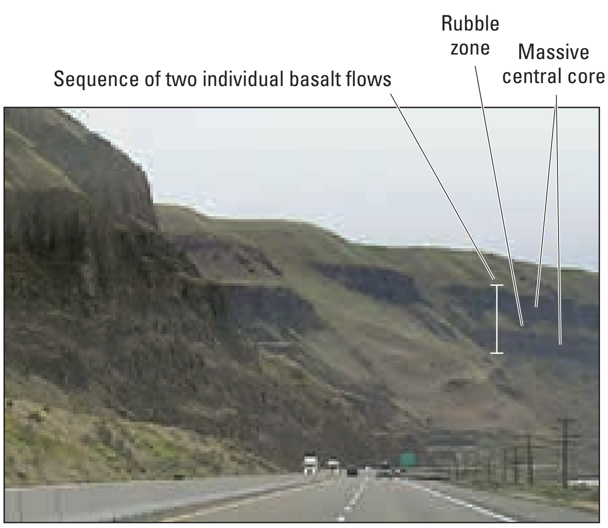
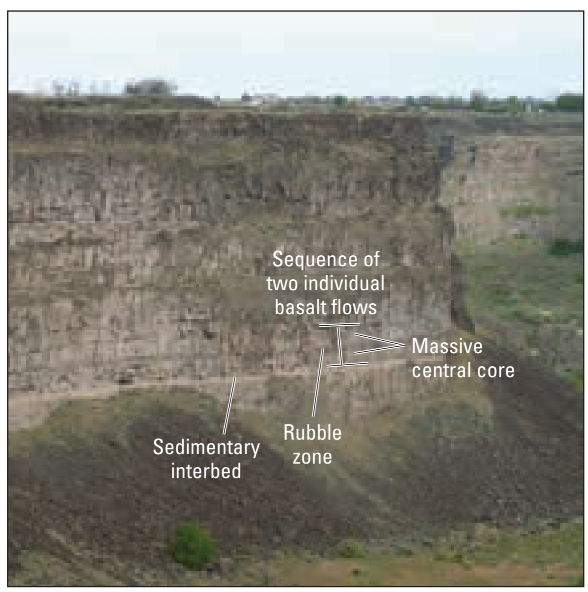


Figure 3–7. A typical basalt flow contains layers of different permeability: a dense, massive central core overlain and underlain with rock fragments known as rubble or “aa clinker” in Hawaii and as flow-top breccia in Washington and Idaho. These rubble zones are very permeable, which allows large amounts of groundwater and contaminants to flow rapidly through them.

In the Columbia Plateau, extremely high-volume eruptions produced individual lava sheets 30 to 300 feet thick that extend over several thousand square miles.[(10)] When all the lava sheets are considered together, the Columbia Plateau basalts are estimated to reach a maximum thickness of as much as 15,000 feet.[(5)] The Columbia Plateau is considered a multi-aquifer system, that is, a layered sequence of several basalt aquifers that are separated by layers of sediments, weathered rock, or massive basalt flow interiors (fig. 3–8).[(11)] The uppermost aquifer is susceptible to contamination from activities at the land surface, but the deeper aquifers are less susceptible because downward groundwater flow is limited by the layers of sediments and (or) the massive central cores of the basalt flows. Groundwater flows horizontally over great distances, as much as 100 miles. Sedimentary basin-fill aquifers are present where sediments have accumulated in low-lying basins to form complex, multilayered aquifer systems on top of the regional basalt aquifer.[(12)] Depth to the water table is 20 to 60 feet in the wells sampled for this study, but depth to the water table can be hundreds of feet in some places.

Eruptions of basaltic lavas in the Snake River Plain were smaller than in the Columbia Plateau. The Snake River lavas typically extend over 50 to 100 square miles and individual lava flows are 20 to 100 feet thick[(13)] with an estimated maximum total thickness of 5,500 feet. Because these flows are smaller in size, the massive central core of the lava flows is smaller than in the Columbia Plateau, and the rubble zones compose a larger percentage of the aquifer materials. Thus, the numerous lava flows behave like one aquifer, rather than several aquifers like the Columbia Plateau. As a result, groundwater and contaminants flow more readily throughout the Snake River Plain aquifer than through the Columbia Plateau aquifers. Although the depth to water is several hundred feet, there is little to obstruct movement of contaminants from the land surface down to the water table. Regional groundwater flow is to the southwest, where the groundwater discharges to the Snake River on the western edge of the study area in an area called Thousand Springs (fig. 3–4). The regionally extensive basaltic-rock aquifers are overlain by a thin layer of alluvial sediments and wind-blown loess, although bare lava is exposed in some areas of the Plain (fig. 3–9). A basin-fill aquifer was formed in the Minidoka area (appendix 1) when a basalt flow dammed the Snake River during the Pleistocene epoch, causing sediments to be deposited on top of the basalt aquifer.[(14)] Sediments that eroded from mountains near the margins of the Snake River Plain washed out onto the plain during its geologic history. As a result, sediments interfinger with basalt along the edges of the plain. Depth to the water table in the basalt is about 50 to 300 feet, and depth to the water table in sediments is 10 to 50 feet in most places.





Photographs by Charles D. Hunt, Jr., USGS

Left: The thick, tabular Columbia River basalts are composed of numerous overlapping basalt flows from 30 to 300 feet thick. Right: The Snake River basalt flows are thinner, from 20 feet to more than 100 feet thick on average. The thick basalt flows in the Columbia Plateau can act as individual aquifers in some places, whereas the thinner flows of the Snake River Plain act as one interconnected aquifer.

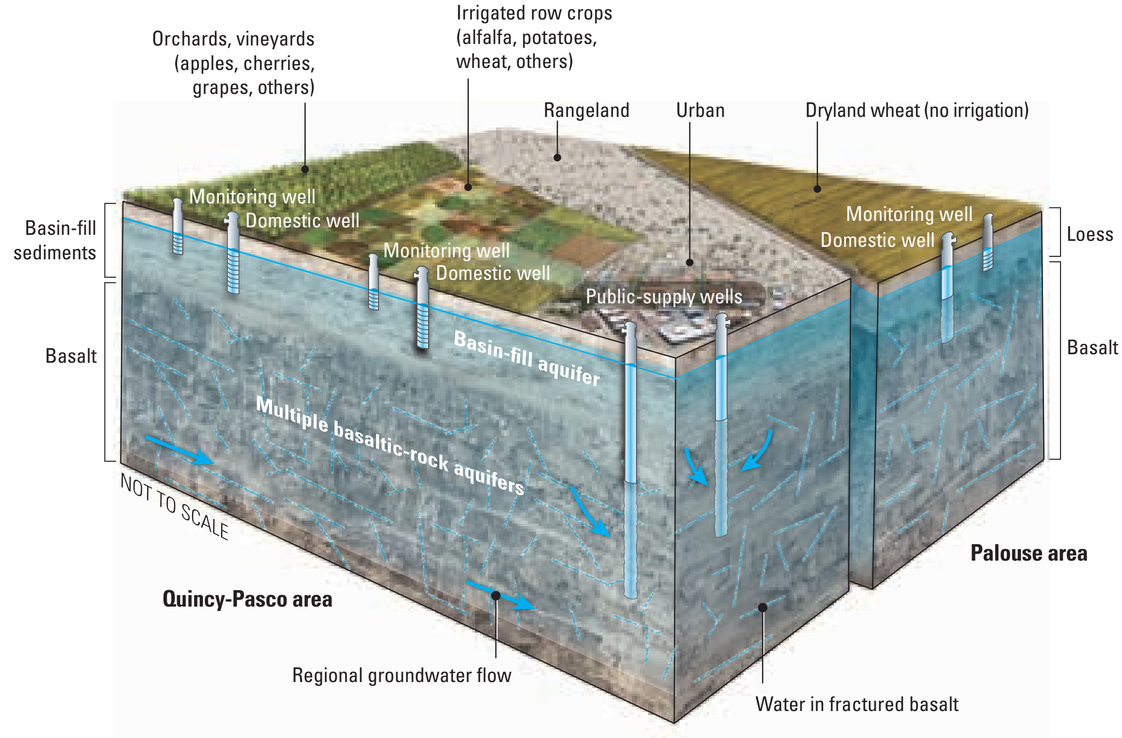


Figure 3–8. In the Columbia Plateau several basaltic-rock aquifers are present within large, individual basalt flows. Basin-fill alluvial sediments and loess (windblown silt) overlie the basalt-rock aquifers throughout much of the Columbia Plateau. Groundwater from both the alluvial sediments and the basalt-rock aquifers is available for use.

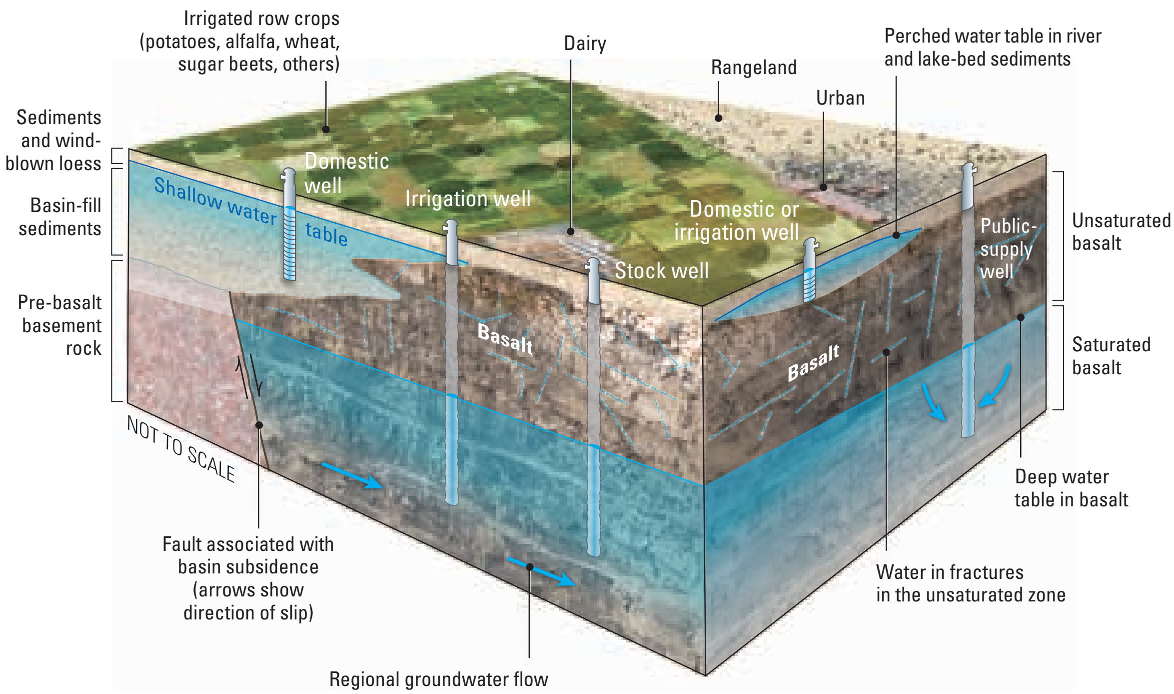


Figure 3–9. The basalt-rock aquifer occupies most of the Snake River Plain. A thin layer of sediments and loess (windblown silt) covers the upper surface of the basalt. Where irrigation water is available, these sediments and loess provide productive farmland, but excess irrigation water can carry nitrate and pesticides to groundwater. Basin-fill sediments encroach from tributary valleys on the edges of the plain.

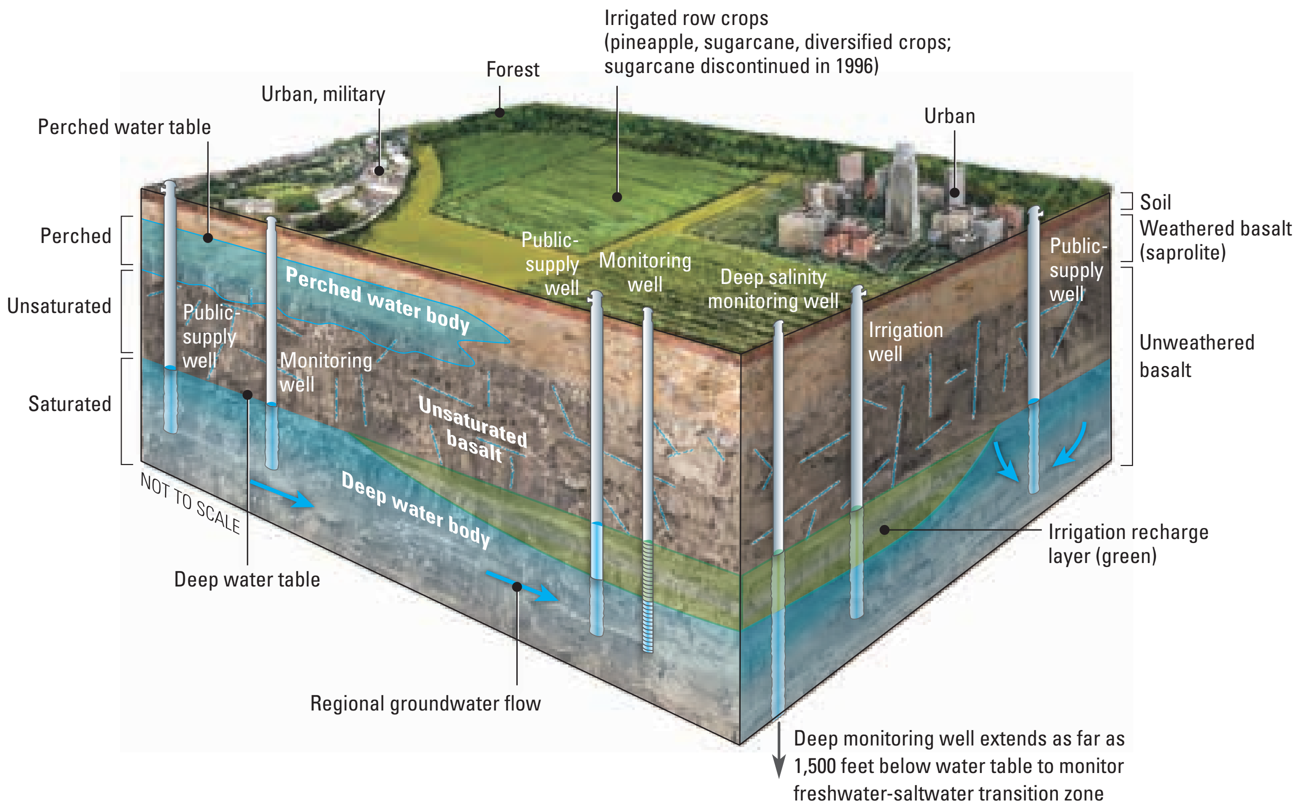


Figure 3–10. The basalt-rock aquifer underlies the entire island of Oahu. Soil and weathered basalt (saprolite) are about 150 feet thick. Unsaturated, unweathered basalt extends several hundred feet below the saprolite to the deep water table. Small bodies of perched water are present on ash beds within the basalt flows. The existence of a distinct layer of “irrigation-induced recharge” containing pesticides and elevated nitrate has been known since the 1960s. Depth to the water table in central Oahu ranges from 100 to 800 feet in most places.

Oahu lava flows are the thinnest and smallest among the three areas, averaging from just a few feet to 30 feet thick, and extending less than 50 square miles. Rubble zones on Oahu compose the largest percentage of the aquifer materials of the three study areas, so the Oahu aquifer is the most susceptible to contamination of the basalt aquifers in the three areas. The unsaturated zone on Oahu has a different composition than that of the Columbia Plateau and Snake River Plain (fig. 3–10). Because of the humid climate on Oahu, the basalt has decomposed, forming a saprolite, which is a red, soft, clay-rich deposit of weathered basalt. The coarse texture of the saprolite speeds the movement of contaminants from the surface down to the water table. Depths to groundwater range from 100 to 800 feet. Freshwater extends 1,000 feet or more below the top of the water table, overlying saltwater from the surrounding ocean (fig. 3–11). The basalts extend to the ocean floor, about 16,000 feet below sea level.

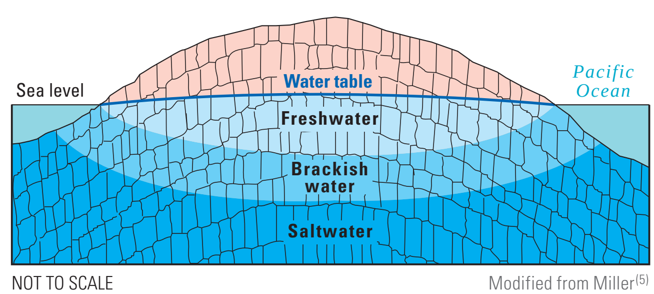


Figure 3–11. On oceanic islands such as Oahu, freshwater commonly develops as a freshwater lens that floats on saltwater and that is separated from the saltwater by a transition zone of brackish water. Drinking water and irrigation water are pumped from the freshwater lens, but wells can become contaminated with brackish water or saltwater if too much groundwater is pumped from the freshwater lens or if the island undergoes prolonged drought.

Chapter 4: *Natural Processes and Human Activities That Affect Groundwater Quality*

This chapter explains and discusses the hydrologic and geochemical processes and human activities that affect the movement and quality of groundwater in the Columbia Plateau, Snake River Plain, and Oahu aquifers.

Aquifer hydrogeology and land-use practices affect the groundwater quality of the Columbia Plateau, Snake River Plain, and Oahu aquifers. For example, the natural characteristics of the materials overlying the Columbia Plateau, Snake River Plain, and Oahu aquifers allow water and chemicals to infiltrate to the water table even though the water table commonly is hundreds of feet below the land surface. Irrigation is intensive in all three study areas, which has caused leaching of fertilizers and pesticides applied at land surface down to the groundwater. The groundwater generally contains dissolved oxygen, which prevents nitrate and many pesticides from breaking down.

Most areas of the Snake River Plain receive less than 15 inches of rainfall each year, so irrigation is required to maintain high crop productivity. Excess irrigation water can infiltrate to the groundwater, transporting nitrate and pesticides with it.

Photograph by Jack Dykinga, USDA ARS

The Geologic Characteristics of the Basalt Aquifers Make Them Susceptible to Contamination

The natural characteristics of basalt aquifers—well-drained soils, permeable volcanic rock, lack of regionally extensive clay layers—make them susceptible to contamination. Water moves from the land surface to the water table primarily through permeable unconsolidated sediments or along fractures and other “fast pathways” in the volcanic rocks. As a result, the water table in the Snake River Plain can rise rapidly (on the order of days or weeks) in response to large rainstorms or seasonal filling of irrigation canals, even though the water table may lie several hundred feet below the land surface.[15] The fractures and fast pathways allow contaminants to be carried along with infiltrating surface water down to the groundwater.

Once water infiltrates to the water table, it becomes part of the regional groundwater flow system. Groundwater flow is mostly horizontal over great distances, but can be vertically downward to deeper parts of the aquifers or upward to areas where groundwater discharges to streams or springs near the land surface (fig. 4–1). Contaminants in the groundwater can enter into drinking-water wells along the way. The time it takes groundwater to move through the entire regional flow system ranges from a few decades on Oahu to as much as 350 years for flow through the entire Eastern Snake River Plain flow system.

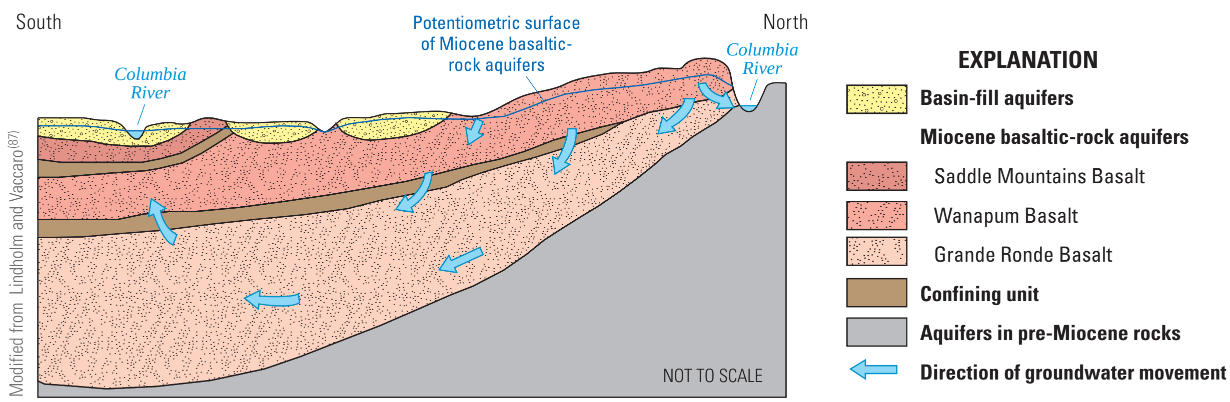


Figure 4–1. In the Columbia Plateau aquifer system, groundwater flow is predominantly horizontal over distances of more than 100 miles, from recharge areas near the boundaries of the plateau eventually to the lower parts of the Columbia River. Groundwater moves through the confining units that separate the aquifers but at a slower rate than through the aquifers.

Basalt aquifers typically have layers of a dense, massive central core that alternate with layers of rock fragments, known as rubble or “aa clinker” in Hawaii and as “flow-top breccia” in Washington and Idaho. The basalt flows can transmit large amounts of groundwater and contaminants because groundwater can flow rapidly through the rubble zones. The photograph shows thin-bedded basalt flows on Hawaii (Chain of Craters Road, Kilauea volcano); basalt flows in the Columbia Plateau and Snake River Plan are much thicker and larger than the basalt flows on the Hawaiian Islands.

Photograph by Clifford Voss, USGS

Certain Types of Irrigation of Agricultural Fields Can Impair Groundwater Quality

The high crop productivity in the Columbia Plateau and Snake River Plain and on Oahu is possible through the use of irrigation water diverted from rivers or pumped from underlying aquifers. When irrigation water is applied to fields, however, not all of it is used by plants. Some of the irrigation water can seep beyond the reach of plant roots and travel downward to the water table, carrying chemicals, such as fertilizers and pesticides, with it. This process is referred to in this report as "irrigation recharge." When irrigation water is applied to fields, a portion of the water evaporates, leaving behind concentrations of dissolved minerals, nitrate, and salts, which further degrade the quality of the irrigation recharge. In some areas in the Snake River Plain, that groundwater is withdrawn again by wells and applied to fields, which sets up a cycle in which dissolved constituents such as salts and nitrate become more and more concentrated.[14]

The amount of irrigation water that infiltrates from the land surface depends on the irrigation method. Flooding fields with irrigation water is the least efficient method; on Oahu, about half of the water used in flood irrigation is lost to deep infiltration. Spray and drip irrigation are more efficient methods than flood irrigation. These more efficient irrigation methods can reduce the amount of contaminants that leach to the water table, because the total amount of irrigation recharge is reduced. Although most farmers have transitioned to more efficient irrigation methods, prior decades of flood/furrow irrigation contributed large volumes of irrigation recharge, which increased the amount and speed of groundwater flow in the three study areas.

On Oahu, fertilizers, pesticides, and soil fumigants applied at the land surface have leached from the soil and have been transported to the water table with the infiltrating irrigation recharge and precipitation, forming a distinct zone of groundwater about 50 to 200 feet thick near the top of the water table that has elevated concentrations of nitrate, pesticides, and other constituents (fig. 3–10).[16, 17] Public-supply wells on Oahu typically have a solid, unscreened casing for the first 100 feet or so below the water table to prevent this poor-quality water from flowing into the wells.

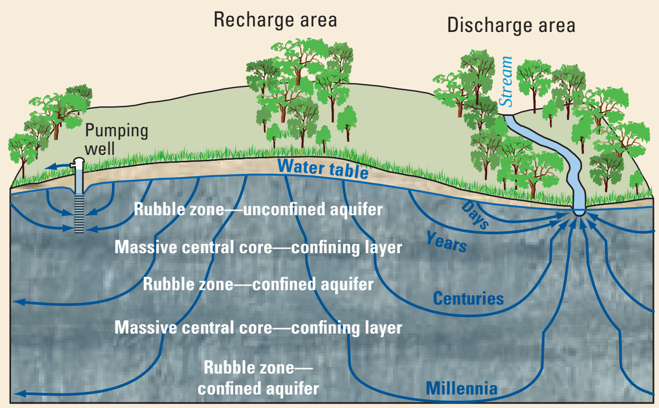
Chapter 4

Photographs by Charles D. Hunt, Jr., USGS

Left: Plowed furrows in the silty soils of the Snake River Plain are flooded from feeder ditches, and water flows down the furrows, wetting adjacent plant rows. Right: Most farmers in the Snake River Plain have converted to sprinkler irrigation systems, similar to that shown on the right, which are more efficient than furrow irrigation systems.

What is groundwater age?

Groundwater age refers to the time elapsed since recharge water reached the groundwater table and became isolated from the atmosphere.[18, 19] The term "age" is sometimes qualified with the word "apparent" to signify that the accuracy of the determined age depends on many variables. Groundwater age can provide information on the susceptibility of the aquifer to contamination from chemicals related to human activities. Many chemicals related to human activities have no natural sources and were only developed during the last 60 years or so; these chemicals are unlikely to be detected in groundwater older than that. Estimates of groundwater age can be made by measuring a number of compounds and radioactive substances that infiltrate into the ground with the water and travel to the sampling point.[20, 21] Generally speaking, groundwater ages of less than 60 years (recharged after 1952) are classified as "young" in the Principal Aquifers reported on in this series of circulars.



NOT TO SCALE

Young Groundwater Age Indicates a High Susceptibility to Contamination

Groundwater ages were determined for samples from a small number of wells in the Columbia Plateau and Snake River Plain and on Oahu. Most of the water sampled was recharged less than 60 years ago, indicating that groundwater in the sampled areas is susceptible to contamination from human activities because most contaminants associated with human activities came into use within the last 60 years. Groundwater age was determined for water from only 10 shallow wells in the Columbia Plateau, but the ages were quite young; the average age of shallow groundwater sampled from the sedimentary deposits in the Quincy-Pasco, Washington, area was only 17.5 years.[22] Groundwater sampled from the Snake River Plain basalt aquifer was also quite young; the average groundwater age of water from 39 wells sampled was only 15 years.[23] On Oahu, wells in two networks were sampled; one set of 15 monitoring wells that withdraw groundwater from near the water table, and one set of 30 public-supply wells that withdraw groundwater much deeper below the water table. The average age of groundwater sampled near the water table was 20 years, and the average age of groundwater sampled much deeper below the water table was 32 years. The young groundwater ages at both depths indicates that the source of the groundwater is irrigation recharge that infiltrates to the water table from the cultivated fields and leaky irrigation canals.

Groundwater recharged after 1952 is more likely to contain contaminants related to human activities than older groundwater. For example, nitrate concentrations in groundwater in the three study areas tended to be higher in young groundwater (fig. 4–2). Before 1945, the primary sources of supplemental nitrogen (N) for crops were animal manure, mineral sources (such as potassium nitrate), and crop rotation with legume crops (such as alfalfa). After World War II (1945), facilities that had produced ammonia and synthetic nitrates for explosives were converted to the production of N-based fertilizers and fertilizer production rates increased dramatically. Nationally, the use of N fertilizer increased rapidly from 1950 through about 1980 and has continued to increase at a slower rate since about 1980 (fig. 4–2). Nitrate concentrations in groundwater from the Columbia Plateau, the Snake River Plain, and Oahu reflect that increase in fertilizer use.

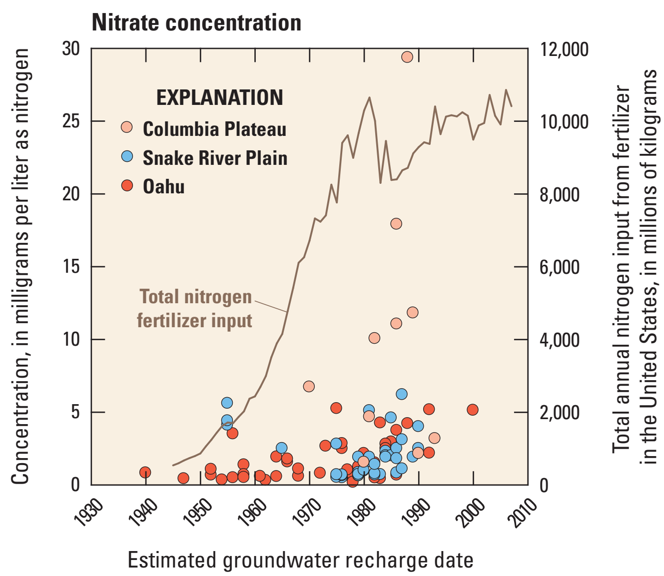


Figure 4–2. Nitrate concentrations are higher in groundwater recharged after 1952 because fertilizer use has increased in the United States since the 1950s.

The Amount of Oxygen in Groundwater Can Affect the Mobility and Persistence of Contaminants

The amount of dissolved oxygen in groundwater, which is the primary information used to classify the reduction-oxidation or "redox state" of groundwater, is an indicator of the geochemical processes that can affect whether or not contaminants breakdown in groundwater.[24] The redox state of groundwater is classified as oxic if the groundwater contains at least 0.5 milligram per liter (mg/L) dissolved oxygen (fig. 4–3). Groundwater is classified as anoxic if it contains less than 0.5 mg/L of dissolved oxygen. Sometimes, both oxic and reduced groundwater can be drawn into the same well from different zones in the aquifer. If this happens, the groundwater is classified as mixed. If groundwater is oxic, nitrate is unlikely to break down and can persist in groundwater, sometimes for decades.[25] Under anoxic conditions, nitrate concentrations can decrease through a process called denitrification in which bacteria convert nitrate to inert nitrogen gas. Many pesticides, such as atrazine, can break down more quickly under anoxic conditions than under oxic conditions. In contrast, concentrations of other chemicals, such as petroleum hydrocarbons, can decrease more quickly under oxic conditions because the bacteria that consume petroleum hydrocarbons require water with dissolved oxygen.

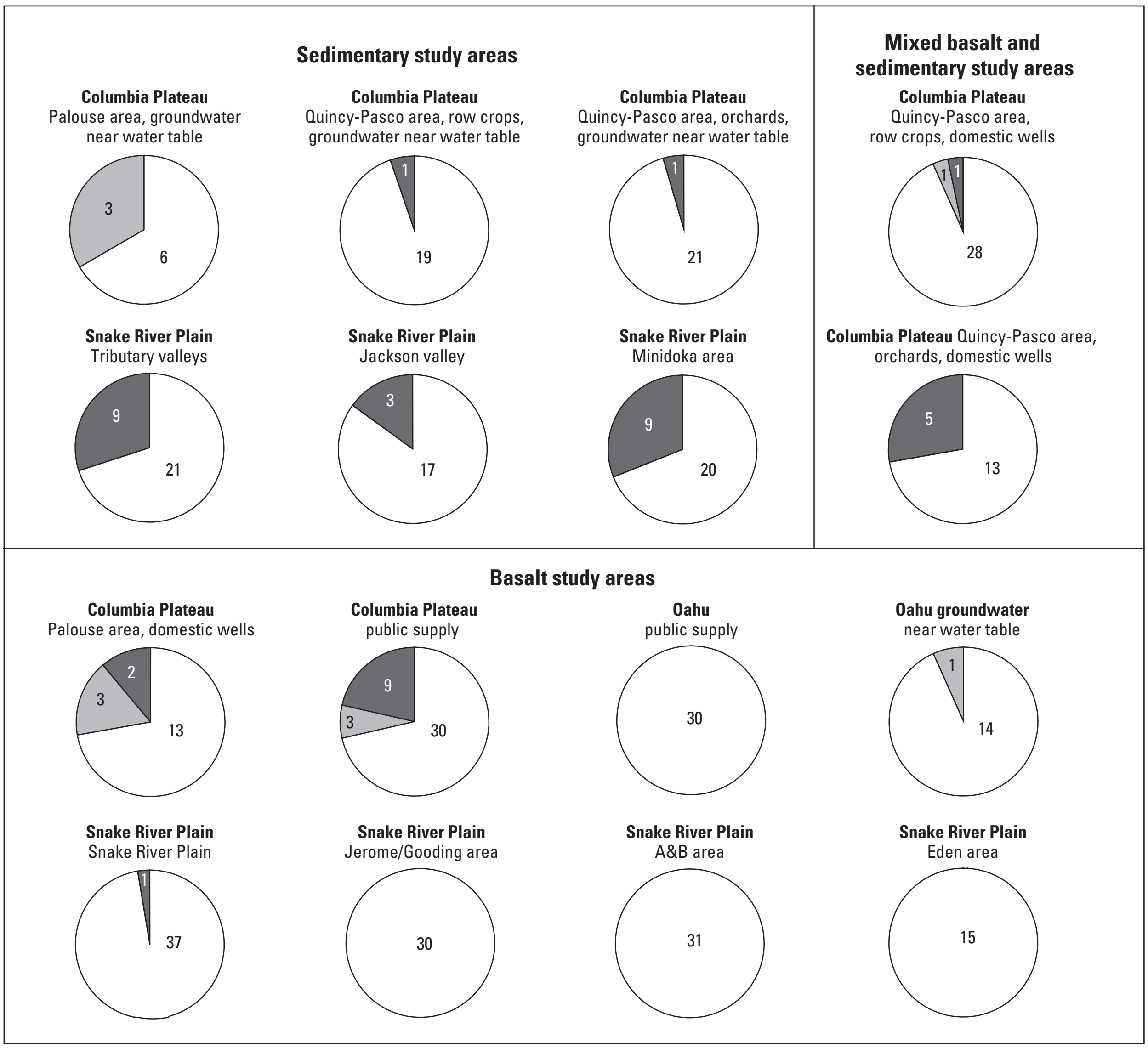
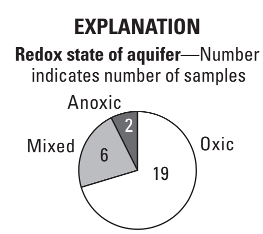
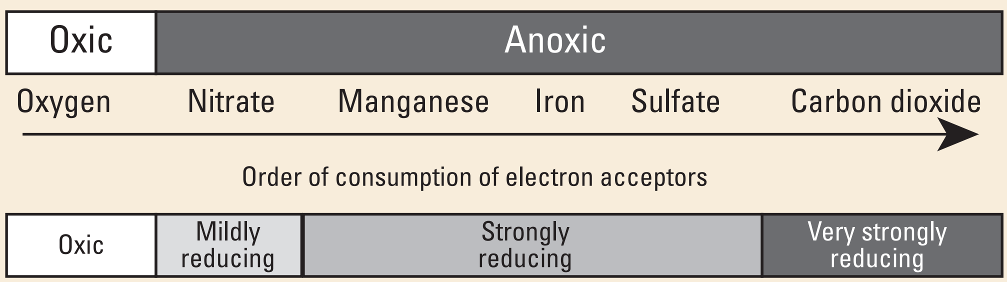


Figure 4–3. Most groundwater samples collected in the Columbia Plateau, the Snake River Plain, and Oahu were found to represent oxic conditions. Oxic conditions were more common in groundwater from the basalt aquifers than from the sedimentary aquifers at least partly because greater amounts of organic material in the sedimentary aquifers lead to anoxic conditions. Some contaminants, such as nitrate and atrazine, can persist for decades in oxic groundwater, but other contaminants, such as hydrocarbons—components of gasoline—degrade in oxic groundwater.



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.

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

Concentrations of at least one contaminant exceeded its human-health benchmark in 14 percent of drinking-water wells sampled in the Columbia Plateau, Snake River Plain, and Oahu aquifers. Some of these contaminants—radon, arsenic, manganese, and molybdenum—have geologic sources, and others—nitrate, pesticides, soil fumigants, solvents—have sources associated with human activities. Contaminants from geologic sources were more commonly detected in drinking water sampled in the Columbia Plateau and Snake River Plain than on Oahu, whereas contaminants related to human activities were more commonly detected in drinking water on Oahu.

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 Columbia Plateau, Snake River Plain, and Oahu aquifers.

This large public-supply well provides drinking water to several thousand residents in the Snake River Plain. These residents depend on a high quality, reliable source of drinking water. Other key aspects of the economy, such as livestock production and food processing, also require clean water.

Photograph by Kenneth Skinner, USGS

Radon, arsenic, manganese, and molybdenum from geologic sources are present at levels of concern for human health in some groundwater used for drinking

Concentrations of contaminants from geologic sources—radon, arsenic, manganese, and molybdenum—were assessed by comparing them to a concentration equivalent to one-tenth of the human-health benchmark for that specific contaminant (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 36). A higher percentage of samples from the Columbia Plateau and the Snake River plain contained at least one constituent at a concentration exceeding one-tenth of the human-health benchmark than from Oahu (fig. 5–1). Radon exceeded its proposed U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) of 300 picocuries per liter (pCi/L) in more than 70 percent of samples from the Columbia Plateau and Snake River Plain, but exceeded its alternate proposed USEPA MCL of 4,000 pCi/L in less than 2 percent of samples from these aquifers (table 5–1). The two MCLs for radon were proposed by USEPA in 1999—the lower MCL is for public water systems in States without programs to mitigate risk from other sources of radon, and the higher level is for water systems in areas that do have multimedia mitigation programs. In samples from Oahu, radon rarely was measured at a concentration that exceeded even the lower proposed MCL. Arsenic and manganese exceeded a human-health benchmark in less than 7 percent of samples from either the Columbia Plateau or the Snake River Plain, and none exceeded the benchmark on Oahu. Arsenic, however, was detected at a concentration greater than 1 microgram per liter (µg/L), one-tenth of the USEPA MCL, in about three of every four wells sampled in the Columbia Plateau and Snake River Plain. Molybdenum exceeded its Health-Based Screening Level (HBSL) in 7 percent of samples from the Snake River Plain, but in no samples from either the Columbia Plateau or Oahu—in fact, exceedance of even one-tenth of the HBSL was rare in samples from these two aquifers.

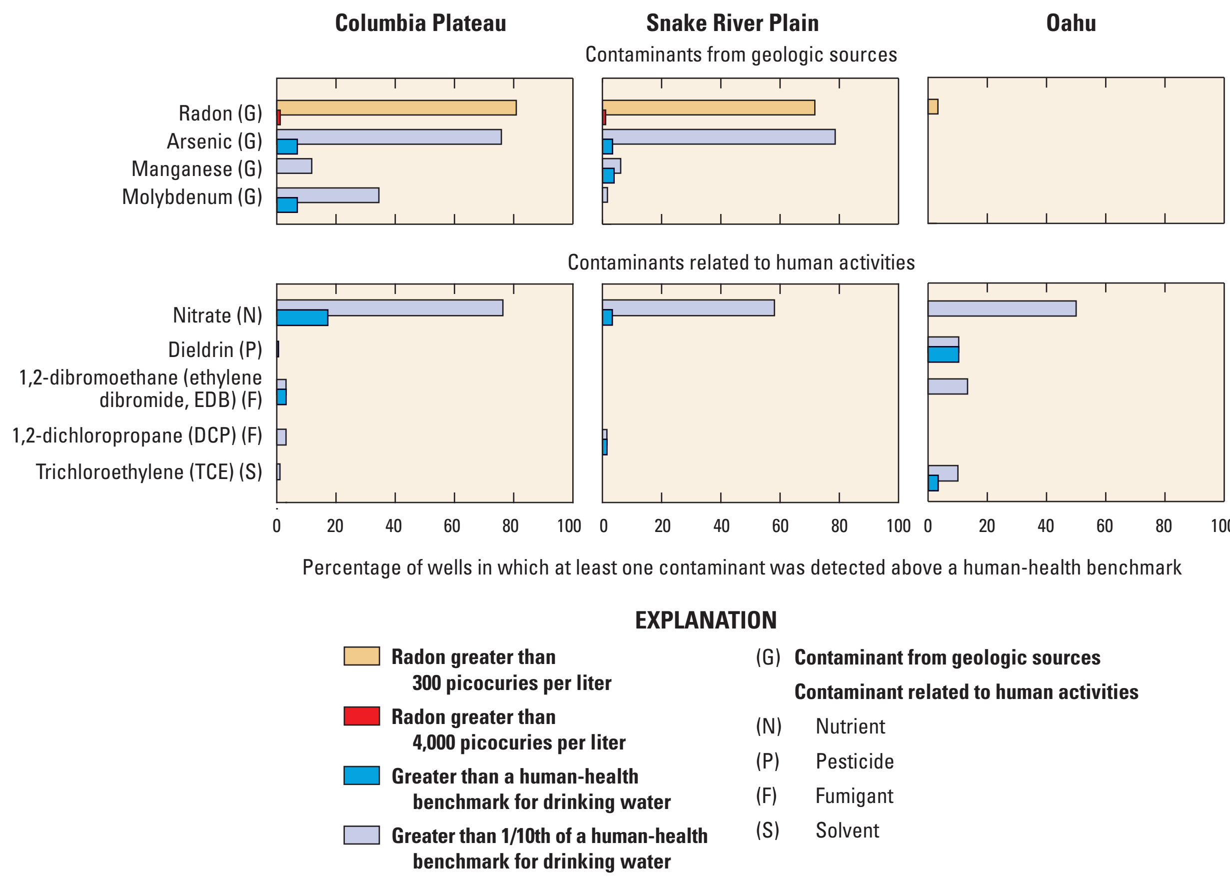


Figure 5–1. Water from some drinking-water wells sampled in the Columbia Plateau, Snake River Plain, and Oahu aquifers contained at least one of these contaminants above its human-health benchmark. Contaminants from geologic sources were more frequently detected in drinking-water samples from the Columbia Plateau and Snake River Plain aquifers than in samples from Oahu. Conversely, several contaminants related to human activities were more frequently detected in drinking-water samples from Oahu than from the Columbia Plateau or Snake River Plain.

Table 5–1. Some samples of drinking water from domestic and public-supply wells located in the Columbia Plateau and Snake River Plain and on Oahu contained at least one of these nine contaminants at concentrations greater than human-health benchmarks. Contaminants from geologic sources and nitrate were more commonly detected above human-health benchmarks in drinking water from the Columbia Plateau and Snake River Plain, but were rarely detected above human-health benchmarks on Oahu.

[pCi/L, picocuries per liter; MCL, Maximum Contaminant Level established by the U.S. Environmental Protection Agency (USEPA); µg/L, micrograms per liter; HBSL, Health-Based Screening Level developed by the U.S. Geological Survey (USGS) for constituents that have no MCL; Nitrate, nitrite plus nitrate as nitrogen; mg/L, milligrams per liter; shaded cells indicate water from at least one percent of wells exceeded the human-health benchmark]

Type of drinking-water contaminant	Constituent	Human-health benchmark* (HHB)		Columbia Plateau		Snake River Plain		Oahu	
				Number of drinking-water wells sampled†	Percent of drinking-water well samples exceeding HHB†	Number of drinking-water wells sampled†	Percent of drinking-water well samples exceeding HHB†	Number of drinking-water wells sampled†	Percent of drinking-water well samples exceeding HHB†
Geologic source	Radon	300 pCi/L	Proposed MCL‡	89	81	92	72	30	3
		4,000 pCi/L	Proposed alternative MCL‡	89	1	92	1	30	0
	Arsenic	10 µg/L	MCL	29	7	117	3	30	0
	Manganese	300 µg/L	HBSL	93	2	178	4	30	0
	Molybdenum	40 µg/L	HBSL	29	7	59	0	30	0
Human source	Nitrate	10 mg/L	MCL	93	17	179	3	30	0
	Dieldrin	0.002 µg/L	HBSL low§	186	1	176	0	29	10
	1,2-dibromoethane (ethylene dibromide, EDB)	0.05 µg/L	MCL	64	3	61	0	30	0
	1,2-dichloropropane (DCP)	5 µg/L	MCL	93	0	65	2	30	0
	Trichloroethylene (TCE)	5 µg/L	MCL	93	0	65	0	30	3

*Human-health benchmarks are concentrations of constituents in drinking water that may be of potential concern for human health, if exceeded. The USEPA has established MCLs for some constituents.[95] The USGS has established HBSLs for additional constituents that do not have MCLs established.[96]

†Domestic and public-supply drinking-water wells were sampled in the Columbia Plateau and Snake River Plain (and used in this table), but only public-supply wells were sampled on Oahu.

‡There is currently no federally enforced drinking-water standard for radon. The USEPA has proposed to require community water suppliers to provide water with radon levels no higher than 4,000 pCi/L, which contributes about 0.4 pCi/L of radon to the air in your home from showering and other household uses. Under the proposed regulation, States that choose not to develop enhanced indoor air programs will be required to reduce radon levels in drinking water to 300 pCi/L. This amount of radon in water contributes about 0.03 pCi/L of radon to the air in your home. (See *http://water.epa.gov/lawsregs/rulesregs/sdwa/radon/basicinformation.cfm* and *http://water.epa.gov/lawsregs/rulesregs/sdwa/radon/regulations.cfm*.)

§The HBSL for dieldrin is a range of values. The low value (0.002 µg/L) corresponds to a one in one million cancer risk; the high value (0.2 µg/L) corresponds to a one in ten thousand cancer risk.

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 200 constituents and properties measured for this assessment (appendix 2). Two types of human-health benchmarks were used: U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) (*http://water.epa.gov/drink/contaminants/index.cfm*) and U.S. Geological Survey (USGS) Health-Based Screening Levels (HBSLs). MCLs are legally enforceable drinking-water standards that specify the maximum permissible level of a constituent in water that is delivered to any user of a public water system[26] (values used in this report were current as of February 2012). Some States, such as Hawaii, have set more stringent MCLs than the USEPA for some constituents. 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 42 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[94, 96, 98] (values used in this report were current as of February 2012; see *http://water.usgs.gov/nawqa/HBSL*). An HBSL was available for 94 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.[99]

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[92]; New Jersey Department of Environmental Protection[100]).

Screening-level assessments, such as this one, provide perspective on the potential relevance of detected contaminants to human health and can help in planning future studies.[94] 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.

Dairies (foreground) and agricultural fields (background) can be major sources of nitrate to groundwater.

Photographs by Michael G. Rupert, USGS

This makeshift chemigation system supplies fertilizers and (or) pesticides to irrigation water pumped by this large-capacity irrigation well. The water is then applied to the fields. Groundwater contamination can occur if a backflow preventer is not properly installed in the chemigation system or if the chemicals are applied at rates in excess of what the plants can use.

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.

Nitrate exceeded human-health benchmarks more frequently in groundwater from drinking-water supply wells in the Columbia Plateau than in groundwater in the Snake River Plain or on Oahu, whereas pesticides exceeded human-health benchmarks more frequently in groundwater from drinking-water supply wells on Oahu than in groundwater in the Columbia Plateau and Snake River Plain

Nitrate, a contaminant largely related to human activities, was frequently measured at a concentration exceeding one-tenth of the USEPA MCL in some drinking-water samples from all three aquifers. Nitrate exceeded the USEPA MCL of 10 mg/L as nitrogen most frequently in samples from the Columbia Plateau—in 17 percent of wells—but in only 3 percent of samples from the Snake River Plain and no samples from Oahu. In contrast, pesticides, also associated with human activities, exceeded one-tenth of a human-health benchmark more often in some samples from Oahu than in samples from either the Columbia Plateau or the Snake River Plain. Concentrations of the pesticide dieldrin, the use of which was banned in 1987, exceeded the lower human-health benchmark value of 0.002 µg/L in 10 percent of drinking-water samples from Oahu, but in only 1 percent of drinking-water samples from the Columbia Plateau and in no samples from the Snake River Plain. The human-health benchmark for dieldrin is a range of values; the low value (0.002 µg/L) corresponds to a one in one million cancer risk, and the high value (0.2 µg/L) corresponds to a one in ten thousand cancer risk.

Concentrations of several constituents in water from drinking-water supply wells exceeded USEPA guidelines for taste, odor, and corrosivity

Water from some drinking-water wells in all three study areas contained concentrations of dissolved solids, sulfate, chloride, manganese, and iron above Secondary Maximum Contaminant Levels (SMCLs) established by the USEPA to avoid problems, such as unpleasant taste and odor, staining, and corrosion, which make drinking water undesirable (fig. 5–2; table 5–2).[99] Dissolved solids (also called total dissolved solids, or TDS) was the constituent that most commonly exceeded its SMCL (500 mg/L) in drinking water in all three study areas, and the percentage of exceedances was similar to that in the Nation as a whole.[97] Dissolved solids is a measure of all inorganic and organic constituents dissolved in a water sample, and is an overall indication of the quality of drinking water.

Elevated concentrations of dissolved solids are not a health hazard, but can indicate the potential presence of other constituents that, at elevated concentrations, are a concern for human health.

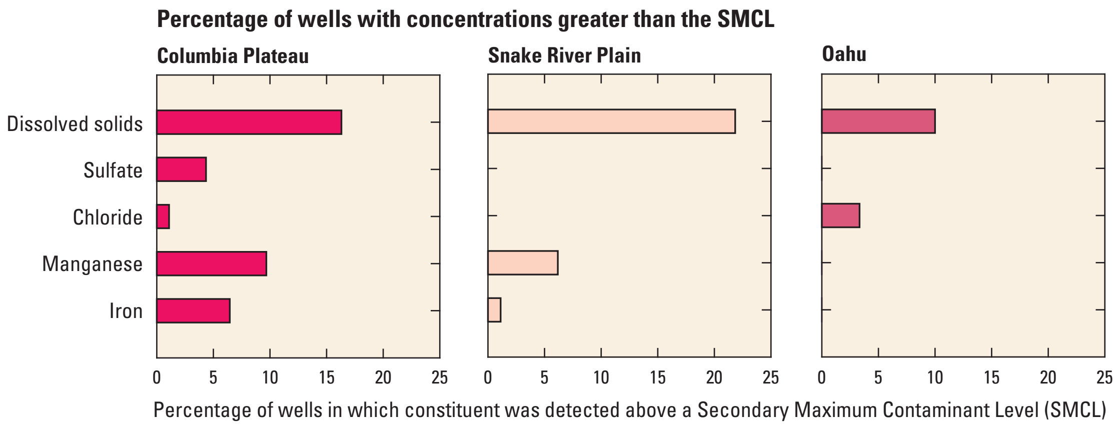


Figure 5–2. Concentrations of dissolved solids, sulfate, chloride, manganese, and iron exceeded the USEPA SMCLs in samples from drinking-water (domestic and public supply) wells in the Columbia Plateau and Snake River Plain and on Oahu. SMCLs are non-enforceable guidelines for constituents that can cause drinking water to have an unpleasant taste or smell, stain plumbing fixtures and laundry, or corrode pipes.

Table 5–2. SMCLs were exceeded for dissolved solids, sulfate, chloride, manganese, and iron in water from domestic and public-supply wells sampled in the Columbia Plateau and Snake River Plain and on Oahu. SMCLs are non-enforceable guidelines for constituents that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as an unpleasant taste, odor, or color) in drinking water. Water sampled from domestic and public-supply wells on Oahu generally had fewer exceedances of SMCLs than water sampled in the Columbia Plateau or Snake River Plain.

[SMCL, Secondary Maximum Contaminant Level established by the U.S. Environmental Protection Agency; mg/L, milligrams per liter; µg/L micrograms per liter]

Constituent	SMCL value	The Columbia Plateau, Snake River Plain, and Oahu combined		Columbia Plateau		Snake River Plain		Oahu	
		Number of drinking-water wells sampled*	Percent of drinking-water well samples exceeding SMCL	Number of drinking-water wells sampled*	Percent of drinking-water well samples exceeding SMCL	Number of drinking-water wells sampled*	Percent of drinking-water well samples exceeding SMCL	Number of drinking-water wells sampled*	Percent of drinking-water well samples exceeding SMCL
Dissolved solids	500 mg/L	241	18	92	16	119	22	30	10
Sulfate	250 mg/L	300	2	92	4	178	0	30	0
Chloride	250 mg/L	300	1	92	1	178	0	30	3
Manganese	50 µg/L	301	7	93	10	178	6	30	0
Iron	300 µg/L	301	3	93	6	178	1	30	0

*Domestic and public-supply drinking-water wells were sampled in the Columbia Plateau and Snake River Plain (and used in this table), but only public-supply wells were sampled on Oahu.

Chapter 6: *Understanding Where and Why Key Contaminants Occur in Groundwater*

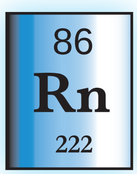
Constituents from geologic sources and contaminants from human activities were commonly detected in groundwater in many areas of the Columbia Plateau and Snake River Plain and on Oahu. The occurrence of constituents from geologic sources is related to the basin-fill sediments and basaltic rocks that make up the aquifers, and the geochemical conditions within those aquifers. The occurrence of nitrate, pesticides, and volatile organic compounds (VOCs) is related to human activities, primarily agricultural, but also urban and military.

This chapter describes the sources of and factors that affect constituents from geologic sources and contaminants from human activities in the Columbia Plateau, Snake River Plain, and Oahu aquifers.

There were five times as many dairies in the Snake River Plain in 2007 as there were in 1987. Many of these dairies house several thousand cattle, and resemble industrial facilities in their planning and design. Three lagoons, which store liquid wastes, are shown here—two in the front of the facility and one in the back. The solid and liquid wastes can be applied as fertilizer to the surrounding agricultural lands, but groundwater contamination can result if those waste materials are applied in excess of what can be taken up by plants (agronomic rate). Groundwater contamination also can result from infiltration of nitrate-laden leachate from the facility itself.

Concentrations of Constituents from Geologic Sources—Radon, Arsenic, Molybdenum, and Manganese—Exceeded Human-Health Benchmarks in Water From Some Wells in the Columbia Plateau and Snake River Plain, but Not in Water From Wells on Oahu

Concentrations of constituents from geologic sources in groundwater are related to the materials that make up the aquifer and to the geochemical conditions in the aquifer. For example, in the Snake River Plain, elevated radon activities in groundwater are associated with uranium-rich aquifer minerals contained in basin-fill sediments. Elevated concentrations of radon, arsenic, molybdenum, and manganese were detected in water from some wells in the Columbia Plateau and Snake River Plain, but not in water from wells on Oahu, because the aquifer materials and geochemical conditions on Oahu do not promote mobilization of these constituents in groundwater.



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

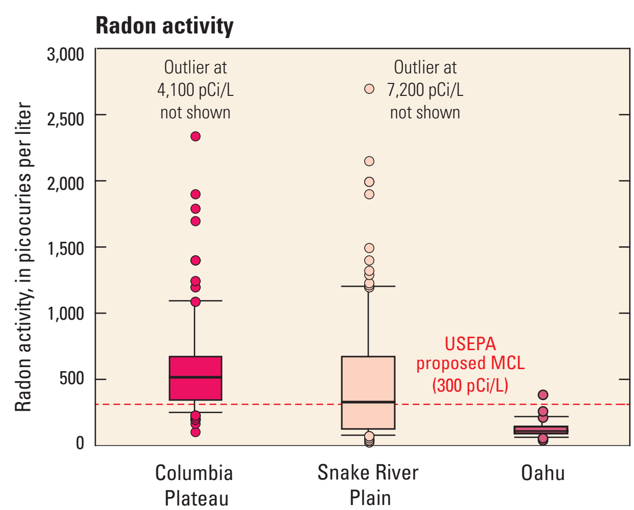
Radon activities were much higher in groundwater from the Columbia Plateau and Snake River Plain aquifers than in groundwater from the Oahu aquifer

Radon is a naturally occurring, radioactive, colorless, odorless, tasteless gas that is formed as part of the normal radioactive decay of uranium, a radioactive element. Most rocks contain some uranium, but some types of rocks—such as dark shales and granites—have higher-than-average uranium contents. Radon exposure is the second most frequent cause of lung cancer, after cigarette smoking, causing between 15,000 and 22,000 lung cancer deaths each year in the United States.[27, 28] One of the greatest risks for radon exposure from groundwater occurs when radon in water is released into the air during showering, which poses a much greater risk than ingesting the same water.

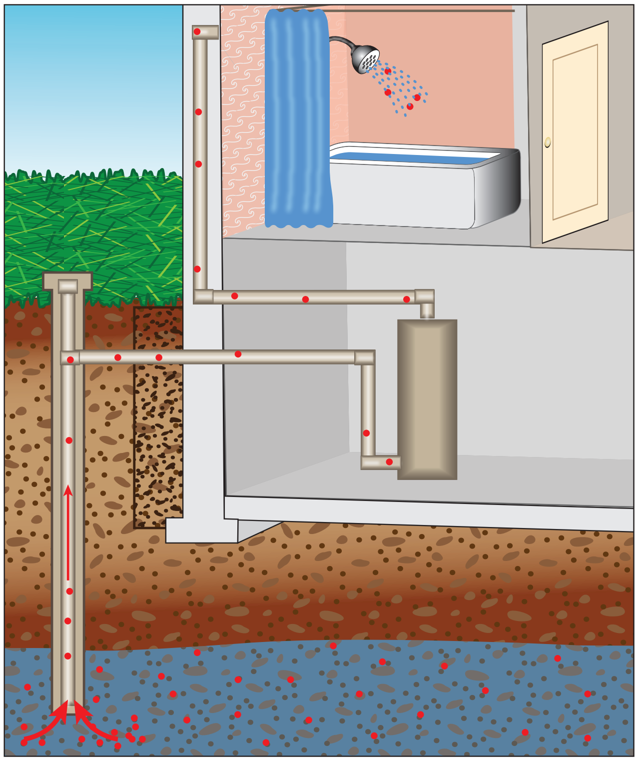
The USEPA has proposed both an MCL of 300 pCi/L and an alternative MCL of 4,000 pCi/L for radon in public water systems.[29] The lower proposed MCL for radon applies to States and public water systems that have not established programs to address health risks from radon in indoor air; the higher proposed alternative MCL applies to States and public water systems that have established such programs.[29, 30]

Radon was detected in water from more than 99 percent of the wells sampled in the Columbia Plateau and Snake River Plain and on Oahu. Radon activities exceeded the lower proposed USEPA MCL of 300 pCi/L in about 75 percent of samples from the Columbia Plateau and about 50 percent of samples from the Snake River Plain aquifers (fig. 6–1), although the proposed alternative USEPA MCL of 4,000 pCi/L was exceeded in water from only two wells—one in the Columbia Plateau and one in the Snake River Plain. On Oahu, radon activities in water from only one well exceeded the lower proposed USEPA MCL of 300 pCi/L, and none exceeded the higher proposed alternative USEPA MCL of 4,000 pCi/L.

Figure 6–1. Radon activities in water were greater than the proposed USEPA MCL of 300 pCi/L from most of the wells sampled in the Columbia Plateau and Snake River Plain, but only one well sampled on Oahu. Radon activities in water were above the proposed alternative USEPA MCL of 4,000 pCi/L from only one well sampled in the Columbia Plateau and one well in the Snake River Plain.



See sidebar, Boxplots, p. 41



Otton and others [89]

Radon gas (represented by red dots) dissolved in groundwater can move with water from a domestic well into household plumbing. When the water is aerated at faucets, radon can be released into the air and inhaled while people shower or run faucets.

One of the greatest risks for radon exposure from groundwater with high radon concentrations occurs when radon in water is released into the air during showering, which poses a much greater risk than ingesting the same water.

Photographs by Andrew Silver, USGS

The dissolution and weathering of rocks and minerals that make up aquifers and soils contribute constituents to groundwater. Sources of constituents that, at high concentrations, are of concern for human health include pyrolusite (top), a manganese oxide mineral, and granite (bottom), an igneous rock that can be enriched in uranium.

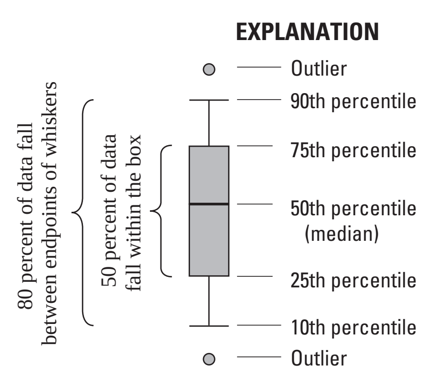
Boxplots

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

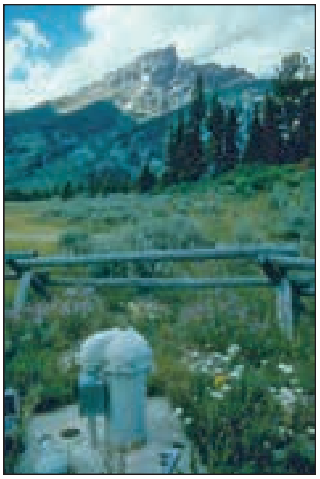
Percentiles describe the percentage of values in a group that are less than the given value: 25 percent of the values in a group are less than the 25th percentile; 75 percent of the values in a group are less than the 75th percentile. The median is also the 50th percentile.

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

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

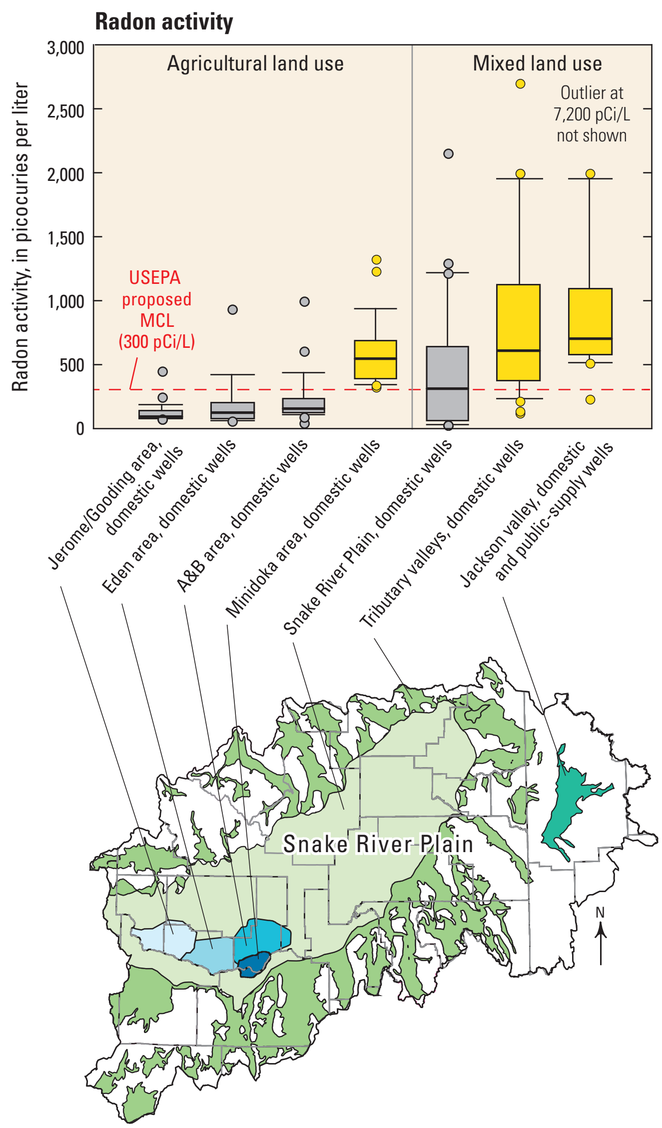


Elevated radon activities in groundwater in the Snake River Plain were associated with uranium-rich aquifer minerals contained in basin-fill sediments (fig. 6–2). Radon activities in groundwater sampled from the basalt aquifer in the A&B, Eden, and Jerome/Gooding areas of the Snake River Plain were low because the basaltic rocks contain relatively low concentrations of uranium. Radon activities in groundwater sampled in the tributary valleys and the Jackson valley were higher because the sedimentary aquifers contain sediments eroded from the surrounding mountains, which are partly composed of granitic and metamorphic rocks that contain higher concentrations of uranium than does basalt. Groundwater sampled from the sedimentary aquifer in the Minidoka area has higher radon activities than groundwater sampled from the underlying basalt aquifer because the sediments were deposited by the Snake River, which transported uranium-bearing sediments from distant places. Groundwater sampled on Oahu had much lower radon activities than did groundwater sampled in the Columbia Plateau or the Snake River Plain because all the groundwater sampled on Oahu was withdrawn from the basalt aquifer.



Photograph by Michael G. Rupert, USGS

Constituents from geologic sources, such as radon, can occur in groundwater at concentrations of potential human-health concern even in undeveloped areas where contamination typically is not expected, such as near Grand Teton, Wyoming, where this well is located. Traditional wellhead protection approaches designed to reduce sources of manmade contaminants to groundwater generally are not designed to prevent groundwater contamination from geologic sources.



EXPLANATION

Lithology within well network (graph)

- Basin-fill sediments
- Basaltic rock

Snake River Plain study areas (map)

- Minidoka area
- A&B area
- Eden area
- Jerome/Gooding area
- Snake River Plain
- Tributary valleys
- Jackson valley

See sidebar, Boxplots, p. 41

Figure 6–2. Radon activities are relatively low in groundwater samples collected from the basalt aquifer in the Snake River Plain because the basaltic rocks have relatively low concentrations of uranium. Radon activities were higher in groundwater sampled from the basin-fill aquifers because they contain uranium-rich granitic and metamorphic sediments that eroded from the surrounding mountains.

Arsenic concentrations exceeded the USEPA MCL more commonly in groundwater from the Columbia Plateau and Snake River Plain than in groundwater from Oahu

Arsenic is a nonmetallic trace element in rocks and soils that has many geologic sources, including sulfide minerals and geothermal deposits; it also has been used in some pesticides. Arsenic is toxic to humans and, in drinking water, can contribute to skin, bladder, and lung cancers.[31] Arsenic in drinking water is one of the leading environmental causes of cancer mortality in the world.[32]

Arsenic concentrations exceeded the USEPA MCL of 10 µg/L more commonly in groundwater from the Columbia Plateau (24 percent of wells) than in groundwater from the Snake River Plain (5 percent of wells) or Oahu (no wells). In fact, arsenic concentrations did not exceed one-tenth of the USEPA MCL in water from any wells sampled on Oahu, indicating that arsenic in groundwater on the island is not a human-health concern. McMahon and Chapelle[33] reported that the Columbia Plateau and Snake River Plain had some of the highest arsenic concentrations of the 15 Principal Aquifers studied by NAWQA, but few investigations have been conducted into the cause of those elevated arsenic concentrations.

The factors related to elevated arsenic concentrations in groundwater are complex and are related to geochemical conditions in the aquifer. The most common cause of elevated arsenic concentrations in groundwater is the release of arsenic from iron oxides in the aquifer materials.[34] Elevated arsenic concentrations can occur if the groundwater has low dissolved oxygen (anoxic conditions) or high pH (alkaline conditions); elevated arsenic concentrations also can occur if the arsenic has been concentrated by evaporation.[35] In the Columbia Plateau and Snake River Plain, all pH levels were above 7 and the groundwater was oxic. Under these conditions, arsenic can be released from aquifer materials by pH-driven desorption.[35] Elevated arsenic concentrations in groundwater from the Snake River Plain also were associated with elevated concentrations of dissolved solids, silica, and alkalinity (fig. 6–3), indicating that arsenic occurrence also could be related to geochemical changes resulting from evaporative concentration.[34] Another possibility is that that elevated alkalinity in irrigation recharge may be desorbing arsenic.[36] The low arsenic concentrations in groundwater from Oahu probably are related to the humid climate, iron-rich soils, and oxic condition of the groundwater. The humid climate of Oahu would preclude evaporative concentration, and the iron-rich soils and oxic conditions would tend to bind arsenic in the soil and aquifer materials. Although sodium arsenate was widely used as a pesticide on sugarcane on the Hawaiian Islands from about 1913 to 1945, the arsenic is tightly bound in the iron oxides in the soil and, therefore, unlikely to be released to groundwater.[37]

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

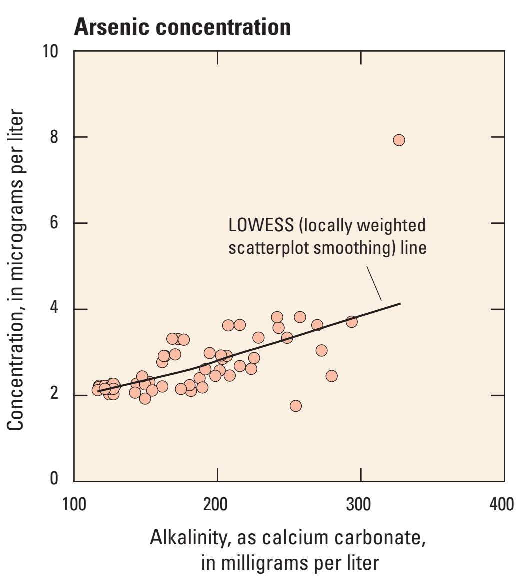
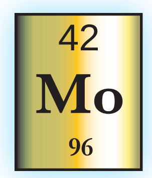


Figure 6–3. In the Snake River Plain, arsenic concentrations tend to increase when alkalinity increases, indicating that elevated arsenic concentrations may result from concentration of arsenic (and other constituents, such as dissolved solids and silica) during evaporation.

Concentrations of molybdenum were much higher in groundwater in the Columbia Plateau than groundwater in the Snake River Plain or on Oahu



Molybdenum is a trace element that is naturally present, usually at low levels, in aquifer materials. Trace amounts of molybdenum are necessary for human health, but consumption of molybdenum above the human-health benchmark of 40 µg/L can lead to enlarged liver, gastrointestinal and kidney disorders, and a gout-like disease that causes joint pain in the hands and feet.

Molybdenum is an essential trace element for animals and humans,[38] but long-term consumption of drinking water with high concentrations of molybdenum can affect human health. The adverse effects include enlarged liver, gastrointestinal and kidney disorders, and a gout-like disease that causes joint pain in the hands and feet.[39]

Concentrations of molybdenum in water from 4 of 76 wells (5 percent) sampled in the Columbia Plateau were above the human-health benchmark of 40 µg/L; molybdenum concentrations were much lower in groundwater in the Snake River Plain and Oahu, where there were no exceedances of the benchmark. Similar to arsenic, the factors related to molybdenum concentrations in groundwater are complex and are related to geochemical conditions in the aquifer. The cause of the elevated molybdenum concentrations in groundwater in the Columbia Plateau is unknown. In the Snake River Plain, where molybdenum concentrations are much lower, concentrations increase with increasing pH levels (fig. 6–4), suggesting release of molybdenum from aquifer materials by pH-driven desorption.[35]

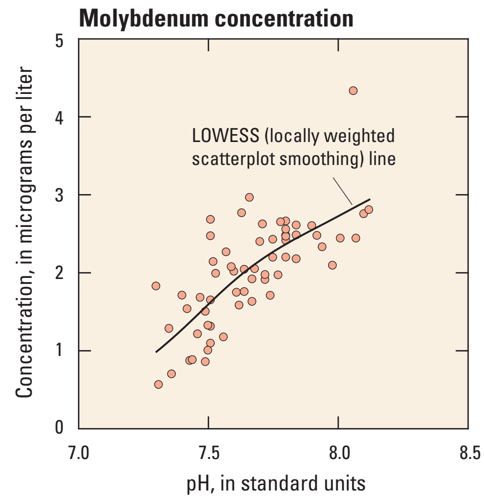
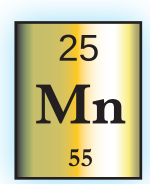


Figure 6–4. Molybdenum concentrations in groundwater in the Snake River Plain are associated with elevated pH levels, indicating that molybdenum could be released from the aquifer materials by pH-driven desorption.

Manganese in groundwater rarely occurred at elevated concentrations because groundwater in all three study areas mostly is oxic



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

Manganese, which is found in many types of rocks and soils, is an essential trace element for human health. Studies indicate that exposure to extremely high levels of manganese could produce undesirable effects on brain development in children, including changes in behavior and impairing the ability to learn and retain information.[40] High manganese concentrations in drinking water also can harm the livers of adults and children.[41]

Manganese concentrations exceeded the human-health benchmark of 300 µg/L in water from only two wells (1 percent) sampled in the Columbia Plateau and from only seven wells (3 percent) sampled in the Snake River Plain; manganese did not exceed the benchmark in water from any of the wells sampled on Oahu. In addition to having some human-health concerns, manganese can cause black staining on plumbing fixtures and can give drinking water an unpleasant taste, so it has an SMCL of 50 µg/L. Concentrations of manganese in water from 7 percent of the wells sampled in the Columbia Plateau and 6 percent of the wells sampled in the Snake River Plain exceeded the SMCL. Water from none of the wells sampled on Oahu exceeded the SMCL.

Manganese concentrations in groundwater rarely exceeded the human-health benchmark or the SMCL because most groundwater in the three study areas is oxic (fig. 4–3). Elevated manganese concentrations typically occur under anoxic conditions (low dissolved-oxygen concentrations) because manganese-containing minerals dissolve more readily in anoxic water. All of the samples with manganese concentrations that exceeded the human-health benchmark or the SMCL were collected in groundwater under mixed oxic/anoxic or anoxic conditions. Ayotte and others[35] also noted the association between elevated manganese concentrations and anoxic conditions in groundwater from the Columbia Plateau and Snake River Plain.

Nitrate in the Columbia Plateau, Snake River Plain, and Oahu aquifers

Nitrate concentrations in groundwater exceeded the USEPA MCL of 10 mg/L as nitrogen in 20 percent of the wells sampled in the Columbia Plateau and in 4 percent of the wells sampled in the Snake River Plain, but did not exceed the USEPA MCL in water from any of the wells sampled on Oahu. The highest concentrations of nitrate are associated with shallow groundwater in basin-fill sediments beneath agricultural land, such as in the Quincy-Pasco, Washington, area of the Columbia Plateau, where concentrations of nitrate in almost 40 percent of the wells exceeded the USEPA MCL. Nitrate concentrations in groundwater have increased in the Snake River Plain from 1993 to 2005, where nitrogen inputs from fertilizers and cattle manure have been increasing since the 1950s; however, nitrate concentrations did not change in the Columbia Plateau from 1993 to 2002, and there is insufficient information on Oahu to determine if nitrate concentrations have changed since 2000.

What is nitrate?

Nitrogen, which is essential for plant growth, occurs in several forms, including nitrate, ammonia, and organic nitrogen, but most of the nitrogen in groundwater is in the form of nitrate. Efforts to increase food production to meet the demands of a growing global population have greatly increased the use of nitrogen fertilizers, which has, in turn, increased the occurrence and concentrations of nitrate in groundwater.

Nitrate has some natural sources, but most of the nitrate in the environment has been contributed by human activities, including production and application of nitrogen fertilizers, cultivation of nitrogen-fixing crops, animal waste disposal, wastewater discharge, industrial discharges, and combustion of fossil fuels.[42, 43] Human activities have nearly doubled the rate of nitrogen inputs into the terrestrial nitrogen cycle, which is reflected in higher nitrate concentrations in groundwater.

Chapter 6

Photograph by Charles D. Hunt, Jr., USGS

Lush crop growth in the desert environment of the Snake River Plain requires application of fertilizers, pesticides, and irrigation water, supplied here by roller-wheel spray lines watering this field. Fertilizers and pesticides can be carried to the water table by excess irrigation water. A low shield volcano, evidence of the volcanic environment that affects groundwater occurrence and movement in the area, lies in the far distance.

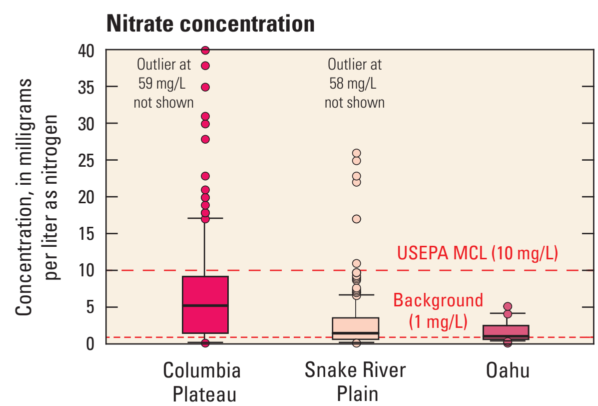
What would nitrate concentrations be in groundwater if there were no effects of human development?

Nitrate occurs naturally, but the largest sources of nitrate are from human activities. Studies in the Snake River Plain[14, 44] and on Oahu[16, 45, 46] indicate that natural "background" nitrate concentrations in the study areas are less than 1 mg/L as nitrogen. This finding is consistent with information gathered by NAWQA in many areas of the Nation that have little or no development: background concentrations of nitrate in groundwater in many areas across the United States are less than 1 mg/L.[25, 93]

The primary sources of elevated nitrate in the Columbia Plateau and Snake River Plain and on Oahu are associated with agricultural activities

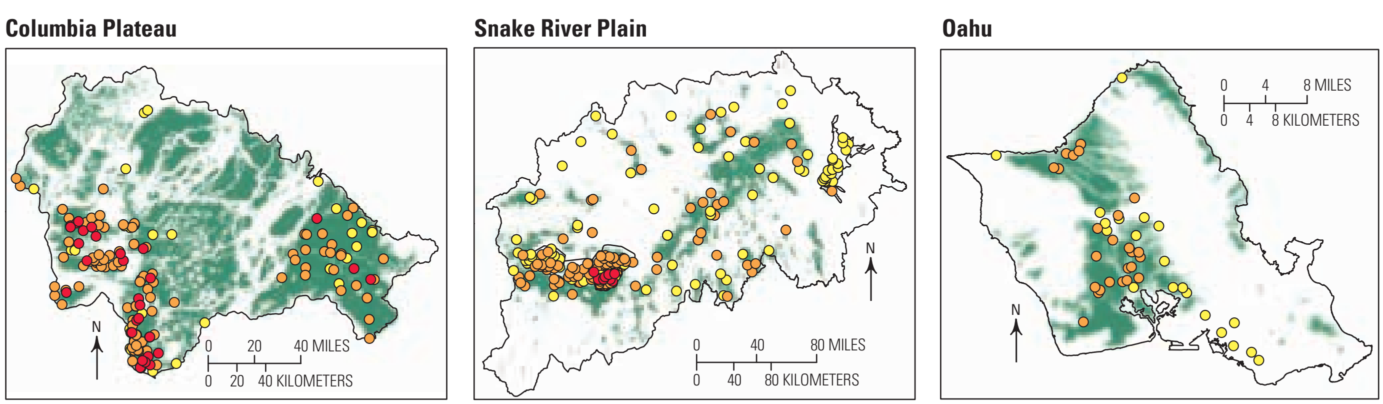
Nitrate concentrations exceeded the USEPA MCL of 10 mg/L as nitrogen in water from 20 percent of the wells sampled in the Columbia Plateau and in 4 percent of the wells sampled in the Snake River Plain, but did not exceed the USEPA MCL in water from any of the wells sampled on Oahu (fig. 6–5). More than 65 percent of all groundwater samples collected in the three study areas combined had nitrate concentrations above the background concentration of 1 mg/L as nitrogen; in the Columbia Plateau, water from 80 percent of the wells sampled had nitrate concentrations above the background concentration. The primary sources of elevated nitrate concentrations in groundwater from the Columbia Plateau and Snake River Plain above background concentrations are nitrogen fertilizers and animal manure.(44, 47, 48) Elevated nitrate concentrations in groundwater on Oahu are the result of decades of agricultural activities, particularly in sugarcane fields.(46) Because the primary sources of elevated nitrate are associated with agricultural activities, elevated nitrate concentrations were most common in groundwater underlying agricultural lands (fig. 6–6).

Elevated concentrations of nitrate in drinking water are associated with several human-health concerns. Nitrate at concentrations above the USEPA MCL of 10 mg/L as nitrogen can cause low oxygen levels in the blood of infants (a disorder called methemoglobinemia, or blue-baby syndrome). Long-term exposure to nitrate at concentrations of 2 to 4 mg/L in drinking water has possible links to bladder and ovarian cancer,(49) and to a type of cancer called non-Hodgkins lymphoma.(50)



See sidebar, Boxplots, p. 41

Figure 6–5. Groundwater in the Columbia Plateau had higher nitrate concentrations than groundwater in the Snake River Plain and Oahu aquifers; concentrations in 20 percent of the wells sampled exceeded the USEPA MCL of 10 mg/L as nitrogen. Groundwater on Oahu had the lowest nitrate concentrations, none of which exceeded the USEPA MCL.



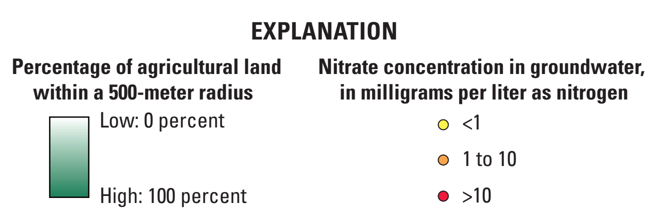


Figure 6–6. Elevated nitrate concentrations in groundwater coincide with agricultural areas in the Columbia Plateau and Snake River Plain and on Oahu.

Nitrate concentrations of groundwater in the Columbia Plateau are elevated

The highest nitrate concentrations measured in groundwater from any localized area of the Columbia Plateau, Snake River Plain, or Oahu aquifers were from the Quincy-Pasco, Washington, area of the Columbia Plateau, where concentrations in almost one of every three wells sampled (30 percent) were above the USEPA MCL of 10 mg/L as nitrogen (fig. 6–7). Groundwater underlying two types of land use—irrigated row crops and orchards—was sampled in the Quincy-Pasco area. In addition, groundwater at two depths was sampled: shallow groundwater near the water table was sampled from monitoring wells, which withdraw groundwater from the basin-fill sediments, and deeper groundwater was sampled from domestic wells, which withdraw groundwater from a mixture of basin-fill sediments and basalt rock. Nitrate concentrations in almost 40 percent of the wells sampled near the water table underlying row crops in the Quincy-Pasco area exceeded the USEPA MCL of 10 mg/L as nitrogen. Nitrate concentrations in groundwater from the deeper domestic wells also underlying row crops were lower, but still, more than 30 percent of these samples contained nitrate at a concentration that exceeded the USEPA MCL. Nitrate concentrations also were elevated in groundwater underlying orchards in the Quincy-Pasco area, but were not as high as in groundwater underlying row crops.

Concentrations of nitrate in water from one-third of the wells sampled in the Quincy-Pasco, Washington, area exceeded the USEPA Maximum Contaminant Level.

Nitrate concentrations also were elevated in groundwater sampled in the Palouse, Washington, area of the Columbia Plateau. Two types of wells were sampled in the Palouse area: shallow monitoring wells that withdraw groundwater from near the water table in wind-blown silt (loess) sediments and deeper domestic wells that withdraw groundwater from the underlying basalt aquifer. Groundwater in shallow monitoring wells had higher nitrate concentrations than groundwater in the deeper domestic wells—nitrate concentrations of water from 20 percent of the wells sampled near the water table exceeded the USEPA MCL, whereas water from only one deeper domestic well exceeded the USEPA MCL. The crops grown in the Palouse area are dryland (non-irrigated) winter and spring wheat, barley, peas, and lentils. Although the crops are not irrigated, they are heavily fertilized, which has caused elevated nitrate concentrations.[47]

Groundwater sampled from parts of the Columbia Plateau with a mix of land uses had the lowest nitrate concentrations measured in the Columbia Plateau. This finding likely is the result of a smaller contribution of nitrate from agriculture, and because the wells are deeper than the wells sampled in agricultural land-use areas.

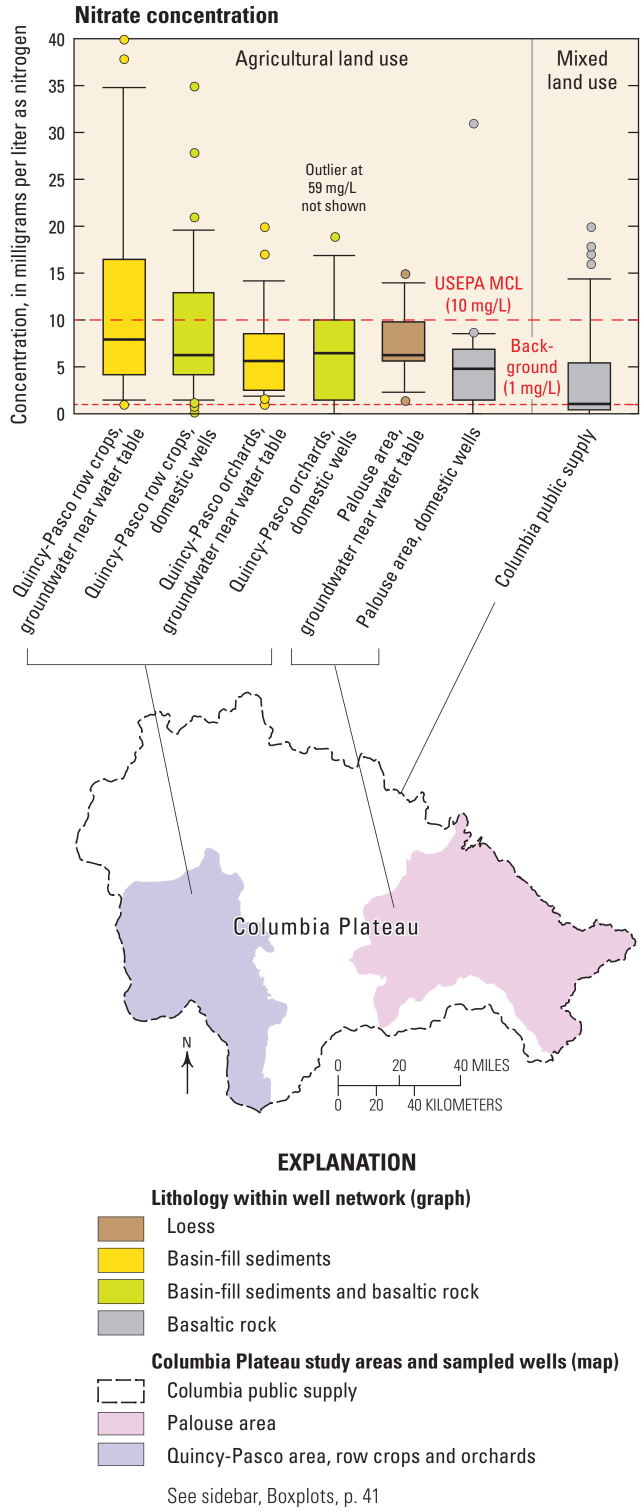


Figure 6–7. Nitrate concentrations in groundwater sampled from basin-fill sediments underlying row crops in the Quincy-Pasco, Washington, area were the highest of those measured in the Columbia Plateau. Nitrate concentrations in almost 40 percent of the wells completed near the water table and in 33 percent of the deeper domestic wells sampled in the same area were above the USEPA MCL of 10 mg/L as nitrogen.

Chapter 6

Concentrations of nitrate are high in groundwater in some areas of the Snake River Plain, but in other areas are diluted by upwelling of deep, regional groundwater

The highest nitrate concentrations measured in groundwater in the Snake River Plain were in the Minidoka, Idaho, area, where the samples were collected from domestic wells that tap a shallow alluvial aquifer perched above the regional basalt aquifer (fig. 6–8). Water from more than one of every four wells sampled (over 25 percent) in the Minidoka area had nitrate concentrations above the USEPA MCL of 10 mg/L as nitrogen. Nitrate concentrations likely are elevated because of shallow depth to groundwater, permeable soils, and oxic groundwater conditions, which prevent the transformation of nitrate to harmless nitrogen gas (see chapter 4).[14]

In the deeper basalt aquifer underlying agricultural lands of the Snake River Plain, nitrate concentrations are elevated in the A&B area and decrease in the direction of groundwater flow (westward) to the Eden area and then the Jerome/Gooding area (fig. 6–8). The decrease in concentrations is caused by the geometry of the aquifer and the effect the geometry has on groundwater flow.[51]

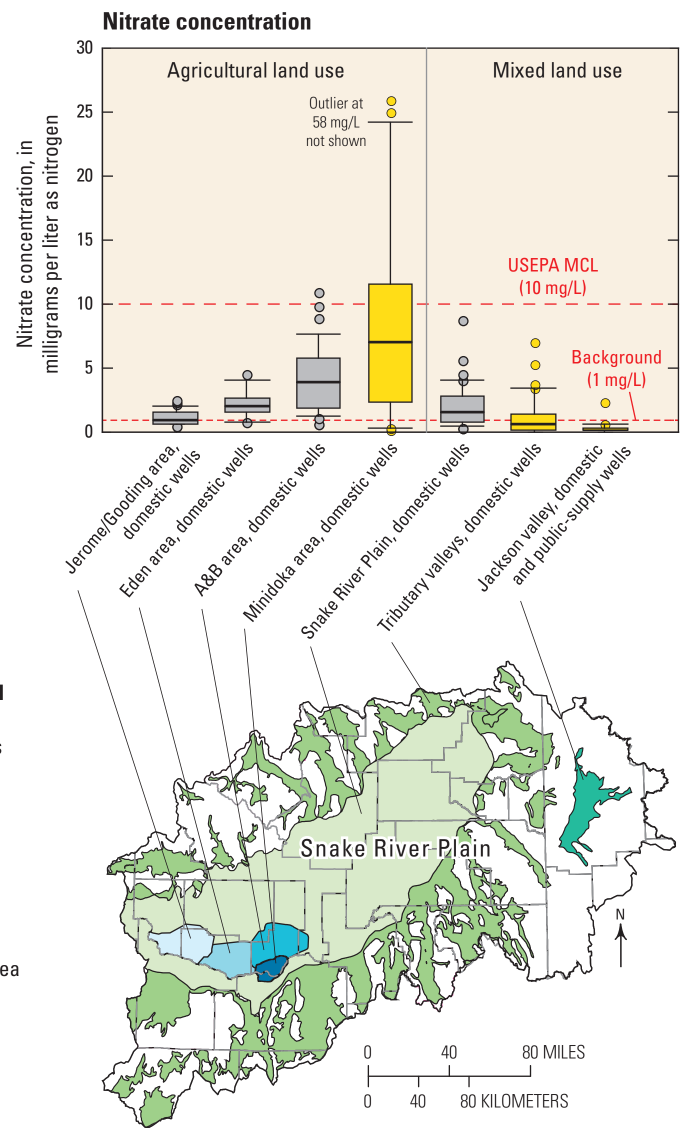


Figure 6–8. In the Snake River Plain, nitrate concentrations were highest in samples of groundwater from basin-fill sediments underlying agricultural lands in the southwestern part of the plain, where irrigation and cultivation of row crops, such as potatoes and sugar beets, are intensive. Nitrate concentrations decrease as groundwater flows from the A&B area, to the Eden area, and finally to the Jerome/Gooding area, as a result of the upwelling and mixing of nitrate-poor regional groundwater with nitrate-rich recharge from overlying agricultural lands. Nitrate concentrations in almost all wells sampled in the Jackson valley, in the eastern part of the study area, were below the background concentration of 1 mg/L as nitrogen because the source of the groundwater recharge mostly is runoff of snowmelt from an area with very little agriculture.

EXPLANATION

Lithology within well network (graph)

- Basin-fill sediments
- Basaltic rock

Snake River Plain study areas (map)

- Minidoka area
- A&B area
- Eden area
- Jerome/Gooding area
- Snake River Plain
- Tributary valleys
- Jackson valley

See sidebar, Boxplots, p. 41

The upward flow of deep groundwater with low nitrate concentrations mixes with and dilutes the nitrate-contaminated groundwater in the upper portion of the basalt aquifer, where it then discharges to the Snake River in a series of large springs.

The Eastern Snake River Plain aquifer reaches a maximum saturated thickness of about 4,000 feet in the central part of the plain and becomes thinner to the west (fig. 6–9). Thinning of the aquifer forces the deep regional groundwater flow to converge, essentially “squeezing” it closer to the land surface to the west. Much of this deep groundwater has nitrate at background concentrations, because the groundwater was recharged primarily as snowmelt in undeveloped areas in the eastern part of the basin. As the deep groundwater with low nitrate concentrations is squeezed upward, it mixes with and dilutes nitrate-contaminated groundwater in the upper part of the basalt aquifer. This mixture of deep and shallow groundwater, with nitrate concentrations above background levels, discharges to the Snake River in the Thousand Springs area.

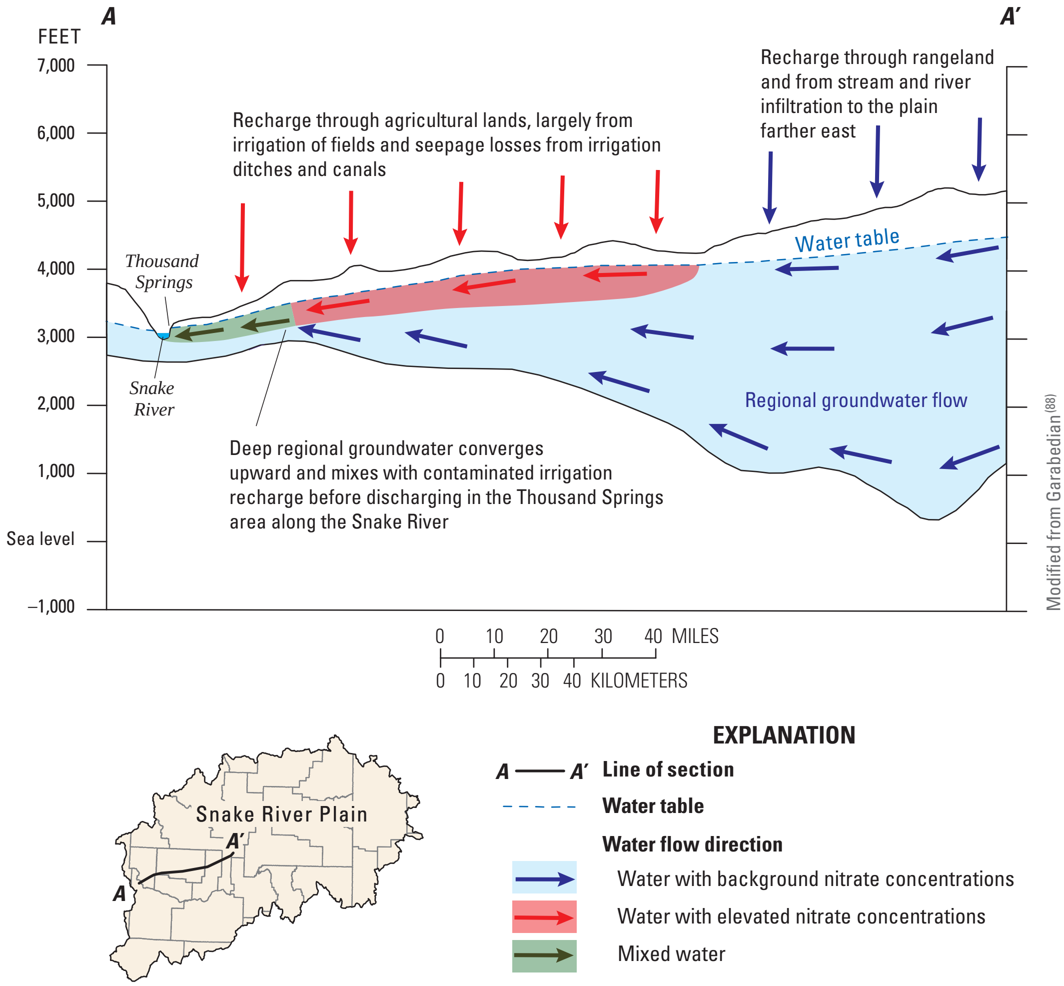
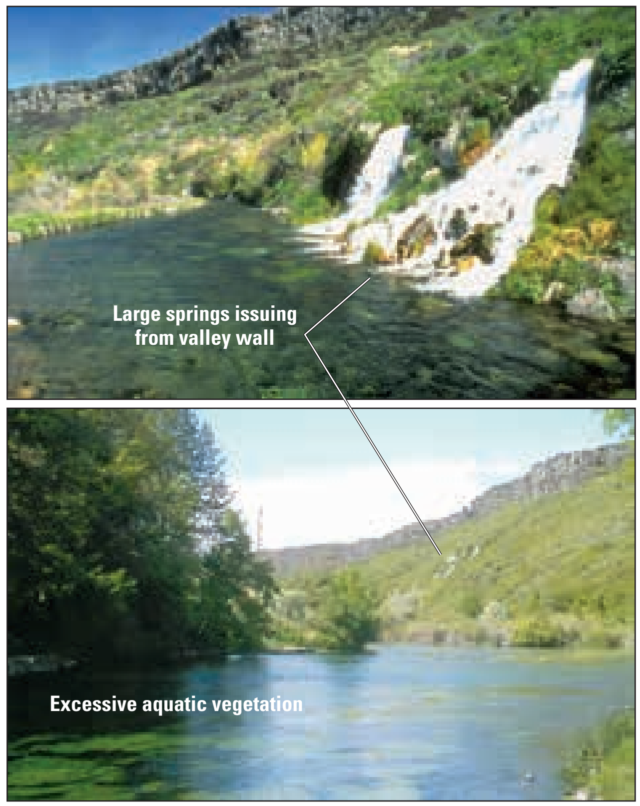


Figure 6–9. The Eastern Snake River Plain basalt aquifer thins to the west toward the Thousand Springs discharge area. As groundwater flows to the southwest in Jerome and Gooding Counties, Idaho, deep groundwater with low nitrate concentrations moves upward, mixing with and diluting nitrate-rich recharge from overlying agricultural lands. Consequently, nitrate concentrations in groundwater discharging in the Thousand Springs area are relatively low—but higher than background—despite large amounts of nitrogen input from fertilizers and cattle manure.

Nitrate concentrations in groundwater sampled in the three areas of the Snake River Plain with mixed land uses tend to be lower than those in groundwater sampled in agricultural lands (fig. 6–8), because sources of nitrate, such as fertilizers and animal manure, are fewer and smaller. Of the three areas, the tributary valleys, which are located at higher elevations than the agricultural lands, have cooler temperatures, so agricultural production is limited to grazing and hay production, which supply lower amounts of nitrate to groundwater than the agricultural lands. The lowest nitrate concentrations of the three areas were measured in the Jackson valley area of the Snake River Plain study area (also known as Jackson Hole, Wyoming). In this area, nitrate concentrations are near background because most groundwater originates as snowmelt runoff from the surrounding mountains where there is very little agricultural land use.



The Eastern Snake River Plain aquifer discharges from the valley walls in the Thousand Springs area as numerous large springs (top photograph). The nitrate contributed by the spring water, combined with excess phosphorous already present in the Snake River, feeds excessive aquatic vegetation (bottom photograph) leading to fish kills in the Snake River.

Ammonia nitrogen fertilizer is injected into irrigation water in the A&B area of the Snake River Plain, as indicated by the gray discoloration of the water. The concrete ditch conveys water to the fields where it irrigates and fertilizes the crops. Excess irrigation water can infiltrate to groundwater, carrying dissolved nitrogen with it.

Photograph by Michael G. Rupert, USGS

Nitrate concentrations in Oahu groundwater were relatively low but substantially greater than background concentrations because of fertilizer application and irrigation recharge

Groundwater samples collected on Oahu generally had lower nitrate concentrations than those from the Columbia Plateau or the Snake River Plain aquifers. The highest concentration of nitrate in groundwater was only 5.2 mg/L—more than 10 times lower than the highest concentration of nitrate measured in groundwater in the Columbia Plateau (59 mg/L) or the Snake River Plain (58 mg/L). No groundwater samples collected on Oahu had nitrate concentrations greater than the USEPA MCL, but more than half had a nitrate concentration greater than the background concentration of 1 mg/L (fig. 6–10), indicating that human activities have contributed nitrate to the groundwater. Most wells sampled on Oahu with background nitrate concentrations are in forested areas east and upgradient of the agricultural lands. Groundwater from these forested areas flows southwest beneath agricultural croplands, where large volumes of irrigation recharge have percolated down to the top of the water table, creating a distinct upper layer of groundwater that contains elevated concentrations of nitrate, pesticides, and other constituents. This irrigation-recharge layer is about 100 to 150 feet thick in south Oahu and has been studied in detail since the 1960s.[16, 17]

No groundwater samples collected on Oahu had nitrate concentrations greater than the USEPA MCL, but more than half had a nitrate concentration greater than the background concentration of 1 mg/L as nitrogen.

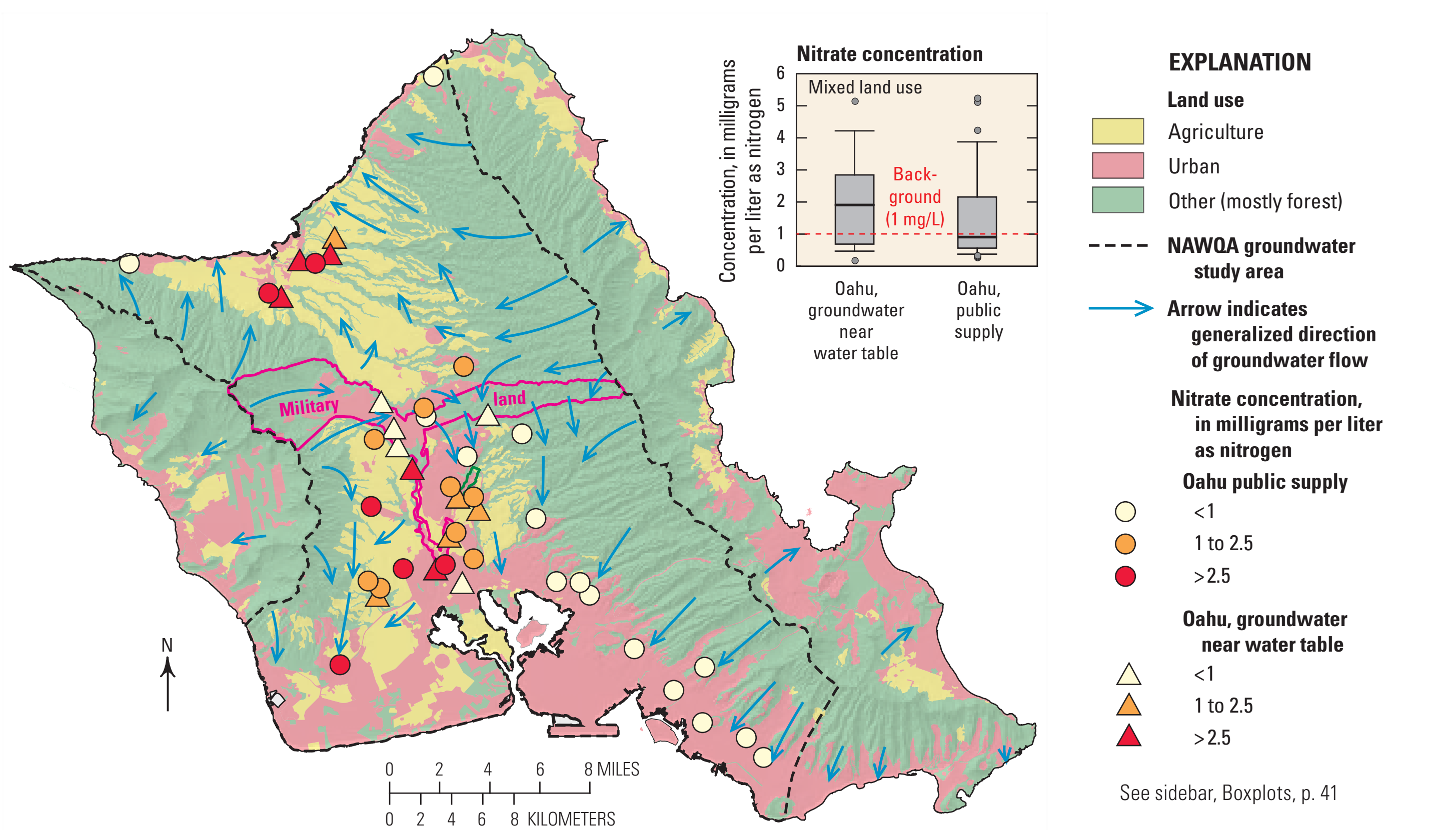


Figure 6–10. Nitrate concentrations in water from wells that withdraw groundwater near the water table on Oahu were higher than nitrate concentrations in water from the deeper public-supply wells. The shallower wells withdraw groundwater from the irrigation-recharge layer, which is a distinct upper layer of groundwater near the top of the water table that contains elevated nitrate, pesticides, and other constituents.

Chapter 6

Nitrate concentrations in groundwater in the Columbia Plateau generally have stayed the same, but nitrate concentrations in groundwater in the Snake River Plain have increased in response to increasing agricultural sources

During 1993–2005, nitrate concentrations in Columbia Plateau groundwater, overall, have stayed the same.[52] The lack of any significant change in nitrate concentrations reflects the relatively constant fertilizer use in the Columbia Plateau since the 1980s (fig. 6–11). Groundwater samples were collected in three areas (the Quincy-Pasco row-crop area, the Quincy-Pascoe orchard area, and from the Columbia Plateau public-supply wells) once during 1993–95 and once almost 10 years later (2002). The amount of change in nitrate concentrations was different from one site to the next, but overall there was no net change—nitrate concentrations in water from about half of the wells increased and nitrate concentrations in water from about half of the wells decreased. These results are consistent with another study of the Columbia Plateau[53] that reported no significant change of nitrate concentrations in water from 474 wells sampled in the plateau, with the exception of wells with nitrate concentrations greater than 10 mg/L as nitrogen—those wells had a significant decrease in nitrate concentrations.

Nitrate concentrations in wells and springs sampled in some areas of the Snake River Plain were higher in 2005 than 10 years earlier. Sixty-one wells in the Jerome/Gooding and A&B areas of the Snake River Plain were sampled during 1993–94 and again about 10 years later (2005). Nitrate concentrations in water from about two-thirds of the wells were higher in 2005 than in 1993–94, and nitrate concentrations in water from about one-third of the wells were lower. Some of the largest changes in nitrate concentrations occurred in the A&B area, where the median nitrate concentration increased by more than 1 mg/L as nitrogen. Nitrogen input from fertilizers has increased steadily in the Snake River Plain since 1950,

Nitrogen input from fertilizers has increased greatly in the Snake River Plain since 1950, and the number of dairy cattle in the Snake River Plain has increased by fivefold since 1987.

and there has been a fivefold increase in the number of dairy cattle in a six-county region of the Snake River Plain from 1987 to 2007 (fig. 6–12). Dairies can be a source of nitrate to groundwater if the waste-management controls in the area are ineffective.[54] Nitrogen from cattle manure used as fertilizer on surrounding fields also can contaminate groundwater if the manure is applied in excess of agronomic rates. The number of dairy cattle and fertilizer use in the Snake River Plain is projected to continue to increase and nitrate concentrations in groundwater are likely to increase.

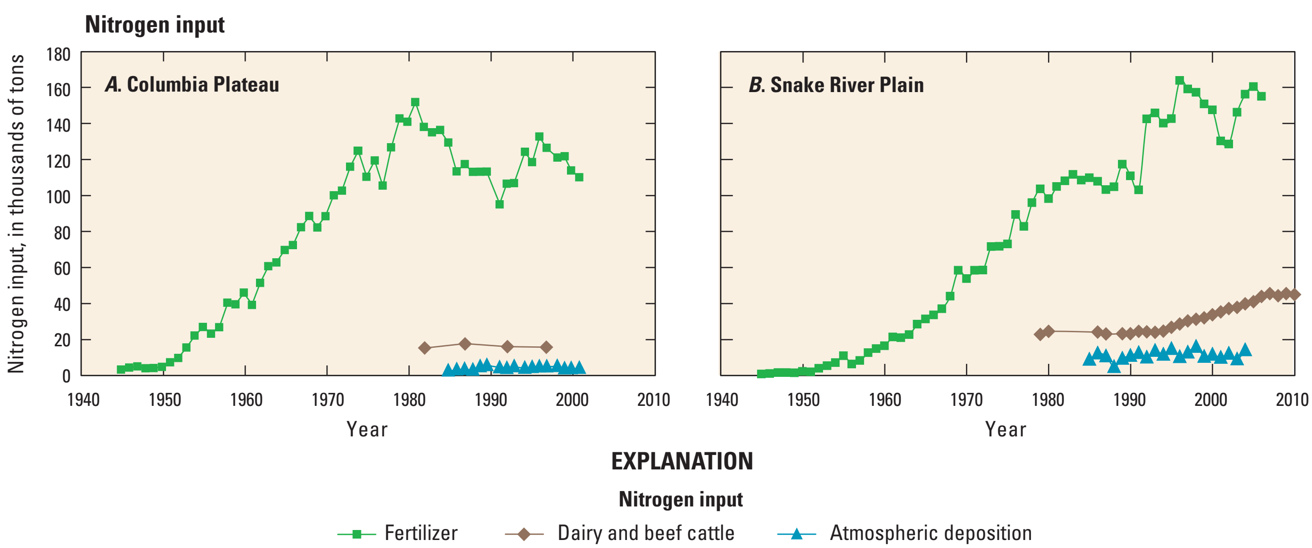
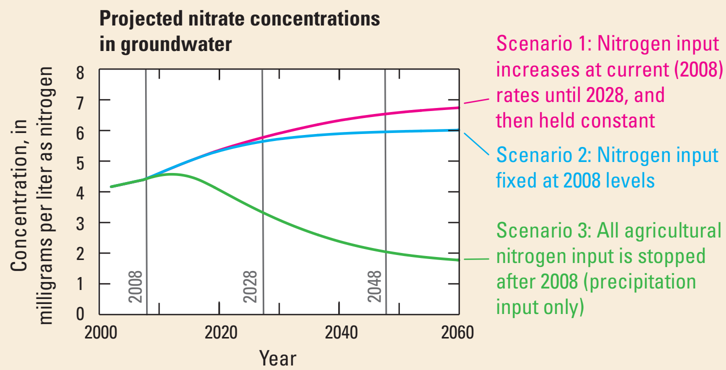


Figure 6–11. Nitrogen input from fertilizers in *A*, the Columbia Plateau and *B*, the Snake River Plain began to increase in the 1950s. In the Columbia Plateau, nitrogen input from fertilizers generally stabilized in about 1980, but in the Snake River Plain, nitrogen input from cattle manure and fertilizers has continued to increase through 2007. Before 1945, the primary sources of supplemental nitrogen for crops were natural sources such as animal manure, mineral sources such as potassium nitrate, and crop rotation with legume crops such as alfalfa. Inorganic nitrogen fertilizers came into widespread use following World War II, when facilities that had produced ammonia and synthetic nitrates for explosives were converted to the production of nitrogen-based fertilizers. Nitrogen input data from cattle manure and fertilizers are not available for Oahu.

It can take more than 50 years for nitrate concentrations in groundwater from the Snake River Plain to respond to changes in nitrogen input at the land surface

What will the quality of Snake River Plain groundwater be in the future if nitrogen inputs continue to increase? What will it be if inputs stay the same? If nitrogen inputs were ceased entirely, how long would it take for nitrate concentrations in groundwater to return to background levels? These questions were addressed using groundwater-flow models that make it possible to project future nitrate concentrations on the basis of current and future agricultural practices.[51] Three scenarios were investigated: (1) nitrogen input continues to increase at the 2008 rate of increase until 2028 and then levels off; (2) nitrogen input is fixed at 2008 levels; and (3) all nitrogen input from fertilizer and dairy manure ceases in 2008. The results are illustrated for a well located in the A&B area. Under the first scenario, nitrate concentrations in groundwater are predicted to increase by as much as 2 to 4 mg/L over a period of about 50 years, reaching or exceeding the USEPA MCL of 10 mg/L in some areas. Under the second scenario, nitrate concentrations in groundwater continue to increase—even though inputs do not increase—for about 40 years, leveling off at a concentration slightly less than that of scenario 1. Under the third scenario, it could take as much as 50 years for nitrate concentrations to return to background concentrations near 1 mg/L even if all input related to human activities were stopped in 2008. This period of 50 years represents the “flushing time” of the aquifer. The results highlight the lag time between actions at the land surface and changes in the water quality of the aquifer. The lag occurs because of the time it takes for groundwater to move from the point of recharge at the land surface through the aquifer to a well.



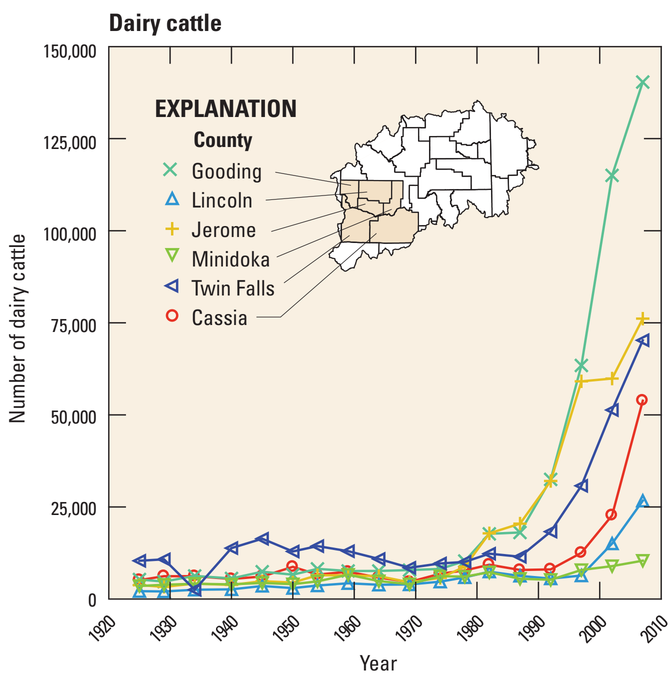


Figure 6–12. The combined number of dairy cattle in a six-county region of the Snake River Plain increased over 300,000 head between 1987 and 2007. The resulting increase in nitrogen input is roughly equivalent to an increase of 4.6 million to 6.2 million humans.

Photograph by Tim McCabe, USDA NRC

Photograph by USDA

Upper: Wastewater and manure from dairies that are used to fertilize crops can be a source of nutrients to groundwater. Lower: Dairy cows being cooled by sprayers during the summer in order to maintain milk production. Nitrate-laden wastewater from dairies can contaminate groundwater if the wastewater is not managed properly.

Pesticides in the Columbia Plateau, Snake River Plain, and Oahu aquifers

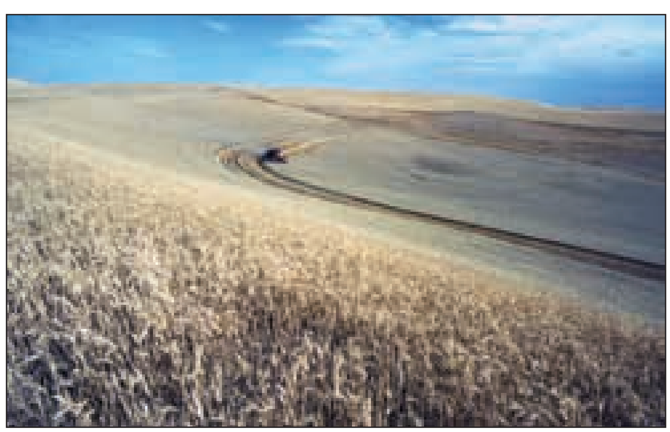
In the Columbia Plateau and Snake River Plain and on Oahu, at least one pesticide was detected in water from about one of every two wells sampled in the three study areas combined. Only concentrations of diuron and dieldrin exceeded their human-health benchmarks, and in only a small number of wells. Patterns of detection reflect how pesticides are used—some broad-spectrum pesticides were detected in groundwater samples from all three areas, but other, more targeted pesticides were detected only in samples from the Columbia Plateau and Snake River Plain, or only in samples from Oahu. Samples commonly contained mixtures of several different pesticides—the health risks of mixtures of pesticides are not well known.

What is a pesticide?

A pesticide is any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest.[55] Pests can be insects, mice and other animals, unwanted plants (weeds), fungi, or microorganisms such as bacteria and viruses. Though often misunderstood to refer only to insecticides, the term pesticide also applies to herbicides, fungicides, and various other substances used to control pests. Most pesticides investigated in this report are herbicides (designed to control plants) and insecticides (designed to control insects). Generally speaking, insecticides are more toxic to humans and animals than are herbicides. As of 1997, about 900 pesticides were registered in the United States for use in more than 20,000 different pesticide products.[56] New pesticides are introduced every year—for example, approximately 10 to 20 new active ingredients were registered each year from 1967 to 1997. Volatile pesticides that are used as soil fumigants are discussed in the Volatile Organic Compound section of this chapter.

A crop duster sprays a sugar beet field with fungicide. The fungus *Cercospora beticola*, which causes leaf spot disease, is developing resistance to some fungicides currently used to control its growth.

Photograph by USDA ARS, Northern Plains Agricultural Research Laboratory, Sidney, Montana



Wheat harvest on the Palouse hills of the Columbia Plateau. Herbicides, such as diuron or metribuzin, are used to maximize crop yields and improve the purity of the harvested grain.

Photograph by USDA ARS

Pesticides were detected in half of the groundwater samples in the Columbia Plateau and Snake River Plain and on Oahu, but rarely at concentrations of concern for human health

Pesticides were detected in water from about 50 percent of wells sampled in the Columbia Plateau, the Snake River Plain, and Oahu aquifers, but only diuron and dieldrin were measured at concentrations that exceeded their human-health benchmarks. Diuron exceeded its benchmark of 2.0 µg/L in water from only one well (less than 1 percent of wells sampled), and dieldrin exceeded its HBSL of 0.002 µg/L in water from about 2 percent of wells sampled.

Ten pesticide compounds were detected in groundwater from at least 5 percent of the wells sampled in at least one of the three study areas (fig. 6–13). Of those 10 compounds, 8 are herbicides, 1 is an insecticide, and 1 is a breakdown product of one of the herbicides. Atrazine and its breakdown product deethylatrazine were the most commonly detected pesticides in groundwater from the Columbia Plateau and the Snake River Plain, and the third and second most frequently detected pesticides on Oahu. Bromacil was the most commonly detected pesticide in groundwater on Oahu, but was much less commonly detected in the other two study areas.

Groundwater sampled in agricultural lands of the Snake River Plain had a greater occurrence of pesticides than groundwater sampled in areas of mixed land uses in the Snake River Plain, because pesticide use is much greater on agricultural lands than areas of mixed land uses. Many of the wells sampled in areas of mixed land uses in the Snake River Plain are located in the tributary valleys and Jackson valley where much of the land is pastureland and rangeland, and pesticide use is much lower than in agricultural lands. There was little difference in pesticide occurrence in groundwater in agricultural lands and areas of mixed land uses of the Columbia Plateau, because the percentage of agricultural lands is greater in the areas of mixed land uses of the Columbia Plateau than in the Snake River Plain.

Pesticides detected in groundwater of the Columbia Plateau, Snake River Plain, and Oahu aquifers reflect the different crops grown and pesticides used in those areas.

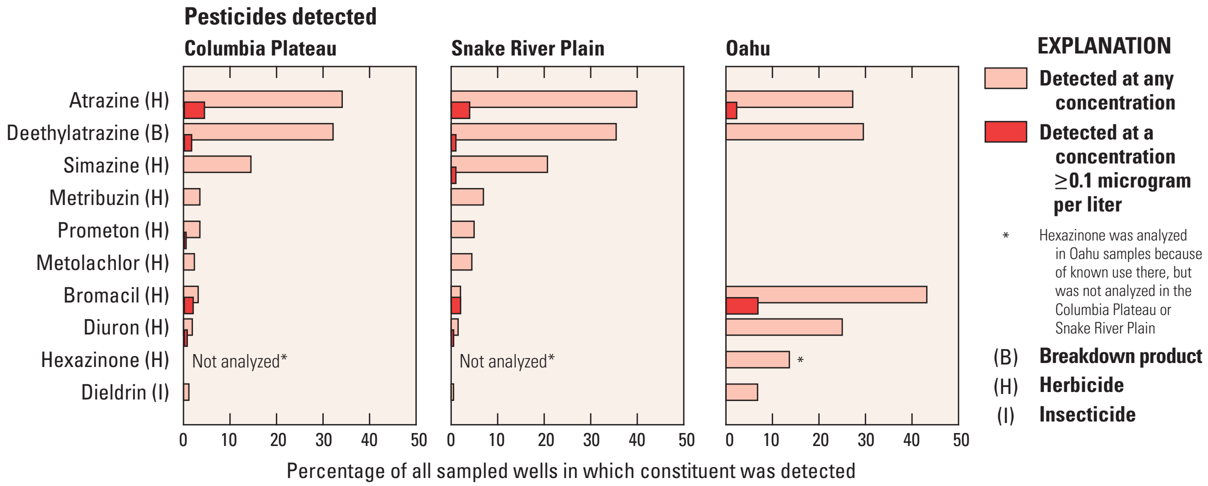


Figure 6–13. Atrazine and its breakdown product deethylatrazine were the most commonly detected pesticides in groundwater samples from the Columbia Plateau, the Snake River Plain, and Oahu aquifers. Other pesticides detected reflect the diversity of crops grown. In groundwater samples from the Columbia Plateau and Snake River Plain, simazine, metribuzin, and metolachlor, which are used on row crops such as corn and potatoes, were detected. In groundwater samples from Oahu, bromacil, which is applied to pineapple crops, was the most commonly detected pesticide. Diuron and hexazinone, which are used on sugarcane and pineapple, also were detected in groundwater in Oahu.

Some pesticides were detected in groundwater samples from all three areas, but other pesticides were detected only in samples from the Columbia Plateau and Snake River Plain, or only in samples from Oahu. This difference is because some pesticides are broad-spectrum pesticides that are used on many crops in different areas of the United States, whereas other pesticides are used on specific crops. Simazine, metribuzin, metolachlor, and prometon were detected in groundwater from the Columbia Plateau and the Snake River Plain, but were not detected in groundwater from Oahu. These pesticides are used on the row crops grown in the Columbia Plateau and Snake River Plain, such as potatoes, barley, and alfalfa, but not on any major crops grown on Oahu (such as pineapple and sugarcane).[57, 58] Bromacil, diuron, and hexazinone were detected frequently in groundwater from Oahu because they were used for weed control on sugarcane and pineapple crops (historically the major cash crops on Oahu). Broad-spectrum herbicides, such as atrazine, that are used on many crops in many different areas of the United States were detected frequently in groundwater from all three study areas.

Mixtures of pesticides commonly are detected in groundwater, and the health effects of these mixtures are unknown

Water samples from about 35 percent of all wells sampled in the three study areas contained two or more pesticides (fig. 6–14). Results are similar on a national basis: 47 percent of wells sampled in agricultural lands across the United States had detections of two or more pesticide compounds, and about 20 percent of wells in areas of mixed land uses had detections of two or more pesticide compounds.[59] Toxicologists have evaluated the health risks and established drinking-water regulations for many individual chemicals, but risks associated with mixtures of chemicals are far less known and, in some cases, may be greater than those of individual chemicals.[60, 61]

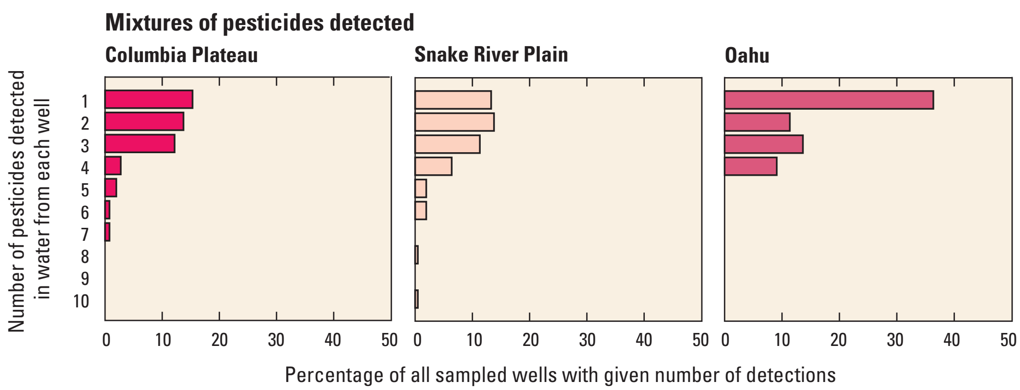


Figure 6–14. Pesticides most commonly occur in groundwater as mixtures—detections of two or more pesticides in a sample were more common than detection of just one pesticide. It is unknown what the health effects might be from drinking water with mixtures of pesticides, because health-based standards are based on individual compounds.

Mixtures of pesticides in groundwater may occur because combinations of pesticides are more effective at controlling weeds, and thus the practice of combining pesticides is widely used. For example, simazine and metribuzin can be combined with atrazine for more effective weed control in row crops.[62] In other cases, one pesticide may be applied one year, and a different pesticide may be applied the following year. In areas of mixed land use, different pesticides may be applied to adjacent agricultural and urban lands, thus creating mixtures of pesticide compounds in the groundwater that were not applied together at the land surface.

Just as individual pesticides detected in groundwater can reflect the crops on which they were applied (and therefore the region), so too can pesticide mixtures. For example, simazine and metolachlor are commonly used in combination with atrazine, but not on crops grown on Oahu.[63] Consequently, atrazine and simazine, and atrazine and metolachlor, were two of the most common pesticide mixtures in groundwater samples from the Columbia Plateau and the

Snake River Plain aquifers, but these mixtures were not detected in groundwater samples from Oahu (fig. 6–15). As another example, atrazine, bromacil, and diuron are all applied to pineapple,[64, 65] and the mixture of atrazine (and its breakdown product deethylatrazine), bromacil, and diuron was the fourth most commonly detected mixture, but this mixture was detected only on Oahu. These observations indicate that certain mixtures could be anticipated by scientists, depending on the regions they are studying. Once information on the toxicity of mixtures is better known, then the potential health effects can be better estimated.

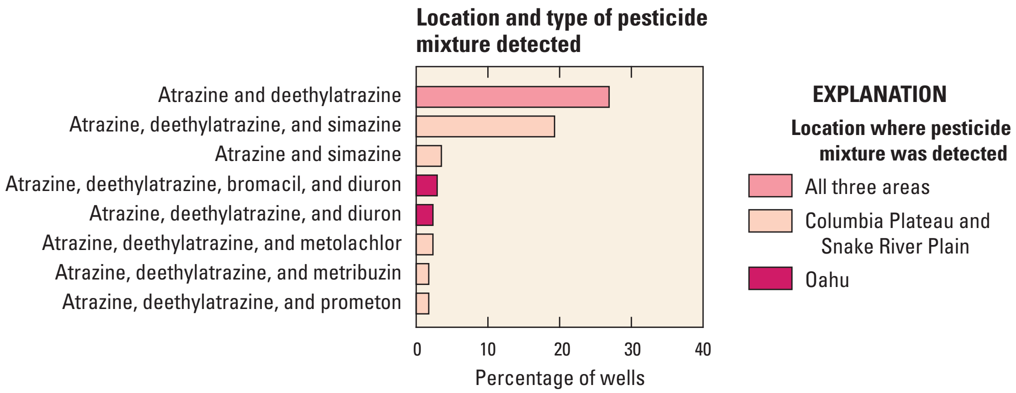


Figure 6–15. The types of crops grown in an area determine the mixtures of pesticides that are likely to be detected in groundwater. For example, the mixture of atrazine, deethylatrazine, and simazine was detected in groundwater from the Columbia Plateau and the Snake River Plain, but not in groundwater from Oahu, because simazine is not used on crops grown on Oahu. Atrazine and its breakdown product deethylatrazine were detected in all three areas because atrazine is widely used in all of them.

Trace concentrations of atrazine and its breakdown product deethylatrazine in groundwater appear to be an unavoidable consequence of atrazine use

Atrazine and deethylatrazine are the most commonly detected pesticides in groundwater across the United States,[59] including groundwater from the Columbia Plateau and Snake River Plain aquifers (see appendix 3); atrazine and deethylatrazine were the second most commonly detected pesticides on Oahu (fig. 6–13). Atrazine has been widely detected in groundwater in Europe, where it was banned for use in all of the European Union member states in 2005 because of concerns for groundwater contamination.[66] Swiss-based Syngenta, the company that manufactures atrazine, agreed to set up a $105 million fund in 2012 to cover the costs of removing the herbicide from drinking water for as many as 2,000 water suppliers in six States of the United States.[67] Statistical correlations show that atrazine is detected most frequently in areas with a high percentage of land in row crops on which atrazine is used (such as corn or sugarcane) and highly permeable soils with low amounts of organic matter.[68]

Photograph by David Nance, USDA ARS

Sugarcane being harvested into high dump trailers for transport to a sugar mill. Atrazine was used on sugarcane on Oahu until the sugarcane industry was phased out in 1996.

Although dieldrin and its parent compound, aldrin, were banned about 16 years prior to sample collection, dieldrin is still detected in groundwater

Dieldrin was detected in groundwater above the low HBSL of 0.002 µg/L in water from 3 of the 44 wells sampled on Oahu (almost 7 percent of the wells) (fig. 6–13). The HBSL for dieldrin is a range of values; the low value (0.002 µg/L) corresponds to a one in one million cancer risk, the high value (0.2 µg/L) corresponds to a one in ten thousand cancer risk. The range of HBSLs is set at these very low concentrations because dieldrin is very toxic to humans.

Dieldrin is very toxic to humans, so the HBSL was set at a very low concentration.

Historically, dieldrin was used as an insecticide, but dieldrin is also a breakdown product of the insecticide aldrin, which rapidly breaks down to dieldrin once in the environment. Aldrin was used heavily as a termiticide in urban areas on Oahu prior to 1984, although dieldrin itself was not commonly used.[69] Even though aldrin has not been used on Oahu since 1984, its breakdown product dieldrin is still detected in groundwater. Aldrin and dieldrin are organochlorine pesticides, which in the past were used heavily in agriculture and to control termites and mosquitoes. DDT (dichloro-diphenyl-trichloroethane) also is an organochlorine pesticide. In the United States, the use of most organochlorine pesticides was discontinued in the 1970s for agriculture, and in the 1980s for termite control, because these pesticides do not readily break down in the environment and because concentrations tend to increase in animal tissue as they are passed up the food chain.[70] Dieldrin was detected more frequently in groundwater samples from Oahu than from the Columbia Plateau or the Snake River Plain aquifers, possibly because Oahu is more urbanized than the Columbia Plateau and the Snake River Plain and because termite damage is a greater problem in the tropical climate of Oahu.

Photograph by Scott Bauer, USDA ARS

Termites cause more than $100 million in damage each year to wooden structures on Hawaii. The Formosan subterranean termite shown here is one of the most destructive of the seven termite varieties found on Hawaii.[90] Aldrin was an effective control for termites, but has not been used on Oahu since 1984 because of environmental concerns. Even though aldrin has not been used on Oahu since 1984, dieldrin (a breakdown product of aldrin) is still being detected in Oahu groundwater.

Photograph by Scott Bauer, USDA ARS

Sugarcane production on Oahu used atrazine for weed control. Even though sugarcane has not been grown on Oahu since 1996, atrazine is still detected in Oahu groundwater.

Volatile Organic Compounds (VOCs) in the Columbia Plateau, Snake River Plain, and Oahu aquifers

Solvents and soil fumigants were the VOCs most frequently detected in groundwater from the Columbia Plateau, Snake River Plain, and Oahu aquifers. VOCs were detected much more commonly on Oahu than in the Columbia Plateau and Snake River Plain. For example, more than half of the wells sampled on Oahu contained at least one VOC, whereas in the Snake River Plain, only 2 percent of the wells contained at least one VOC. The Columbia Plateau, the Snake River Plain, and Oahu are among the few areas in the United States where soil fumigants have been detected in groundwater at concentrations above human-health benchmarks. Although several soil fumigants were banned from use during the late 1970s, they are still being detected in groundwater decades later.

What are volatile organic compounds?

Volatile organic compounds make up a broad class of organic compounds that volatilize (evaporate) readily, and most are soluble in water. Many everyday chemicals are VOCs, including solvents and degreasers, refrigerants, soil fumigants, gasoline, and chlorination disinfection byproducts. Many VOCs have multiple uses—for example, some solvents also are used as additives in pesticide formulations. Groundwater can be contaminated by VOCs in a number of ways: accidental spills, improper disposal, leakage from point sources (such as storage tanks), and widespread application of chemical products to the land surface (such as for agriculture) are just some examples. VOCs can even dissolve into water from the atmosphere, where they are present at low concentrations from industrial and manufacturing releases.[71]

VOCs were commonly detected in groundwater samples from Oahu, less frequently in the Columbia Plateau, and rarely in the Snake River Plain

Volatile organic compounds were far more commonly detected in groundwater samples from Oahu than in groundwater samples from the Columbia Plateau or Snake River Plain (fig. 6–16). Water from more than half of the wells sampled on Oahu contained at least one VOC, and water from one well contained four VOCs in the same sample.[68] In comparison, water from only 2 percent of the wells sampled in the Snake River Plain contained at least one VOC.

More solvents were detected than soil fumigants; of the nine VOCs detected in groundwater at or above the laboratory reporting level of 0.2 µg/L, six were solvents and three were soil fumigants. The most commonly detected VOC was the soil fumigant 1,2,3-trichloropropane (TCP), followed by the solvent trichloroethylene (TCE) and the soil fumigant 1,2-dichloropropane (DCP).

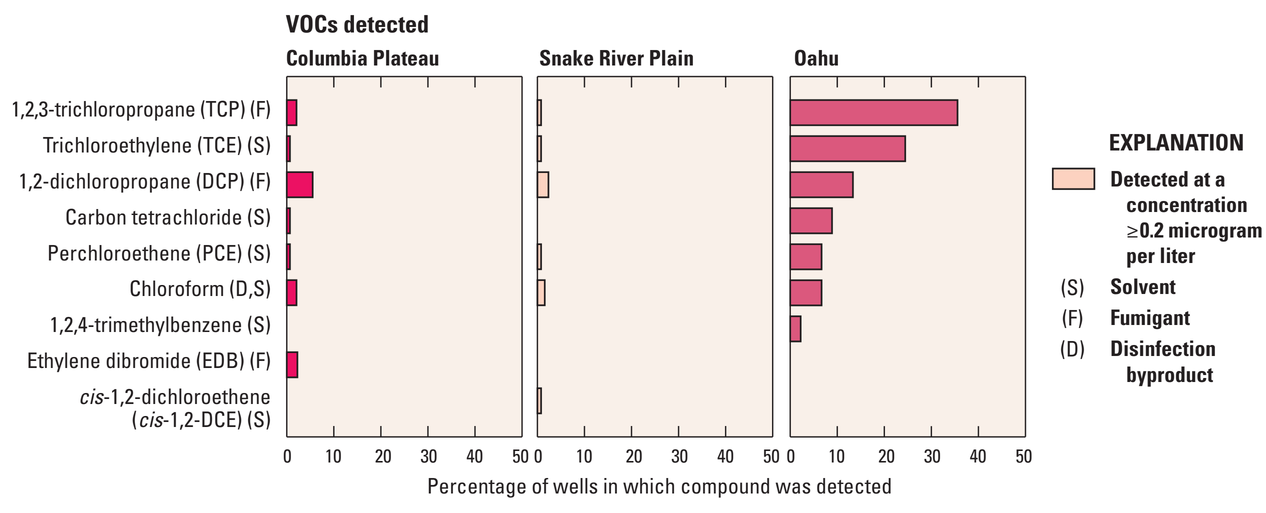


Figure 6–16. VOCs were detected more frequently in wells on Oahu than in wells in the Columbia Plateau or the Snake River Plain. Of the nine VOCs detected at or above the laboratory reporting level of 0.2 µg/L, six were solvents and three were soil fumigants.

Soil fumigants were commonly detected in groundwater on Oahu, in some cases at concentrations that exceed human-health benchmarks

Some high-capacity public-supply wells on Oahu have been closed because soil fumigants were detected in the groundwater.

Soil fumigants were frequently detected in groundwater on Oahu, less frequently in groundwater in the Columbia Plateau, and in only one well in the Snake River Plain (table 6–1). Soil fumigants historically have been the most intensively used class of pesticides on Hawaii. On Oahu, soil fumigants were detected in almost half—44 percent—of the wells sampled.[46] Concentrations of DBCP and TCP were greater than Hawaii MCLs in water from about 10 percent of the wells sampled on Oahu. Hawaii MCLs for some soil fumigants are lower than the MCLs established by the USEPA.[75]

Although soil fumigants were detected less frequently in groundwater from the Columbia Plateau and Snake River Plain than Oahu, a few samples contained soil fumigants at concentrations greater than human-health benchmarks. In the Columbia Plateau, two water samples had concentrations of EDB greater than its USEPA MCL of 0.05 µg/L, and one groundwater sample from the Columbia Plateau and one from the Snake River Plain had a concentration of DCP that was greater than its USEPA MCL of 5 µg/L.

Several of the soil fumigants detected in groundwater from the Columbia Plateau, the Snake River Plain, and Oahu are highly carcinogenic (cancer causing), which is reflected in the very low concentrations considered safe for drinking water by the USEPA and the State of Hawaii (fig. 6–17; table 6–2). Detection of soil fumigants in groundwater on Oahu has resulted in closures of some high-capacity public-supply wells and in others has required installation of costly carbon filtration systems to make the water drinkable (see sidebar, History of soil fumigant detection and water treatment on Oahu, p. 63).

Even though most of the soil fumigants reported here have not been used since the early 1980s, they are persistent and can be detected in groundwater for decades.[76] Thus, soil fumigants are considered "legacy contaminants"—current contamination originating from use decades ago.

What is a soil fumigant?

Soil fumigants are VOCs and also pesticides that are applied to soils to reduce populations of nematodes, weeds, fungal pathogens, and other soil-borne microorganisms.[72, 73] Soil fumigants are injected or incorporated into the soil before crops are planted; the fumigant vapor permeates the soil and kills soil-borne pests. Soil fumigants are used on many different crops across the Nation.[72] In the Columbia Plateau and the Snake River Plain, soil fumigants are used most commonly on potatoes and sugar beets, and on Oahu they are used most commonly on pineapple (table 6–2).

Although most of the soil fumigants detected in groundwater in the Columbia Plateau and Snake River Plain and on Oahu have been banned for use in the United States, they have been replaced by other soil fumigant compounds such as metam sodium, methyl bromide (bromomethane), and chloropicrin.[72] Although there are no chemical-use estimates of soil fumigants in the three study areas, during 2001, metam sodium was the third most commonly used pesticide in the United States (57 to 62 million pounds), methyl bromide was the seventh most commonly used pesticide (20 to 25 million pounds), and chloropicrin was the eighteenth most commonly used pesticide (5 to 9 million pounds).[74] To date (2012), these new soil fumigants have not been routinely detected in groundwater in the United States, although only methyl bromide can be analyzed by using common laboratory methods.

Photograph by USDA ARS, U.S. Salinity Laboratory

A tractor is used to inject the fumigant 1,3-dichloropropene into the soil at a depth of 46 inches. Following the tractor is a disk and ring roller, which compacts the soil and closes any fractures to lessen the release of the fumigant vapor to the atmosphere.

Table 6–1. Soil fumigants were detected most frequently in wells on Oahu. Groundwater sampled on Oahu had the greatest number of concentrations greater than human-health benchmarks, in part because Hawaii MCLs are lower than those set by the USEPA. These results are for samples collected from all types of wells sampled for soil fumigants, not just the drinking-water wells discussed in chapter 5.

[µg/L, micrograms per liter (parts per billion); nd, not detected; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; MCL, Maximum Contaminant Level; HBSL, Health-Based Screening Level; H-MCL, Hawaii MCL; MCLs and HBSLs are human-health benchmarks for drinking water (for regulated and unregulated compounds, respectively) and are in micrograms per liter (parts per billion)]

Fumigant compound	Columbia Plateau			Snake River Plain			Oahu			
	Number of wells sampled	Number of detections	Number of detections above USEPA MCL or USGS HBSL	Number of wells sampled	Number of detections	Number of detections above USEPA MCL or USGS HBSL	Number of wells sampled	Number of detections	Number of detections above USEPA MCL or USGS HBSL	Number of detections above Hawaii MCL
1,2-dibromo-3-chloropropane (DBCP)	162	nd	nd	124	nd	nd	45	8	0 (USEPA MCL = 0.2 µg/L)	4 (H-MCL = 0.04 µg/L)
1,2-dibromo-ethane (EDB, ethylene dibromide)	162	3	2 (MCL = 0.05 µg/L)	124	nd	nd	45	4	0 (USEPA MCL = 0.05 µg/L)	0 (H-MCL = 0.04 µg/L)
1,2-dichloro-propane (DCP)	151	9	1 (MCL = 5 µg/L)	128	1	1 (MCL = 5 µg/L)	45	19	0 (USEPA MCL = 5 µg/L)	No H-MCL established
1,1-dichloro-propene (DCPe)*	151	nd	nd	128	nd	nd	45	1	No human-health benchmark established	No H-MCL established
1,2,3-trichloro-propane (TCP)	151	4	0 (HBSL = 40 µg/L)	128	nd	nd	45	18	0 (USGS HBSL = 40 µg/L)	6 (H-MCL = 0.8 µg/L)

*The detected compound, 1,1-dichloropropene, is a breakdown product of 1,3-dichloropropene (DCPe) still used in fumigant formulations.

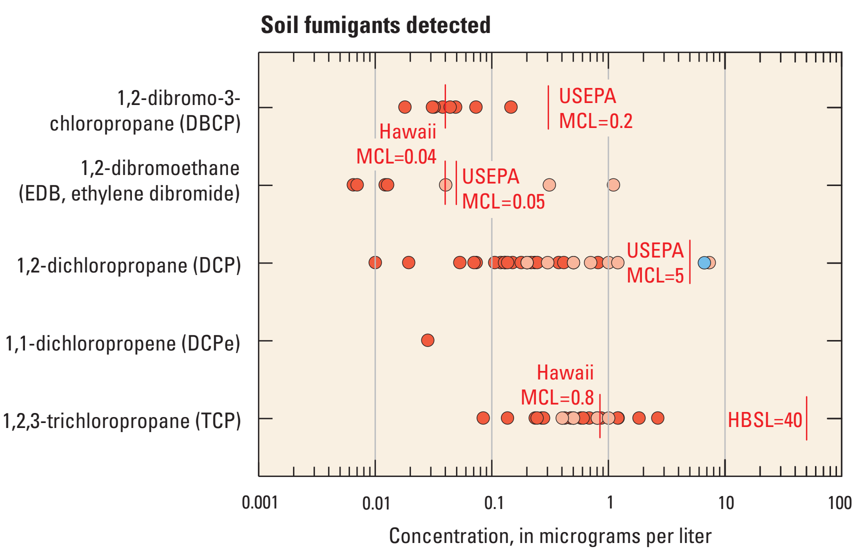


Figure 6–17. Soil fumigants were detected in groundwater samples from all three study areas, but most frequently in samples from wells on Oahu. Several wells on Oahu contained one or more soil fumigants at a concentration exceeding the Hawaii MCL, which are more stringent than the USEPA MCLs. There are no USEPA MCLs for DCPe or TCP and no Hawaii MCLs for DCP or DCPe.

EXPLANATION

- Columbia Plateau
- Snake River Plain
- Oahu

Table 6–2. Soil fumigants detected in groundwater in the Columbia Plateau, Snake River Plain, and Oahu aquifers have long histories of use, dating back to the 1940s and 1950s. Only 1,3-dichloropropene is still used as a soil fumigant in the United States; the other compounds have been banned for soil application because of environmental concerns. Hawaii MCLs are lower than those set by the USEPA.

[USEPA, U.S. Environmental Protection Agency; MCL, Maximum Contaminant Level; USGS, U.S. Geological Survey; HBSL, Health-Based Screening Level; MCLs and HBSLs are human-health benchmarks for drinking water (for regulated and unregulated compounds, respectively) and are in micrograms per liter (parts per billion)]

Fumigant compound	Years of use as a soil fumigant in the three study areas	Used principally for these crops	Human-health benchmarks (micrograms per liter)		
			USEPA MCL	Hawaii MCL	USGS HBSL
1,2-dibromo-3-chloropropane (DBCP)	1955–1977	Pineapple, potatoes, sugar beets, orchards	0.2	0.04	None
1,2-dibromoethane (EDB, ethylene dibromide)	1948–1983	Pineapple, potatoes	0.05	0.04	None
1,2-dichloropropane (DCP)	1943–1977	Pineapple, potatoes	5	None	None
1,3-dichloropropene (DCPe)*	1956–present (2012)	Pineapple, potatoes, sugar beets, carrots	None	None	None
1,2,3-trichloropropane (TCP)	1943–1977	Pineapple, potatoes	None	0.8	40

*The detected compound, 1,1-dichloropropene, is a breakdown product of 1,3-dichloropropene (DCPe) still used in fumigant formulations.

Scientists examine a sugar beet damaged by root-knot nematodes. Root-knot nematodes cause extensive damage to a wide variety of economically important crops, including sugar beets, by reducing the yields and quality of the crops. The soil fumigant 1,3-dichloropropene is an effective chemical control against the root-knot nematode.

Photograph by Scott Bauer, USDA ARS

History of soil fumigant detection and water treatment on Oahu

Soil fumigants have been detected in Oahu groundwater since 1980.[77–79] Detection of soil fumigants by interagency sampling led by the Hawaii Department of Health resulted in temporary closures of public-supply wells during the 1980s. Ten high-capacity public-supply wells had been ordered closed by 1983, with each closure resulting in front-page newspaper headlines, great concern in the affected communities, and substantial challenges to public agencies tasked with addressing the problem. Eventually, costly granular activated carbon filters were installed at affected wells to treat pumped groundwater to levels meeting drinking-water standards so that public use of the water could resume. Carbon filtration still is being used today with associated operating costs to maintain the filter apparatus and replace the carbon when it reaches its sorption limit. In 2002, the Honolulu Board of Water Supply (the operator of the affected public wells) was awarded nearly $20 million from three chemical manufacturers and three Oahu pineapple growers as compensation for the contaminated groundwater source.[80]

Photograph courtesy of GMP International

These large vessels contain granular activated carbon, which is used to remove soil fumigants from drinking water at a Honolulu Board of Water Supply well field in central Oahu. Prior to discovery of soil fumigants in the 1980s, water from Oahu's volcanic-rock aquifers typically required no treatment or only slight chlorination before use.

Photograph by Stephen S. Anthony, USGS

Because VOCs in air can readily dissolve into water, groundwater samples for VOCs are collected from Teflon tubing within a bagged enclosure to reduce the possibility of contamination. The tubing is directly connected at its far end to the wellhead (out of view) so that the water sample does not come in contact with the air until it is placed in the sample bottle. For more information on groundwater sampling methods used by the USGS, see the USGS National Field Manual.[91]

On Oahu, VOCs commonly occur in groundwater that also contains pesticides and nitrate

Groundwater samples on Oahu commonly contain mixtures of solvents, soil fumigants, pesticides, and elevated nitrate concentrations (fig. 6–18), indicating that water from many wells contains contaminants originating from several sources or activities at the land surface. Some samples contained as many as four VOCs, as well as trace concentrations of pesticides and elevated concentrations of nitrate.

Specific sources of the solvent contamination in groundwater on Oahu have not been determined despite a decade of investigations.[81] The most likely sources of solvent contamination on Oahu include the use of solvents at military bases, aircraft and automotive maintenance shops, painting shops, drum-disposal and burn areas, and dry cleaners.[46, 82] Solvents were used intensively at military installations in central Oahu as early as the 1940s.

Soil fumigants in groundwater on Oahu are attributable mainly to pineapple cultivation. The pesticides in groundwater on Oahu originated from agricultural and urban use. The largest source of elevated nitrate concentrations in groundwater on Oahu is agricultural activities, primarily pineapple and sugarcane cultivation.

Chloroform, a VOC, generally was detected in groundwater samples from Oahu that also contained other solvents, soil fumigants, or pesticides. The chloroform might have contaminated Oahu's groundwater as a mixture with other VOCs, as a carrier agent in pesticides or soil fumigants, or as a breakdown product of carbon tetrachloride.[46] The chlorination of drinking water, a common source of chloroform in many settings, is not a likely source on Oahu because most wells are located where lawn and landscape irrigation are not likely to be important sources of recharge to groundwater.[46]

Pineapple cultivation in Hawaii uses soil fumigants to control damaging nematodes. Soil fumigants historically have been the most intensively used class of pesticides in Hawaii, with 2,200 tons applied statewide in 1977 compared to 1,400 tons of herbicides. Many of these soil fumigants have been discontinued or banned.

Photograph by Michael G. Rupert, USGS

Groundwater in Honolulu is free of most contaminants because it receives recharge from a mountainous area with no major contaminant sources. Groundwater in Honolulu flows upward, which inhibits transport of contaminants from land surface down into the aquifer. These factors combine to produce a well-protected urban groundwater resource.

Photograph by Douglas Peebles, Douglas Peebles Photography

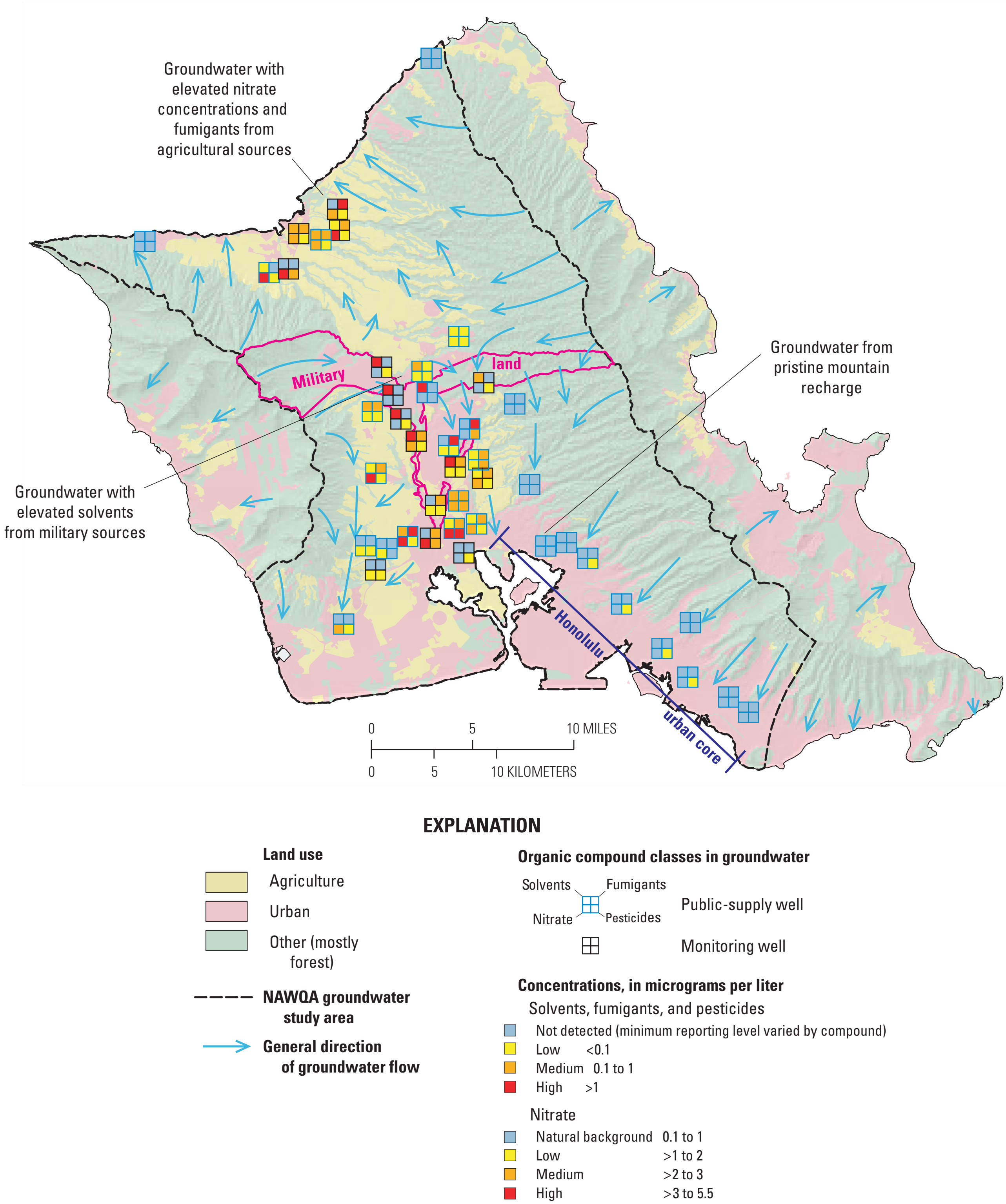
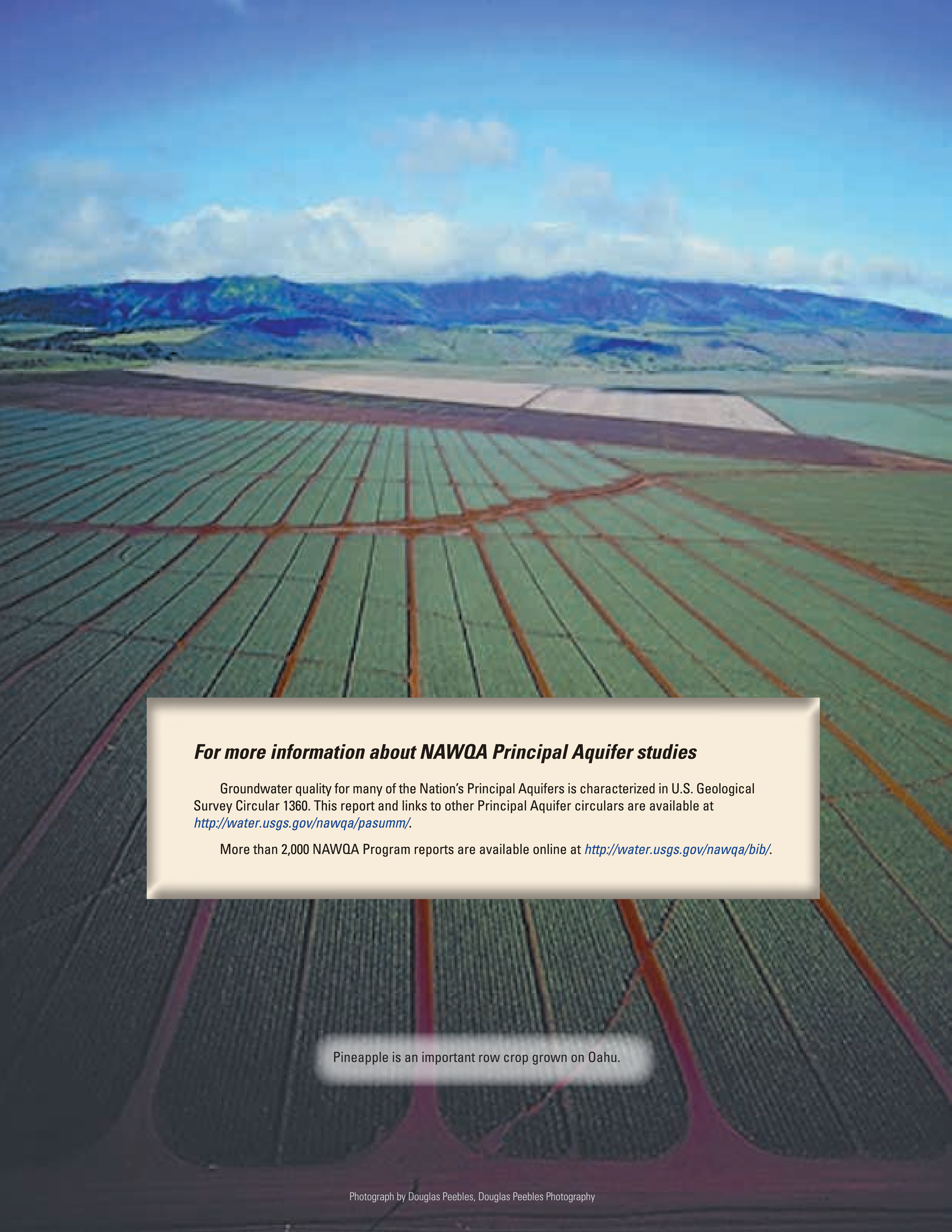


Figure 6–18. Mixtures of solvents, soil fumigants, pesticides, and elevated nitrate concentrations were common in groundwater samples on Oahu. Many samples from central Oahu contained moderate to high concentrations in several of those chemical classes, reflecting inputs from agricultural, military, and urban sources. Concentrations were low, or not detected, in water from wells in the Honolulu urban core because most of the groundwater pumped from these wells originates as recharge in the undeveloped mountains to the northeast. The color-coded squares in this figure represent the maximum concentration in each of three chemical classes (solvents, soil fumigants, and pesticides) and nitrate concentration. Blue colors indicate that no contamination was detected; warmer colors indicate increasingly higher concentrations.



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/*.

Pineapple is an important row crop grown on Oahu.

Photograph by Douglas Peebles, Douglas Peebles Photography

References Cited

1. Gilliom, R.J., Alley, W.M., and Gurtz, M.E., 1995, Design of the National Water-Quality Assessment Program—Occurrence and distribution of water-quality conditions: U.S. Geological Survey Circular 1112, 33 p., accessed August 14, 2013, at *http://pubs.usgs.gov/circ/circ1112/*.

2. DeSimone, L.A., Hamilton, P.A., and Gilliom, R.J., 2009, Quality of water from domestic wells in Principal Aquifers of the United States, 1991–2004—Overview of major findings: U.S. Geological Survey Circular 1332, 48 p., accessed May 22, 2012, at *http://pubs.usgs.gov/circ/circ1332/*.

3. Toccalino, P.L., and Hopple, J.A., 2010, The quality of our Nation's waters—Quality of water from public-supply wells in the United States, 1993–2007—Overview of major findings: U.S. Geological Survey Circular 1346, 58 p. (Also available at *http://pubs.er.usgs.gov/publication/cir1346*.)

4. Scott, J.C., 1990, Computerized stratified random site-selection approaches for design of a ground-water-quality sampling network: U.S. Geological Survey Water-Resources Investigations Report 90–4101, 109 p. (Also available at *http://pubs.er.usgs.gov/publication/wri904101*.)

5. Miller, J.A., ed., 1999, Ground-water atlas of the United States: U.S. Geological Survey Hydrologic Atlas 730, accessed June 11, 2013, at *http://pubs.usgs.gov/ha/ha730/*.

6. Nelson, L.M., 1991, Surface-water resources for the Columbia Plateau, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Resources Investigations Report 88–4105, 4 p.

7. Clark, G.M., Maret, T.R., Rupert, M.G., Maupin, M.A., Low, W.H., and Ott, D.S., 1998, Water quality in the Upper Snake River Basin, Idaho and Wyoming, 1992–95: U.S. Geological Survey Circular 1160, 35 p.

8. Oki, D.S., and Brasher, A.M.D., 2003, Environmental setting and the effects of natural and human-related factors on water quality and aquatic biota, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 03–4156, 98 p., accessed June 11, 2013, at *http://pubs.usgs.gov/wri/wri034156/*.

9. Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Hawaii rainfall atlas: Honolulu, Hawaii, Department of Land and Natural Resources Hawaii Division of Water and Land Development Report R76, 267 p.

10. Tolan, T.L., Martin, B.S., Reidel, S.P., Kauffman, J.D., Garwood, D.L., and Anderson, J.L., 2009, Stratigraphy and tectonics of the central and eastern portions of the Columbia River flood-basalt province—An overview of our current state of knowledge, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to vineyards—Geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 645–672.

11. Whiteman, K.J., 1986, Ground-water levels in three basalt hydrologic units underlying the Columbia plateau, Washington and Oregon, spring 1984: U.S. Geological Survey Water-Resources Investigations Report 86–4046, 4 sheets.

12. Whiteman, K.J., Vaccaro, J.J., Gonthier, J.B., and Bauer, H.H., 1994, The hydrogeologic framework and geochemistry of the Columbia plateau aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey Professional Paper 1413–B, 73 p. (Also available at *http://pubs.er.usgs.gov/publication/pp1413B*.)

13. Mundorff, M.J., Crosthwaite, E.G., and Kilburn, Chabot, 1964, Ground water for irrigation in the Snake River Basin in Idaho: U.S. Geological Survey Water Supply Paper 1654, 224 p.

14. Rupert, M.G., 1997, Nitrate (NO_2+NO_3–N) in ground water of the upper Snake River Basin, Idaho and western Wyoming, 1991–95: U.S. Geological Survey Water-Resources Investigations Report 97–4174, 47 p., accessed June 1, 2012, at *http://pubs.er.usgs.gov/publication/wri974174*.

15. Wylie, Allan, Quinn, Bill, McVay, Michael, Scheidt, Nicholas, and Pennington, Larry, 2008, Analysis of the 2007 post season recharge using North Side canal: Boise, Idaho, Idaho Department of Water Resources Open-File Report, 22 p.

16. Visher, F.N., and Mink, J.F., 1964, Ground-water resources in southern Oahu, Hawaii: U.S. Geological Survey Water-Supply Paper 1778, 133 p.

17. Tenorio, P.A., Young, R.H.F., and Whitehead, H.C., 1969, Identification of return irrigation water in the subsurface—Water quality: Honolulu, Hawaii, University of Hawaii at Manoa Water Resources Research Center Technical Report 33, 90 p.

18. Plummer, L.N., Michel, R.L., Thurman, E.M., and Glynn, P.D., 1993, Environmental tracers for age-dating young ground water, chap. 11 *of* Alley, W.M., ed., Regional ground-water quality: New York, Van Nostrand Reinhold, p. 255–294.

19. Plummer, L.N., and Friedman, L.C., 1999, Tracing and dating young ground water: U.S. Geological Survey Fact Sheet 134–99, 4 p.

20. Plummer, L.N., and Busenberg, Eurybiades, 1999, Chlorofluorocarbons, chap. 15 *of* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Mass., Kluwer Academic Publishers, p. 441–478.

21. Solomon, D.K., and Cook, P.G., 1999, ^{3}H and ^{3}He, chap. 13 *of* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Mass., Kluwer Academic Publishers, p. 397–424.

22. Hinkle, S.R., Shapiro, S.D., Plummer, L.N., Busenberg, Eurybiades, Widman, P.K., Casile, G.C., and Wayland, J.E., 2010, Estimates of tracer-based piston-flow ages of groundwater from selected sites—National Water-Quality Assessment Program, 1992–2005: U.S. Geological Survey Scientific Investigations Report 2010–5229, 15 p., accessed August 30, 2011, at *http://pubs.usgs.gov/sir/2010/5229/*.

23. Plummer, L.N., Rupert, M.G., Busenberg, Eurybiades, and Schlosser, Peter, 2000, Age of irrigation water in ground water from the Eastern Snake River Plain aquifer, south-central Idaho: Ground Water, v. 38, no. 2, p. 264–283.

24. McMahon, P.B., Cowdery, T.K., Chapelle, F.H., and Jurgens, B.C., 2009, Redox conditions in selected Principal Aquifers of the United States: U.S. Geological Survey Fact Sheet 2009–3041, 6 p. (Also available at *http://pubs.usgs.gov/fs/2009/3041/*.)

25. Dubrovsky, N.M., Burow, K.R., Clark, G.M., Gronberg, J.M., Hamilton, P.A., Hitt, K.J., Mueller, D.K., Munn, M.D., Nolan, B.T., Puckett, L.J., Rupert, M.G., Short, T.M., Spahr, N.E., Sprague, L.A., and Wilber, W.G., 2010, The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350, 174 p., accessed March 14, 2012, at *http://water.usgs.gov/nawqa/nutrients/pubs/circ1350/*.

26. U.S. Environmental Protection Agency, [undated], National primary drinking water regulations—Drinking water contaminants: U.S. Environmental Protection Agency Web site, accessed May 25, 2012, at *http://water.epa.gov/drink/contaminants/index.cfm*.

27. National Research Council, 1999, Risk assessment of radon in drinking water: Washington, D.C., National Academy Press, 296 p.

28. U.S. Environmental Protection Agency, 1999, National primary drinking water regulations; radon-222; proposed rule: Federal Register, v. 64, no. 211, November 2, p. 59245–59294, accessed June 5, 2012, at *http://www.epa.gov/fedrgstr/EPA-WATER/1999/November/Day-02/w27741a.htm*.

29. U.S. Environmental Protection Agency, 2009, Proposed radon in drinking water rule: U.S. Environmental Protection Agency Web site, accessed February 24, 2010, at *http://www.epa.gov/safewater/radon/proposal.html*.

30. U.S. Environmental Protection Agency, 1999, Proposed radon in drinking water rule: U.S. Environmental Protection Agency Technical Fact Sheet 815–F–99–006, 6 p., accessed February 8, 2012, at *http://www.epa.gov/ogwdw000/radon/fact10.pdf*.

31. National Research Council, 2001, Arsenic in drinking water—2001 update: Washington, D.C., National Academy Press, 225 p.

32. Smith, A.H., Hopenhayn-Rich, C., Bates, M.N., Goeden, H.M., Hertz-Picciotto, I., Duggan, H.M., Wood, R., Kosnett, M.J., and Smith, M.T., 1992, Cancer risks from arsenic in drinking water: Environmental Health Perspectives, v. 97, p. 259–267.

33. McMahon, P.B., and Chapelle, F.H., 2008, Redox processes and water quality of selected Principal Aquifer systems: Ground Water, v. 46, no. 2, p. 259–271.

34. Welch, A.H., Westjohn, D.B., Helsel, D.R., and Wanty, R.B., 2000, Arsenic in ground water of the United States—Occurrence and geochemistry: Ground Water, v. 38, no. 4, p. 589–604.

35. Ayotte, J.D., Gronberg, J.M., and Apodaca, L.E., 2011, Trace elements and radon in groundwater across the United States, 1992–2003: U.S. Geological Survey Scientific Investigations Report 2011–5059, 115 p. (Also available at *http://pubs.usgs.gov/sir/2011/5059/*.)

36. Frau, Franco, Biddau, Riccardo, and Fanfani, Luca, 2008, Effect of major anions on arsenate desorption from ferrihydrite-bearing natural samples: Applied Geochemistry, v. 23, no. 6, p. 1451–1466, accessed April 12, 2013, at *http://www.sciencedirect.com/science/article/pii/S0883292708000541*.

37. Cutler, William, Hue, Nguyen, Ortiz-Escobar, M.E., and Martin, Todd, 2006, Approaches to reduce bioaccessible As in Hawaii soils, *in* Proceedings of the Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 22–25, 2006: Columbus, Ohio, Battelle Press, [n.p.], accessed November 14, 2012, at *http://www.ctahr.hawaii.edu/huen/Cutler_As.pdf*.

38. World Health Organization, 2003, Molybdenum in drinking water, *in* Guidelines for drinking-water quality (2d ed.): Geneva, Switzerland, World Health Organization, accessed November 14, 2012, at *http://www.who.int/water_sanitation_health/dwq/chemicals/molybdenum.pdf*.

39. Wisconsin Department of Health Services, 2010, Molybdenum in drinking water: Madison, Wis., Wisconsin Department of Health Services Division of Public Health P–00150 (02/2010), 2 p., accessed June 15, 2011, at *http://www.dhs.wisconsin.gov/publications/P0/P00150.pdf* .

40. Wasserman, G.A., Liu, Xinxua, Parvez, Faruque, Ahsan, Habibul, Levy, Diane, Factor-Litvak, Pam, Kline, Jennie, van Geen, Alexander, Slavkovich, Vesna, Lolacono, N.J., Cheng, Zhonggi, Zheng, Yan, and Graziano, J.H., 2006, Water manganese exposure and children's intellectual function in Araihazar, Bangladesh: Environmental Health Perspectives, v. 114, no. 1, p. 124–129.

41. U.S. Environmental Protection Agency, 2004, Drinking water health advisory for manganese: U.S. Environmental Protection Agency Office of Water EPA–822–R–04–003, 49 p., accessed September 17, 2012, at *http://www.epa.gov/safewater/ccl/pdfs/reg_determine1/support_cc1_magnese_dwreport.pdf*.

42. Galloway, J.N., Schlesinger, W.H., Levy, Hiram, II, Michaels, Anthony, and Schnoor, J.L., 1995, Nitrogen fixation—Anthropogenic enhancement-environmental response: Global Biogeochemical Cycles, v. 9, no. 2, p. 235–252.

43. Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., and Tilman, D.G., 1997, Human alteration of the global nitrogen cycle—Sources and consequences: Ecological Applications, v. 7, no. 3, p. 737–750.

44. Rupert, M.G., 1996, Major sources of nitrogen input and loss in the upper Snake River Basin, Idaho and western Wyoming, 1990: U.S. Geological Survey Water-Resources Investigations Report 96-4008, 15 p., accessed June 2, 2011, at *http://pubs.er.usgs.gov/publication/wri964008/*.

45. Anthony, S.S., Hunt, C.D., Jr., Brasher, A.M., Miller, L.D., and Tomlinson, M.S., 2004, Water quality on the island of Oahu, Hawaii, 1999–2001: U.S. Geological Survey Circular 1239, 37 p. (Also available at *http://pubs.usgs.gov/circ/2004/1239/*.)

46. Hunt, C.D., Jr., 2004, Ground-water quality and its relation to land use on Oahu, Hawaii, 2000–01: U.S. Geological Survey Water-Resources Investigations Report 03–4305, 76 p., accessed June 2, 2011, at *http://pubs.usgs.gov/wri/wri034305/*.

47. Jones, J.L., and Wagner, R.J., 1995, Water-quality assessment of the central Columbia plateau in Washington and Idaho; analysis of available nutrient and pesticide data for ground water, 1942–92: U.S. Geological Survey Water-Resources Investigations Report 94–4258, 119 p., accessed June 2, 2011, at *http://pubs.er.usgs.gov/publication/wri944258/*.

48. Skinner, K.D., and Donato, M.M., 2003, Probability of detecting elevated concentrations of nitrate in ground water in a six-county area of south-central Idaho: U.S. Geological Survey Water-Resources Investigations Report 2003–4143, 29 p.

49. Weyer, P.J., Cerhan, J.R., Kross, B.C., Hallberg, G.R., Kantamneni, Jiji, Breuer, George, Jones, M.P., Zheng, Wei, and Lynch, C.F., 2001, Municipal drinking water nitrate level and cancer risk in older women—The Iowa women's health study: Epidemiology, v. 11, no. 3, p. 327–338.

50. Ward, M.H., Mark, S.D., Cantor, K.P., Weisenburger, D.D., Correa-Villaseñor, A., and Zahm, S.H., 1996, Drinking water nitrate and the risk of non-Hodgkin's lymphoma: Epidemiology, v. 7, no. 5, p. 465–471.

51. Skinner, K.D., and Rupert, M.G., 2012, Numerical model simulations of nitrate concentrations in groundwater using various nitrogen input scenarios, mid-Snake region, south-central Idaho: U.S. Geological Survey Scientific Investigations Report 2012–5237, 30 p. Also available at *http://pubs.usgs.gov/sir/2012/5237/*.)

52. Lindsey, B.D., and Rupert, M.G., 2012, Methods for evaluating temporal groundwater quality data and results of decadal-scale changes in chloride, dissolved solids, and nitrate concentrations in groundwater in the United States, 1988–2010: U.S. Geological Survey Scientific Investigations Report 2012–5049, 46 p. (Also available at *http://pubs.usgs.gov/sir/2012/5049/*.)

53. Frans, L.M., and Helsel, D.R., 2005, Evaluating regional trends in ground-water nitrate concentrations of the Columbia Basin ground water management area: U.S. Geological Survey Scientific Investigations Report 2005–5078, 7 p. (Also available at *http://pubs.usgs.gov/sir/2005/5078/*.)

54. Hutchins, S.R., White, M.V., and Mravik, S.C., 2012, Case studies on the impact of concentrated animal feeding operations (CAFOs) on ground water quality: U.S. Environmental Protection Agency Office of Research and Development Publication 600/R–12/052, 265 p., accessed April 12, 2013, at *http://nepis.epa.gov/Adobe/PDF/P100F9DI.pdf*.

55. U.S. Environmental Protection Agency, 2011, About pesticides: U.S. Environmental Protection Agency Web site, accessed June 27, 2011, at *http://www.epa.gov/pesticides/about/*.

56. Aspelin, A.L., and Grube, A.H., 1999, Pesticides industry sales and usage—1996 and 1997 market estimates: U.S. Environmental Protection Agency Office of Prevention, Pesticides and Toxic Substances 733–R–99–001, 39 p.

57. U.S. Environmental Protection Agency, 1995, R.E.D. Facts—Metolachlor: U.S. Environmental Protection Agency Prevention, Pesticides, and Toxic Substances EPA–738–F–95–007, 14 p., accessed July 11, 2011, at *http://www.epa.gov/oppsrrd1/REDs/factsheets/0001fact.pdf*.

58. U.S. Environmental Protection Agency, 2003, Health effects support document for metribuzin: U.S. Environmental Protection Agency Office of Water EPA 822–R–03–004, 84 p., accessed July 8, 2011, at *http://water.epa.gov/action/advisories/drinking/upload/2004_01_16_support_cc1_metribuzin_healtheffects.pdf*.

59. Gilliom, R.J., Barbash, J.E., Crawford, C.G., Hamilton, P.A., Martin, J.D., Nakagaki, Naomi, Nowell, L.H., Scott, J.C., Stackelberg, P.E., Thelin, G.P., and Wolock, D.M., 2006, The quality of our Nation's waters—Pesticides in the Nation's streams and ground water, 1992–2001: U.S. Geological Survey Circular 1291, 172 p. (Also available at *http://pubs.usgs.gov/circ/2005/1291/*.)

60. Bartsch, R., Forderkunz, S., Reuter, U., Sterzl-Eckert, H., and Greim, H., 1998, Maximum workplace concentration values and carcinogenicity classification for mixtures: Environmental Health Perspectives, v. 106, supp. 6, p. 1291–1293.

61. Carpenter, D.O., Arcaro, K.F., Bush, B., Niemi, W.D., Pang, S., and Vakharia, D.D., 1998, Human health and chemical mixtures—An overview: Environmental Health Perspectives, v. 106, supp. 6, p. 1263–1270.

62. U.S. Environmental Protection Agency, 2011, Basic information about simazine in drinking water: U.S. Environmental Protection Agency Web site, accessed June 27, 2011, at *http://water.epa.gov/drink/contaminants/basicinformation/simazine.cfm*.

63. U.S. Environmental Protection Agency, 2011, Atrazine updates: U.S. Environmental Protection Agency Web site, accessed June 27, 2011, at *http://www.epa.gov/opp00001/reregistration/atrazine/atrazine_update.htm*.

64. Pesticide Management Education Program, 1993, Hexazinone: Ithaca, N.Y., Cornell University Pesticide Management Education Program Pesticide Information Profile, accessed June 28, 2011, at *http://pmep.cce.cornell.edu/profiles/extoxnet/haloxyfop-methylparathion/hexazinone-ext.html*.

65. U.S. Environmental Protection Agency, 1995, National primary drinking water regulations—Atrazine: U.S. Environmental Protection Agency Office of Water EPA 811–F–95–003 d-T, accessed July 19, 2011, at *http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9100PO32.txt*.

66. Ackerman, Frank, 2007, The economics of atrazine: International Journal of Occupational and Environmental Health, v. 13, no. 4, p. 441–449, accessed August 10, 2011, at *http://ase.tufts.edu/gdae/Pubs/rp/EconAtrazine.pdf*.

67. Tarter, Steve, 2012, Atrazine maker settles class action: The Peoria Journal Star [Peoria, Ill.], June 4, accessed July 19, 2012, at *http://www.pjstar.com/business/x1040016246/Atrazine-maker-settles-class-action*.

68. Frans, L.M., Rupert, M.G., Hunt, C.D., Jr., and Skinner, K.D., 2012, Groundwater quality in Columbia Plateau, Snake River Plain, and Oahu basaltic-rock and basin-fill aquifers in the northwestern United States and Hawaii, 1992–2010: U.S. Geological Survey Scientific Investigations Report 2012–5123, 84 p., accessed June 11, 2013, at *http://pubs.usgs.gov/sir/2012/5123/*.

69. Brasher, A.M., and Anthony, S.S., 2000, Occurrence of organochlorine pesticides in stream bed sediment and fish from selected streams on the island of Oahu, Hawaii, 1998: U.S. Geological Survey Fact Sheet 140–00, 6 p.

70. U.S. Environmental Protection Agency, 2003, Health effects support document for aldrin/dieldrin: U.S. Environmental Protection Agency Office of Water EPA 822–R–03–001, 255 p., accessed June 10, 2011, at *http://water.epa.gov/action/advisories/drinking/upload/2004_1_16_support_cc1_aldrin-dieldrin_healtheffects.pdf*.

71. Belitz, Kenneth, Hamlin, S.N., Burton, C.A., Kent, Robert, Fay, R.G., and Johnson, Tyler, 2004, Water quality in the Santa Ana Basin, California, 1999–2001: U.S. Geological Survey Circular 1238, 38 p. (Also available at *http://pubs.usgs.gov/circ/2004/1238/*.)

72. U.S. Environmental Protection Agency, 2005, Overview of the use and usage of soil fumigants: U.S. Environmental Protection Agency Office of Prevention, Pesticides and Toxic Substances Memorandum, accessed February 26, 2014, at *http://www.epa.gov/oppsrrd1/reregistration/x-soil-fum-HOLD/soil_fumigant_use.pdf*.

73. U.S. Environmental Protection Agency, 2008, Health effects support document for 1,3-dichloropropene: U.S. Environmental Protection Agency Office of Water EPA 822–R–08–008, January, 142 p., accessed April 14, 2011, at *http://www.epa.gov/ogwdw000/ccl/pdfs/reg_determine2/healtheffects_ccl2-reg2_13dichloropropene.pdf*.

74. U.S. Environmental Protection Agency, 2004, Pesticides industry sales and usage, 2000 and 2001 market estimates: U.S. Environmental Protection Agency Office of Prevention, Pesticides, and Toxic Substances EPA–733–R–04–001.

75. Hawaii Department of Health, 2011, Amendment and compilation of chapter 11–20—Hawaii administrative rules: Honolulu, Hawaii, Department of Health, [n.p.], accessed December 9, 2012, at *http://gen.doh.hawaii.gov/sites/har/AdmRules1/11-20.pdf*.

76. Burlinson, N.E., Lee, L.A., and Rosenblatt, D.H., 1982, Kinetics and products of hydrolysis of 1,2-dibromo-3-chloropropane: Environmental Science and Technology, v. 16, issue 9, p. 627–632.

77. Lau, L.S., 1987, Organic chemical contamination of Oahu groundwater: Honolulu, Hawaii, University of Hawaii at Manoa Water Resources Research Center Technical Report 181, 153 p.

78. Oki, D.S., and Giambelluca, T.W., 1987, DBCP, EDB, and TCP contamination of ground water in Hawaii: Ground Water, v. 25, no. 6, p. 693–702.

79. Orr, Shlomo, and Lau, L.S., 1987, Trace organic (DBCP) transport simulation of Pearl Harbor aquifer, Oahu, Hawaii—Multiple mixing-cell model, phase I: Honolulu, Hawaii, University of Hawaii at Manoa Water Resources Research Center Technical Report 174, 60 p.

80. Ishikawa, Scott, 2002, Honolulu settling water lawsuit: Honolulu Star-Advertiser, January 16, accessed March 7, 2014, at *http://www.croninfried.com/Articles/Honolulu-Settling-Water-Lawsuit.shtml*.

81. U.S. Environmental Protection Agency, 2000, Final closeout report—Schofield army barracks, Oahu, Hawaii: U.S. Environmental Protection Agency Superfund Records Center 3315–00044 DD40, 18 p. plus appendixes.

82. Harding Lawson Associates, 1995, Final sampling and analysis plan for operable unit 2 phase II remedial investigation, Schofield army barracks, Island of Oahu Hawaii: Aberdeen Proving Ground, Md., U.S. Army Environmental Center, [variously paged].

83. U.S. Census Bureau, 2008, Population estimates and projections: U.S. Census Bureau, accessed February 25, 2014, at *http://www.census.gov/popest/data/historical/index.html*.

84. Homer, C.H., Fry, J.A., and Barnes, C.A., 2012, The National Land Cover Database: U.S. Geological Survey Fact Sheet 2012–3020, 4 p. (Also available at *http://pubs.usgs.gov/fs/2012/3020/fs2012-3020.pdf*.)

85. Klasner, F.L., and Mikami, C.D., 2003, Land use on the island of Oahu, Hawaii, 1998: U.S. Geological Survey Water-Resources Investigations Report 02–4301, 20 p., accessed August 14, 2013, at *http://pubs.usgs.gov/wri/wri024301/*.

86. Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and Eastern Oregon: U.S. Geological Survey Professional Paper 1408–B, 32 p. and 6 plates.

87. Lindholm, G.F., and Vaccaro, J.J., 1988, Region 2—Columbia lava plateau, *in* Back, W., Rosenshein, J.S., and Seabar, P.R., eds., Hydrogeology, v. O–2 *of* Geology of North America: Boulder, Colo., Geological Society of America Decade of North American Geology, p. 37–50.

88. Garabedian, S.P., 1992, Hydrology and digital simulation of the regional aquifer system, eastern Snake River Plain, Idaho: Hydrology and digital simulation of the regional aquifer system, eastern Snake River Plain, Idaho Professional Paper 1408F, 102 p., 10 pls., accessed July 18, 2013, at *http://pubs.er.usgs.gov/publication/pp1408F*.

89. Otton, J.K., Gundersen, L.C.S., and Schumann, R.R., 1993, The geology of radon: U.S. Geological Survey General Interest Publication, 29 p.

90. College of Tropical Agriculture and Human Resources, 1999, Hawaii's termites—An identification guide: Honolulu, Hawaii, University of Hawaii at Manoa Household and Structural Pests HSP–1, 6 p., accessed October 25, 2012, at *http://www2.hawaii.edu/~entomol/pdf_files/hsp-1.pdf*.

91. U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations book 9, chaps. A1–A9, [variously paged], accessed June 11, 2013, at *http://pubs.water.usgs.gov/twri9A*.

92. U.S. Environmental Protection Agency, 1994, Evaluating and identifying contaminants of concern for human health: U.S. Environmental Protection Agency Region 8 Superfund Technical Guidance RA–03, 10 p., accessed September 23, 2013, at *http://www2.epa.gov/sites/production/files/documents/r8_ra03-cocs.pdf*.

93. Nolan, B.T., and Hitt, K.J., 2003, Nutrients in shallow ground waters beneath relatively undeveloped areas in the conterminous United States: U.S. Geological Survey Water-Resources Investigations Report 2002–4289, 17 p., accessed August 14, 2013, at *http://pubs.usgs.gov/wri/wri024289/*.

94. Toccalino, P.L., 2007, Development and application of health-based screening levels for use in water-quality assessments: U.S. Geological Survey Scientific Investigations Report 2007–5106, 12 p. (Also available at *http://pubs.usgs.gov/sir/2007/5106/*.)

95. U.S. Environmental Protection Agency, 2011, 2011 edition of the drinking water standards and health advisories: U.S. Environmental Protection Agency Office of Water EPA 822–R–11–002, 12 p., accessed August 12, 2013, at *http://water.epa.gov/action/advisories/drinking/upload/dwstandards2011.pdf*.

96. Toccalino, P.L., Norman, J.E., Booth, N.L., Thompson, J.L., and Zogorski, J.S., 2012, Health-based screening levels—Benchmarks for evaluating water-quality data: U.S. Geological Survey Web site, accessed April 24, 2013, at *http://water.usgs.gov/nawqa/HBSL/*.

97. DeSimone, L.A., McMahon, P.B., and Rosen, M.R., 2014, The quality of our Nation's waters—Summary of water quality in Principal Aquifers of the United States, 1991–2010: U.S. Geological Survey Circular 1360, 151 p. (Also available at *http://dx.doi.org/10.3133/cir1360*.)

98. Toccalino, P.L., Norman, J.E., Phillips, R.H., Kauffman, L.J., Stackelberg, P.E., Nowell, L.H., Krietzman, S.J., and Post, G.B., 2004, Application of health-based screening levels to ground-water quality data in a state-scale pilot effort: U.S. Geological Survey Scientific Investigations Report 2004–5174, 64 p. (Also available at *http://pubs.usgs.gov/sir/2004/5174/*.)

99. U.S. Environmental Protection Agency, [undated], Secondary drinking water regulations—Guidance for nuisance chemicals: U.S. Environmental Protection Agency 816–F–10–079, accessed April 24, 2013, at *http://water.epa.gov/drink/contaminants/secondarystandards.cfm*.

100. New Jersey Department of Environmental Protection, 2003, Susceptibility of source water to community water-supply wells in New Jersey to contamination by volatile organic compounds: New Jersey Department of Environmental Protection, 21 p. (Also available at *http://www.state.nj.us/dep/swap/reports/gw_voc.pdf*.)

Photograph by Michael G. Rupert, USGS

View of the Grand Teton, Jackson valley study area.

Glossary

A

agronomic rate An application rate of nutrients that matches the annual requirements of a specific crop. Nutrients (including nitrogen and phosphorous) applied to a crop in excess of the agronomic rate can leach down to the groundwater.

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

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

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

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

B

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

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

breakdown product A compound derived by chemical, biological, or physical action upon a pesticide. The breakdown is a natural process that may result in a more toxic or less toxic compound and a more persistent or less persistent compound.

C

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

confining layer Geologic material with little or no permeability or hydraulic conductivity. Water does not pass through this layer or the rate of movement is extremely slow.

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

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

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

D

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

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

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

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

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

E

eutrophication The enrichment of water by nutrients, most commonly phosphorus and nitrogen. During eutrophication, respiration processes that use organic matter cause a marked decline in dissolved-oxygen concentrations of water.

F

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

fumigant A pesticide in the volatile organic compound (VOC) chemical class that is applied to soils to reduce populations of plant parasitic nematodes (harmful root-worms), weeds, fungal pathogens, and other soil-borne microorganisms.

G

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

groundwater age *See* apparent groundwater age.

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

groundwater flow path *See* flow path.

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

groundwater sustainability The amount of groundwater that will be available to support future uses of a particular aquifer or groundwater resource. The development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

H

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

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

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

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

hydraulic conductivity The volume of water that will move in a porous medium in a given amount of time under a given hydraulic gradient through a given area measured at right angles to the direction of flow. A measure of the ease with which a fluid moves through a porous or fractured material.

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

hydrologic system The assemblage of pathways by which water travels as it circulates beneath, at, and above the Earth's surface during precipitation, runoff, evaporation, infiltration, transpiration, and groundwater discharge.

I

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

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

irrigation recharge layer A layer of poor-quality groundwater (resulting from irrigation return flow) that overlies better-quality groundwater recharged under background conditions from distant sources.

irrigation return flow The part of irrigation water applied to the surface that is not taken up by plants or lost by evaporation and that migrates to an aquifer or surface-water body.

L

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

leaching The removal of materials in solution from soil or rock to groundwater; refers to movement of pesticides or nutrients from land surface to groundwater.

legume A member of the large plant family Leguminosae, many of which harbor nitrogen-fixing bacteria on their roots, and many of which contain edible parts. Beans, alfalfa, and mesquite are examples of legumes.

M

major aquifer A regionally extensive subsurface geologic formation or group of formations that is used, or has the potential to be used, as a substantial groundwater resource.

major aquifer study 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.

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

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

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

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

N

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

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.

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

O

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

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

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

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

P

perched groundwater Unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone.

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

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

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

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

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

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

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

R

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

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

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

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

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

S

saprolite A soft, earthy, thoroughly decomposed rock, typically clay-rich, occurring in the lowest zone of the soil profile and resulting from the deep weathering of the bedrock surface.

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

saturated zone The region in the subsurface in which all the spaces (pores and fractures) are filled with water and are under pressure greater than atmospheric pressure.

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. Sandstone and limestone are examples of sedimentary rocks.

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

Study Unit A major hydrologic system of the United States, geographically defined by surface- or groundwater features, in which U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program sampling studies are focused.

susceptibility *See* intrinsic susceptibility.

T

trace element An element found in only minor amounts (concentrations less than 1 milligram per liter) in water or sediment; includes arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc.

U

unconfined aquifer An aquifer that has a water table; an aquifer containing unconfined groundwater.

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

unsaturated zone A subsurface zone containing both water and air. The unsaturated zone is limited above by the land surface and below by the water table.

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.

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

W

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

Y

young groundwater Groundwater that was recharged since the mid-1950s, as indicated by tritium concentrations in groundwater greater than 0.5 tritium unit.

A basaltic-rock aquifer is actively being formed during a December 2011 eruption by the Kilauea Volcano, Hawaii Volcanoes National Park, Hawaii.

Photograph by Alan M. Cressler, USGS

Appendix 1. NAWQA Groundwater Sampling Networks in the Columbia Plateau, Snake River Plain, and Oahu Aquifers

How does land use affect groundwater quality? How does water quality change as it moves through an aquifer? What is the quality of the drinking-water resource? NAWQA groundwater assessments include different types of studies, specifically designed to answer questions such as these.

- Land-use studies sampled water from water-table monitoring wells and (or) domestic wells installed in agricultural lands to assess the effects of agricultural land use on the quality of the underlying groundwater.
- Major aquifer studies provide a broad overview of the quality of the aquifer system used for drinking-water supply. Most of the wells sampled were domestic or public-supply wells that were distributed across a large area in a mixture of land uses.
- Special studies were designed to assess groundwater quality in particular areas of concern, or to sample for particular constituents of concern using laboratory methods that report concentrations much lower than standard laboratory methods.

Each study sampled water from a network of 10 to as many as 65 wells. Results of these studies were reinforced by locating some of the studies within the boundaries of larger studies. For example, the area sampled by the special studies was within the area sampled by the land-use studies, which in turn was within the area sampled by the major aquifer studies.

Table A1–1. NAWQA groundwater sampling studies conducted in the Columbia Plateau and Snake River Plain and on Oahu.

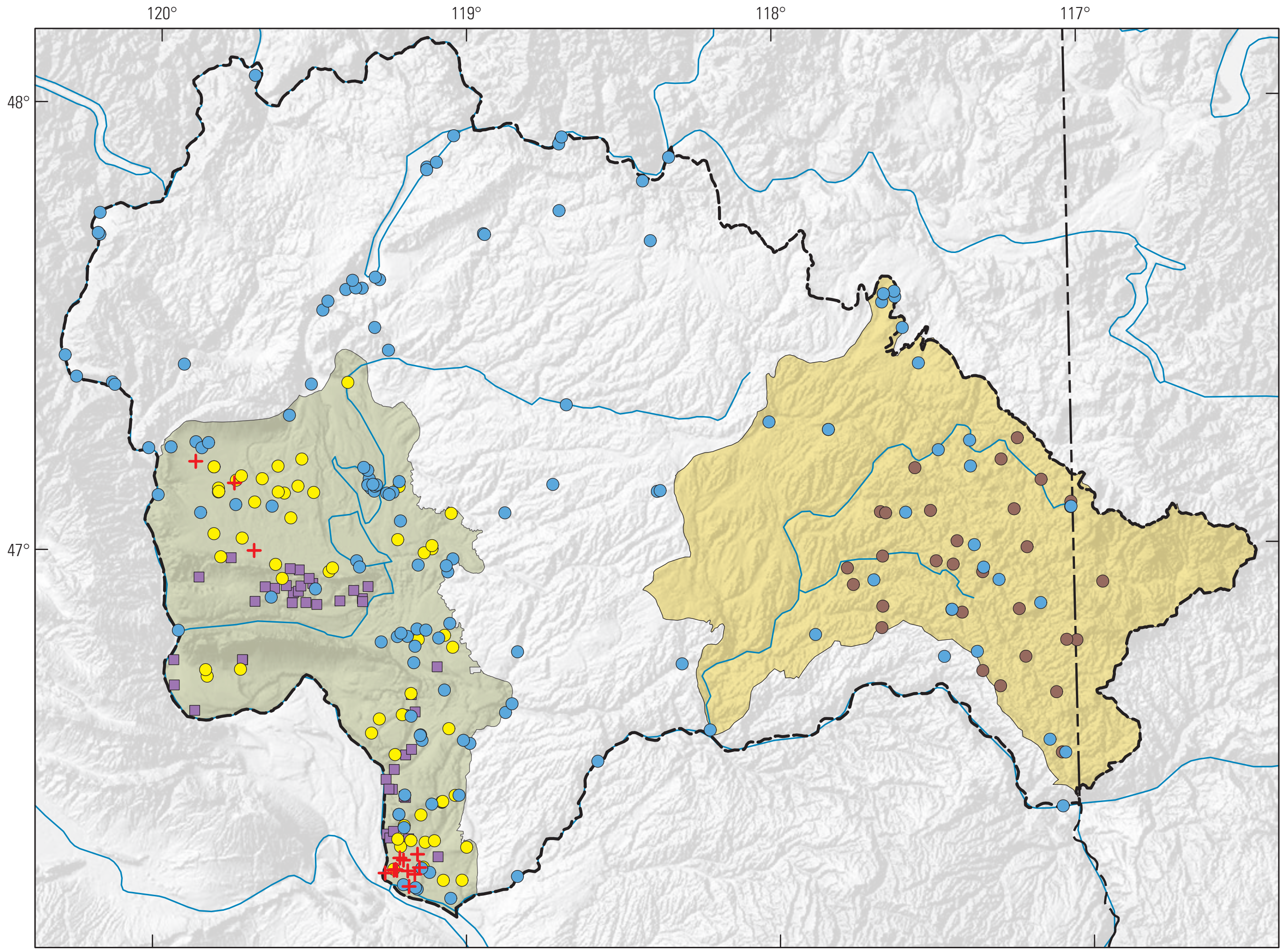
[*, resampled in NAWQA Cycle II; —, not applicable or data insufficient to compute value; Abbreviations: DOH, Department of Health; EDB, ethylene dibromide; DBCP, dibromochloropropane; mg/L, milligrams per liter; CFC, chlorofluorocarbon; SF_6, sulfur hexafluoride; ccpt, Central Columbia Plateau; usnk, Upper Snake River Basin; lus; land-use study; sus, study-unit (major aquifer) survey; spc, special study; the first four letters in the NAWQA groundwater study name abbreviation indicate the study area, the next three letters indicate if the network is a lus, sus, or spc, and the remaining letters are unique identifiers]

Groundwater study name used in this report	NAWQA well network type	What data were collected and why	NAWQA groundwater study name abbreviation	Type of sites sampled
		Columbia Plateau, Washington		
Columbia public supply*	Major aquifer study	Occurrence and distribution of chemicals in major aquifers. Major ions, nutrients, 85 pesticides, 60 volatile organic compounds, dissolved organic carbon, and radon. USGS collected, randomly selected wells.	ccptsus1b*	Public-supply wells
		Estimate risks of pesticide detection. Data included 47 pesticides. DOH collected pesticide kit. These well networks were not sampled for nitrate.	ccptsus1a	Public-supply wells
			ccptsus1c	Public-supply wells with nitrate concentrations greater than 2 mg/L
Palouse area	Agricultural land-use study—dryland grains	Describe effects of agricultural land use on shallow groundwater in the Palouse subunit. Data included major ions, nutrients, 85 pesticides, 60 volatile organic compounds, dissolved organic carbon, and radon. Wells were generally next to fields in the road right-of-way.	ccptlusag1a	Shallow domestic wells
			ccptlusag1b	Very shallow monitoring wells
Quincy-Pasco row crops*	Agricultural land-use study—irrigated row crops	Describe effects of agricultural land use on shallow groundwater in the Quincy-Pasco subunit. Data same as above. Wells were generally within 100 feet of row-cropped fields.	ccptlusag2a	Shallow domestic wells
			ccptlusag2b*	Very shallow monitoring wells
Quincy-Pasco orchards*	Agricultural land-use study—orchards	Describe effects of agricultural land use on shallow ground-water in the Quincy-Pasco subunit. Data same as above. Wells were generally within 100 feet of orchards/vineyards.	ccptlusor1a	Shallow domestic wells
			ccptlusor1b*	Very shallow monitoring wells
Quincy-Pasco fumigant study	Special study—EDB synoptic	Fumigants EDB and DBCP at low reporting levels.	ccptspcb2	Shallow domestic wells
		Snake River Plain and Upper Snake River Basin, Idaho and Wyoming		
Snake River Plain	Major aquifer study	Occurrence and distribution of chemicals in major aquifers. Major ions, nutrients, 87 pesticides, volatile organic compounds, and radon. Data collected in cooperation with the Idaho Statewide Ground-Water Monitoring Program.	usnksus1	Domestic wells
Tributary valleys			usnksus2	Domestic wells
Jackson valley			usnksus3	Domestic and public-supply wells
Minidoka area	Agricultural land-use study—irrigated row crops	Major ions, nutrients, 87 pesticides, volatile organic compounds, and radon. Data collected in cooperation with the Idaho Statewide Ground-Water Monitoring Program.	usnkluscr1	Domestic wells
A&B area*			usnkluscr2	Domestic wells
Jerome/Gooding area*			usnkluscr3	Domestic wells
Eden area			usnkluscr4	Domestic wells
		Oahu, Hawaii		
Oahu public supply	Major aquifer study	Occurrence and distribution of chemicals in major aquifers. Major ions, nutrients, trace elements, 87 pesticides, volatile organic compounds, and radon. CFC and tritium-helium dates.	oahusus1	Public-supply wells
Oahu, ground-water near water table	Special study—young ground-water in irrigation-recharge layer	Occurrence and distribution of chemicals in irrigation-recharge layer near the water table. Major ions, nutrients, trace elements, 87 pesticides, and volatile organic compounds. CFC, SF_6, and tritium-helium dates.	oahuspcg1	Monitoring wells

Table A1–1. NAWQA groundwater sampling studies conducted in the Columbia Plateau and Snake River Plain and on Oahu.—Continued

[*, resampled in NAWQA Cycle II; —, not applicable or data insufficient to compute value; Abbreviations: DOH, Department of Health; EDB, ethylene dibromide; DBCP, dibromochloropropane; mg/L, milligrams per liter; CFC, chlorofluorocarbon; SF_6, sulfur hexafluoride; ccpt, Central Columbia Plateau; usnk, Upper Snake River Basin; lus; land-use study; sus, study-unit (major aquifer) survey; spc, special study; the first four letters in the NAWQA groundwater study name abbreviation indicate the study area, the next three letters indicate if the network is a lus, sus, or spc, and the remaining letters are unique identifiers]

Groundwater study name used in this report	Number of sites	Aquifer lithology	Median well depth (feet)	Median depth to water (feet)	Sampling frequency	Predominant land use or crop type
Columbia Plateau, Washington						
Columbia public supply*	43	Basalt	175	—	Once in 1994; resampled in 2002	Mixed: agriculture, rangeland, and urban
	65	Basalt	200	—	Once in 1994	
	31	Basalt	185	—	Once in 1994	
Palouse area	18	Basalt	102	—	Once in 1993–94	Agriculture (mostly wheat and small grains)
	10	Loess (silt)	37	14	Once in 1993–94	
Quincy-Pasco row crops*	30	Sand, gravel, basalt	134	—	Once in 1993–95	Agriculture (mostly potatoes and corn)
	19	Sand, gravel	38	17	Once in 1993–95; resampled in 2002	
Quincy-Pasco orchards*	18	Sand, gravel, basalt	165	55	Once in 1994–95	Agriculture (orchards and vineyards)
	22	Sand, gravel	29	13	Once in 1994–95; resampled in 2002	
Quincy-Pasco fumigant study	11	Sand, gravel	—	—	Once in 1994	Agriculture (including potatoes in rotation)
Snake River Plain and Upper Snake River Basin, Idaho and Wyoming						
Snake River Plain	43	Basalt	260	—	Once in 1994	Mixed: agriculture and rangeland
Tributary valleys	38	Alluvium	204	—	Once in 1995	Mixed: agriculture and rangeland
Jackson valley	20	Alluvium	101	7	Once in 1995	Mixed: forest and rangeland
Minidoka area	29	Sand, gravel	34	8	Once in 1993	Agriculture (mixed crops)
A&B area*	31	Basalt	228	178	Once in 1993; resampled in 2005	Agriculture (mixed crops)
Jerome/Gooding area*	30	Basalt	200	149	Once in 1994; resampled in 2005	Agriculture (mixed crops)
Eden area	15	Basalt	360	292	Once in 1995	Agriculture (mixed crops)
Oahu, Hawaii						
Oahu public supply	30	Basalt	512	320	Once in 2000	Mixed: forest, urban, and agriculture (sugarcane, pineapple, mixed crops)
Oahu, ground-water near water table	15	Basalt	693	339	Once in 2001	Mixed: forest, urban, and agriculture (sugarcane, pineapple, mixed crops)



Base modified from U.S. Geological Survey 1:2,000,000-scale digital data (2005), NAD 83 datum
Albers Equal Area Conic projection, standard parallels 29°30'N and 45°30'N, central meridian 119°W

0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS

EXPLANATION

Palouse area, agricultural lands—Dryland grains (ccptlusag1, see table A1–1)

Quincy-Pasco area, agricultural lands—Irrigated row crops (ccptlusag2) and orchards (ccptlusor1)

NAWQA Central Columbia Plateau study area—Columbia public supply, mixed land uses (the entire Central Columbia Plateau study area (ccptsus1))

Well sampling groundwater underlying

Mixed land uses, public-supply wells (ccptsus1)

Agricultural lands, Palouse area, domestic wells (ccptlusag1a) and monitoring wells (ccptlusag1b)

Agricultural lands, Quincy-Pasco row crops, domestic wells (ccptlusag2a) and monitoring wells (ccptlusag2b)

Agricultural lands, Quincy-Pasco orchards, domestic wells (ccptlusor1a) and monitoring wells (ccptlusor1b)

Agricultural lands, Quincy-Pasco fumigant study, domestic wells (ccptspcb2)

Figure A1–1. Location of all sampled wells in the Columbia Plateau.

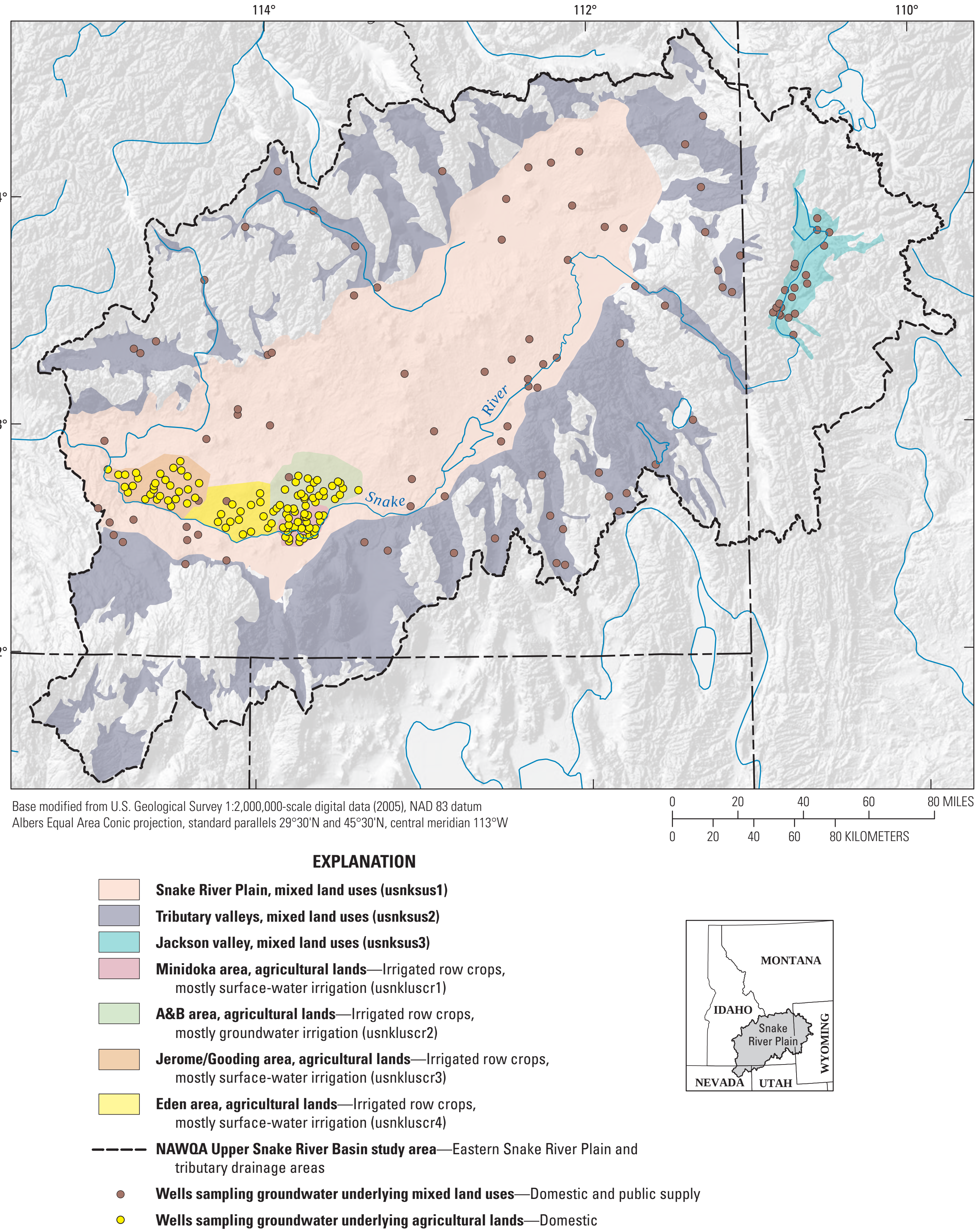


Figure A1–2. Location of all sampled wells in the Snake River Plain.

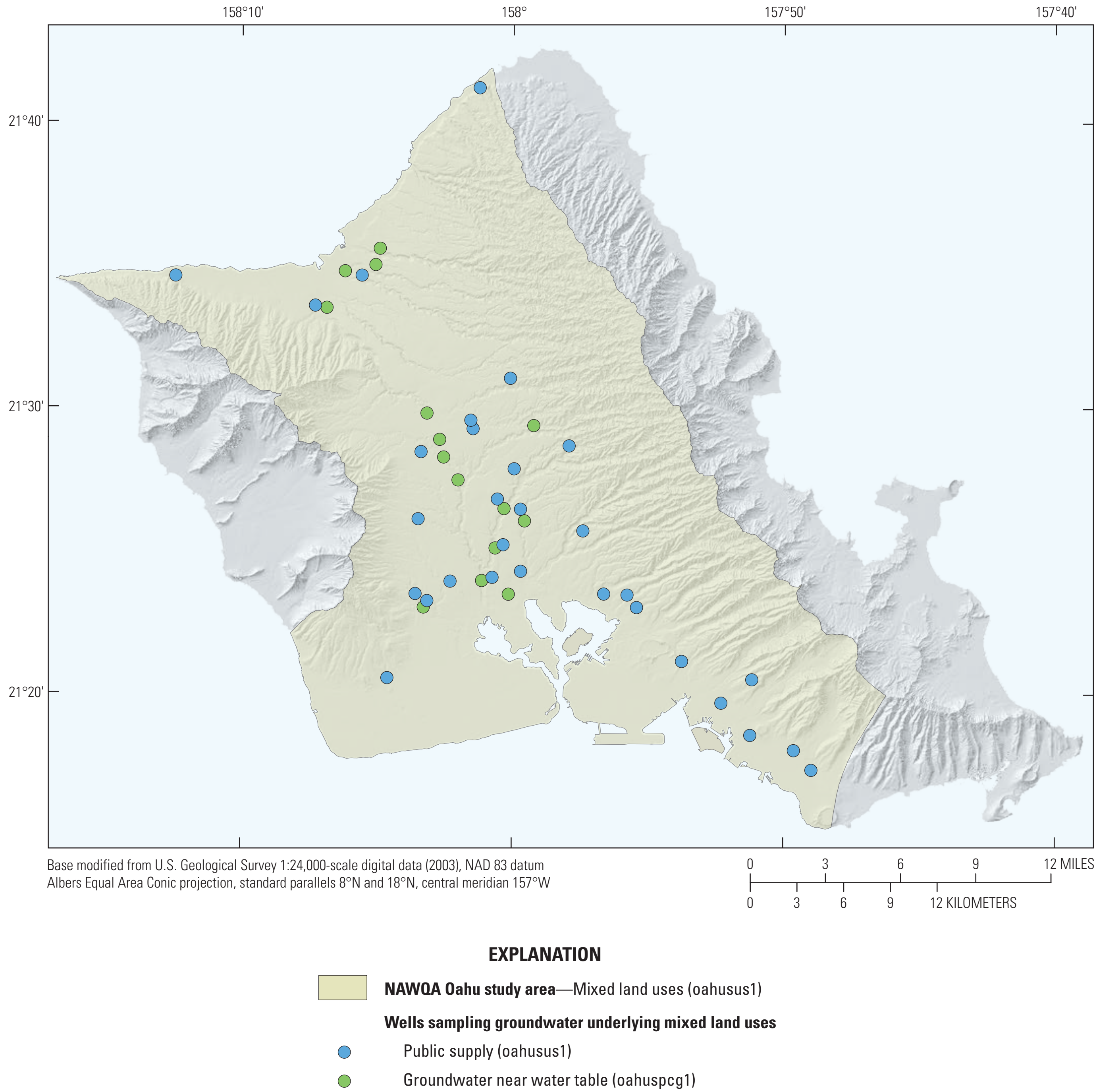


Figure A1–3. Location of all sampled wells on Oahu.

Appendix 2. Groundwater-Quality Properties and Constituents Measured, a Summary of Data, and Complete Data Archive for 1993–2005

Groundwater-quality properties and constituents measured and a summary of data for 1993–2005, including laboratory reporting levels and human-health benchmarks for drinking water, are presented only online. The data summary and a complete data archive are available for download at *http://pubs.usgs.gov/circ/1359/*.

Appendix 3. Groundwater Quality of the Columbia Plateau, Snake River Plain, and Oahu Aquifers in a National Context

Principal Aquifer (number of samples)

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

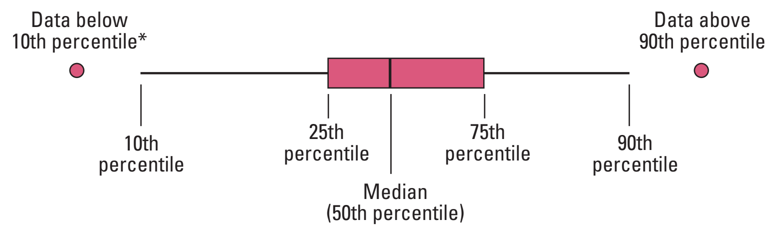
U.S. Environmental Protection Agency contaminant levels for drinking water

- - - - - 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.

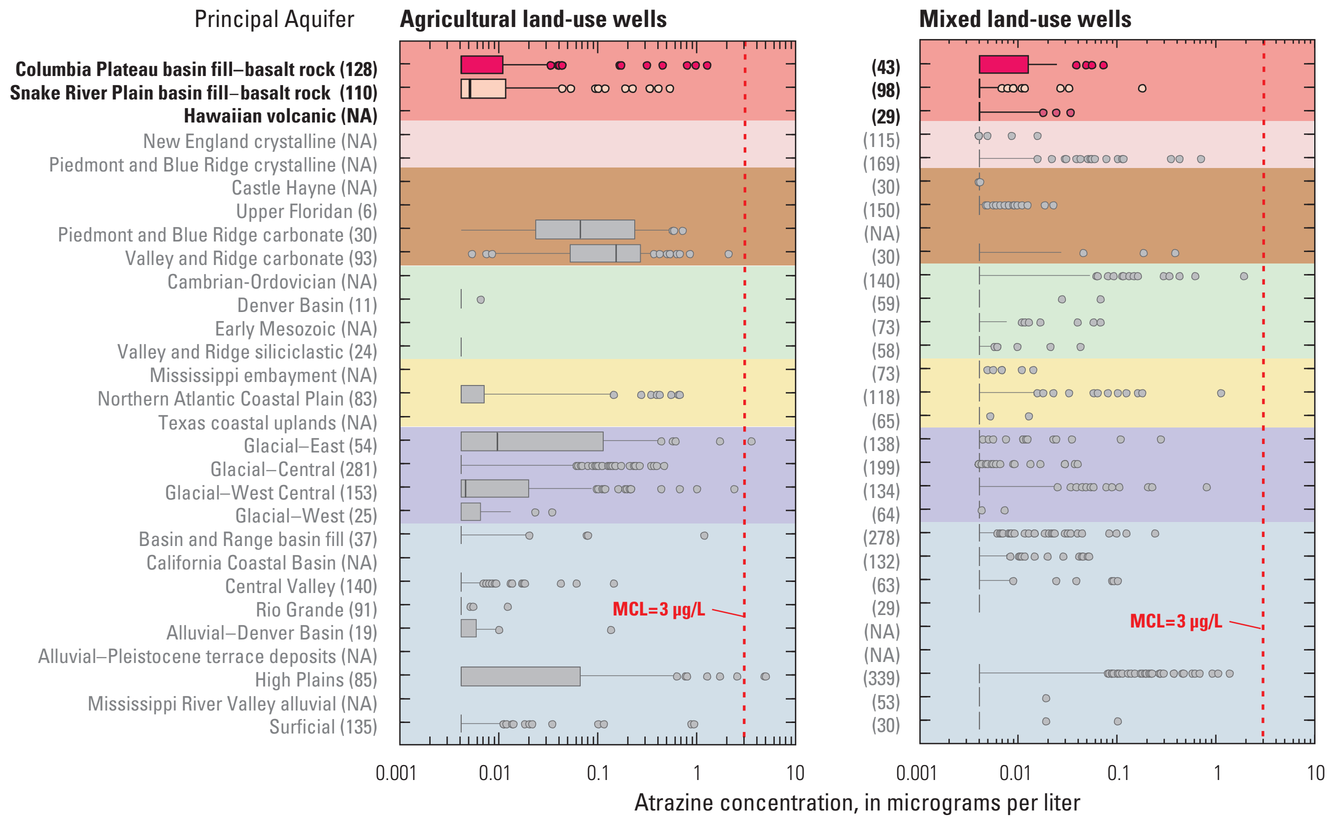
Lithology

Basalt and volcanics** | Crystalline | Carbonate | Sandstone | Semiconsolidated sand and gravel | Glacial unconsolidated sand and gravel | Unconsolidated sand and gravel (nonglacial)

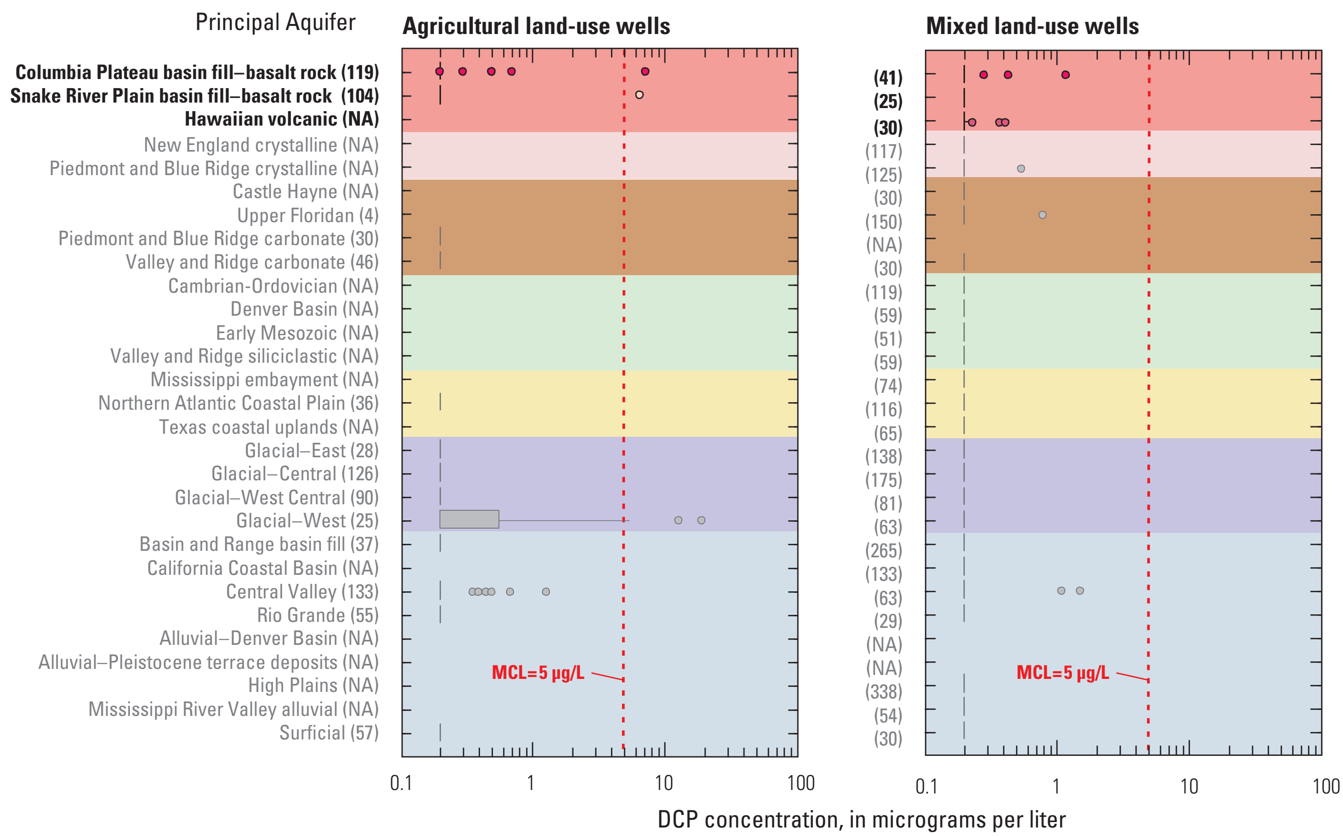
This appendix shows graphical comparisons of chemical concentrations (1991 to 2010) for atrazine, 1,2-dichloropropane (DCP), and nitrate in groundwater in selected Principal Aquifers of the United States. For each constituent, the concentration data are grouped according to two land uses: agricultural land use and mixed land uses. For each land use, the aquifers also are grouped according to aquifer lithology: basalt and volcanics,** crystalline, carbonate, sandstone, semiconsolidated sand and gravel, glacial unconsolidated sand and gravel, and unconsolidated sand and gravel (nonglacial). Data for a particular compound were not plotted if there were fewer than 10 samples for a particular well network in a Principal Aquifer; not all Principal Aquifers for which data were available are shown. Note that analytical detection limits varied among the constituents and that the number of samples for a constituent can vary greatly between Principal Aquifers. The data used in this appendix and boxplots for additional constituents are available at *http://pubs.usgs.gov/circ/1360/*.

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

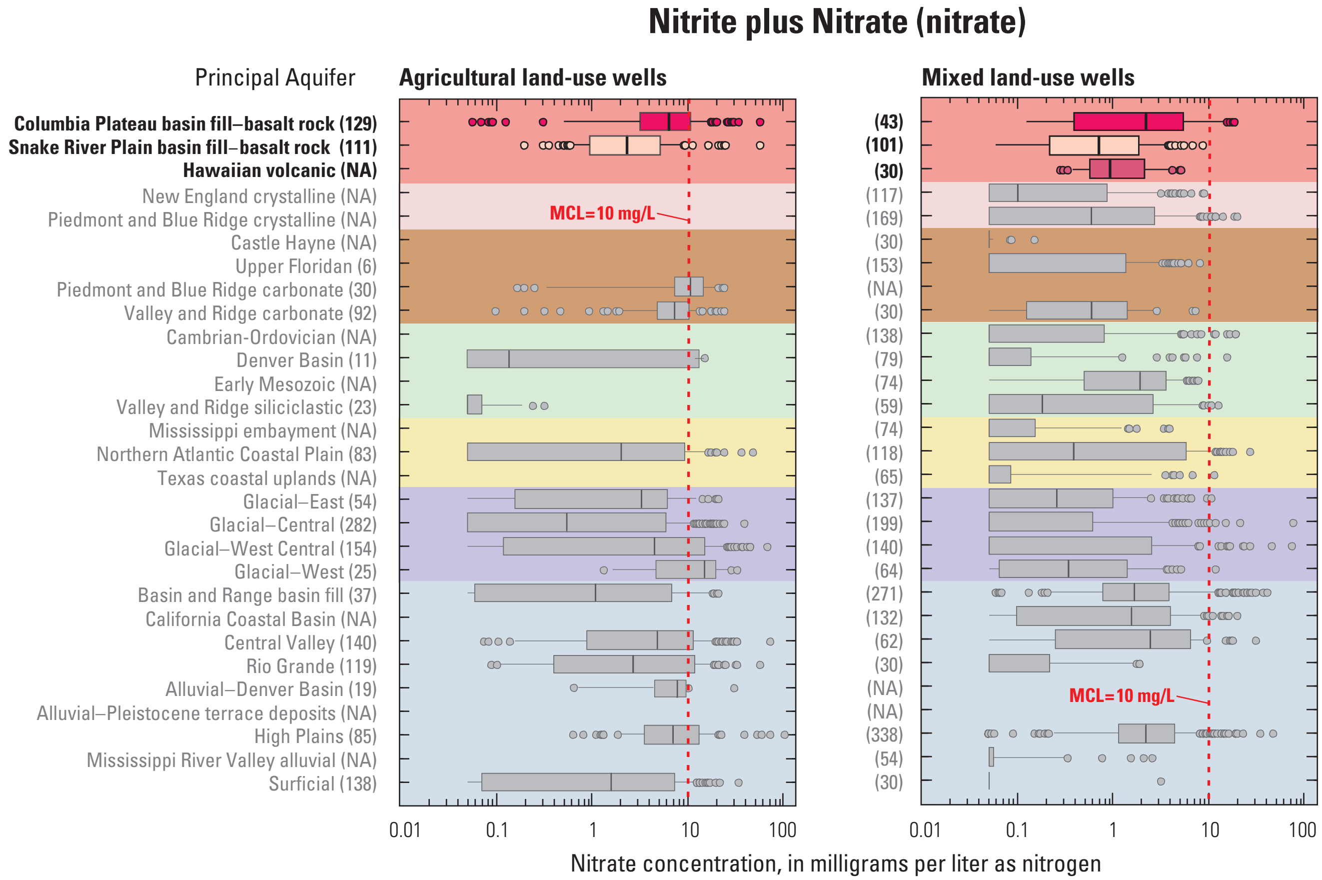
Atrazine



1,2-dichloropropane (DCP)

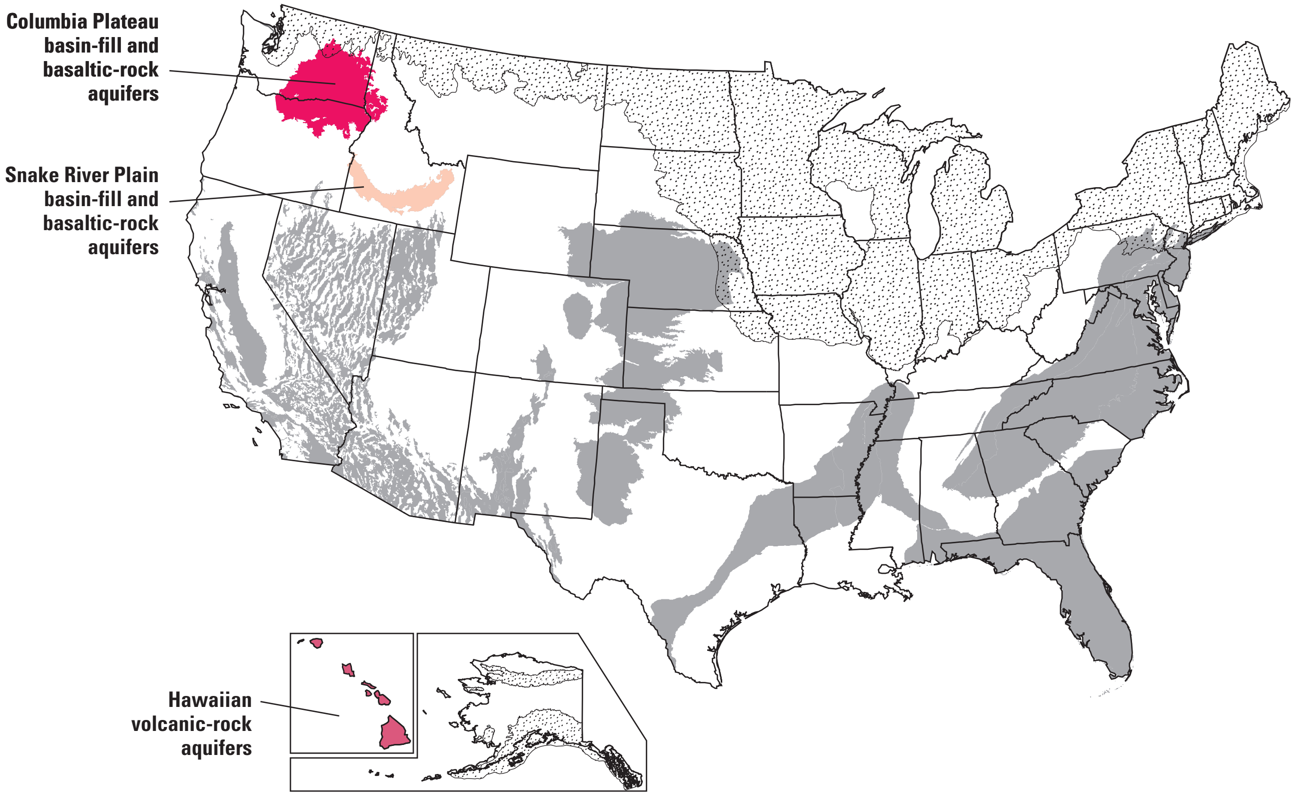


Appendixes


Nitrite plus Nitrate (nitrate)
Principal Aquifer
Agricultural land-use wells
Mixed land-use wells
Columbia Plateau basin fill–basalt rock (129)
Snake River Plain basin fill–basalt rock (111)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (NA)
Castle Hayne (NA)
Upper Floridan (6)
Piedmont and Blue Ridge carbonate (30)
Valley and Ridge carbonate (92)
Cambrian-Ordovician (NA)
Denver Basin (11)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (23)
Mississippi embayment (NA)
Northern Atlantic Coastal Plain (83)
Texas coastal uplands (NA)
Glacial–East (54)
Glacial–Central (282)
Glacial–West Central (154)
Glacial–West (25)
Basin and Range basin fill (37)
California Coastal Basin (NA)
Central Valley (140)
Rio Grande (119)
Alluvial–Denver Basin (19)
Alluvial–Pleistocene terrace deposits (NA)
High Plains (85)
Mississippi River Valley alluvial (NA)
Surficial (138)
(43)
(101)
(30)
(117)
(169)
(30)
(153)
(NA)
(30)
(138)
(79)
(74)
(59)
(74)
(118)
(65)
(137)
(199)
(140)
(64)
(271)
(132)
(62)
(30)
(NA)
(NA)
(338)
(54)
(30)
MCL=10 mg/L
MCL=10 mg/L
0.01
0.1
1
10
100
0.01
0.1
1
10
100
Nitrate concentration, in milligrams per liter as nitrogen

Prepared by the USGS Science Publishing Network
Publishing Service Centers
Edited by Kay P. Naugle, Raleigh
Illustrations by Luis E. Menoyo, Tacoma
and Caryl J. Wipperfurth, Raleigh
Layout by Caryl J. Wipperfurth

For more information concerning this report, contact:
Chief, National Water-Quality Assessment Program
U.S. Geological Survey
413 National Center
12201 Sunrise Valley Drive
Reston, VA 20192
http://water.usgs.gov/nawqa/



ISBN 978-1-4113-3757-2
ISSN 1067-084X (print)
ISSN 2330-5703 (online)
http://dx.doi.org/10.3133/cir1359