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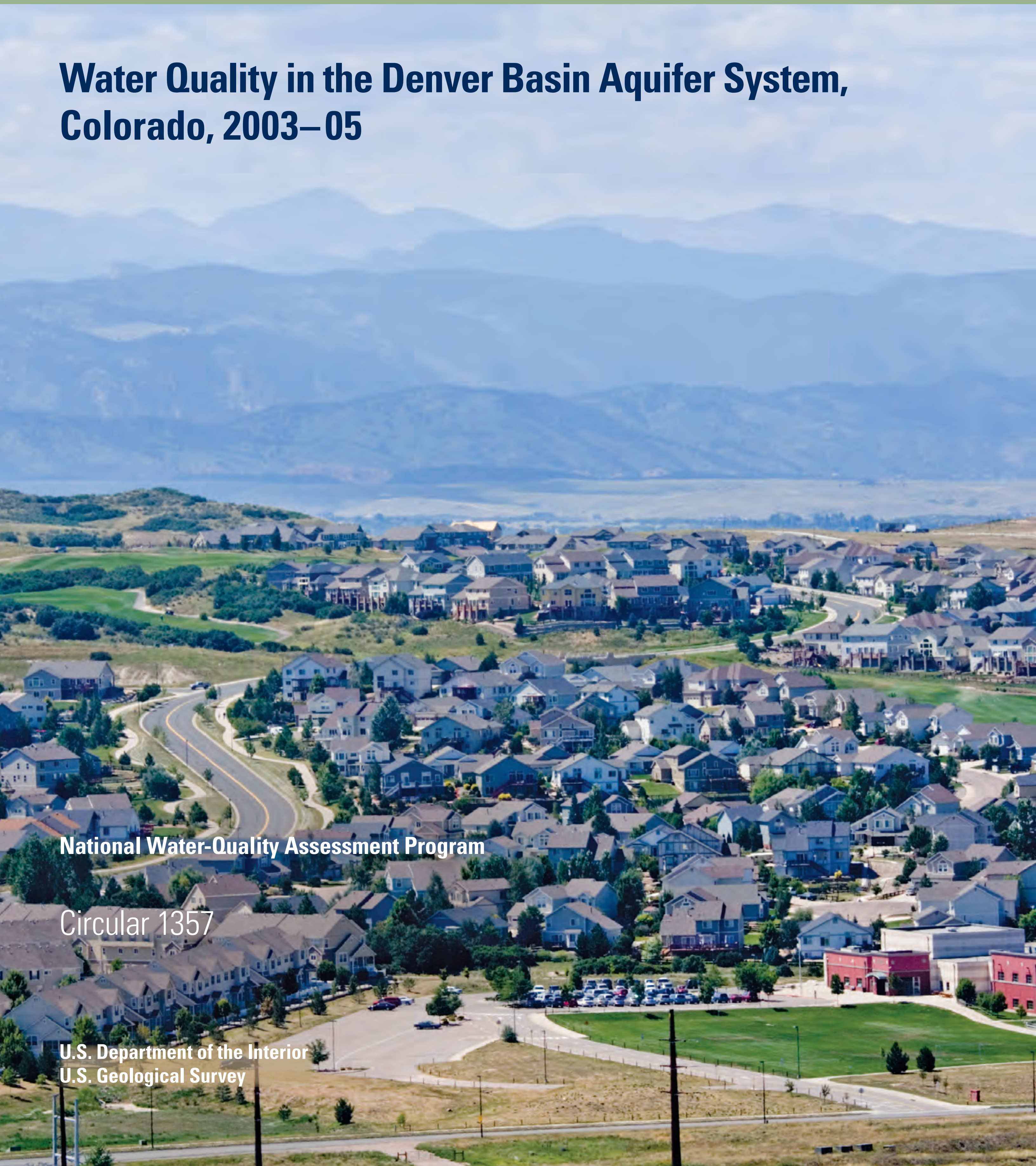
The Quality of Our Nation's Waters

Water Quality in the Denver Basin Aquifer System, Colorado, 2003–05



National Water-Quality Assessment Program

Circular 1357

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

Cover. View of Castle Rock, Colorado, with the Rocky Mountains to the west (photograph by Steve Krull, copyright istockphoto.com).

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By Nancy J. Bauch, MaryLynn Musgrove, Barbara J. Mahler, and Suzanne S. Paschke

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U.S. Department of the Interior
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NAWQA

The National Water-Quality Assessment Program

"The USGS NAWQA Program provides the power of knowledge. Results of NAWQA studies are an invaluable resource for public health officials, water and land use planners, and the community that relies on Denver Basin groundwater as a vital source of drinking water."

Hope Dalton
Water Specialist
Tri-County Health Department
Greenwood Village

Foreword

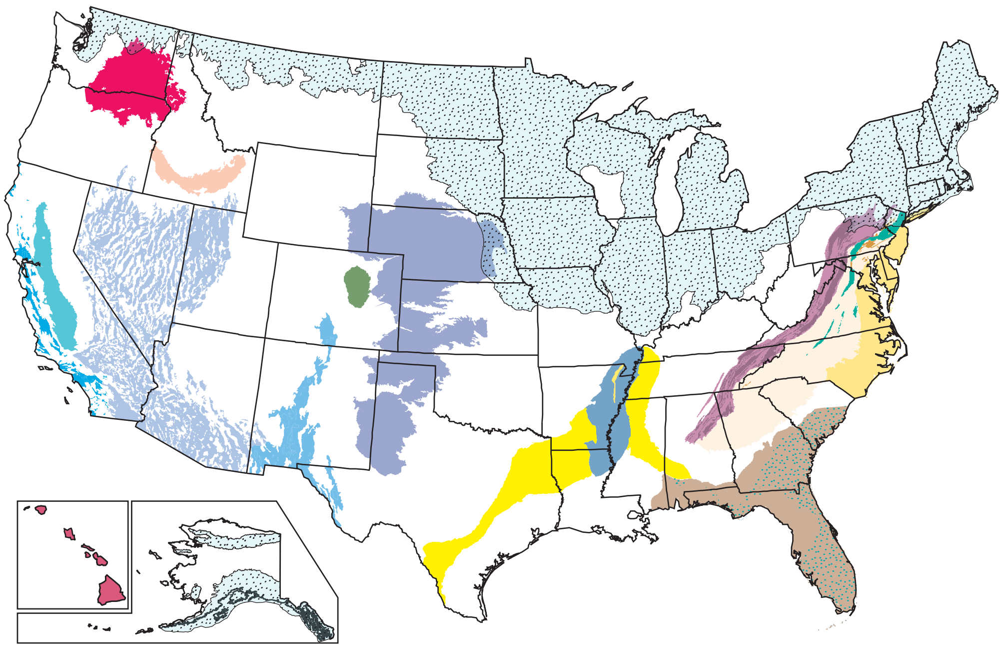
The United States has made major investments in assessing, managing, regulating, and conserving natural resources, such as water and a variety of ecosystems. Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources 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 water quality in the Denver Basin aquifer system. 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. Water-quality conditions in the Denver Basin aquifer system are compared to conditions found elsewhere and to selected national water-quality benchmarks, such as those for drinking water.

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 also will be useful for individuals who wish to know more about the quality of groundwater in areas near where they live and how that quality of water compares to the quality of water in other areas across the region and the Nation.

Water-quality conditions in the Denver Basin aquifer system summarized in this report are discussed in greater detail in other reports listed in the references. Detailed technical information, data and analyses, 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 Denver Basin aquifer system are discussed in the following reports:

Quality of Groundwater in the Denver Basin Aquifer System, Colorado, 2003–5

U.S. Geological Survey Scientific Investigations Report 2014–5051

By MaryLynn Musgrove, Jennifer A. Beck, Suzanne S. Paschke, Nancy J. Bauch, and Shana L. Mashburn

(Also available at *http://pubs.usgs.gov/sir/2014/5051/*)

Occurrence of Selected Organic Compounds in Groundwater Used for Public Supply in the Plio-Pleistocene Deposits Near East-Central Nebraska and the Dawson and Denver Aquifers Near Denver, Colorado, 2002–2004

U.S. Geological Survey Scientific Investigations Report 2008–5243

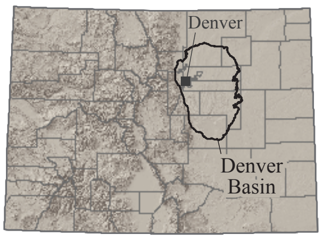
By Jeffrey B. Bails, Benjamin J. Dietsch, Matthew K. Landon, and Suzanne S. Paschke

(Also available at *http://pubs.usgs.gov/sir/2008/5243/*)

Photograph by Lynn Bashaw, used with permission

An April dusting of snow covers the south metropolitan area of Denver and the foothills of the Front Range of the Rocky Mountains at sunrise.

Chapter 1: *Overview of Major Findings and Implications*



Groundwater from the Denver Basin aquifer system is a critical water resource for the semiarid Front Range urban corridor of Colorado. Population in the Denver metropolitan area has more than doubled in the last 40 years as a result of Colorado's reputation for a high quality of life and favorable business climate.[(1)] Much of this growth has taken place in areas that rely primarily or solely on Denver Basin groundwater for supply. Pumping of groundwater from the Denver Basin bedrock aquifers has more than quadrupled since 1970,[(2)] and Denver Basin groundwater provides about 70 percent of the water supply in the south Denver metropolitan area.[(3)] Population in the Denver Basin study area is projected to continue to grow, particularly in areas that rely on groundwater for drinking water and other municipal, industrial, and domestic uses, further straining surface-water and groundwater resources.

Development of agricultural and urban areas has adversely affected groundwater quality in the alluvial aquifer and shallow bedrock aquifer system, but the quality of water produced by private (domestic) and public-supply wells completed in deeper parts of the Denver Basin aquifer system remains suitable for drinking. However, the presence of contaminants from human sources and other evidence of recently recharged water from the shallow system in some parts of the deeper aquifer system indicate that deeper groundwater may be vulnerable to contamination from the land surface as a result of high-volume pumping.

Water managers in the Denver Basin area are concerned primarily with the quantity of groundwater available for human use because high-volume pumping of deep parts of bedrock aquifers has caused water-level declines and removal of water from storage in some parts of the system. The concern is that the availability of groundwater is insufficient for meeting long-term demands. However, there also are concerns about the quality of Denver Basin groundwater, which could limit water availability in the future.

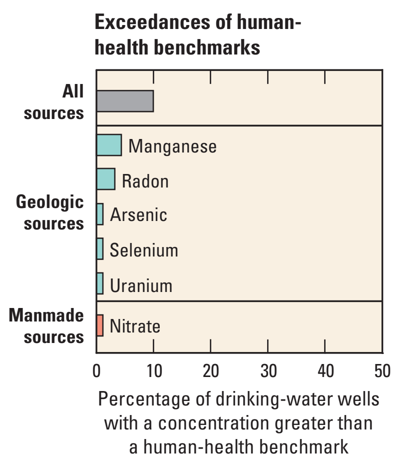
The conversion of undeveloped or rural land to agricultural and developed land in areas along the Front Range of the Rocky Mountains in Colorado has affected water quality in the Denver Basin aquifer system.

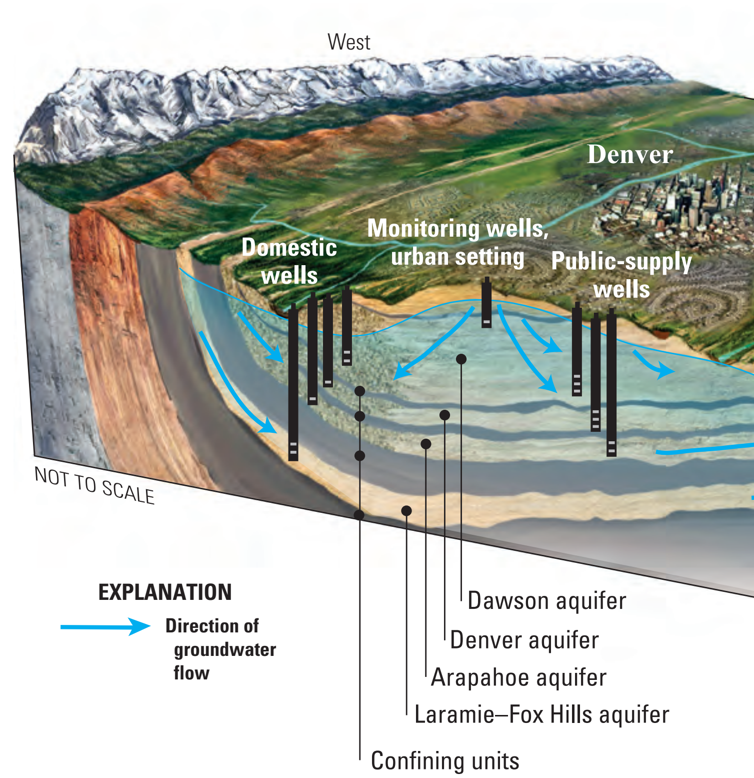
Overview of Major Findings and Implications for the Denver

Availability and sustainability of groundwater in the Denver Basin aquifer system depend on water quantity and water quality. The Denver Basin aquifer system underlies about 7,000 square miles of the Great Plains in eastern Colorado and is the primary or sole source of water for domestic and public supply in many areas of the basin. Use of groundwater from the Denver Basin sandstone aquifers has been instrumental for development of the south Denver metropolitan area and other areas, but has resulted in a decline in water levels in some parts of the system. Human activities in many areas have adversely affected the quality of water in the aquifer system, especially the shallow parts. Groundwater in deeper parts of the system used for drinking water, once considered isolated from the effects of overlying land use, is increasingly vulnerable to contamination from human activities and geologic materials. Availability and sustainability of high-quality groundwater for supply is vital for private well owners, water managers, and other stakeholders and is important for the economic health of the Denver Basin area.

1 The quality of groundwater used for drinking water generally is very good

Only 1 in 10 drinking-water wells had a contaminant detected at a concentration of potential human-health concern. Exceedances of human-health benchmarks in samples from wells used for drinking water were measured for just six constituents. Only benchmarks for manganese and radon were exceeded in more than one sample. Management practices that limit the migration of poor-quality shallow groundwater into deeper parts of the aquifer system where groundwater is used for drinking will help maintain the high quality of the drinking-water resource.





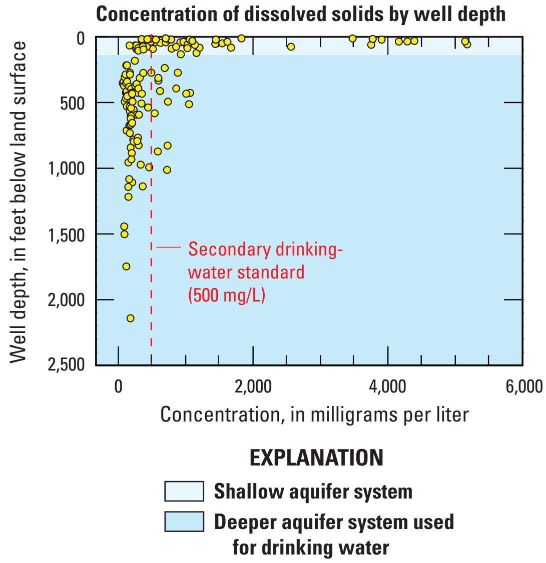
2 Most constituents at a concentration of concern for human health were from geologic sources

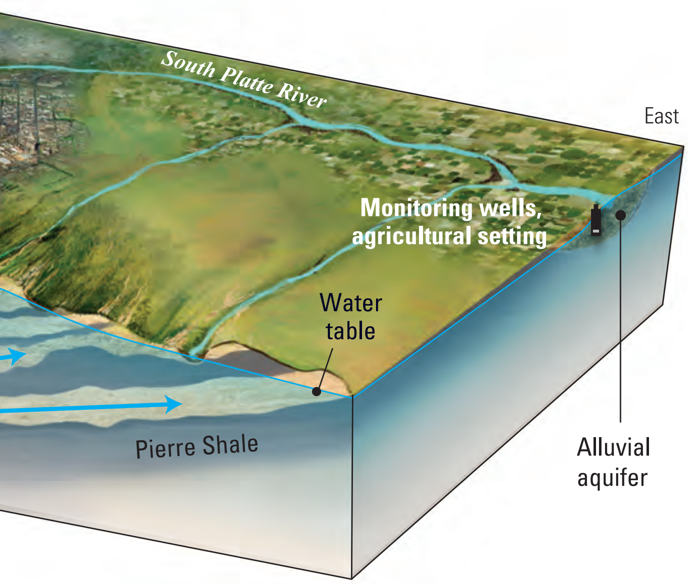
Five of the six contaminants with potential human-health concerns were from geologic sources. Granitic sediments in the Dawson Arkose, for example, shown at right, are a source of radon in the Dawson aquifer. Hydrologic and geochemical factors, such as groundwater age and dissolved oxygen content, and human activities affect the distribution of constituents of concern in Denver Basin groundwater.

Basin Aquifer System

3 Irrigation of agricultural and urban lands has adversely affected the quality of shallow groundwater

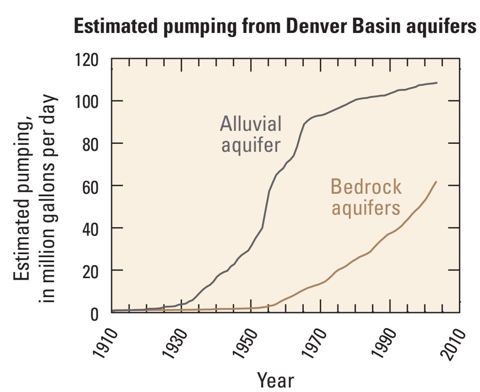
The interaction of infiltrating irrigation water with minerals in the subsurface increases the amount of dissolved constituents in water that recharges the shallow aquifer system. Concentrations of dissolved solids and dissolved constituents, such as nitrate, were greater in wells tapping shallow groundwater than those tapping deeper groundwater used for drinking. Shallow groundwater typically is not used as a drinking-water resource, but high concentrations of dissolved solids, nitrate, and other contaminants resulting from human activities on the land surface could limit even nonpotable uses of the resource.





4 High-volume pumping of groundwater can increase the vulnerability of the Denver Basin bedrock aquifers to contamination

Pumping of groundwater from the Denver Basin alluvial and sandstone bedrock aquifers has steadily increased since the 1930s and 1950s, mirroring increased production of irrigated crops in agricultural parts of the basin, residential growth in rural areas, and large increases in population in urban areas. One effect of higher pumping rates, as indicated by groundwater-flow models, chemistry, and groundwater-age tracers, is the potential for shallow groundwater of poor quality to migrate downward into deeper parts of bedrock aquifers that are tapped by domestic and public-supply wells, such as the one shown at the left.



Overview of Major Findings

Photographs from top to bottom: Steve Krull, copyright istockphoto.com; USGS; copyright istockphoto.com; USGS

1 The quality of groundwater used for drinking water generally is very good.

Contaminants were present at a concentration of potential concern for human health in water from only 10 percent of drinking-water wells sampled. Only two constituents—manganese and radon—were measured at a concentration that exceeded a human-health benchmark in more than one sample. These constituents, both from geologic sources, each exceeded their benchmark in less than 5 percent of samples from drinking-water wells. Human-health benchmarks for arsenic, nitrate, selenium, and uranium were exceeded in only one sample each. Manmade contaminants, such as pesticides and volatile organic compounds (VOCs), were detected in some samples from drinking-water wells but at low concentrations (near laboratory reporting levels).

The quality of the resource could be affected in the future by the downward movement of poor-quality shallow groundwater into the deeper parts of the aquifer system where groundwater is used for drinking. Management practices that limit this downward migration will help maintain drinking-water quality.

2 Most constituents at a concentration of concern for human health were from geologic sources.

Rocks and minerals in Denver Basin soils and aquifer sediments are natural geologic sources of arsenic, manganese, radon, selenium, and uranium—five of the six constituents detected at a concentration that exceeded a human-health benchmark in at least one sample from a drinking-water well. Other constituents from geologic sources, such as dissolved solids, fluoride, iron, manganese and sulfate, can affect the use of drinking water because they impair the taste or odor of the water or cause other non-health based concerns. Concentrations of these five constituents exceeded a non-regulatory and non-human health benchmark (called a Secondary Maximum Contaminant Level (SMCL) in almost half (42 percent) of the samples from drinking-water wells.

The sources and depositional environments of soils and aquifer sediments, groundwater-flow patterns, and groundwater age contribute to variations in the chemical composition of the Denver Basin groundwater. Chemical processes that typically occur in the Denver Basin aquifer system, such as precipitation/dissolution reactions, evaporative concentration, and oxidation/reduction, can increase concentrations of dissolved constituents in groundwater. Understanding how hydrologic and geochemical conditions affect groundwater quality and the effect that human activities have on groundwater quality can help identify which contaminants might affect the quality of current or future water supplies.

Water-Quality Issues for the Denver Basin Aquifer System

3 Irrigation of agricultural and urban lands has adversely affected the quality of shallow groundwater.

Irrigation in agricultural and urban areas of the semiarid Denver Basin has increased groundwater recharge. As irrigation water infiltrates the subsurface, the water reacts with minerals in soils and underlying aquifer sediments, increasing the amount of dissolved solids in water that recharges the shallow aquifer system. As a result, about two-thirds of the samples of shallow groundwater contained dissolved solids at a concentration that exceeded the SMCL. The interaction of dissolved oxygen in recharge water with uranium-rich sediments has released uranium to shallow groundwater at levels that exceeded the human-health benchmark in about 27 percent of the samples from shallow groundwater. Fertilizers and pesticides that are applied to the land surface and VOCs that are generated from human activities also are transported by irrigation recharge water to shallow groundwater.

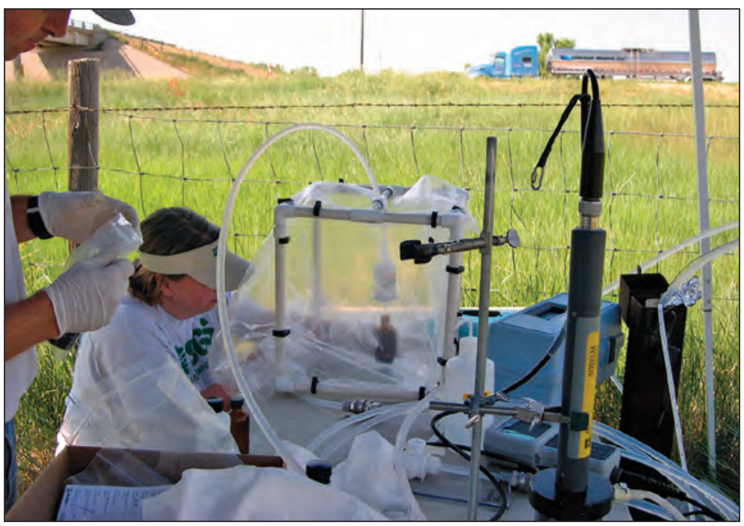
Although the shallow aquifer system typically is not used as a source of drinking water, high concentrations of dissolved solids and dissolved constituents in shallow groundwater could limit even nonpotable uses of the water, such as for irrigation.

4 High-volume pumping of groundwater can increase the vulnerability of the Denver Basin bedrock aquifers to contamination.

Pumping of water from the alluvial and bedrock aquifers has steadily increased since the 1930s and 1950s to meet increasing supply needs for agricultural irrigation, domestic purposes in rural areas, and recently developed urban areas in the basin. About 30 times more water was pumped from the alluvial aquifer in 2003 than in 1930, and about 25 times more water was pumped from bedrock aquifers in 2003 than in 1950. Denver Basin groundwater-flow models indicate that pumping has caused the flow of shallow ground-water from the alluvial aquifer down to the bedrock aquifers to increase by 50 percent from predevelopment conditions. This downward migration of groundwater can cause constituents in the shallow aquifer system to migrate into the deeper system used for drinking water. There is some evidence that this migration already is occurring—dissolved oxygen, nitrate, tritium, and other constituents associated with shallow oxic groundwater or human activities at the land surface were found in deeper parts of the aquifer system, and young groundwater has mixed with older groundwater at intermediate aquifer depths. Continued development of land and water resources likely will result in additional movement of constituents in shallow groundwater to deeper parts of the Denver Basin bedrock aquifers, including uranium, selenium, and other constituents that are stable in oxic groundwater.

Treating groundwater to decrease contaminant concentrations is costly, so management practices that prevent migration of poor-quality shallow groundwater are likely to be a more effective way to maintain the current high quality of drinking water in the Denver Basin. Understanding the effects of continued development of the Denver Basin area on groundwater resources provides insight on how human activities might affect groundwater quality and availability in other less developed basins in similar hydrogeologic settings.

Photographs from top to bottom: Jon Mullen, copyright istockphoto.com; Scott Bauer, USDA ARS; USGS; USGS



Sampling of groundwater included the use of a mobile laboratory and the collection of water samples in bagged chambers to protect against airborne contaminants. Samples to be analyzed for dissolved constituents were filtered in the field before collection in sample bottles.

In the south Denver metropolitan area, about 70 percent of the water supply is from wells that tap Denver Basin bedrock aquifers, such as the public-supply well shown here. Collecting water samples from public-supply wells is important for assessing the vulnerability of groundwater used for drinking to contamination from geologic sources and human activities on the land surface.

Chapter 2: *NAWQA Approach to Assessing Groundwater Quality*

Groundwater from the sandstone bedrock aquifers of the Denver Basin is the primary or sole source of water for domestic use in rural areas and public supply in the south Denver metropolitan area and other locations with growing population. Availability and sustainability of high-quality groundwater for supply are vital for private well owners, water managers, and other stakeholders and for the overall economic health of the Denver Basin area. The studies conducted as part of the USGS NAWQA Program were designed to answer broad questions about the occurrence, fate, and transport of contaminants in these bedrock aquifers used as sources of drinking water and the effects of human activities in agricultural and urban areas on groundwater quality.

This chapter summarizes the study design used to investigate the quality of Denver Basin groundwater.

Installation of shallow water-table monitoring wells and sampling of those wells were part of the systematic evaluation of groundwater quality in the Denver Basin.

Assessing Water Quality in the Denver Basin Aquifer System

How does one go about characterizing the quality of groundwater over an area as large as that covered by the Denver Basin, let alone the whole United States? The approach taken by the USGS is to use different types of groundwater studies to gain a better understanding of how and why water quality varies (see sidebar, Understanding study results, below). These groundwater studies are the building blocks of NAWQA's water-quality assessment of Principal Aquifers. Many studies have been conducted in each Principal Aquifer, each with a different focus on information needs about groundwater quality and the natural and human-related factors that affect the aquifer. Groundwater studies designed to broadly assess water-quality conditions in parts of aquifers used for drinking-water supply focused on sampling networks of domestic (private) and public-supply wells (see sidebar, What types of wells were sampled?, p. 9). Agricultural and urban land-use studies designed to characterize and explain the quality of young groundwater recently recharged (in the last 50 years or so) in these land-use settings focused on sampling shallow monitoring (nonpumping) wells that were installed as part of the NAWQA Program. Other studies focused on public water supplies or groundwater quality along individual flow paths (appendix 1).[4–7] The design of the Principal Aquifer assessments enables comparisons of groundwater quality to be made at regional and national scales for a wide suite of contaminants in different aquifer and environmental settings.

This Principal Aquifer assessment brings together and interprets results from all of the NAWQA groundwater studies in the Denver Basin conducted during 2003–05 (appendix 1). Throughout this assessment, the results are grouped as those that characterize the quality of deep groundwater used as a drinking-water supply and those that characterize the quality of shallow groundwater that was recharged in either an agricultural or an urban land-use setting (fig. 2–1; table 2–1). Groundwater in deep parts of the aquifer system was recharged many years ago, in some cases long before any manmade chemicals were used on the land surface. The results of the land-use studies allow us to evaluate the effect of recent human activities on groundwater quality and can provide an early warning for issues that might adversely affect drinking-water resources in the future. Land-use studies also can provide an indication of degradation or improvement in water quality related to changes in chemical use.

Understanding study results

Important aspects of the NAWQA Principal Aquifer assessments:

- Water samples were collected at the wellhead (see sidebar, Anatomy of a well, p. 12) prior to any treatment. They represent the quality of the groundwater resource but not necessarily the quality of tap water.
- The focus of the assessments is the condition of the total resource, including groundwater in a wide range of hydrologic and land-use settings across the Nation, rather than conditions at specific sites with known water-quality concerns.
- The assessments are guided by a nationally consistent study design, and all assessments use the same methods of sampling and analysis. Findings apply to water quality of a particular aquifer but also contribute to the larger picture of how and why water quality varies regionally and nationally. This consistent approach helps to determine if a water-quality issue is isolated or widespread. (See *http://water.usgs.gov/nawqa/about.html* for more information.)
- The assessments focus on aquifers used for water supply or on shallow groundwater that underlies an area with a particular type of land use. Because the NAWQA groundwater study areas do not cover the full spatial extent of the targeted Principal Aquifer, the findings might not represent the effects of the full range of geology, climate, and land use present.
- Analytical methods used by USGS chemists for assessments of water quality in Principal Aquifers are designed to measure constituents at as low a concentration as possible. As a result, constituents frequently are detected at concentrations far below human-health benchmarks for drinking water (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 40). Low-level detections allow scientists to identify and evaluate emerging issues and to track contaminant levels over time.

What types of wells were sampled?

Two types of wells used for drinking water were sampled in the Denver Basin: domestic (private) wells and public-supply wells. Domestic wells typically are shallower than public-supply wells and, therefore, pump water that is nearer to sources of manmade contaminants, such as fertilizers and pesticides, applied at the land surface. Domestic wells commonly are located in rural areas, so they are more likely than public-supply wells to be vulnerable to contamination from agricultural chemicals. Public-supply wells pump water from deeper in aquifers, have high pumping rates, and commonly are located in urban and suburban areas and so are more likely than domestic wells to be vulnerable to contamination from chemicals associated with urban activities. Public-supply wells have larger well diameters and longer screened intervals than domestic wells and are pumped for longer periods of time. As a result, public-supply wells pump much larger volumes of water than domestic wells, and so have much larger capture zones and thus are more vulnerable than 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 groundwater, which in turn can affect the groundwater geochemistry and the constituents contained in the water. Routine testing of water from domestic wells is not required, and homeowners are responsible for testing, maintenance, or treatment of the water from their private well. Water from public-supply wells is required to be tested by the well operator on a routine basis to help assure that the water provided to consumers meets Federal and State water-quality standards. Some groundwater samples were collected from monitoring wells. Monitoring wells are not pumped regularly—they are used for measuring water levels or occasionally for collecting water samples but are not used for drinking water, irrigation, or other purposes. Monitoring wells sampled in the NAWQA groundwater studies were installed by the USGS to monitor the quality of recently recharged water and were purged several borehole volumes prior to collection of water-quality samples.

Top, wells, such as this domestic well that taps the Arapahoe aquifer, were sampled for water quality and measurements related to water quality, such as pH and dissolved-oxygen concentration. Bottom, a hydrologist carefully measures the water level in a monitoring well in an agricultural area. Information on groundwater sampling methods used by the USGS can be found in the USGS National Field Manual.[51]

Photograph by Scott Bauer, USDA ARS

Groundwater beneath agricultural and urban areas was the focus of land-use studies in NAWQA Principal Aquifer assessments because of the potential contaminant sources associated with activities in these areas. For the Denver Basin assessment, samples were collected from shallow monitoring wells underlying non-irrigated wheat fields (left) and suburban residential areas developed primarily after about 1970 in the south metropolitan area of Denver (right) (fig. 2–1).

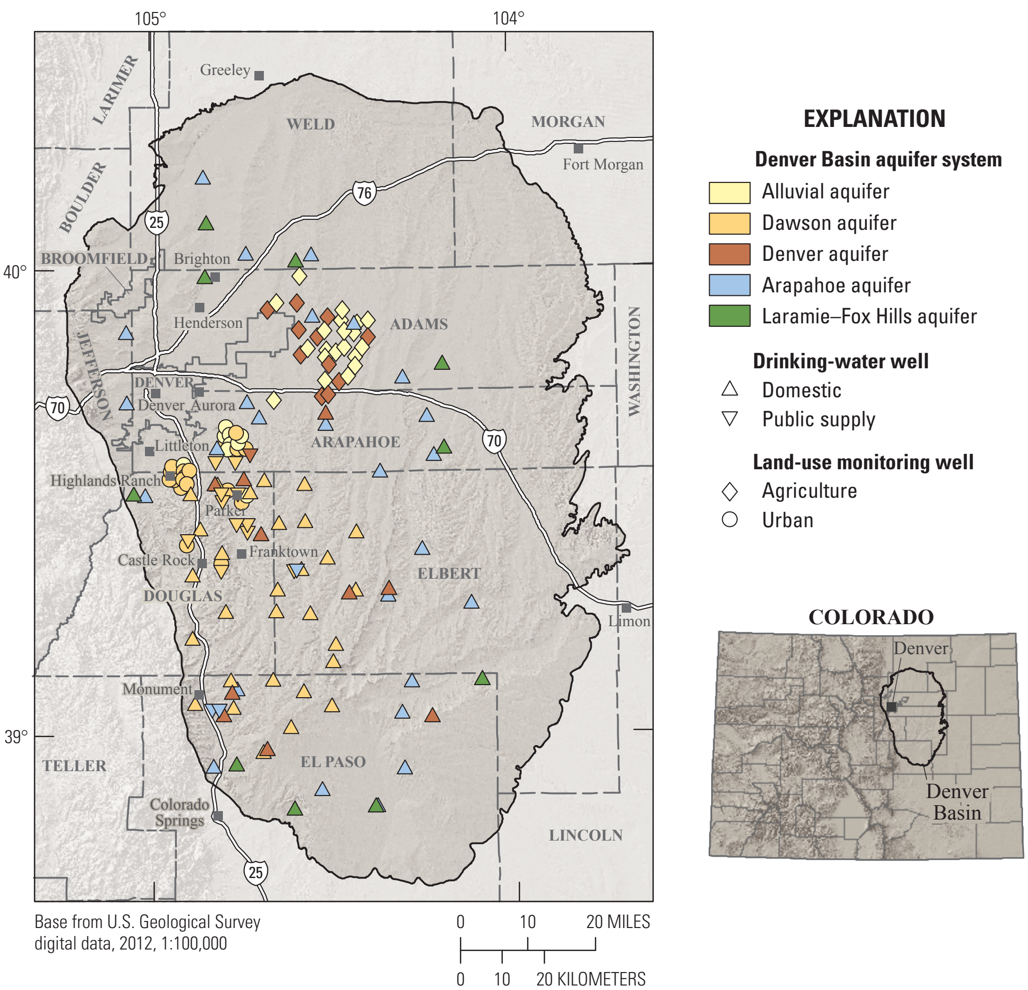


Figure 2–1. The wells sampled by the NAWQA Program for the study of groundwater quality in the Denver Basin were deep drinking-water wells used for domestic and public supply in rural and urban settings or shallow monitoring wells near the water table underlying agricultural and urban areas.

Table 2–1. The objectives of the different studies determined the types of wells sampled in the Denver Basin. Some studies focused on sampling wells screened at deeper depths that represent the part of the aquifers used for drinking water, whereas others (termed land-use studies) focused on sampling water from monitoring wells screened just below the water table to assess the quality of shallow groundwater underlying agricultural and urban areas.

Resource targeted	Number of wells			Well depth range, in feet below land surface	Aquifer
	Domestic supply	Public supply	Monitoring		
Drinking water	75	15	0	130–2,149	Dawson, Denver, Arapahoe, Laramie–Fox Hills
Shallow groundwater in agricultural areas	0	0	31	18–113	Alluvial, Denver
Shallow groundwater in urban areas	0	0	29	18–82	Alluvial, Dawson
Total	**75**	**15**	**60**	**8–2,149**	**Alluvial, Dawson, Denver, Arapahoe, Laramie–Fox Hills**

Groundwater-Quality Assessment Design

To assess the water-quality conditions of the groundwater used as a drinking-water resource in the Denver Basin, one sample was analyzed from each of 90 randomly selected existing domestic and public-supply wells in the Dawson, Denver, Arapahoe, and Laramie–Fox Hills bedrock aquifers (fig. 2–1; table 2–1). The samples were analyzed for major and trace inorganic constituents, nutrients, volatile organic compounds (VOCs), and pesticides (see sidebar, NAWQA assessments use a wide range of geochemical data and site information, p. 13; appendix 2). The domestic and public-supply wells (drinking-water wells) are distributed across much of the area overlying the aquifers, but because the wells sampled are located only in NAWQA groundwater study areas, only some parts of the Denver Basin are represented. About 83 percent of the wells sampled were domestic drinking-water wells and about 17 percent were public-supply wells. Because of the asymmetrical bowl shape of the bedrock aquifers (fig. 2–2), wells in the bedrock aquifers sampled as part of the NAWQA study range from very shallow (tens of feet) to very deep (thousands of feet).

To assess the quality of shallow groundwater underlying agricultural and urban areas, one groundwater sample was collected from each of 60 monitoring wells installed as part of the NAWQA Program (fig. 2–1; table 2–1). The agricultural setting for the Denver Basin assessment was non-irrigated wheat fields. In this setting, no supplemental irrigation water is used, but fertilizers and pesticides are applied as needed. The urban land-use setting where samples were collected was similar to that where many Americans work and live—single and multifamily residential and commercial developments built in suburban areas of large cities where agricultural or undeveloped land is being converted to urban land uses. The setting for the urban study in the Denver Basin was the south metropolitan area of Denver. Since the early 1970s, residential and commercial developments in this area have been built on previously undeveloped rangeland. The monitoring wells in the two land-use settings were relatively shallow—from 18 to 113 feet (ft) deep—and tap groundwater just below the water table in the alluvial, Dawson, and Denver aquifers. This water typically is not used as a source of drinking-water supply but is expected to move into deeper parts of the aquifer system. The water quality of these samples is an indication of how the chemicals we use in day-to-day life—fertilizers, pesticides, solvents, gasoline—might affect the quality of a future drinking-water resource.

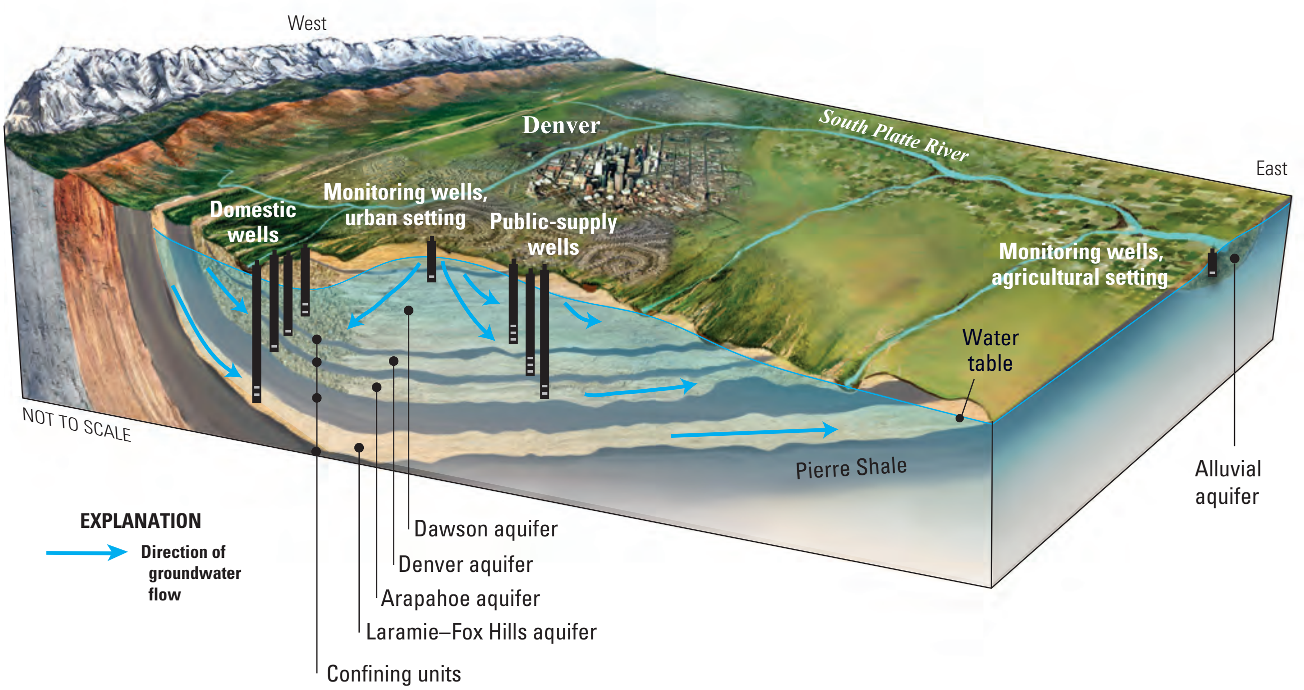


Figure 2–2. The quality of groundwater in the Denver Basin was assessed as it moves from the land surface to the water table and then to deeper parts of the aquifer system that are commonly used to supply water for drinking. Because the Denver Basin has an asymmetrical bowl shape, some aquifers have both shallow and deep parts. The alluvial aquifer and shallow parts of the bedrock (Dawson and Denver) aquifers less than 125 feet below land surface are referred to as the shallow aquifer system. The deeper parts (130–2,149 feet below land surface) of the bedrock aquifers used for drinking-water supply are referred to as the deep aquifer system.

Aquifer (aq.ui.fer)—ăk′wə-fər

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

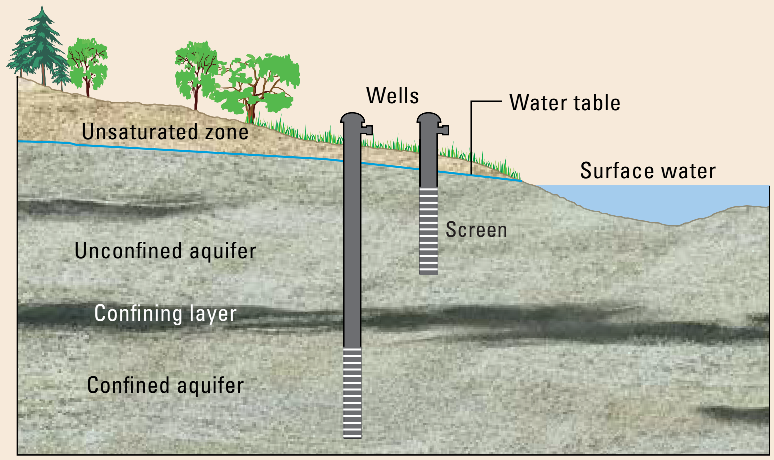
The **unsaturated zone** is the area below the land surface and above an aquifer. In addition to soil, rocks, and air, the unsaturated zone contains water from the land surface (such as rain) that is slowly moving downward to the water table of the aquifer.

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

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

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

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

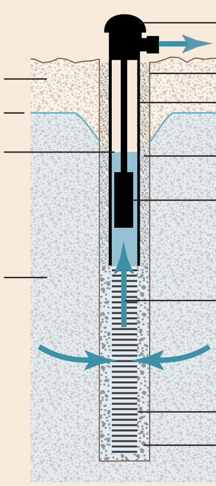


Sedimentary aquifer

Groundwater storage and flow between grains of sediment

Anatomy of a well

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

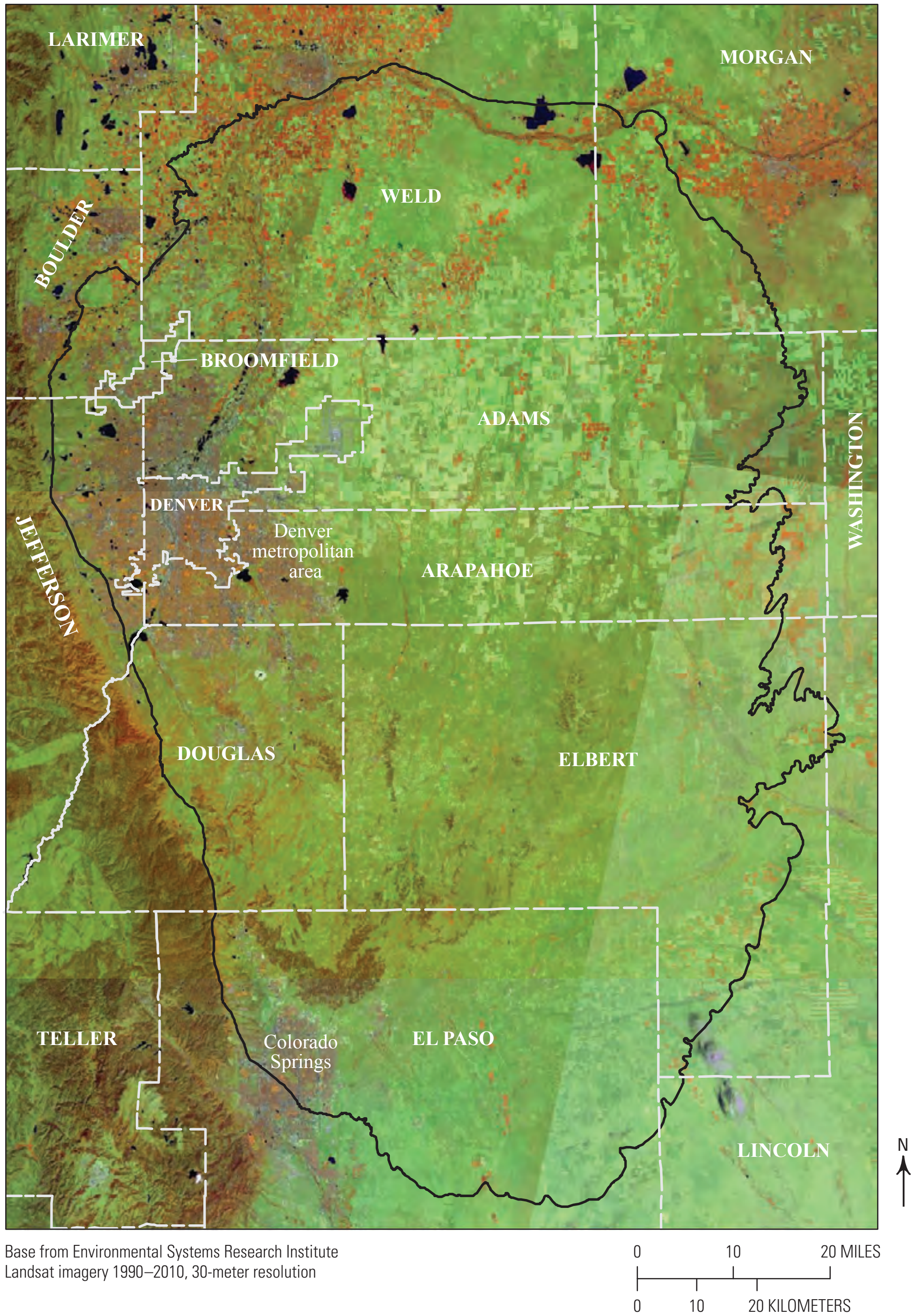


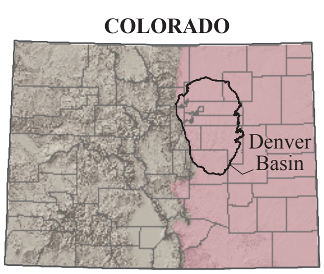
NAWQA assessments use a wide range of geochemical data and site information

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.





EXPLANATION

Landsat color descriptions

Bright orange to red: Vigorous vegetation
Darker oranges and browns: Less vigorous vegetation and natural vegetation
Greens and browns: Cured out (brown) grass or rangeland
Dark purple and grey to white: Urban
Black: Water

Most of the land that overlies the Denver Basin aquifer system is grassland and rangeland or irrigated and non-irrigated agricultural land. Developed areas, primarily the Denver metropolitan area and the Colorado Springs area, are concentrated on the western side of the basin near the mountain foothills.

Chapter 3: *Environmental Setting and Water-Resource Characteristics*

The Denver Basin is a land of contrasts, with its semiarid rangelands and green expanses of irrigated agricultural areas, lawns, and parks, its fast-growing cities and suburbs, dense urban core of Denver, and rural residences, and its use of groundwater and surface water for supply. All these features—climate, land use, population growth, and water use—affect the hydrogeologic system and groundwater quality. Understanding these key background features is essential to assessing the vulnerability of the Denver Basin aquifer system to contamination from human and geologic sources.

This chapter summarizes background information for the Denver Basin aquifer system, thus providing the context for understanding findings about water quality in this Principal Aquifer. This chapter covers the physical setting, climate, hydrogeologic setting, land use, population, and water use.

The Denver Basin forms the western boundary of the Great Plains Physiographic Province where it abuts the Front Range of the Rocky Mountains. Small towns, rural residences, and farms are spread across less-populated parts of the Denver Basin.

Photograph by Ann Cantelow, dreamstime.com

Physical Setting and Climate

The Denver Basin extends eastward from the Rocky Mountains, underlying about 7,000 square miles of the Great Plains in eastern Colorado (fig. 3–1). The basin extends from Greeley in the north to Colorado Springs in the south and from the Front Range east to Limon. The Palmer Divide forms the topographic high in the basin and is the drainage divide between the tributaries of the South Platte River Basin to the north and those of the Arkansas River to the south. Ponderosa pine forests cover the highest altitudes, shrubs and mixed prairie grasslands grow from mid-altitude to low-altitude areas of the plains, and cottonwood trees and willows line low-lying riparian areas.

The climate of the Denver Basin is semiarid. The long-term average annual precipitation of the Denver Basin is only about 15 inches per year (in/yr). Weather conditions vary dramatically from one season to the next. Summer high temperatures range from the 80s to the low 100s (degrees Fahrenheit, °F), and summer thunderstorms that develop over the mountains and Palmer Divide can produce several inches of rain or hail in a few hours or less. During the summer, evapotranspiration rates are high, so only a small fraction of precipitation infiltrates to groundwater. Winter low temperatures can range from 0 to –30 °F or lower, and winter storms can deposit several feet of snow in eastern Colorado. Long-term precipitation records indicate that average annual precipitation increased over the period 1978–2000, after which a regional drought began. Drought conditions persisted through 2004; precipitation was near average during 2005–11, after which drought conditions again set in.

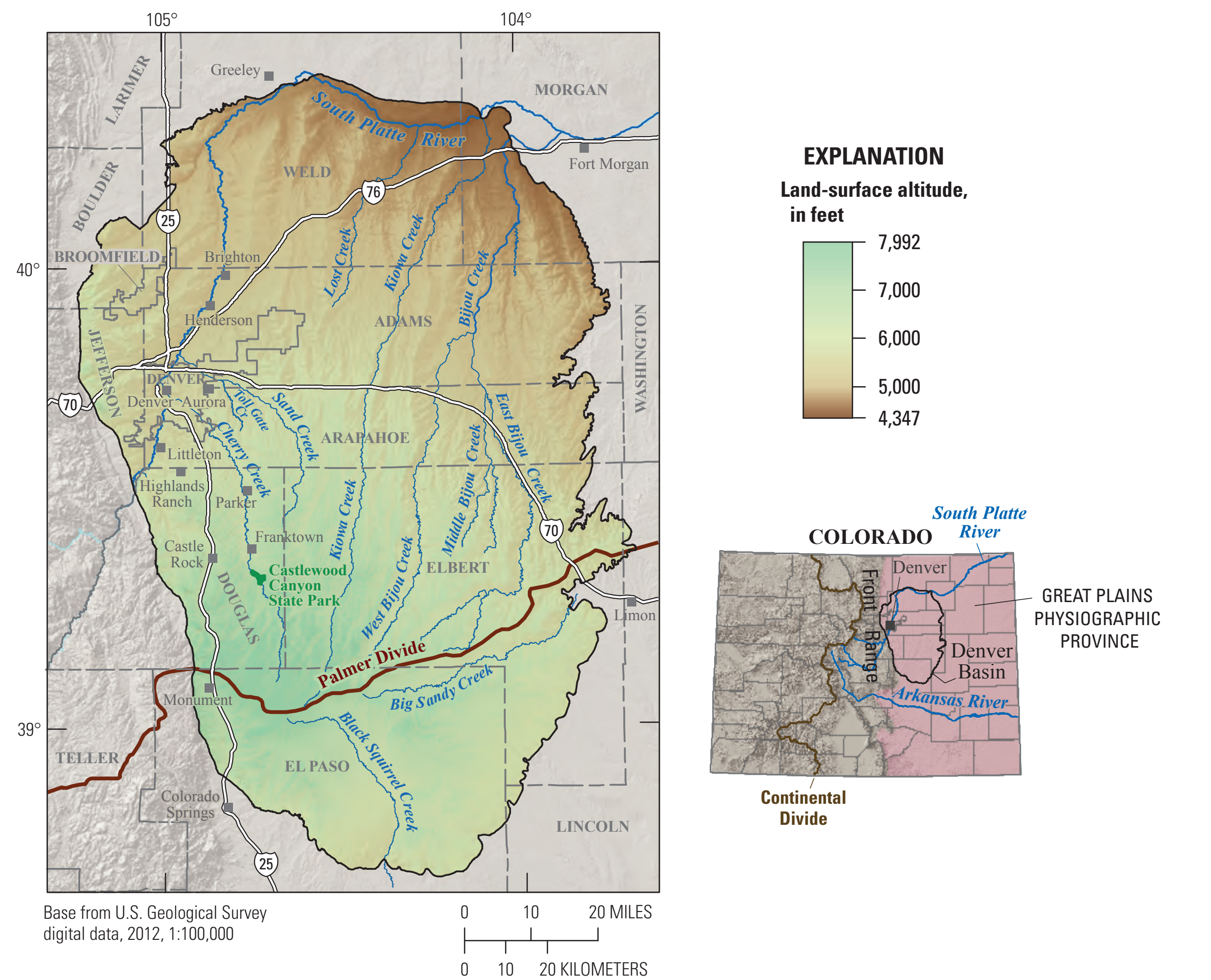
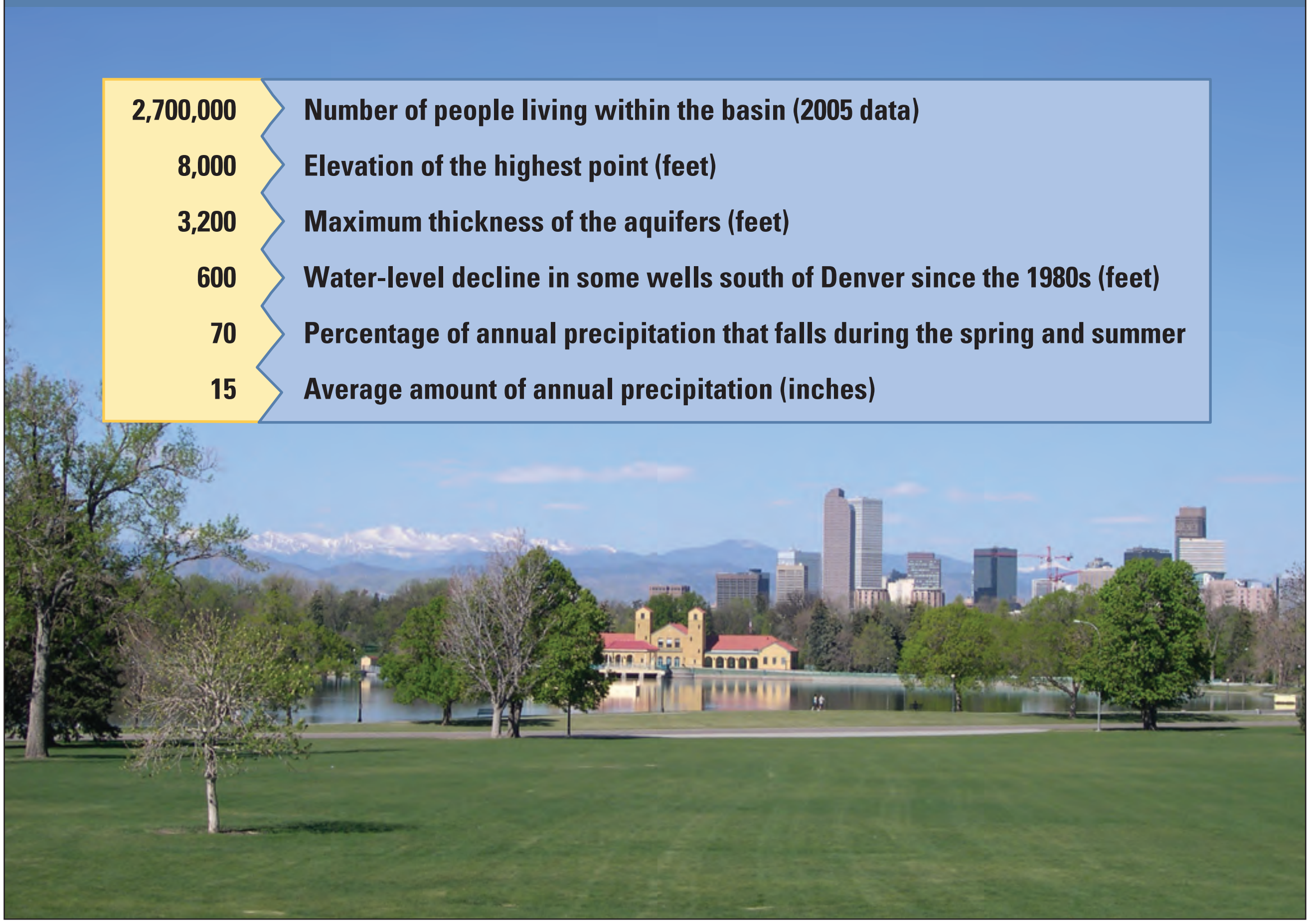


Figure 3–1. The highest point in the Denver Basin is about 8,000 feet and is located along the Palmer Divide, from which streams flow to the north and south. The topographic low of approximately 4,300 feet lies along the South Platte River on the northeastern edge of the basin. Topography has a strong effect on climate in the Denver Basin—precipitation falls primarily in the mountains to the west and at higher altitudes along the Palmer Divide.

The Denver Basin at a glance

2,700,000	Number of people living within the basin (2005 data)
8,000	Elevation of the highest point (feet)
3,200	Maximum thickness of the aquifers (feet)
600	Water-level decline in some wells south of Denver since the 1980s (feet)
70	Percentage of annual precipitation that falls during the spring and summer
15	Average amount of annual precipitation (inches)



More than two-thirds of the average annual precipitation of 15 inches in the Denver Basin area falls from April through September; several inches of rain can fall in a few hours or less during summer thunderstorms. Because of the semiarid climate and lack of surface-water supply, recently developed (since about 1970) suburban areas south of Denver rely heavily on groundwater from the Denver Basin bedrock aquifers for their water needs.

Hydrogeologic Setting

The Denver Basin aquifer system is composed of upper Cretaceous- to Tertiary-age bedrock sandstones that overlie the Cretaceous-age Pierre Shale (fig. 3–2). The four primary sedimentary rock aquifers are (from oldest to youngest) the Laramie–Fox Hills aquifer, Arapahoe aquifer, Denver aquifer, and Dawson aquifer. The deepest part of the aquifer system is in Douglas County, at an altitude of approximately 3,410 ft.[2] In parts of the basin, the bedrock aquifers are overlain by the alluvial aquifer, which is primarily along stream channels (fig. 3–3).

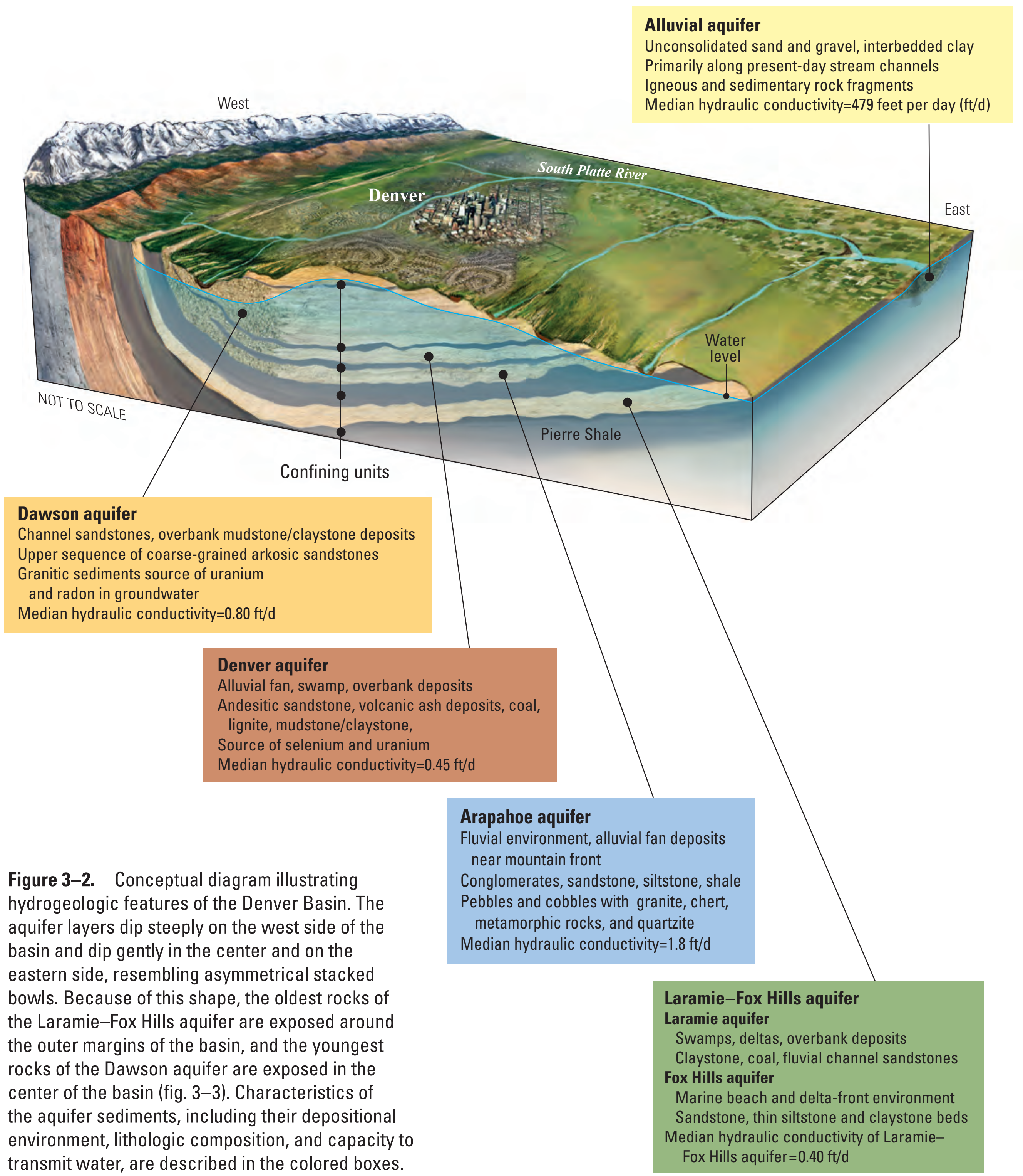


Figure 3–2. Conceptual diagram illustrating hydrogeologic features of the Denver Basin. The aquifer layers dip steeply on the west side of the basin and dip gently in the center and on the eastern side, resembling asymmetrical stacked bowls. Because of this shape, the oldest rocks of the Laramie–Fox Hills aquifer are exposed around the outer margins of the basin, and the youngest rocks of the Dawson aquifer are exposed in the center of the basin (fig. 3–3). Characteristics of the aquifer sediments, including their depositional environment, lithologic composition, and capacity to transmit water, are described in the colored boxes.

To understand the hydrogeology of the Denver Basin, it is important to understand how the depositional environment of the sediments that form the bedrock aquifers changed over geologic time. In the mid-Cretaceous period, an ancient sea (the Western Interior Seabed) occupied much of Colorado. The Pierre Shale, the geologic unit forming the base of the aquifer system, consists of mudstones and other rocks that were deposited on the ancient sea floor. As the sea retreated to the east, sands were deposited along beaches, forming the Fox Hills Sandstone. With additional sea level change, claystones, coal beds, and sandstones that now make up the Laramie Formation accumulated in swamps and deltas. The Laramie–Fox Hills aquifer includes the Fox Hills Sandstone and lowermost part of the Laramie Formation. As mountains rose up during the late Cretaceous period, rivers began draining the mountains, and alluvial sediments were carried eastward. On the western side of the basin, sandstones and conglomerates were deposited as coarse-grained alluvial fans, forming the lowermost sediments of the Arapahoe aquifer; farther to the east, the Arapahoe aquifer sediments are finer grained. Denver aquifer sediments also were deposited as alluvial fans near the mountain front where they are composed largely of volcanic debris, but to the east are made up of fine-grained sediment and coal that accumulated near streams and in swamps. Sediments of the lowermost part of the Dawson aquifer are similar to sediments of the Denver aquifer, but the uppermost part of the Dawson aquifer is composed of debris weathered from Front Range granitic rock. Confining units, primarily interbedded claystone and shale, separate the Denver Basin aquifers, and confining units also separate the lowermost and uppermost parts of the Arapahoe and Dawson aquifers in some parts of the basin. Because depositional environments varied spatially and through geologic time, aquifer sediments throughout the basin exhibit substantial horizontal and vertical differences in lithologic composition and hydrogeologic characteristics.

Unconsolidated, coarse-grained Quaternary-age sand and gravel deposits that are saturated form an alluvial aquifer that overlies parts of the bedrock aquifers (fig. 3–3). The alluvial aquifer lies primarily along modern stream channels, such as the South Platte River, and is composed of granitic and gneissic rock fragments, sedimentary rock fragments, quartz, and feldspar, with interbedded clay in some areas.

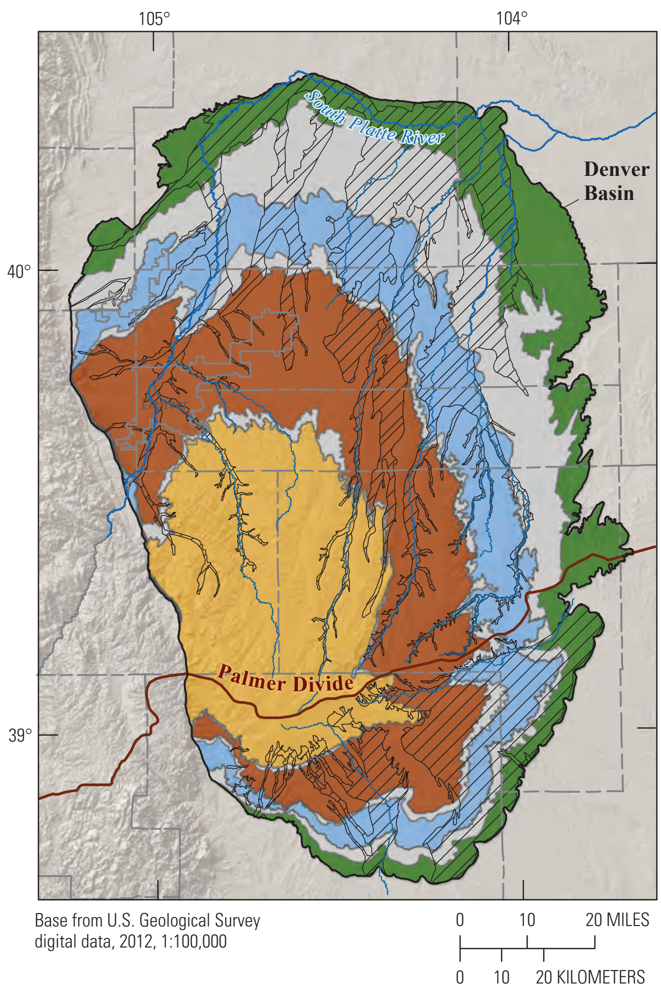


Figure 3–3. The bedrock units of the Denver Basin aquifer system crop out in a ring pattern around the basin. Groundwater is generally confined at depth in bedrock aquifers and unconfined in the alluvial aquifer and in bedrock aquifers where they are exposed at the land surface. Unconfined parts of the aquifer system are more susceptible to contamination from human activities and chemical applications at the land surface than are confined parts.

EXPLANATION

Denver Basin aquifer system

- Alluvial aquifer
- Dawson aquifer
- Denver aquifer
- Arapahoe aquifer
- Laramie–Fox Hills aquifer
- Confining unit

The amount and quality of groundwater in the Denver Basin reflect the depositional setting of the aquifer sediments (fig. 3–2). Course-grained sediments that were deposited on the west side of the basin near the mountain front form more productive aquifers than do fine-grained sediments on the east side of the basin. The sandstones and conglomerates of the lower part of the Arapahoe aquifer on the west side of the basin, for example, form a highly productive aquifer that is heavily used for municipal and domestic supply in Douglas and El Paso Counties. The minerals that make up the sediments affect groundwater quality—granite clasts contain uranium, and volcanic ash and lignite contain selenium and other trace elements.

Most groundwater recharge that occurs naturally is from precipitation that infiltrates unconsolidated and porous sand and gravel alluvial aquifers at the land surface. Additionally, bedrock aquifers are recharged directly where the bedrock is exposed at land surface. Infiltration to bedrock aquifers primarily is to the upper part of the Dawson aquifer at higher altitudes. Recharge to the alluvial and bedrock aquifers naturally is low—about 7 percent of annual precipitation (or about 1 inch) is estimated to recharge the alluvial aquifer and from 1 to 2 percent recharges the bedrock aquifers.(2) Regional groundwater flow in the bedrock and alluvial aquifers generally is away from the topographic high and recharge area of the Palmer Divide (fig. 3–1) toward the north and south.(2, 8) More locally, water moves from upland recharge areas through the near-surface parts of the aquifers to discharge areas in nearby stream valleys. Groundwater also moves vertically down to underlying bedrock aquifers.

In the bedrock aquifers, groundwater exists primarily under confined conditions, although conditions are unconfined where the bedrock crops out or is near the land surface. Although downward water movement through confining units is very slow (3.5×10^{-5} feet per day [ft/d]) for the Denver-Dawson confining unit, in contrast to 0.4–1.8 ft/d for the bedrock aquifers,(2, 8) this vertical leakage is an important source of recharge to underlying bedrock aquifers. Compared to the rate of lateral flow in the bedrock aquifers, the rate of downward flow is small. However, the downward flow takes place over a large area and likely results in large volumes of water moving between aquifers.(2, 8) The estimated downward flow in 2003 was about 148 million gallons per day (Mgal/d).(2)

Sediments of the Dawson Arkose are exposed along a stream bank in Castlewood Canyon State Park near Franktown, Colo. The geologic unit contains coarse-grained arkosic sandstones and granitic sediments, a source of uranium and radon in the upper part of the Dawson aquifer.

Photograph by David M. Miller, USGS

Alluvial fans, such as the example shown on the left in Death Valley, Calif., were deposited on the west side of the Denver Basin. Near the mountain front, the deposits are coarse-grained, such as those for the Arapahoe Formation (above, 12-inch ruler for scale). Remnants of prehistoric alluvial fans, such as those near Highlands Ranch and northwest of Littleton, Colo. (fig. 3–1), can be productive sources of groundwater.

Land Use and Population

Although some settlers came to Denver hoping to strike it rich during the gold rushes of 1849 and 1859, many found that they could turn a greater profit by developing commercial businesses and farms to support the growing population. Horace Greeley, the famous editor of the New York Tribune newspaper and promoter of Colorado, said "…the hardest way to obtain gold is to mine for it. A good farmer, or merchant, will usually make money faster… by sticking to his business than by deserting it for gold digging."[9] Historically, native grassland and rangeland in the Denver Basin were converted to agricultural and urban land; more recently, grassland, rangeland, and agricultural land are being converted to suburban (commercial and residential) land use. Land use overlying the Denver Basin aquifer system ranges from high-density urban development in downtown Denver to irrigated agriculture along the South Platte River (fig. 3–4). Urban and suburban development is mostly along the west side of the Denver Basin in and around the metropolitan areas of Denver and Colorado Springs. Agricultural land is primarily in the northern part of the basin, and grassland and rangeland cover much of the central and southern parts of the basin. Human activities in urban, suburban, and agricultural areas can be sources of contaminants, such as fertilizers, gasoline compounds, solvents, and pesticides, to shallow groundwater.

The population of the metropolitan areas overlying the Denver Basin aquifer system more than doubled from 1970 to 2005, from 1.3 million to about 2.7 million (T.L. Arnold, U.S. Geological Survey, written commun., 2009). Development has been especially rapid and extensive on the west side of the basin between Denver and Colorado Springs. From 2000 to 2009, Douglas County (fig. 3–1) was among the fastest growing counties in the United States[10] and also is the area in the Denver Basin with the greatest water-table declines. Three general areas of recent development rely heavily on Denver Basin groundwater for municipal water supply. The area south of the Denver metropolitan area that encompasses Littleton, Parker, Franktown, and Castle Rock has been transformed from a rural residential area to one with sprawling suburbs as part of this population increase (fig. 3–4). A second area includes former rangeland and rural-residential areas around Monument and northeast of Colorado Springs that have undergone similarly rapid development. Suburbs north and northeast of Denver in Weld and Adams Counties represent the third area of intense development.

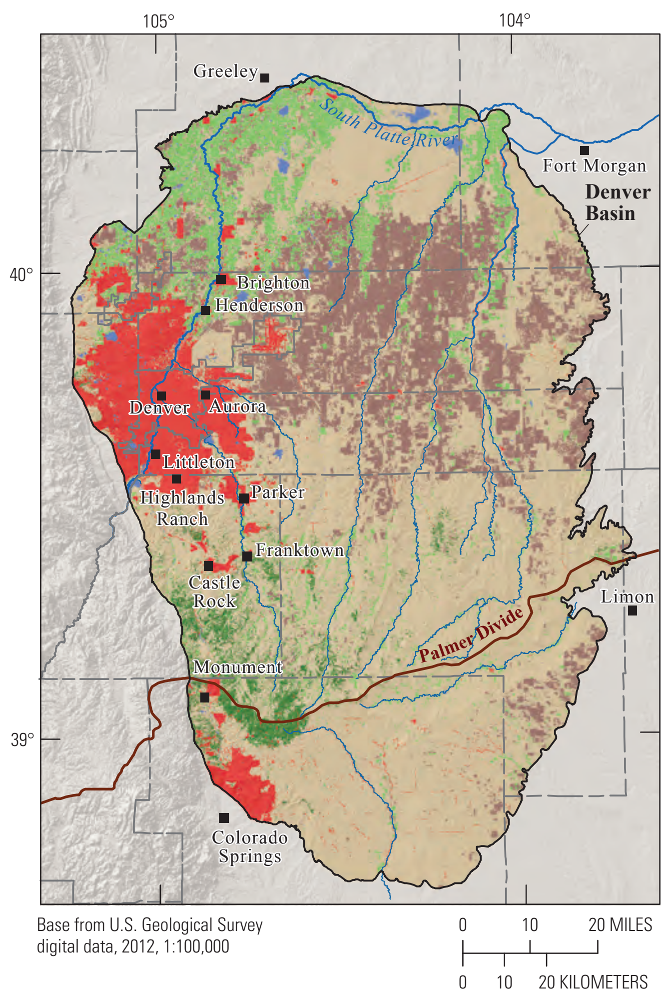
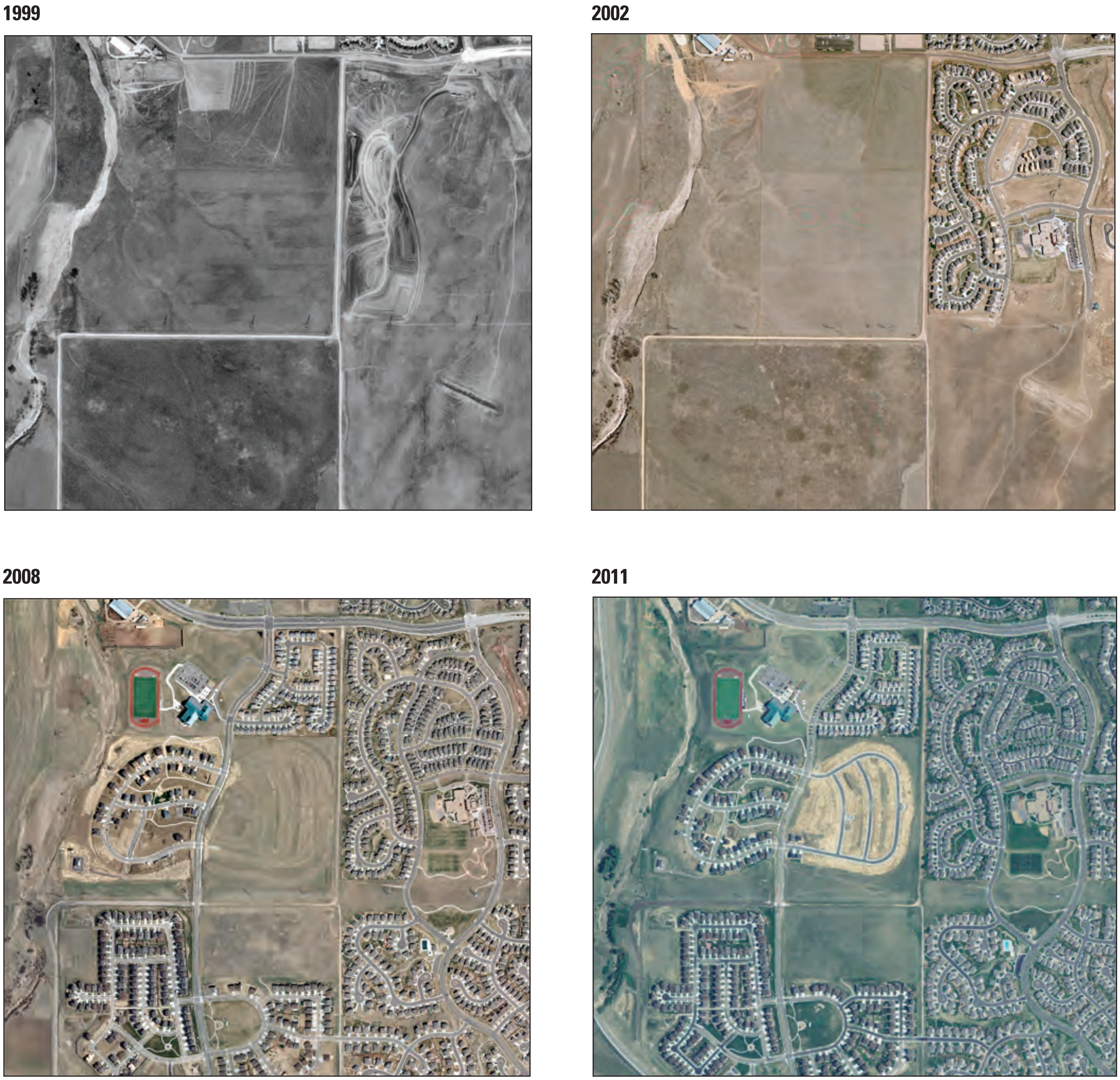


Figure 3–4. About 60 percent of the Denver Basin area is non-irrigated grassland and rangeland; 16 percent is non-irrigated agricultural areas, primarily wheat and small grains; 11 percent is irrigated agricultural areas, primarily corn; 9 percent is developed urban and suburban areas; and 3 percent is forested.[90, 91] The remaining 1 percent of land cover is open water or urban recreational areas.

EXPLANATION

Land-use category

- Urban/suburban development
- Forest
- Grassland and rangeland
- Irrigated pasture or row crops
- Non-irrigated small grains or fallow
- Water



Rangeland in the Parker, Colo., area has rapidly been converted to suburban residential development. Parker and other areas with similar recent development tap the Denver Basin bedrock aquifers for public water supply. Extensive pumping from bedrock aquifers has resulted in a lowering of groundwater levels in some parts of the aquifers. (Imagery for 1999, 2002, and 2008 from U.S. Geological Survey Digital Orthophoto Quarter Quads; imagery for 2011 from U.S. Department of Agriculture National Agricultural Imagery Program).

Water Use

Public water supply along the Front Range urban corridor is a combination of surface water from the Rocky Mountains and groundwater from alluvial and bedrock aquifers (fig. 3–5). In rural areas, domestic water users and irrigators commonly rely on groundwater pumped from private wells. Water use in the State of Colorado is governed by extensive water law. Use of surface water and tributary groundwater—groundwater that is hydraulically connected to surface water—is governed by a system of prior appropriation. Simply, prior appropriation means "first come, first served"—the first user to divert water for beneficial use has a senior water right. Older municipalities, such as Denver and Colorado Springs, and irrigation companies generally hold water rights that are senior to more recently established municipalities and suburbs such as Parker and Castle Rock. Much of the water supply for older municipalities is from surface water. Water for agricultural irrigation along the South Platte River is supplied by surface water delivered through irrigation diversion ditches and by tributary groundwater pumped from the alluvial aquifer.

In more recently developed areas, however, there is little surface water, limited tributary groundwater, or limited available water rights. As a result, municipalities in these areas have tapped the bedrock aquifers for a readily available source of water.[11] Groundwater in the bedrock aquifers is administratively recognized as nonrenewable because the aquifers receive little recharge from precipitation and primarily are confined.[12] A water law passed in 1973 recognized the existence of nontributary groundwater—groundwater with little physical connection to surface water—in the Denver Basin and established criteria for withdrawal of water from the bedrock aquifers. A 1985 water law ruled that a landowner (private or public) could appropriate groundwater from bedrock aquifers beneath the land at a rate that insured at least a 100-year aquifer life.[11] Groundwater in the Denver Basin bedrock aquifers is considered mostly nontributary and therefore is not subject to the prior appropriation doctrine. Because allocation is based on land ownership, the bedrock aquifers tapped by wells on publicly owned land are heavily used for supply by recently established municipalities. Additional information on groundwater law for the Denver Basin is available in Hobbs.[13]

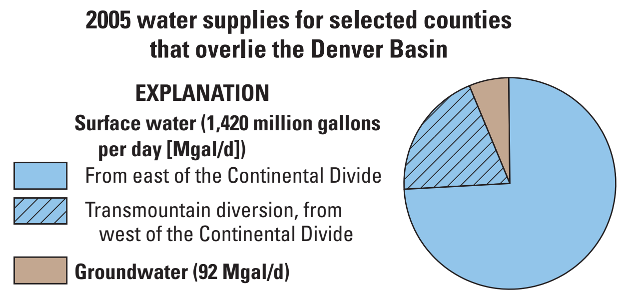


Figure 3–5. About 94 percent of the water supply for eight counties that overlie the Denver Basin aquifer system is surface water from the Front Range mountains or diversions from mountains west of the Continental Divide. Although only 6 percent of the water used in the eight counties is from groundwater, groundwater is an important source of supply for recently developed suburbs between Denver and Colorado Springs and areas north and northeast of Denver and in rural areas. (Water-supply data are estimated values from Ivahnenko[92] and Ivahnenko and Flynn.[93])

Denver Basin groundwater: A source of supply for 130 years

Development of Denver Basin groundwater began in the spring of 1883 when water began to flow from a well that accidentally tapped the Laramie Formation. In the first report on Denver Basin groundwater, published in June 1884, Frederic F. Chisolm of the Colorado Scientific Society wrote:

> "This [artesian] water was characterized by its extreme purity and its superiority over water furnished by the Denver Water Company from the Platte, and the interest created by this discovery was very great."[52]

By late 1886, more than 130 artesian wells had been drilled in Denver.[9] The Denver historian Louisa Ward Arps later wrote:

> "The newspapers were full of the benefits of artesian water…Learned treatises were printed, discussing the mineral content of each well. The opinions of doctors were sought as to which well was best to cure which ailment."[9]

Photograph by C.A. Fisher, U.S. Geological Survey Photographic Library, ID. Fisher, C.A. 16 fca00016

Artesian well.

Extensive development of the bedrock aquifers began in the 1950s to support population growth and increased demand for water supplies by suburban communities in the south metropolitan area, northern El Paso County, and areas north and northeast of Denver (fig. 3–6). Water from bedrock aquifers is used for municipal and commercial/industrial purposes and domestic supply in rural areas, in contrast to water from the alluvial aquifer, which is used mostly for agricultural irrigation (fig. 3–7). Large-volume pumping from deep, confined parts of the bedrock aquifers for public water supply is causing groundwater levels to decline and shallow groundwater in some parts of the aquifer system to move downward. In the south Denver metropolitan area in Douglas County, water levels in the Arapahoe aquifer have declined as much as 600 ft since the 1980s.[14] The drawdown of water (localized decline in the water table) around a well can decrease well production and increase the cost of pumping. Recent levels of pumping from the bedrock aquifers are not indefinitely sustainable. The continued increase in population, development, and associated groundwater pumping in the Denver Basin since the 1980s has caused renewed concern for groundwater availability and the sustainability of the Denver Basin aquifer system.[2, 11]

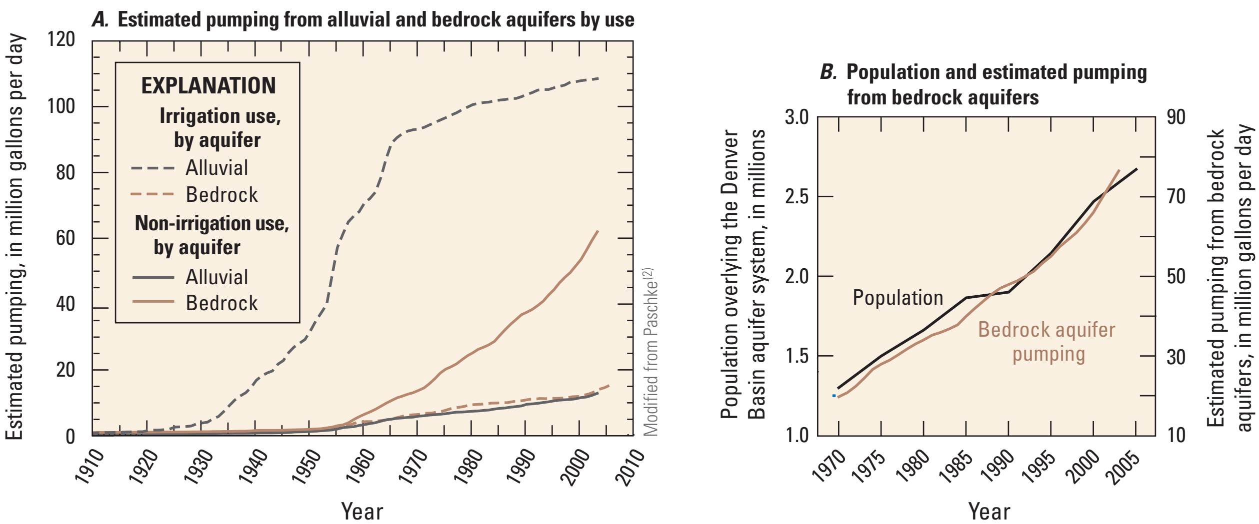
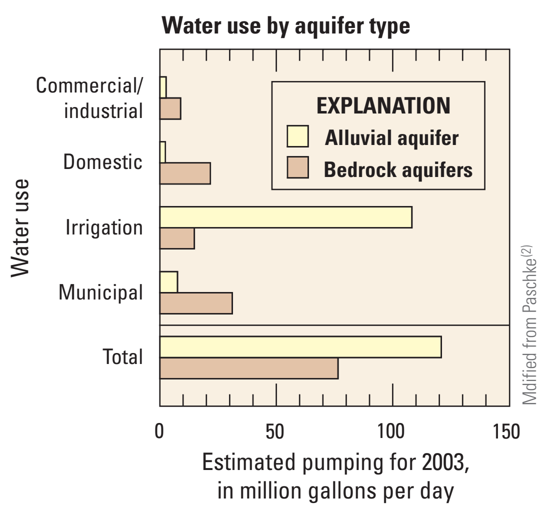


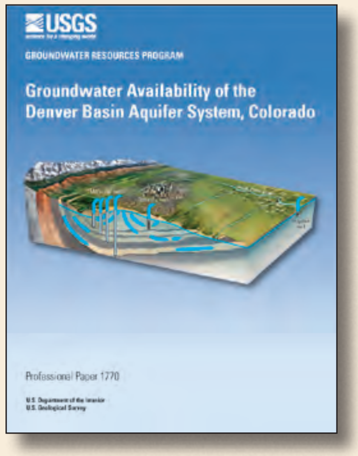
Figure 3–6. *A*, Groundwater withdrawals from the alluvial aquifer to irrigate crops has been the largest component of pumping from Denver Basin wells since substantial withdrawals began around 1925. Although pumping from the alluvial aquifer for irrigation continues to exceed the amount of water pumped from the bedrock aquifers for non-irrigation (municipal, domestic, and commercial, or industrial) uses, pumping from bedrock aquifers is increasing rapidly. *B*, Pumping of groundwater from Denver Basin bedrock aquifers has increased in response to rapid growth in population. Bedrock aquifers provide much of the water supply for those areas with the most rapid growth.

Figure 3–7. Groundwater pumped from bedrock aquifers is used extensively for public supply in areas north and south of Denver and near Colorado Springs and for domestic supply in rural areas. Groundwater pumped from the alluvial aquifer primarily is used for agricultural irrigation.



Evaluating groundwater availability from the Denver Basin aquifer system

As populations continue to grow and more people rely on the Denver Basin aquifer system for their water supply, it is increasingly important to continually monitor and reassess the availability of groundwater resources.[2] In 2004, the U.S. Geological Survey initiated a large regional study of the Denver Basin aquifer system to provide an updated assessment of groundwater availability. The study evaluated the effects of continued pumping on Denver Basin groundwater resources and documented an updated groundwater-flow model useful for assessing hydrologic conditions.[2] The updated model is a fully three-dimensional groundwater-flow model that uses the MODFLOW-2000 computer program[53–56] to simulate transient groundwater flow in the bedrock aquifers and overlying alluvial aquifer from prior to development (pre-1880) through 2003. Model predictions for 2004–2053 were included to provide estimates of how water levels might respond to different scenarios for managing the groundwater resources in the future. Estimated groundwater-flow data and pumping amounts presented in this circular are results from the calibrated groundwater-flow model simulations.[2]



Results of the groundwater-flow simulations indicate that water use at the land surface has increased with development in the basin and that pumping of confined bedrock aquifers has lowered the hydraulic head in some areas and reduced aquifer storage.[2] With a lowered hydraulic head, there is less upward flow from bedrock aquifers to the alluvial aquifer, more downward flow between bedrock aquifers, and a change from confined to unconfined conditions in some parts of the system. Simulating the groundwater-flow system provides a tool for understanding past and present groundwater conditions for the Denver Basin aquifer system, assessing the effects of continued development and pumping on groundwater resources, and predicting future aquifer response to management decisions on the use of the finite groundwater resource.

Photograph copyright istockphoto.com

Photograph by Andrew Silver, Brigham Young University

Processes that affect the quality of Denver Basin groundwater include the infiltration of chemicals applied on the land surface to shallow groundwater along with recharge water (upper left), the weathering of trace elements, such as iron (upper right) from aquifer sediments, and transpiration of water from crops, such as sunflowers (lower left), which can concentrate dissolved solids in the subsurface.

Chapter 4: *Natural and Human Factors That Affect Groundwater Flow and Quality*

This chapter explains and discusses the hydrologic and geochemical processes and human activities that affect the movement and quality of groundwater in the Denver Basin.

The quality of groundwater used for drinking and irrigation in the Denver Basin is determined by natural factors, such as evapotranspiration and geochemical conditions in the aquifer, and human activities, such as urban development, farming, and groundwater pumping. Human activities can introduce a diverse array of contaminants to the land surface and subsurface environment and, equally important, have extensively modified the hydrology in the Denver Basin. Increases in groundwater recharge resulting from irrigation and urban development and increased pumping for water supply have altered groundwater flow paths and geochemistry in the Denver Basin and increased the volume of water moving through the aquifer system. These modifications have the potential to transport contaminants derived from geologic materials and human activities from shallow parts of the aquifer to deep parts of the Denver Basin that are used for drinking-water supply.

For more than 100 years, water fountains in the Brown Palace Hotel in Denver have been supplied by a well tapping the Arapahoe aquifer 750 feet below land surface. The first wells to tap the bedrock aquifers were drilled in downtown Denver in the 1880s; by 2003, about 8,000 alluvial wells and 44,000 bedrock wells were completed in the Denver Basin aquifer system. (Well data from Paschke.[2])

Irrigation and Groundwater Pumping Associated With Development Have Nearly Doubled the Amount of Groundwater Moving Through Shallow Parts of the Denver Basin Aquifer System

Recharge to the Denver Basin aquifer system under natural, predevelopment conditions was primarily from precipitation (fig. 4–1). Under modern developed conditions, recharge from precipitation is enhanced by recharge from irrigation. Irrigation is primarily in agricultural areas, but in a sense urban areas also are irrigated. About 50 percent of residential water use in urban areas along the Front Range is for outdoor watering, most of it on turf (for example, on lawns, golf courses, and parks).[15]

Discharge under predevelopment conditions was primarily evapotranspiration and outflow to streams. Under modern conditions, discharge is greatly enhanced by pumping from wells and, to a lesser extent, by increases in evapotranspiration from irrigated agricultural and urban areas and flow of groundwater to streams and reservoirs. Almost one-third of the modern discharge is groundwater withdrawn through wells. The amount of water removed from the aquifer system is now greater than recharge, which results in a net loss of groundwater and a decline in groundwater levels in some parts of the Denver Basin.

The largest decline in groundwater levels has been in the Arapahoe aquifer in the south Denver metropolitan area.[14] The greatest pumping of groundwater has been from the lowermost part of the Arapahoe aquifer because it is made up of relatively porous and extensive sandstones and is a highly productive source of groundwater for supply. Water levels also have declined in some parts of the Dawson, Denver, and Laramie–Fox Hills aquifers because of pumping. With the

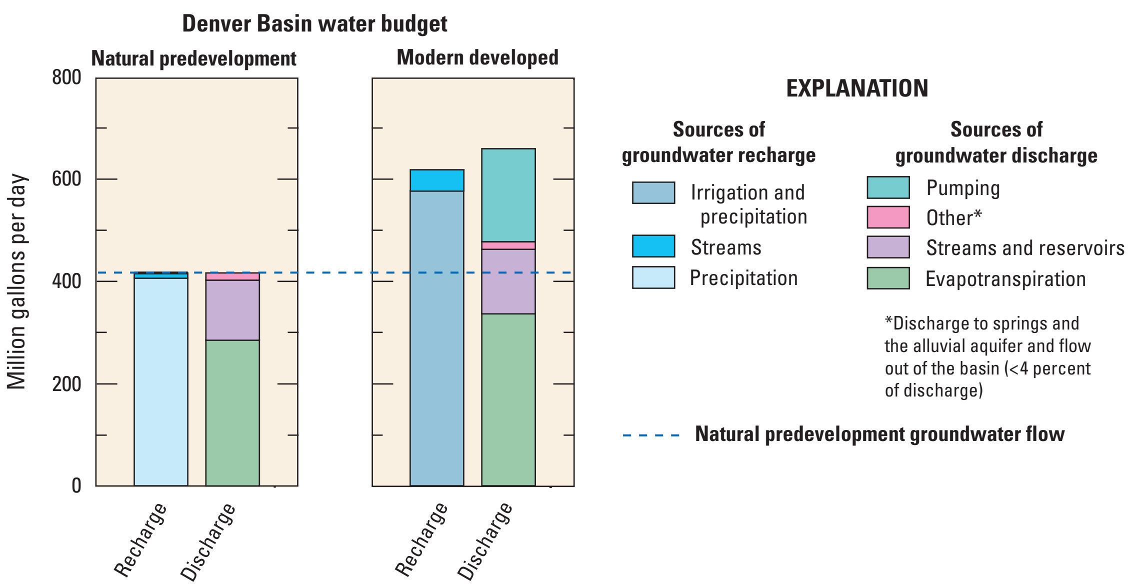
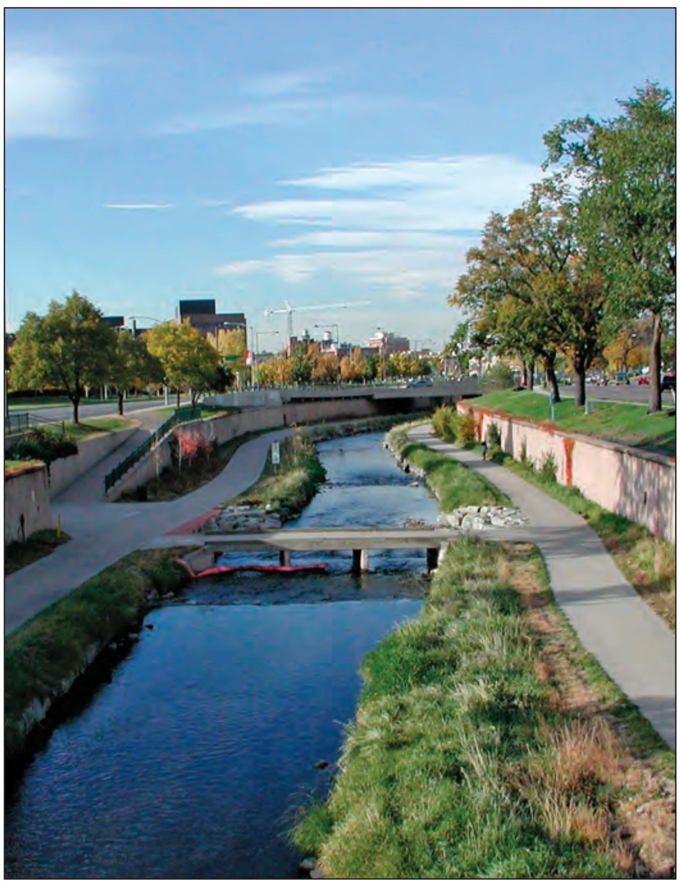


Figure 4–1. Hydrologic conditions in the Denver Basin have changed substantially over the last 130 years because of land and water-resource development. The natural predevelopment hydrologic system was dominated by recharge from precipitation, which was balanced by discharge associated with evapotranspiration. The modern developed hydrologic system includes additional recharge from irrigation and additional discharge from pumped wells. The amount of water moving through the aquifer system has increased by about 160 percent from predevelopment to modern conditions. Currently, discharge exceeds recharge, resulting in a net loss of groundwater, as demonstrated by continued groundwater-level declines in several parts of the Denver Basin. (Simulated recharge and discharge values are from Paschke.[2])

increased pumping and corresponding decline in water levels, the downward flow of water between aquifers has increased, and shallow groundwater is moving to deeper groundwater in larger quantities.[2] Simulated flow from the alluvial aquifer downward to the bedrock aquifers increased by 50 percent from predevelopment conditions, from 5.2 Mgal/d (8 cubic feet per second [ft^3/s]) before 1880 to 7.8 Mgal/d (12 ft^3/s) in 2003. Simulated downward flow from some of the bedrock units to deeper parts of the system has more than doubled since the early 1950s because of increased pumping from the Arapahoe aquifer.[2]

With a decrease in the hydraulic head or water pressure in bedrock aquifers in some areas, upward flow to the alluvial aquifer has been reduced. As a result, lateral groundwater flow in some areas has been redirected toward cones of depressions around supply wells rather than towards natural discharge points in streams, and some formerly perennial (year-round) streams may be dry at certain times of the year. These changes have implications for water quality and biota living in the streams. In addition, parts of some confined aquifers have become unconfined, and artesian conditions have been lost. A change to unconfined conditions can increase the possibility of contamination of groundwater from human activities.

In contrast to declining water levels in some parts of the Denver Basin, water levels in some parts of the alluvial and shallow bedrock aquifers have risen as a result of enhanced recharge from irrigation in agricultural and urban areas. Some streams, such as the South Platte River, Cherry Creek, Sand Creek, and Toll Gate Creek, that historically were dry part of the year before development now have year-round streamflow. A change in streamflow conditions can alter the susceptibility and vulnerability of streams to contamination from groundwater (see sidebar, Effects of groundwater/surface-water interaction on water quantity and quality and ecosystem health in the Denver Basin, p. 30).



"About noon on that day we reached Cherry Creek…The stream, however, like most of the others which we passed, was dried up in the heat and we had to dig holes in the sand to find water for ourselves and our horses."

Francis Parkman from
"The Oregon Trail" (1846)

As noted by early settlers traveling through the Denver Basin area, many streams in the region dried up during summer months. Because the amount of water applied to the land surface has increased as the Denver Basin area has been developed, groundwater discharge to some streams, such as Cherry Creek shown here, has increased, and streamflow has changed from flowing only during wet seasons to flowing year round.

Effects of groundwater/surface-water interaction on water quantity and quality and ecosystem health in the Denver Basin

The interaction of groundwater and surface water affects water supply, water quality, and the health of aquatic ecosystems.[58] Groundwater that discharges to streams, lakes, reservoirs, and wetlands helps sustain the health of the aquatic environment but may also be harmful to aquatic life if groundwater is contaminated.

In the Denver Basin, the amount of water in a stream can be increased by the discharge of excess irrigation water or decreased by a decline in the water table resulting from the pumping of wells. As shown elsewhere in this report (see chapter 6), recharge of oxic irrigation water can mobilize contaminants (uranium, selenium) from geologic sources present in aquifer materials, which, in turn, can be delivered to streams. In Aurora, Colo., for example, groundwater transports selenium to Toll Gate Creek, where the stream aquatic-life standard for selenium of 4.6 micrograms per liter (µg/L) has been exceeded for the past several years (see chapter 6).[20] Groundwater discharges to the stream when the water table near the stream is higher than the stream surface.[58]

Surface water seeps into groundwater through the streambed when the stream surface is higher than the nearby water table.[58] In such situations, the stream is called a "losing stream." Groundwater quality can be adversely affected by losing streams if water in the stream is of poorer quality than water found in the shallow aquifer. Contaminants known to be found at high concentrations in Denver Basin streams include dissolved solids, selected trace elements, and, for some streams heavily affected by human activities, nitrate or organic compounds derived from fertilizers, pesticides, or other sources.

During summer, no water flows in this streambed in Castle Rock, Colo., because the water table is lower than the streambed.

Not All Groundwater in Bedrock Aquifers Is Old Water

The "age" of groundwater is the time elapsed since the recharge water reached the water table and became isolated from the atmosphere. The term "age" typically is qualified with the word "apparent" to signify that the accuracy of the estimated age depends on many variables and the determined age is not certain;[16, 17] however, the term "groundwater age" is used in this report for simplicity. Estimates of groundwater age can be made by analyzing manmade or radioactive compounds that enter the subsurface with recharge water and travel with the water to a sampling point. Groundwater that was recharged within the last 60 or so years contains tritium, a radioactive element released during the testing of atomic bombs in the 1950s. Prior to atomic bomb testing, recharge water contained small amounts of tritium produced naturally; these amounts would have decayed to levels near or below detection levels in present day water samples. Groundwater age estimates are useful for understanding selected aspects of hydrogeology, such as recharge rates, rates of geochemical and microbiological processes, aquifer susceptibility and vulnerability to contamination, and water-resource management.[17]

On the basis of groundwater age estimates, samples collected from the Denver Basin aquifer system were grouped into three age categories: (1) young water (post-1950s), (2) old water (pre-1950s recharge and, for many samples, recharge that is likely thousands of years old), and (3) mixed-age water (mixture of young and old water) (fig. 4–2).[18] Most samples of shallow groundwater from wells in the urban area were young; most of the shallow agricultural well samples were of mixed age. Not all groundwater from deeper parts of bedrock aquifers was old. Samples from drinking-water wells that tap the Dawson aquifer mostly were of mixed age, indicating the likely mixing of old water at depth with young recharge. Mixtures of young and old groundwater at depth in two samples from the Denver aquifer and one sample of young groundwater from the Arapahoe aquifer indicate that groundwater mixing has occurred locally in the two aquifers. Some of the bedrock-aquifer wells used for drinking water can have long screen intervals. These wells likely draw water from multiple depths within the aquifer, such that mixing can occur in the well bore during sampling. With high-volume pumping from deep supply wells, though, there can be a mixture of young and old groundwater at intermediate depths as the downward movement of young groundwater increases due to pumping.

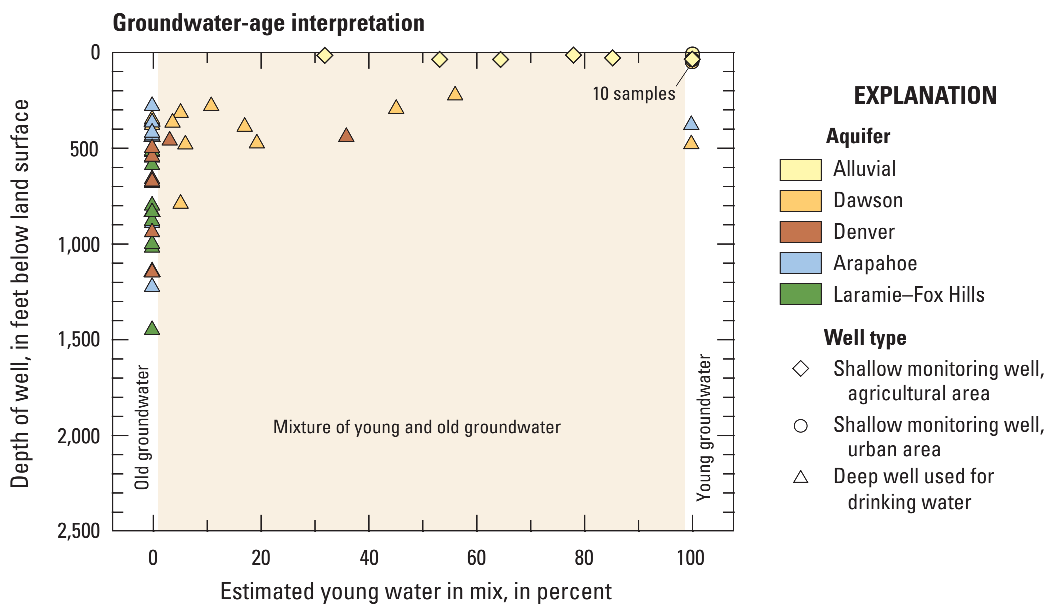


Figure 4–2. Three age categories were identified for Denver Basin groundwater samples—young (post-1950s), old (pre-1950s, some samples likely thousands of years old), and mixed-aged samples (mixtures of young and old groundwater). Mixed-age groundwater at intermediate depths, particularly in the Dawson aquifer but also in a few samples from the Denver aquifer, indicates that young, shallow groundwater has moved into underlying bedrock aquifers where it has mixed with older groundwater. This mixing suggests that the quality of deep groundwater used for drinking-water supply could be affected by contaminants found in poor quality shallow groundwater.

Geologic Materials and Human Activities Are Sources of Contaminants to Groundwater

Aquifer sediments in the Denver Basin contain geologic materials (rock and mineral fragments and particles; fig. 3–2) that are sources of several naturally occurring constituents of concern. The Denver aquifer, for example, contains extensive volcanic ash deposits that contain easily leached sulfate and carbonate minerals that can contribute to high dissolved-solids concentrations in shallow groundwater. Some of the minerals also contain trace elements, such as selenium and uranium, that are released to groundwater when the minerals dissolve during periods of elevated recharge or irrigation.[19, 20] As described in chapter 3, each of the major aquifers of the Denver Basin has varying depositional histories and different sources of sediment. Some of the aquifers are composed of source rocks that are enriched in specific elements; for example, the granitic sediments in the Dawson and Arapahoe aquifers can be a source of uranium to Denver Basin groundwater.

The greatest manmade factor affecting the quality of Denver Basin groundwater is the change in land cover and land uses from natural grassland to agriculture and urbanization. Excess recharge water from irrigation and other sources (leaky water mains and sewer lines, for example) can mobilize contaminants from geologic and manmade sources. Agricultural irrigation can contribute contaminants to the land surface through use of commercial fertilizers, pesticides (herbicides, insecticides, and fungicides), manure, and other substances (fig. 4–3). The predominant source of nitrogen to watersheds in areas heavily used for agriculture is the application of commercial fertilizers.[4, 21] In urban and suburban areas, contaminants from manmade sources, including volatile organic compounds (VOCs), can be added to groundwater through the use of fertilizers, pesticides, commercial and household products, and gasoline. Contaminants are released to the environment from septic tanks, leaking underground storage tanks, chemical spills, leaky sewer lines, treated wastewater, biosolids, urban runoff, and commercial and industrial processes. Pesticides and VOCs can degrade (be transformed) to other chemical compounds through abiotic or biotic processes. Detections of pesticides and VOCs in groundwater samples are dependent on a variety of factors, such as type and source of pesticide and VOC, land use, depth of groundwater, reactions that occur during transport from the land surface to the water table, and geochemical reactions in the aquifer. These factors and others are discussed in more detail in chapter 6.

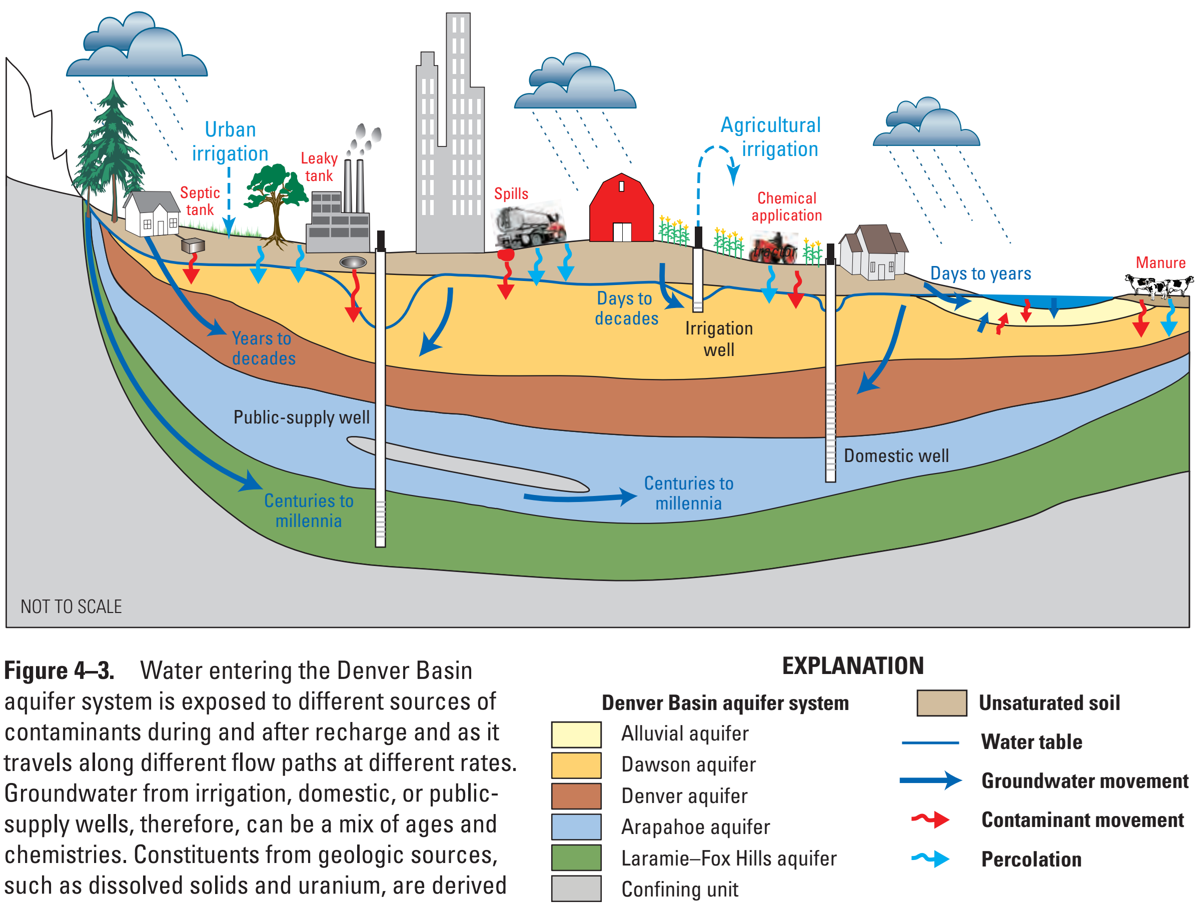
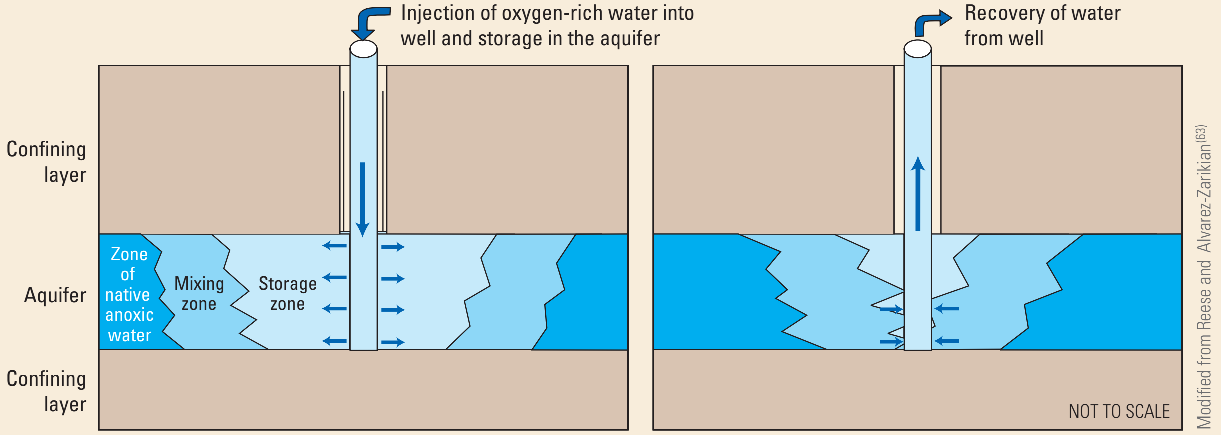


Figure 4–3. Water entering the Denver Basin aquifer system is exposed to different sources of contaminants during and after recharge and as it travels along different flow paths at different rates. Groundwater from irrigation, domestic, or public-supply wells, therefore, can be a mix of ages and chemistries. Constituents from geologic sources, such as dissolved solids and uranium, are derived from soil and aquifer sediments, and their transport may be affected by human activities, such as irrigation. Sources of contaminants in groundwater from human activities on the land surface include point sources, for example, spills and leaking underground storage or septic tanks, and non-point sources, such as fertilizers or pesticides applied to cropland or lawns.

Increased interest in aquifer storage and recovery programs in the Denver Basin

As water levels and aquifer storage have declined in response to high-volume pumping, interest has increased in the south Denver metropolitan area in obtaining additional sources of water. Aquifer storage and recovery (ASR) has been identified as one process for storing water to meet supply needs. For more than two decades, the Centennial Water and Sanitation District (CWSD), the water supplier for Highlands Ranch in the south Denver metropolitan area, has used ASR to augment water withdrawn from wells completed in Denver Basin bedrock aquifers.[59] During ASR, high-quality treated surface water from the South Platte River is injected into wells in the Denver Basin aquifer system and stored when the supply is available. Water is withdrawn from the aquifers when the demand for water is greater than the supply. Through February 2012, CWSD has injected more than 4.5 billion gallons of water into 19 wells.[60] In Colorado, supplemental water for injection is treated and must meet water-quality standards, and injection wells require permits from the U.S. Environmental Protection Agency and Colorado State Engineer's Office. A major concern about the use of ASR has been potential contamination and (or) plugging of an aquifer as a result of geochemical reactions between the injected water and native aquifer water.[61] For example, injection of oxic river water into anoxic aquifer water could potentially mobilize naturally occurring constituents, such as uranium, present in aquifer sediments, resulting in changes in the quality of water produced by nearby supply wells. Treated water typically contains disinfection byproducts formed during chlorination, for example, trihalomethanes, such as chloroform. An ASR study on injection of treated drinking water found that oxygen in the CWSD-stored water was quickly depleted, and disinfection byproducts in the City of Centennial water-distribution system were removed naturally from the stored water in the aquifer over a period of several weeks.[62] ASR projects also have been implemented by other water suppliers in the Denver Basin area, including Colorado Springs Utilities and the Consolidated Mutual Water Company in Lakewood, Colo. Research on the use of aquifer storage and recovery in the Denver Basin is ongoing.



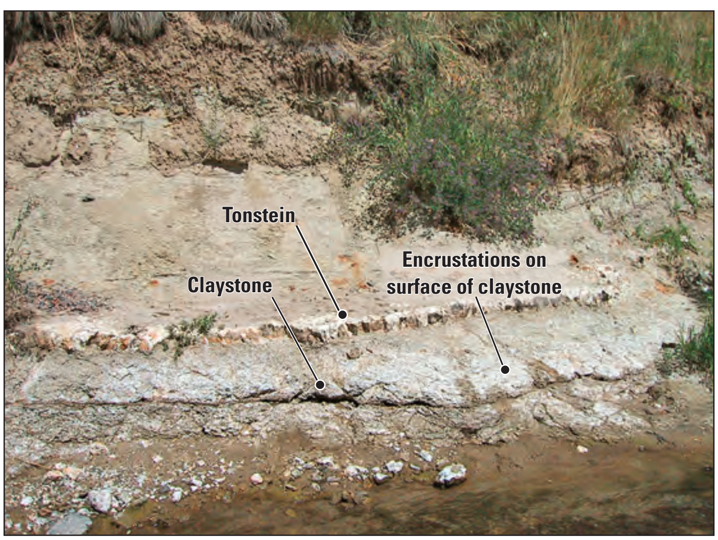
During aquifer storage and recovery, the aquifer essentially acts as a "water bank"—oxygen-rich water is injected into the aquifer and stored during wet periods when there is excess supply and is recovered through pumping during dry periods when additional supply is needed. Contaminants bound to aquifer sediments could potentially dissolve from aquifer sediments when oxic (oxygen-rich) and anoxic (oxygen-reduced) water are mixed.

Natural Processes That Affect Water Quality in the Denver Basin Can Be Accelerated by Human Activities

The chemical composition of recharge water changes as it moves through the unsaturated zone and subsequently through aquifers in the Denver Basin. The composition is controlled by hydrologic and geochemical processes, including precipitation/dissolution reactions, evaporative concentration, and reduction/oxidation reactions that occur naturally in the unsaturated and saturated zones. Each of these processes, however, can be enhanced by human activities, such as irrigation in agricultural and urban areas.

The interaction between water and subsurface materials can add or remove dissolved constituents to water. Precipitation along the Front Range typically contains less than 5 milligrams per liter (mg/L) of dissolved solids.(23) In the same way that water dissolves table salt, recharge water from precipitation dissolves soluble minerals in the unsaturated zone, increasing the concentration of dissolved solids in the water. Once water enters the aquifer, continued reaction of groundwater with aquifer sediments can further increase the dissolved-solids concentration of water, but at a slower rate, as these minerals are less soluble than the salts that accumulate in soils. The dissolution of materials in the subsurface of the Denver Basin, along with evapotranspiration, results in dissolved-solids concentrations that are 100 to 1,000 times more than those of precipitation.

Dissolved solids in the unsaturated zone are concentrated by evapotranspiration as part of annual and long-term (decades to millennia) wetting and drying cycles. As water in the subsurface evaporates or is taken up by plants, soluble salts are left behind. As a result, salts, nitrate, and some trace elements and other dissolved constituents accumulate in the unsaturated zone over time.(24, 25) When recharge water from precipitation reaches zones of salt accumulation, it dissolves the salts and other soluble constituents and transports them downward to the water table. Whether or not these salts actually reach the water table depends on the amount of recharge. Because potential evapotranspiration is five times as high as annual precipitation, the transport of salts to the water table under natural conditions is slow, taking place over hundreds to thousands of years, except in the case of extreme precipitation events or during wet climatic periods.(26) The amount of evaporative concentration, based on results of stable isotope analysis, is estimated to be as high as 36 percent.(20) In practical terms, this means that water with an initial dissolved-solids concentration of 400 mg/L would have a concentration greater than the Secondary Maximum Contaminant Level (SMCL) of 500 mg/L after evaporative concentration. Accumulation of dissolved solids is enhanced with evapotranspiration of excess recharge water from irrigation.



Photograph from Paschke and others(20)

The salt encrustations on the surface of a Denver Formation claystone bedrock outcrop exposed along Toll Gate Creek, Aurora, Colo., are salt deposits formed from ongoing evaporative processes that concentrate selenium and other dissolved materials from underlying bedrock and sediments.(20, 27) An increase in streamflow levels and the water table during storm events and groundwater recharge dissolves the salts, which releases selenium to the stream water. Tonsteins, thin distinct clay deposits of weathered volcanic ash in the Denver Formation, commonly have high selenium concentrations.(22) Bank height is approximately 5 feet; tonstein outcrop is about 3 inches thick.

The presence or absence of oxygen in groundwater affects the occurrence of some contaminants

The amount of dissolved oxygen in groundwater has a substantial effect on geochemical reactions in the subsurface and on water quality (see sidebar, How do redox reactions work?, p. 36). Some naturally occurring trace elements, such as uranium, dissolve when groundwater is oxic (dissolved-oxygen concentration of 0.5 mg/L or more) and precipitate (become solid) when groundwater is anoxic (dissolved-oxygen concentration less than 0.5 mg/L). Conversely, other trace elements, such as iron, precipitate under oxic conditions and dissolve under anoxic conditions (fig. 4–4). Redox (reduction-oxidation) conditions evolve from mostly oxic water in the alluvial aquifer and shallow parts of bedrock aquifers to mostly reducing (anoxic) water in deeper parts of the bedrock aquifers (fig. 4–5). Samples from the Dawson aquifer were mostly oxic; samples from the other bedrock aquifers were mostly anoxic. As oxic water moves deeper along groundwater flow paths, redox conditions commonly change because of biological use of dissolved oxygen and other redox-sensitive constituents by microbes. The downward movement of young, oxic groundwater from the shallow system has resulted in the presence of dissolved oxygen deeper in the aquifer system. Excess irrigation water, heavy pumping, and the injection of oxic surface water during aquifer storage and recovery operations can accelerate this downward movement, which is very slow under natural conditions.

The median concentration of uranium in oxic water was more than 100 times as high as the median concentration of uranium in anoxic water.

The solubility, transport, concentration, and chemical form of many water-quality constituents in groundwater are affected by pH. Some redox-sensitive trace elements, such as iron and manganese, are more soluble under low pH and (or) anoxic conditions. Other trace elements, such as arsenic and selenium, are more mobile when pH is higher. The formation of arsenic minerals, for example, is inhibited as groundwater pH increases. Most (94 percent) pH values in Denver Basin groundwater were between 6.5 and 8.5 (7.0 is neutral). Values of pH outside of this range can affect the concentration of many constituents.

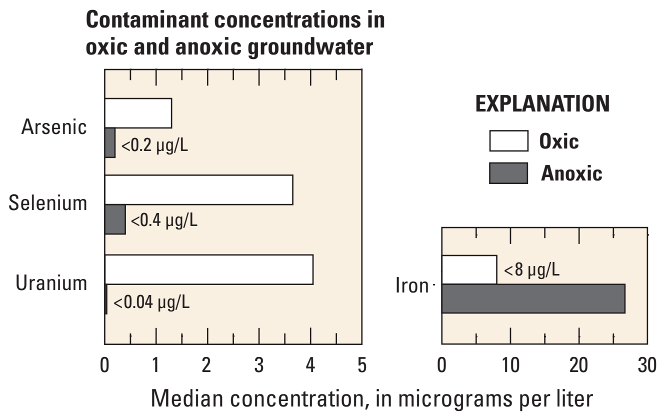


Figure 4–4. Arsenic, selenium, and uranium are readily soluble when groundwater is oxic, so higher concentrations of these constituents are more common in oxic groundwater than anoxic groundwater. The opposite is true for iron. Iron is more soluble when anoxic conditions are present, and concentrations of iron are higher in anoxic groundwater.

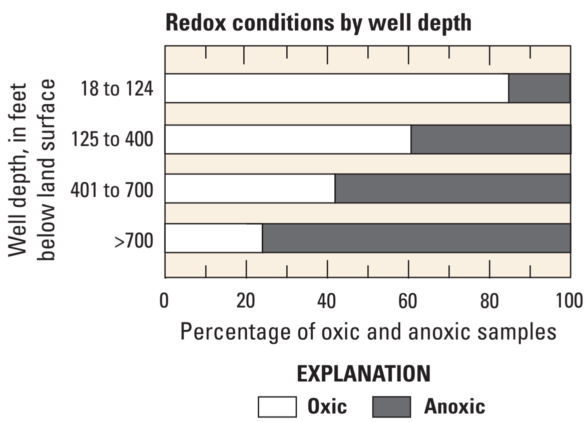
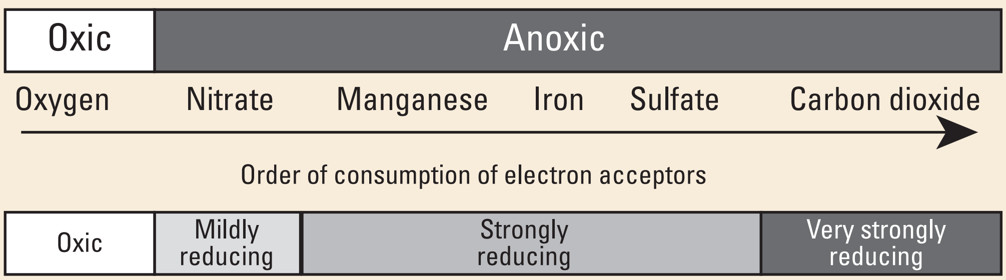


Figure 4–5. Groundwater samples collected from the Denver Basin aquifer system primarily were oxic (dissolved-oxygen concentration of at least 0.5 milligram per liter) at shallow depths and anoxic (dissolved-oxygen concentrations less than 0.5 milligram per liter) at deeper depths.

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 Groundwater Used for Drinking and Irrigation*

Drinking water and irrigation are critical uses of groundwater from the Denver Basin aquifer system. Does the quality of the groundwater support these uses? What are the constituents that might present human-health concerns when the water is used for drinking? What other constituents might adversely affect use of the water? For the Denver Basin aquifer system, chemical constituents of concern for groundwater use originate from geologic sources (uranium, radon, arsenic, selenium, manganese, iron, fluoride, sulfate), human activities (nitrate, pesticides, VOCs), or a combination of both geologic and human sources (dissolved solids).

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

Glass photograph copyright istockphoto.com;
irrigation photograph by Jon Mullen, copyright istockphoto.com

The Quality of Groundwater Used for Drinking Generally Is Very Good

Only about 1 in every 10 Denver Basin wells used for drinking water yielded groundwater that had a concentration of a contaminant that exceeded a human-health benchmark. Concentrations of contaminants from geologic sources exceeded a human-health benchmark seven times more frequently than did concentrations of contaminants from human sources (fig. 5–1). Concentrations of manganese, radon, arsenic, uranium, and selenium—contaminants with geologic sources—each exceeded their human-health benchmark in only a small percentage (less than 5 percent) of drinking-water wells sampled (fig. 5–2; table 5–1). Concentrations of nitrate, which is most commonly associated with human activities, exceeded its human-health benchmark in only 1 percent of drinking-water wells.

In the Denver Basin and nationally, most exceedances of human-health benchmarks were for contaminants from geologic sources.

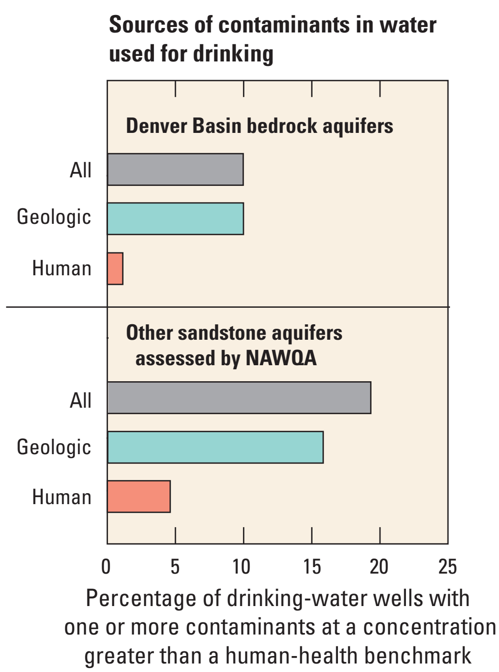


Figure 5–1. Ten percent of wells in the Denver Basin used for drinking water had at least one contaminant with a concentration greater than a human-health benchmark. This was about one-half the frequency of exceedances for drinking-water wells that tap sandstone aquifers nationwide. In the Denver Basin and nationally, most exceedances of human-health benchmarks were for contaminants from geologic sources.

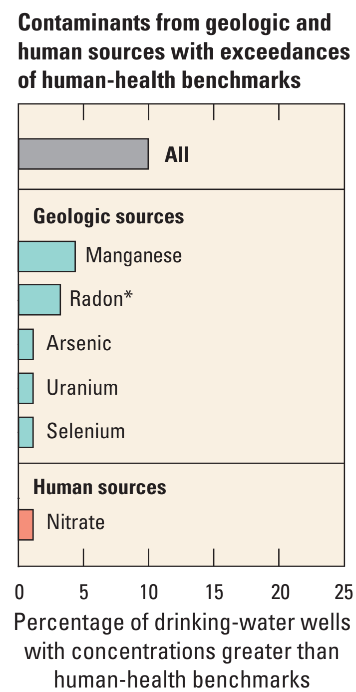


Figure 5–2. Six constituents—five from geologic sources and one from primarily human sources—in Denver Basin groundwater could be a drinking-water concern because concentrations in some wells used for drinking water exceeded human-health benchmarks. Exceedances for arsenic and selenium were slightly more common for Denver Basin groundwater than for other sandstone aquifers across the United States (appendix 3). *Shown here for the proposed Alternative Maximum Contaminant Level (MCL) of 4,000 picocuries per liter (pCi/L); radon values were greater than the proposed MCL of 300 pCi/L in 93 percent of samples.

Table 5–1. Only six constituents were measured in drinking-water wells at a concentration that exceeded a human-health benchmark.

[µg/L, microgram per liter; HBSL, Health-Based Screening Level; pCi/L, picocuries per liter; AMCL, alternative Maximum Contaminant Level; MCL, Maximum Contaminant Level; nitrate, nitrate plus nitrite as nitrogen; mg/L, milligram per liter; N, nitrogen]

Constituent	Human-health benchmark*		Number of wells sampled	Percentage of sampled wells with concentrations greater than	
	Value and unit	Type		Benchmark	One-tenth of benchmark
Contaminants from geologic sources					
Manganese	300 µg/L	HBSL	90	4.4	28
Radon	4,000 pCi/L	Proposed AMCL	58†	3.4	78
	(300 pCi/L)	(Proposed MCL)		93	100
Arsenic	10 µg/L	MCL	90	1.1	27
Uranium	30 µg/L	MCL	90	1.1	13
Selenium	50 µg/L	MCL	90	1.1	8.9
Contaminant from human sources					
Nitrate	10 mg/L as N	MCL	90	1.1	11

* Proposed radon regulations from U.S. Environmental Protection Agency,[76] HBSLs from Toccalino and others,[67] and MCLs from U.S. Environmental Protection Agency.[64]

†Drinking-water wells from the Dawson and Arapahoe aquifers. Samples from the alluvial and shallow bedrock aquifers, drinking-water wells in the Denver and Laramie–Fox Hills aquifers, and samples from most public-supply wells were not analyzed for radon.

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.

"Nuisance" constituents in groundwater used for drinking water might impair taste, odor, and other qualities

"Nuisance" constituents—those that can affect the use of water because they impair the taste or odor of drinking water or cause other non-health-based concerns—were more common in drinking-water wells than were those constituents that can affect human health. The SMCL for at least one nuisance constituent was exceeded in 42 percent of drinking-water wells sampled. An SMCL was exceeded most frequently for manganese and dissolved solids, and somewhat less frequently for iron, fluoride, and sulfate (fig. 5–3; table 5–2). Percentages of exceedances were similar for public-supply wells (40 percent of samples) and domestic wells (43 percent of samples).

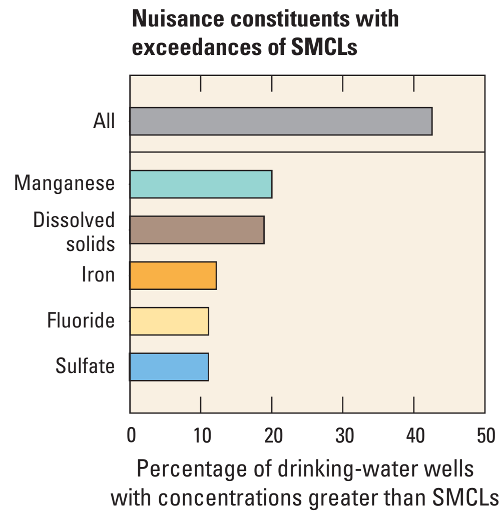


Figure 5–3. Secondary Maximum Contaminant Levels were exceeded more commonly for samples from drinking-water wells than were human-health benchmarks (shown in figure 5–1).

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 292 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 [(64)] (values used in this report were current as of February 2012). Although MCLs are used to regulate the quality of drinking water only from public-supply sources, they also are useful for evaluating the quality of water from domestic and monitoring wells. An MCL was available for 53 of the constituents measured. For some constituents for which an MCL has not been established, the USGS, in collaboration with the USEPA and others, developed non-enforceable HBSLs by using standard USEPA methods for establishing drinking-water guidelines and current toxicity information [(65–67)] (values used in this report were current as of February 2012; see *http://water.usgs.gov/nawqa/HBSL*). An HBSL was available for 135 constituents measured. Radon has neither an MCL nor an HBSL, but two MCLs have been proposed. Copper and lead have USEPA action levels rather than an MCL.

In addition to human-health benchmarks, non-health-based guidelines—Secondary Maximum Contaminant Levels (SMCLs)—were available for some of the constituents measured in this assessment. The SMCLs are non-enforceable guidelines for concentrations of "nuisance" constituents in drinking water that can cause unwanted cosmetic effects, such as skin or tooth discoloration; aesthetic effects, such as unpleasant taste, odor, or color; or technical effects, such as corrosion or sedimentation of plumbing or reduced effectiveness of water treatment.[(68)]

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;[(69)] New Jersey Department of Environmental Protection[(70)]).

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.[(66)] 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.

Table 5–2. Manganese, dissolved solids, and other constituents from geologic sources exceeded values recommended for drinking water for quality reasons other than human health.

[µg/L, microgram per liter; mg/L, milligram per liter. All non-health guidelines are Secondary Maximum Contaminant Levels from the U.S. Environmental Protection Agency.[68] Ninety wells were sampled for each constituent]

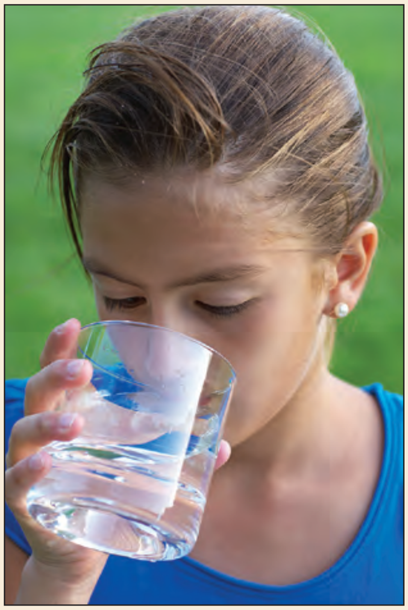
Constituent	Non-health guideline	Percentage of drinking-water wells with concentrations greater than the guideline
Manganese	50 µg/L	20
Dissolved solids	500 mg/L	19
Iron	300 µg/L	12
Fluoride	2.0 mg/L	11
Sulfate	250 mg/L	11

Photograph courtesy of Culligan

Water that contains iron, a nuisance constituent, can have an unpleasant metallic taste and can cause reddish-brown staining of plumbing fixtures, appliances, and laundry. Treatment techniques, including water conditioning and filtration, can remove iron from water.

Why is it important for domestic well owners to understand concentrations of contaminants from geologic and human sources?

Seventy-five of the drinking-water wells sampled in the Denver Basin were domestic wells. Almost all (eight of the nine) samples with at least one exceedance of a human-health benchmark were from domestic wells. Samples from the eight domestic wells had at least one exceedance for contaminants from geologic sources, and one also had an exceedance for a contaminant (nitrate) from human sources. Unlike public-supply wells, routine testing of the quality of water from domestic wells is not required, and domestic well owners rarely test for these contaminants. Domestic well owners in the Denver Basin should be aware of the potential occurrence of contaminants in their well water, especially those from geologic sources, and the potential health risks if contaminants are present at concentrations greater than human-health benchmarks. Information on water testing for domestic wells owners is available from the Colorado Department of Public Health and Environment at *http://www.colorado.gov/cs/Satellite/CDPHE-Lab/CBON/1251594535218*.



Photograph by Gerardo Alvarez, copyright istockphoto.com

Exceedances of benchmarks were common in the shallow aquifer system, which could have implications for water use and the quality of the water in the deeper system used for drinking

Water from wells tapping the shallow aquifer system underlying agricultural and urban areas is less potable than water from deeper wells underlying mixed land uses (figs. 5–4, 5–5). Shallow groundwater is more strongly influenced than deeper groundwater by the release of constituents to water from the interaction of recharge water with minerals in soils and aquifer sediments, by the release of trace elements to groundwater under oxidizing conditions, and by short travel times for contaminants from human sources to reach the water table. Although water from the shallow system typically is not used for drinking, any potential future use of this groundwater for drinking might require treatment or blending with high-quality water from other sources.[28] The deeper drinking-water wells are more isolated from reactions of recharge water with subsurface materials and from potential sources of contamination at land surface than are the shallow monitoring wells. But because of the increase in the downward movement of water with excess recharge from irrigation and high-volume pumping for public supply, the water quality of the shallow system can eventually affect the water quality of the deep system.

Almost 60 percent or more of samples from monitoring wells in the alluvial aquifer and shallow parts of the Dawson and Denver aquifers had concentrations of nuisance constituents (chloride, dissolved solids, fluoride, iron, manganese, and sulfate) that exceeded SMCLs (fig. 5–5), which could affect use of the shallow groundwater. The most common exceedances for the shallow groundwater were for dissolved solids, sulfate, and manganese. Exceedances for manganese and dissolved solids also were most common for the deep groundwater (table 5–2). Fluoride was the only constituent with a low exceedance rate (about 2 percent of wells) of its SMCL for shallow groundwater and a more common exceedance rate (about 11 percent of wells) for deep groundwater.

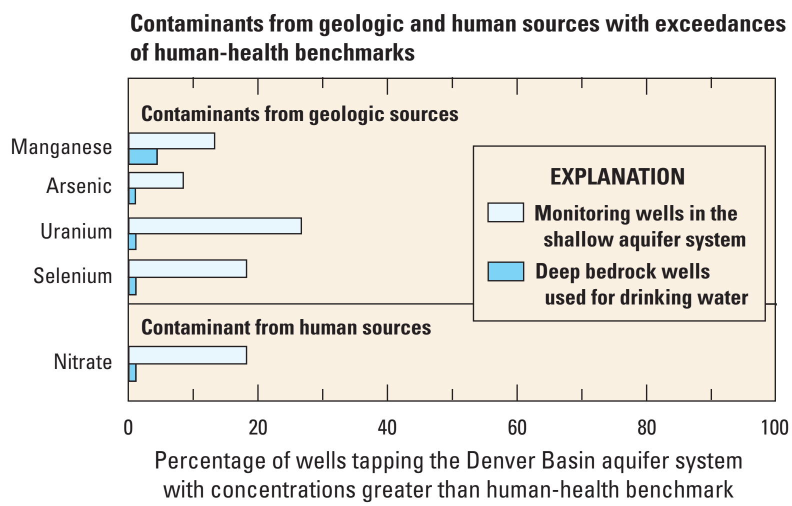


Figure 5–4. Exceedances of human-health benchmarks for five contaminants were common in samples from shallow monitoring wells in agricultural and urban areas but were rare in samples from deeper Denver Basin wells used for drinking water. Human sources of contaminants at or near the land surface and geochemical reactions between infiltrating water and soluble minerals in the unsaturated zone both can contribute contaminants to shallow groundwater but not to deeper groundwater.

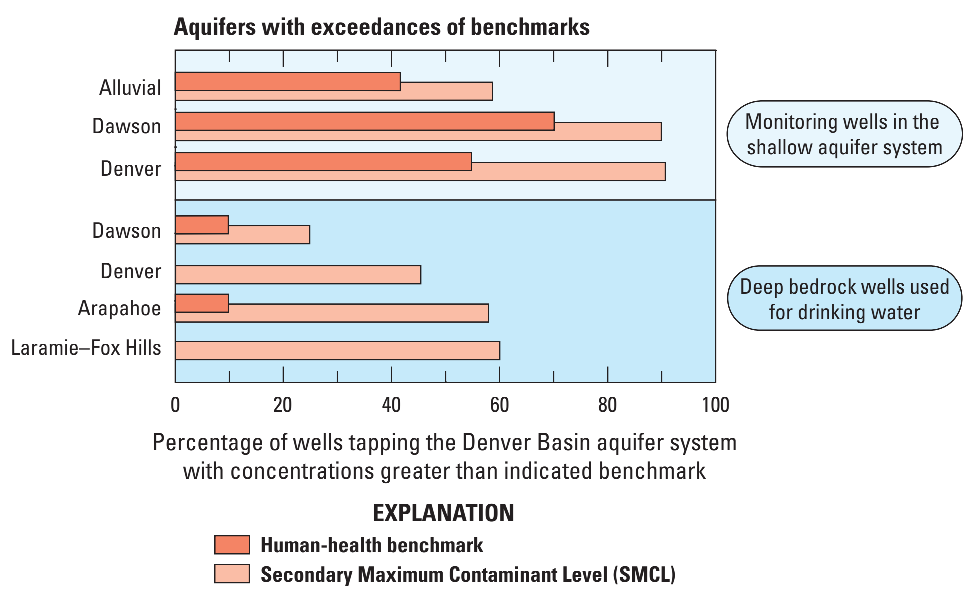


Figure 5–5. The alluvial aquifer and shallow parts of the Dawson and Denver aquifers have poorer water quality relative to benchmarks than do the deeper aquifers used for drinking-water supply. Exceedances of SMCLs for nuisance constituents (chloride, dissolved solids, fluoride, iron, manganese, and sulfate) in all aquifers are much more common than are exceedances for constituents with human-health benchmarks (arsenic, manganese, nitrate, selenium, and uranium).

Quality of water in the alluvial aquifer and potential implications for irrigation

Pumping of water from the alluvial aquifer for irrigation of crops has been the greatest use of shallow groundwater in northeastern Colorado, including parts of the Denver Basin area. The quality of irrigation water can have beneficial or adverse effects on crops, depending on the particular constituents in the water. Use of poor-quality irrigation water in agricultural areas can result in decreased crop production, reduction in water infiltration, scaling of some irrigation systems, ion toxicity (table 5–3), and excessive nutrients.[29, 30] Measurements to evaluate the quality of irrigation water include the total salt content and concentrations of specific constituents in the water.

Water with a low salt content is used to irrigate crops early in the growing season. As plants grow and become less sensitive to salinity, water with a greater amount of salt can be used for irrigation.

In Colorado, excessive amounts of salts in many areas of irrigated agriculture are an ongoing concern. Potential implications from use of Denver Basin alluvial groundwater for irrigation can be evaluated by assessing the quality of water withdrawn from monitoring wells tapping the alluvial aquifer in irrigated crop areas of the South Platte River Basin (see sidebar, Groundwater-quality data from the NAWQA study of the South Platte River Basin, p. 44). On the basis of data for shallow monitoring wells sampled in 1994, salinity hazard and sodium toxicity are potential concerns for farmers irrigating their crops with groundwater pumped from the alluvial aquifer (table 5–3). Water from the monitoring wells was not used for irrigation but can be used to assess potential implications if the water was used for crop irrigation. In some areas of northeastern Colorado, water-use practices have changed because of the poor quality of the alluvial groundwater (see sidebar, The quality of shallow groundwater in agricultural areas has changed water-use practices, below).

Table 5–3. Selected constituents of potential concern for agricultural irrigation.

[mg/L, milligram per liter; —, not applicable; <, less than; >, greater than. General water-quality criteria values are rounded values from milliequivalents per liter. Criteria values from Ayers and Wescot[29]]

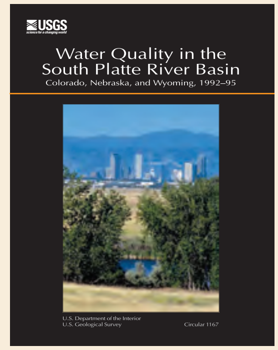
Potential irrigation problem	General water-quality criteria	Percent criteria exceedance for South Platte River alluvial aquifer underlying irrigated cropland
Salinity hazard: Decrease in crop productivity and yield, reduction in water infiltration		
Dissolved solids concentration	mg/L	—
None	<450	0
Slight to moderate	450–2,000	70
Severe	>2,000	30
Excessive bicarbonate: Unsightly deposits on fruits or leaves from overhead sprinklers		
Bicarbonate concentration	mg/L	—
None	<90	0
Slight to moderate	90–520	97
Severe	>520	3
Boron toxicity: Toxic to certain crops, can cause crop damage and reduce crop yield		
Boron concentration	mg/L	—
None	<700	100
Slight to moderate	700–3,000	0
Severe	>3,000	0
Chloride toxicity: Toxic to certain crops, can cause crop damage and reduce crop yield		
Chloride concentration	mg/L	—
None	<140	83
Slight to moderate	140–350	17
Severe	>350	0
Sodium toxicity: Toxic to certain crops, can cause crop damage and reduce crop yield		
Sodium concentration	mg/L	—
None	<70	7
Slight to moderate	70–210	56
Severe	>210	37

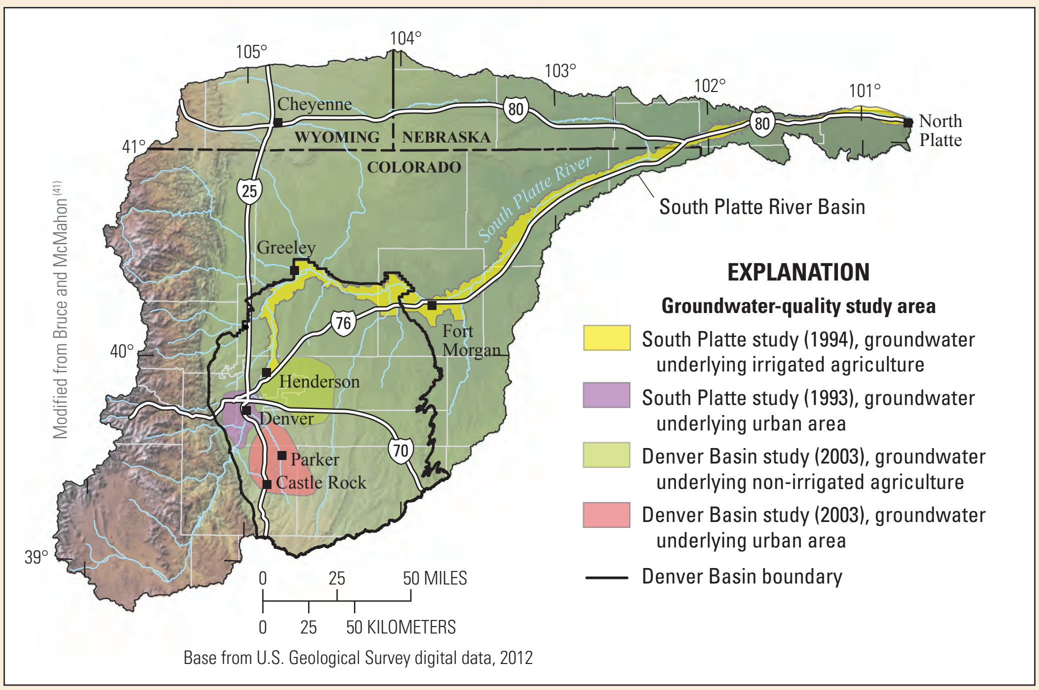
The quality of shallow groundwater in agricultural areas has changed water-use practices

- In far northeastern Colorado, crops that are sensitive to salinity, such as dry beans, are no longer grown. Crop production has changed to crops that are more tolerant of saline soils and water, such as corn (T.A. Bauder, Colorado State University Extension, oral commun., 2013).
- Different sources of water are used on agricultural fields depending on the time of the year. Early in the growing season when crops are most sensitive to saline soils and water, high-quality water from surface-water supplies is used for irrigation. Use of saline groundwater for irrigation increases later in the growing season when plants are more developed and less sensitive to salinity.
- The city of Brighton, Colo., (fig. 2–1), is in a highly productive agricultural area of the Denver Basin. Because of fertilizer used in farming, high concentrations of nitrate can be found in the city's alluvial groundwater supply. In 1993, the city constructed a Reverse Osmosis Water Treatment Plant to reduce the amount of nitrate in the supply water because of health concerns.[71]

Groundwater-quality data from the NAWQA study of the South Platte River Basin

Water quality of the South Platte River Basin, which partially overlies the Denver Basin bedrock aquifers but also extends north and east into western Nebraska, was assessed during 1992–95 as part of the NAWQA Program.[32, 41] Results from two studies of water quality of the alluvial aquifer underlying agricultural and urban areas of the South Platte River Basin are included in this circular to supplement water-quality data for the Denver Basin. The two study areas for the South Platte assessment were (1) the primary irrigated agricultural areas (corn was the major crop in 1994) that overlie the alluvial aquifer along the South Platte River downstream from Denver to the mouth of the basin in North Platte, Nebraska, and (2) the older urban area of Denver and nearby suburbs that overlie the alluvial aquifer along major tributaries to the South Platte River.





Groundwater-quality studies in the South Platte River Basin in 1993–94 and the Denver Basin in 2003–05 both included land-use studies in agricultural and urban areas. Assessing the quality of groundwater that underlies different types of land uses (irrigated corn and non-irrigated wheat in agricultural areas, older urban development and suburban areas developed primarily after about 1970) contributes to the understanding of groundwater resources in the Denver Basin. The quality of groundwater in the South Platte River Basin and Denver Basin are shown in a national context in appendix 4.

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

The quality of Denver Basin groundwater used for drinking is generally good, with very few of the samples collected containing a contaminant at a concentration of concern for human health. The quality of shallow groundwater, however, is quite different—the water is poor quality, with high concentrations of several contaminants making it unsuitable for drinking without costly treatment. Pumping and irrigation have changed the hydrology of the Denver Basin, increasing the downward movement of water from shallow to deep parts of the aquifer system. This change raises a number of questions about Denver Basin groundwater quality. Will human alteration of the hydrology impair the quality of the groundwater in the deep bedrock aquifers used for drinking water? Is degradation of the drinking-water resource already present in some parts of the aquifer system and, if so, where? If not, how soon might such degradation occur and how might such degradation be prevented? Are there geochemical processes that will prevent contamination in shallow groundwater from reaching the deeper groundwater used for drinking? Answering these questions may be critical for water-resource managers who need to forecast how changes in water and land use will affect groundwater quality in the Denver Basin and similar basins along the Front Range.

This chapter describes the sources of and natural and human factors that affect the occurrence and distribution of uranium, radon, arsenic, selenium, manganese, dissolved solids, nitrate, pesticide compounds, and VOCs in Denver Basin groundwater.

Source of contaminants to Denver Basin groundwater include geologic materials and human activities in agricultural and urban areas. Background, outcrop of the Dawson Arkose. Inset, Castle Rock, Colo., a growing bedroom community south of Denver, relies primarily on groundwater for water supply.

Inset photograph by Steve Krull, copyright istockphoto.com

Constituents from Geologic Sources: Uranium and Radon

Concentrations of uranium in drinking-water samples rarely exceeded the MCL of 30 µg/L, but uranium concentrations in one of every four samples of shallow groundwater were greater than the MCL. Two factors control concentrations of uranium in Denver Basin groundwater: (1) whether the soils and aquifer sediments contain uranium and (2) whether the groundwater contains dissolved oxygen. Irrigation in agricultural and urban areas has increased the volume of oxic recharge water that can react with shallow uranium-rich materials in the subsurface, leading to elevated concentrations of uranium in shallow groundwater. Pumping can move oxic recharge water deeper into the aquifer system, potentially releasing uranium in aquifers tapped by drinking-water wells. Consumption of drinking water with high concentrations of uranium can pose a risk to human health. Radon, produced by the radioactive decay of uranium, was measured only in samples from drinking-water wells in the Dawson and Arapahoe aquifers—concentrations rarely exceeded the proposed Alternative Maximum Contaminant Level (AMCL) of 4,000 pCi/L but exceeded the proposed MCL of 300 pCi/L in almost every sample. The use of well water that contains radon, a carcinogen, can be a source of radon detected in indoor air.

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

Aquifer sediments and rocks are the sources of uranium, but human activities have increased concentrations of uranium in shallow groundwater

The reaction between uranium-rich aquifer sediments and oxic recharge water causes uranium, a radionuclide, to be released into groundwater. As a result, high concentrations (greater than 30 µg/L) in the Denver Basin aquifer system were detected about 25 times more frequently in samples of shallow groundwater than in samples from deeper groundwater used for drinking-water supply (fig. 6–1). Exceedances of the MCL for uranium of 30 µg/L were found only in samples from monitoring wells in the alluvial and Dawson aquifers and one relatively shallow drinking-water well, also tapping the Dawson aquifer. Samples from the shallow aquifer system contained concentrations of dissolved uranium as high as 941 µg/L (the maximum concentration measured in all Denver Basin groundwater samples), and almost all of the samples were oxic. In contrast, concentrations of uranium in groundwater samples collected from deeper parts of the aquifer system typically were low and only one contained uranium at a concentration exceeding the MCL; most of these samples were anoxic. High concentrations of uranium in drinking water can lead to increased risk of cancer and kidney toxicity in humans.[31]

Granitic rock eroded from the Rocky Mountains, volcanic ash, claystone, and shale are the main sources of uranium in Denver Basin groundwater. Materials rich in uranium make up parts of the alluvial, Dawson, and Arapaho aquifers, and, to a lesser extent, the Denver aquifer (fig. 6–2).[32, 33]

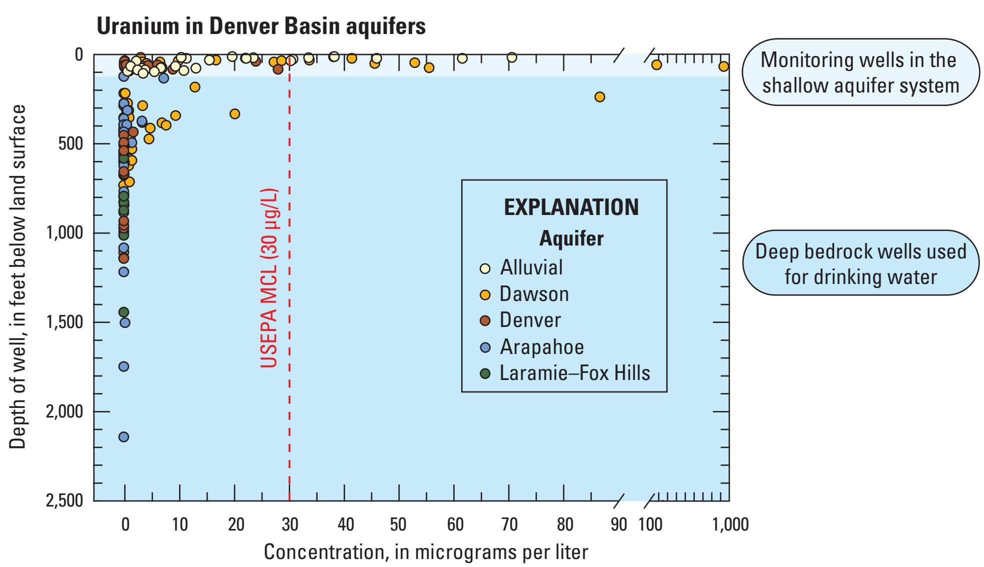
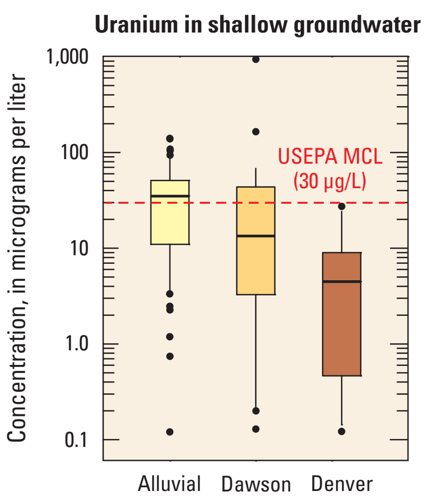


Figure 6–1. Concentrations of dissolved uranium in Denver Basin groundwater were greatest in samples from monitoring wells in the alluvial and shallow bedrock aquifers. Only samples from the alluvial and Dawson aquifers had concentrations that exceeded the MCL for uranium of 30 µg/L.

Sediments from the Pikes Peak granite that have been weathering for millions of years are one source of uranium and radon in the Denver Basin aquifer system.



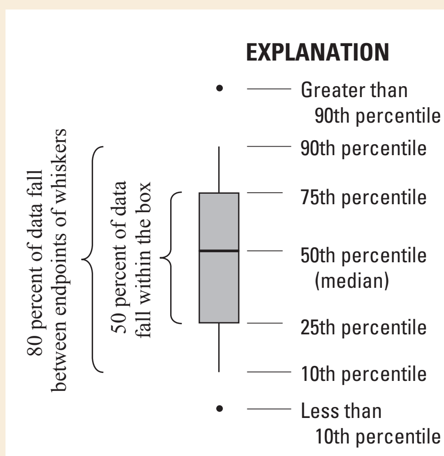
See sidebar, Boxplots, at right

Figure 6–2. Uranium-rich minerals in the sediments that make up the alluvial and Dawson aquifers release uranium to shallow groundwater. Sediments that make up the Denver aquifer contain less uranium, and concentrations in groundwater are lower than those in the alluvial and Dawson aquifers.

Boxplots

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

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



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

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

Uranium is most soluble in water that contains dissolved oxygen. At shallow depths, oxic water releases uranium from the aquifer material. Where water is anoxic, uranium adheres to mineral surfaces or forms insoluble minerals, removing the uranium from groundwater (fig. 6–3).

Recharge to groundwater has increased since development of water resources for irrigation began in earnest around 1925. The amount of recharge in the basin is greatest in irrigated cropland (10 in/yr), intermediate in urban and residential areas (2.5 in/yr), and lowest in non-irrigated areas (0.1 to 1.3 in/yr).[2] Irrigation delivers a large volume of oxic water to uranium-rich sediments in the subsurface. In the alluvial aquifer, median uranium concentrations and related MCL exceedances were highest for groundwater underlying irrigated cropland and lowest for groundwater underlying non-irrigated wheat fields (fig. 6–4). The lithology of aquifer materials also affects uranium concentrations. Monitoring wells in the irrigated cropland and irrigated urban areas tap the alluvial and Dawson aquifers, which are rich in uranium-containing minerals, whereas monitoring wells in the non-irrigated agricultural area tap the Denver aquifer, which contains less uranium (fig. 6–2).[32, 33] Both the amount of uranium in soils and aquifer sediments and oxic recharge control uranium concentrations in Denver Basin groundwater.

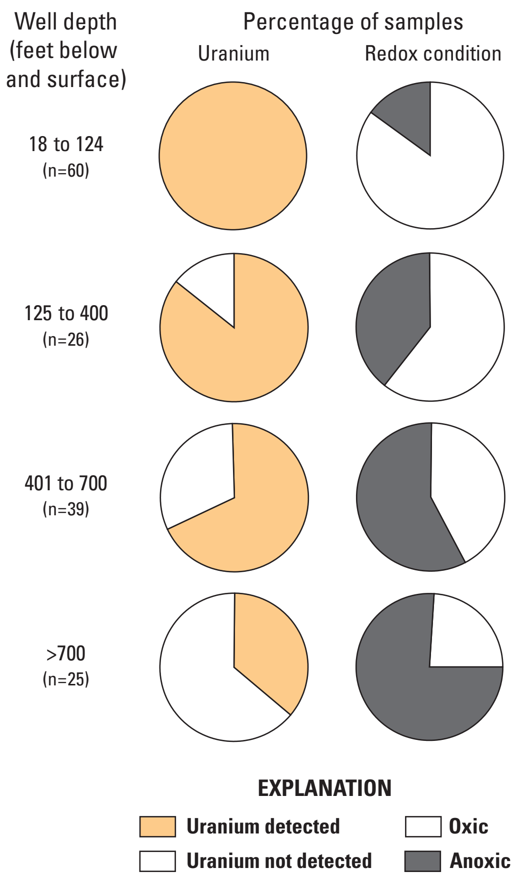


Figure 6–3. Uranium was detected most commonly in samples of shallow groundwater that were oxic. As water moves deeper in the aquifer system, conditions become more anoxic, and dissolved uranium can adsorb to aquifer sediments or precipitate as insoluble uranium minerals and become undetectable in a water sample. [n=number of samples]

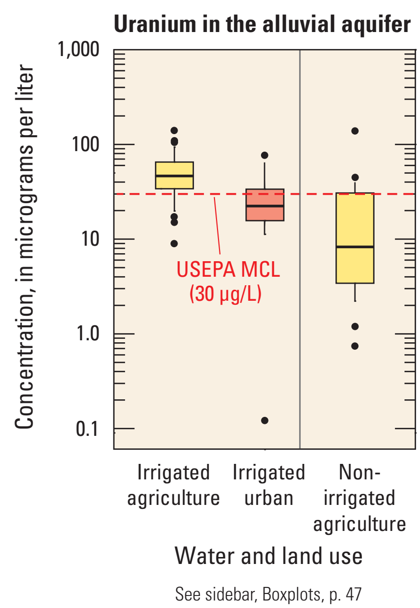
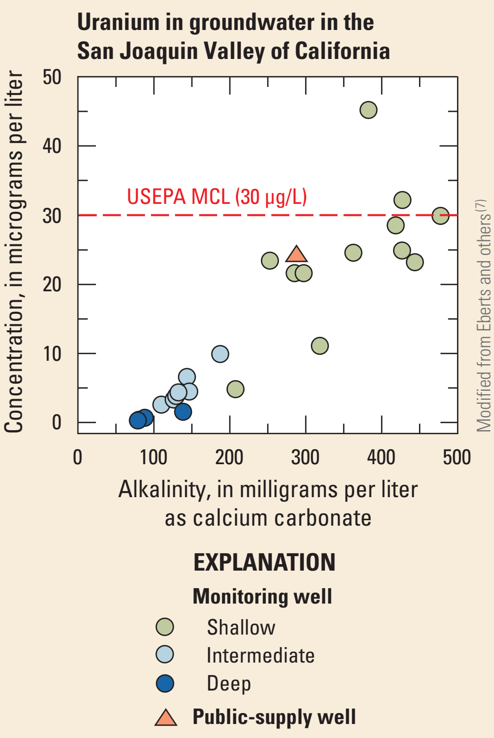


Figure 6–4. Irrigation of agricultural and urban areas provides oxic recharge water to the alluvial aquifer, which can cause uranium in sediments that make up the aquifer to be released to groundwater. Less uranium is found in groundwater beneath agricultural areas that are not irrigated.

A cautionary tale: Irrigation and pumping have increased uranium concentrations in groundwater in the Central Valley of California

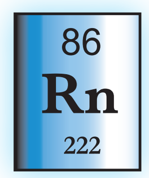
Elevated concentrations of uranium in Denver Basin groundwater are not unique in the western United States. The effects of development in agricultural and urban areas on the presence of uranium in groundwater are illustrated in the Central Valley of California,[7] one of the most productive agricultural areas in the world. In the eastern San Joaquin Valley, which makes up the southern two-thirds of the Central Valley, irrigation and pumping during 100 years of agricultural and urban development have changed the chemistry and magnitude of recharge water and increased the downward flow of water in the basin-fill aquifer system.[49] High-alkalinity (primarily bicarbonate ions) water resulting from irrigation recharge has reacted with sediments in the shallow part of the basin-fill aquifer to dissolve uranium into the groundwater—a process that has increased uranium concentrations in shallow groundwater since agricultural activities began. Additional downward movement of water from pumping and irrigation has caused young shallow groundwater with high alkalinity and uranium concentrations to migrate to deeper parts of the aquifer system tapped by public-supply wells.[49] This downward movement and additional dissolution of uranium likely will increase uranium concentrations in shallow and deeper public-supply wells in the future. Such increases could potentially occur in the Denver Basin and other semiarid to arid regions that have similar alkalinity and uranium occurrence, irrigation recharge, and groundwater pumping as those found in the eastern San Joaquin Valley.



In the eastern San Joaquin Valley near Modesto, Calif., concentrations of alkalinity and uranium were highest in shallow groundwater, which has been altered geochemically by irrigation in agricultural and urban areas.[7] Groundwater in the deepest part of the aquifer system represents water recharged under more natural conditions,[72] and alkalinity and uranium are low. At intermediate depths, shallow groundwater has been drawn downward by pumping and irrigation, and alkalinity and uranium concentrations are characteristic of a mixture of both shallow water and deep groundwater. Elevated concentrations of dissolved uranium have been detected in a public-supply well near Modesto, Calif., and in other public-supply wells in the San Joaquin Valley because the deep wells draw in uranium-rich shallow groundwater.

Photograph from NRCS, California

Radon, a natural decay product of uranium, is found at high concentrations in Denver Basin groundwater

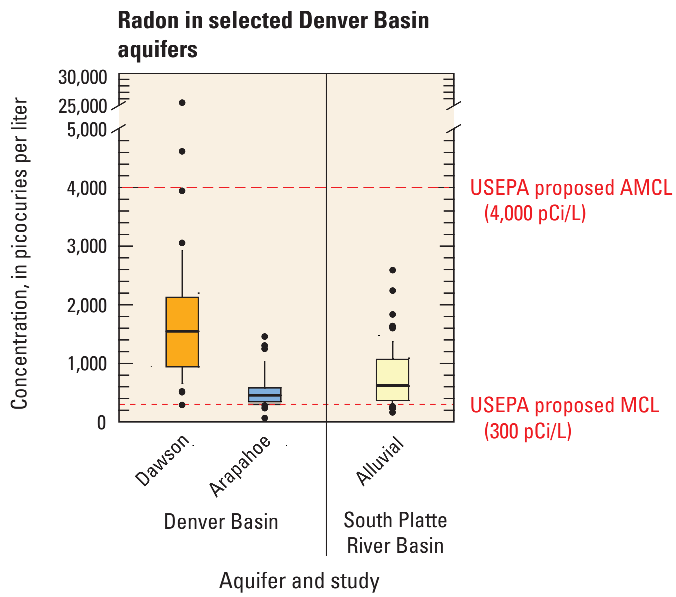


Radon is an element that results from the radioactive decay of uranium in aquifer materials. Radon in drinking water is associated with lung cancer and stomach cancer.

Radon was measured only in samples from drinking-water wells in the Dawson and Arapahoe aquifers. Only 3 percent of those samples had concentrations that exceeded the proposed AMCL of 4,000 pCi/L, but almost all of the samples (93 percent) had concentrations that exceeded the lower proposed MCL of 300 pCi/L (table 5–1). Radon was not measured in samples from the drinking-water wells in the Denver and Laramie–Fox Hills aquifers or the shallow monitoring wells in areas of agricultural and urban land use.

Radon, a radionuclide, is found naturally in rocks, soil, water, and air as a dissolved gas and results from the radioactive decay of uranium and radium. Concentrations of radon in groundwater depend on the uranium and radium content of soils and aquifer sediments, aquifer properties such as porosity, and the proximity of radon to its source materials.[34] Radon decays rapidly in groundwater, and high radon concentrations are not likely to be found in groundwater that is relatively distant from the natural radioactive source.[35] Because radon is a gas, it can dissolve into groundwater and be released into the air of a home when water is used (see sidebar, Facts about radon, p. 51). The primary health risk from radon in water is the inhalation of radon gas, which can cause lung cancer.

Radon concentrations in water from wells in the Dawson aquifer were substantially greater than those for Arapahoe aquifer wells and for alluvial wells from the South Platte River Basin study; the median concentration for the Dawson aquifer was about two or three times more than that for the alluvial and Arapahoe aquifer wells, respectively (fig. 6–5). High concentrations of radon in Dawson aquifer wells are associated with uranium-bearing granitic sediments in the aquifer.



See sidebar, Boxplots, p. 47

Figure 6–5. Concentrations of radon in samples from drinking-water wells in the Dawson aquifer were greater than in those from the Arapahoe aquifer and from monitoring wells in the alluvial aquifer sampled in 1993 during the South Platte River Basin study. Exceedances of the proposed MCL for almost all samples indicate that radon concentrations are of potential concern for human health.

Facts about radon

Why is radon a concern?

Radon is the second-leading cause of lung cancer in the United States after smoking. High concentrations of radon in the air have been linked to an estimated 20,000 lung cancer deaths in the United States each year.[73, 74] Ingestion of radon through drinking water contributes to about 168 cancer deaths each year.[74, 75]

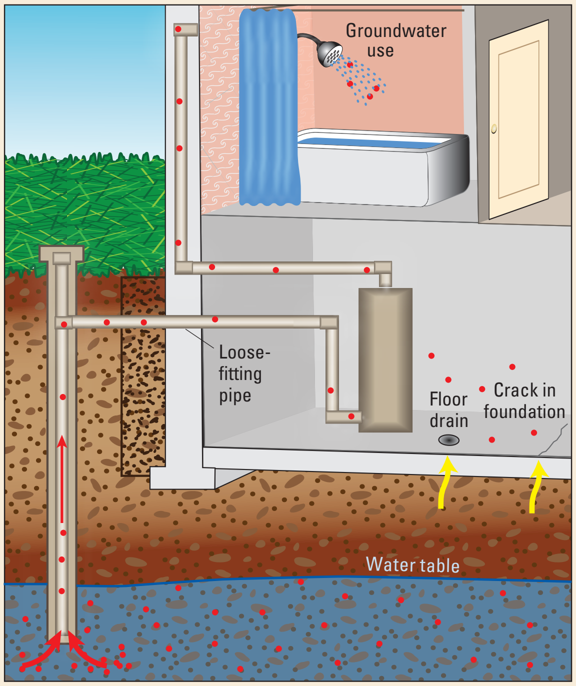
Are there human-health benchmarks for radon?

Because of the radiation emitted by radon and the associated human-health risks, two benchmarks have been proposed by the U.S. Environmental Protection Agency (USEPA) to limit the acceptable amount of radon in drinking water. The proposed MCL of 300 pCi/L and proposed AMCL of 4,000 pCi/L provide two options for the amount of radon that will be allowed in community drinking-water resources.[74] The lower proposed MCL for radon applies to States and public water systems that do not develop programs to address health risks from radon in indoor air, whereas the higher proposed AMCL applies to States and public water systems that have established such programs.[76]

Where can I find more information on radon?

- Colorado Department of Public Health and Environment: Radon outreach, *http://www.colorado.gov/cs/Satellite/CDPHE-HM/CBON/1251617274212* (Hazardous Materials and Waste Management Division, Radiation Program)
- USEPA: Radon information, including "A Citizen's Guide to Radon," *http://www.epa.gov/radon/*
- USGS: The geology of radon, *http://energy.cr.usgs.gov/radon/georadon/1.html*

Ways for radon to enter a home

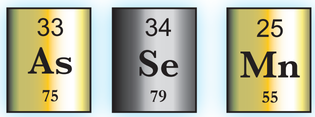


Two sources of radon gas in a home are groundwater use and soil gas. The red dots represent radon. Red arrows represent the movement of radon dissolved in groundwater toward and in the well, and the yellow arrows represent upward diffusion of radon gas from soil, rock, and groundwater beneath the house.

Chapter 6

Radon and Colorado homeowners

The Colorado Department of Public Health and Environment (CDPHE) has estimated that about 50 percent of homes in Colorado have indoor radon gas levels that exceed the USEPA recommended action level of 4 pCi/L, a non-enforceable health advisory.[78] In the Denver Basin, indoor air radon levels were tested in more than 120,000 homes and businesses from 1995 through 2011 (data by zip code, provided by Chrys Kelley, CDPHE). The median concentration for all tests was about 3.6 pCi/L. About 46 percent of the concentrations were greater than 4.0 pCi/L. The CDPHE recommends that all homes in Colorado be tested for the presence of indoor air radon gas and that homeowners in Colorado using a domestic well test their well water for radon if the concentration of radon gas in indoor air is greater than the action level. The CDPHE Web site[78] addresses radon issues in the State and provides information on radon risks and radon test kits.



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.

In small amounts, the trace element selenium is essential for human and animal health, but excessive concentrations can be toxic. Some aquatic biota are particularly sensitive to the amount of selenium in water.

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.

Other Constituents from Geologic Sources: Arsenic, Selenium, and Manganese

Similar to uranium, exceedances of human-health benchmarks for arsenic, selenium, and manganese were more common in samples from alluvial and shallow bedrock wells than in those from drinking-water wells. Concentrations of these three trace elements in Denver Basin groundwater depend in part on the composition of geologic source material, redox conditions, and pH of groundwater. Arsenic and selenium in Denver Basin sediments dissolve more readily with recharge of oxic groundwater. In contrast, manganese in Denver Basin sediments dissolves more readily into anoxic groundwater, particularly if the groundwater has low pH, but also can dissolve in oxic groundwater. High concentrations of arsenic, selenium, and manganese in drinking water can adversely affect human health.

Concentrations of dissolved arsenic, selenium, and manganese that exceeded their respective human-health benchmark primarily were detected in groundwater from wells that tap the alluvial aquifer and (or) shallow parts of the Dawson and Denver aquifers but were rare in groundwater from drinking-water wells (fig. 6–6). There was only one exceedance of benchmarks for arsenic and selenium and only four exceedances for manganese in wells used for drinking water, and all of these wells were in the Dawson or Arapahoe aquifers.

At high concentrations, all three trace elements can affect human and aquatic health and (or) water use. Arsenic is a known human carcinogen and can harm the gastrointestinal, cardiovascular, and nervous systems.[36] Selenium has been linked to circulatory system dysfunction in humans, and skeletal deformities, decreased reproduction, and mortality in animals, birds, and fish.[37, 38] Manganese can impair neurological function.[39] High concentrations of manganese in water also can cause drinking water to taste bad, increase water treatment costs, and cause staining and mineral deposits in plumbing systems.

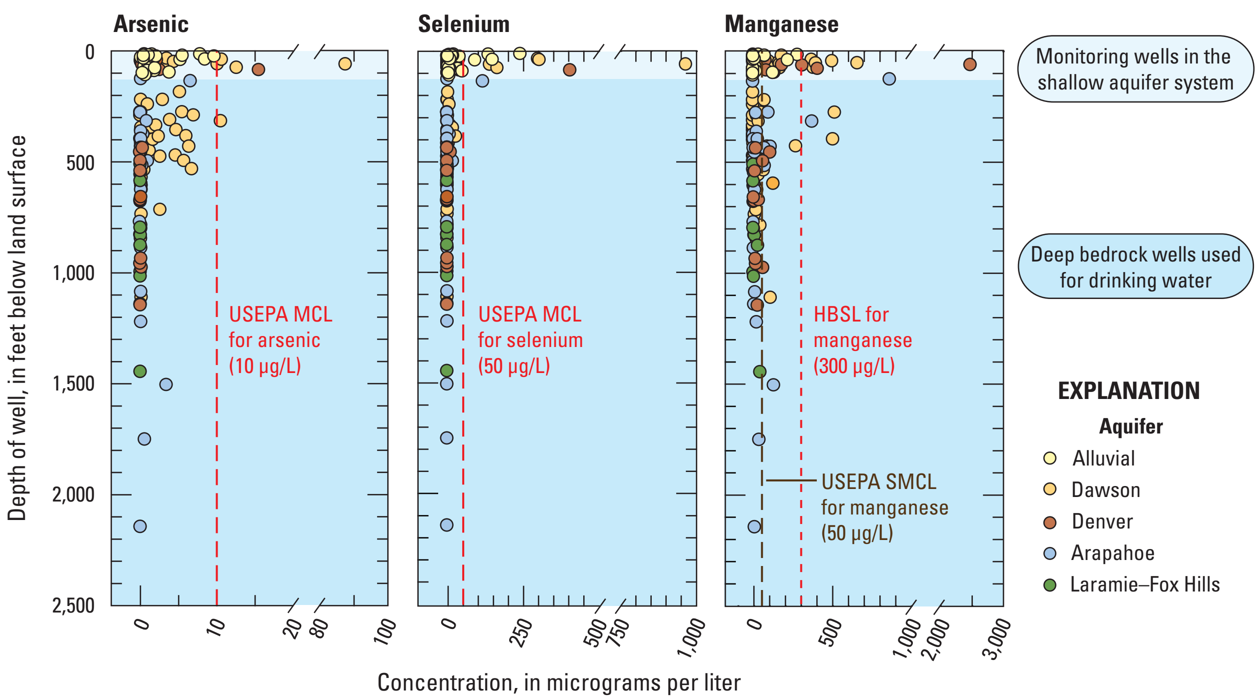


Figure 6–6. Concentrations of dissolved arsenic, selenium, and manganese were greater than MCLs, the HBSL, and the SMCL in samples from all aquifers except the Laramie–Fox Hills aquifer. Exceedances of the human-health benchmarks (MCLs and HBSL) for the three trace elements and the SMCL for manganese were less common for samples from drinking-water wells than for those from monitoring wells that tap the shallow aquifer system. Human-health benchmark exceedances for drinking-water wells only were found in samples from the Dawson and Arapahoe aquifers. These wells were relatively shallow—the maximum well depth for a sample from a drinking-water well with an exceedance was 400 feet below land surface.

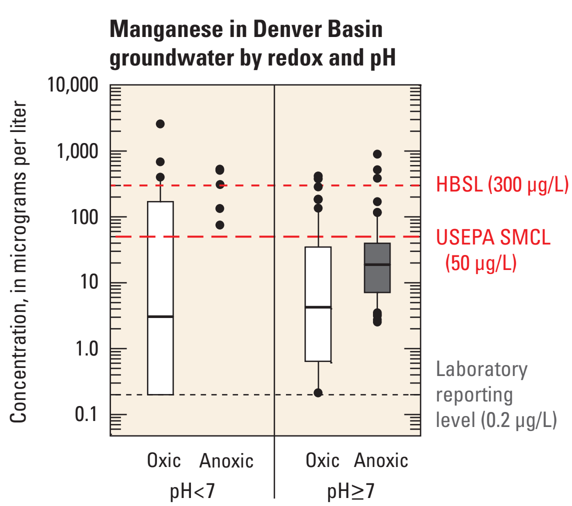
Geologic source material, redox, and pH account for differences in the occurrence and distribution of arsenic, selenium, and manganese in Denver Basin groundwater

Concentrations of arsenic, selenium, and manganese in Denver Basin groundwater, which ranged from less than laboratory reporting levels to exceedances of human-health benchmarks, depend on many factors including the composition of aquifer rock and sediment, redox conditions, pH, chemical adsorption and desorption, mineral precipitation, and biological activity. Understanding the occurrence of these trace elements in groundwater and the sources and mechanisms that affect their release into groundwater is important for human health and the health of animals and aquatic biota.

Arsenic, selenium, and manganese are found naturally in many minerals, rocks, and soils. Possible sources of arsenic in the Denver Basin include volcanic-ash deposits, shales, pyrite, and iron-oxide grain coating on sediment. Organic-rich bentonite claystones, lignite deposits, and tonsteins in the Denver Formation are sources of selenium.[22] Some rocks and sediment of the Denver Basin contain high concentrations of manganese, which, under the right geochemical conditions, can dissolve into groundwater.

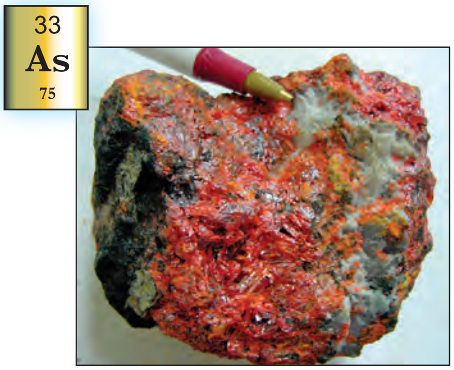
Similar to patterns observed for uranium, the occurrence and distribution of arsenic and selenium in shallow groundwater have been affected by increased recharge of oxic irrigation waters and minerals present in subsurface sediments. For samples from all wells, median arsenic and selenium concentrations were greater in oxic groundwater than in anoxic groundwater (fig. 4–4). Five of the six arsenic samples and all selenium samples with exceedances of the respective MCLs were oxic. Most samples with detectable concentrations of arsenic were from Dawson aquifer wells (fig. 6–6).

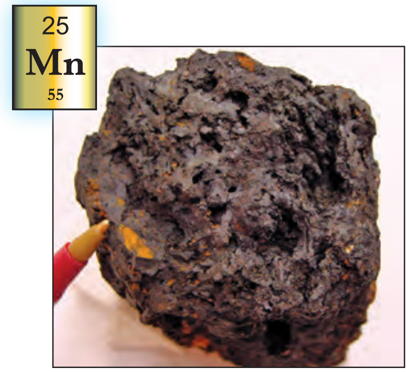
Manganese typically dissolves more readily in groundwater when dissolved-oxygen concentrations are low; therefore, manganese concentrations commonly are greater in anoxic groundwater than in oxic groundwater. In the Denver Basin, the median manganese concentration in samples of anoxic groundwater was about five times more than that in samples of oxic groundwater. Concentrations of manganese, however, exceeded benchmarks with similar frequencies for anoxic and oxic samples—6 to 10 percent for the Health-Based Screening Level (HBSL) and 20 to 21 percent for the SMCL. The similarity in frequency of exceedances likely results from the widespread occurrence of manganese in aquifer sediments and mixed redox conditions; more than 50 percent of samples with benchmark exceedances had chemical signatures suggestive of mixed redox conditions. For anoxic samples, pH also affected manganese solubility. All anoxic samples with pH less than 7 had manganese concentrations greater than 50 µg/L; most anoxic samples with pH of 7 or more had manganese concentrations less than 50 µg/L (fig. 6–7).



See sidebar, Boxplots, p. 47

Figure 6–7. Manganese concentrations in Denver Basin groundwater tended to be greater in anoxic groundwater than in oxic groundwater, regardless of pH. This finding is consistent with results from a study of trace elements in groundwater from across the Nation that reported that some trace elements, such as iron and manganese, are more likely to be released from aquifer sediments to groundwater under low pH and (or) anoxic conditions.[87]





Photographs by Andrew Silver, Brigham Young University

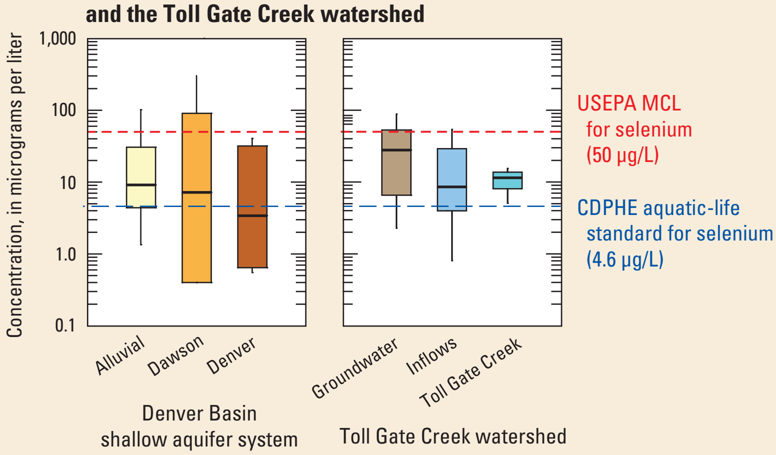
Many contaminants from geologic sources originate from the weathering and dissolution of rocks and minerals that make up Denver Basin soils and aquifer sediments. Example sources include realgar, an arsenic sulfide; native selenium; and pyrolusite, a manganese oxide.

Selenium in Denver Basin groundwater can impair water quality in streams

In the Denver Basin, the interaction of recharge water from agricultural and urban irrigation with selenium-bearing rocks and soils can cause selenium to dissolve and move down with the recharge water to the water table. Samples from wells in the shallow aquifer system commonly had selenium concentrations that exceeded the CDPHE aquatic-life standard of 4.6 µg/L. Where Denver Basin groundwater provides base flow to streams, such as the South Platte River and Toll Gate Creek in Aurora, Colo., high concentrations of selenium in groundwater pose a threat to aquatic life. This threat is more important in streams where the streamflow has changed from ephemeral to perennial because of increased discharge of groundwater associated with a higher water table.

Since the early 2000s, selenium concentrations in Toll Gate Creek (fig. 3–1) have consistently been greater than the CDPHE aquatic-life standard of 4.6 µg/L. Previous studies of selenium in Toll Gate Creek provide specific examples of the effects of groundwater on surface-water quality and ecosystem health.[20, 27] The primary geologic source of selenium to Toll Gate Creek is organic-rich claystone contained in the Denver Formation.[22] Selenium in the claystone dissolves when selenium-bearing minerals react with oxic water, and selenium in evaporative salt deposits dissolves during groundwater recharge and high streamflow events. Concentrations of selenium in more than 84 percent of groundwater samples from wells in the Toll Gate Creek watershed were greater than the aquatic-life standard, and some concentrations were greater than the MCL of 50 µg/L. Most concentrations of selenium in inflows to Toll Gate Creek that represent groundwater discharge to the stream were greater than the aquatic-life standard, as were concentrations in almost all downstream reaches of Toll Gate Creek. Data for Toll Gate Creek graph and other information from Paschke and others.[20]

Selenium in Denver Basin shallow groundwater and the Toll Gate Creek watershed



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High concentrations of selenium in surface water and groundwater can adversely affect the health of wildlife and aquatic biota. About 45 to 72 percent of samples from the alluvial aquifer and shallow parts of the Dawson and Denver aquifers had selenium concentrations that were greater than the Colorado Department of Public Health and Environment aquatic-life standard for selenium of 4.6 µg/L. Concentrations in about 72 to 97 percent of samples collected from groundwater, inflows, or streams in the Toll Gate Creek watershed in Aurora, Colo., during July and August 2007 also were greater than the aquatic-life standard.

Dissolved Solids

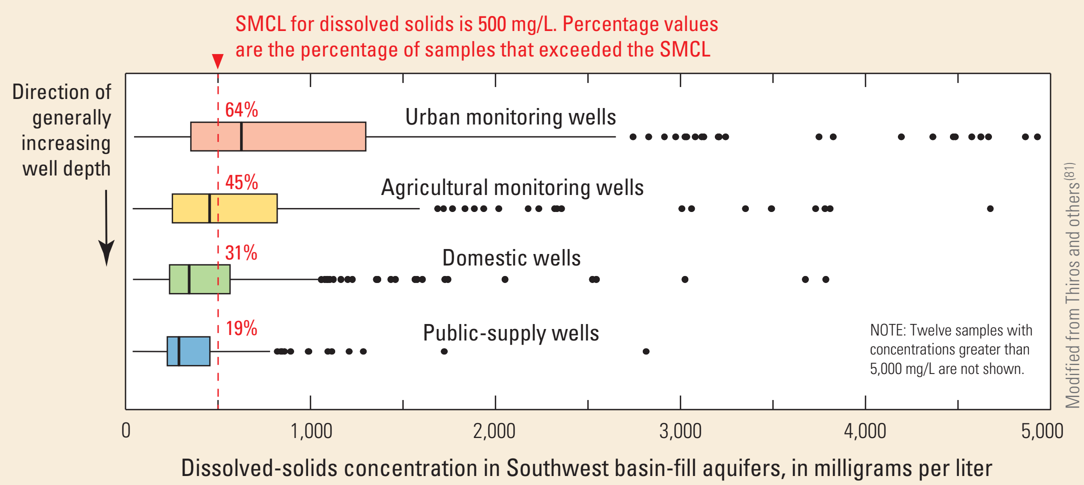
Two of every three samples of shallow groundwater contained dissolved solids at concentrations that exceeded the SMCL of 500 mg/L, which could limit use of shallow groundwater as a future source of drinking water or even irrigation supply without costly treatment or blending. One of every five drinking-water wells sampled, which pump water from deep parts of the aquifer system, had dissolved-solids concentrations that exceeded the SMCL. Dissolved solids that result naturally from mineral dissolution and evaporative concentration in the subsurface are carried to the water table with precipitation recharge. In areas of urban and agricultural development, excess recharge water associated with irrigation leads to further dissolution of soluble salts and minerals and high concentrations of dissolved solids in shallow groundwater underlying these areas. Concentrations of dissolved solids in deeper parts of bedrock aquifers likely result from natural interactions between the groundwater and the rock that are found with distance along with flow paths over long residence times.

What are dissolved solids?

The term “dissolved solids” is a measure of all substances dissolved in water. Calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and silica typically constitute most of the dissolved solids in water. The concentration of dissolved solids is reported in milligrams per liter and represents the total amount of dry solids, in milligrams, that remain after all the water in a 1-liter sample is evaporated at a temperature of 180 degrees Celsius. Water with a concentration of dissolved solids less than 1,000 mg/L is referred to as “fresh.” Slightly or moderately saline water typically is considered to have 1,000–10,000 mg/L dissolved solids.[79] Whether water with high dissolved solids tastes good or bad depends on personal preference, but water containing more than 3,000 mg/L dissolved solids generally is too salty to drink.[80]

Dissolved solids in the Denver Basin, High Plains, and Southwest basin-fill aquifers

The decrease in dissolved-solids concentrations that occurs with depth in the Denver Basin also occurs in the High Plains aquifer system, which underlies a large area of the Great Plains. Although dissolved- solids concentrations typically increase with depth in rangeland and undeveloped areas of the Great Plains,[25] dissolved-solids concentrations in groundwater underlying agricultural areas are high in shallow groundwater because of agricultural recharge. In Southwest basin-fill aquifers—the Basin and Range basin-fill aquifers, California Coastal Basin, Central Valley aquifer system, and Rio Grande aquifer system—salts in the subsurface are concentrated by evapotranspiration in the semiarid to arid regions.[81] As in the Denver Basin, dissolved-solids concentrations are high in shallower parts of Southwest basin-fill aquifers, and the SMCL for dissolved solids was exceeded more commonly in shallow groundwater beneath agricultural and urban areas than in deeper parts used for domestic and public supply.[81]



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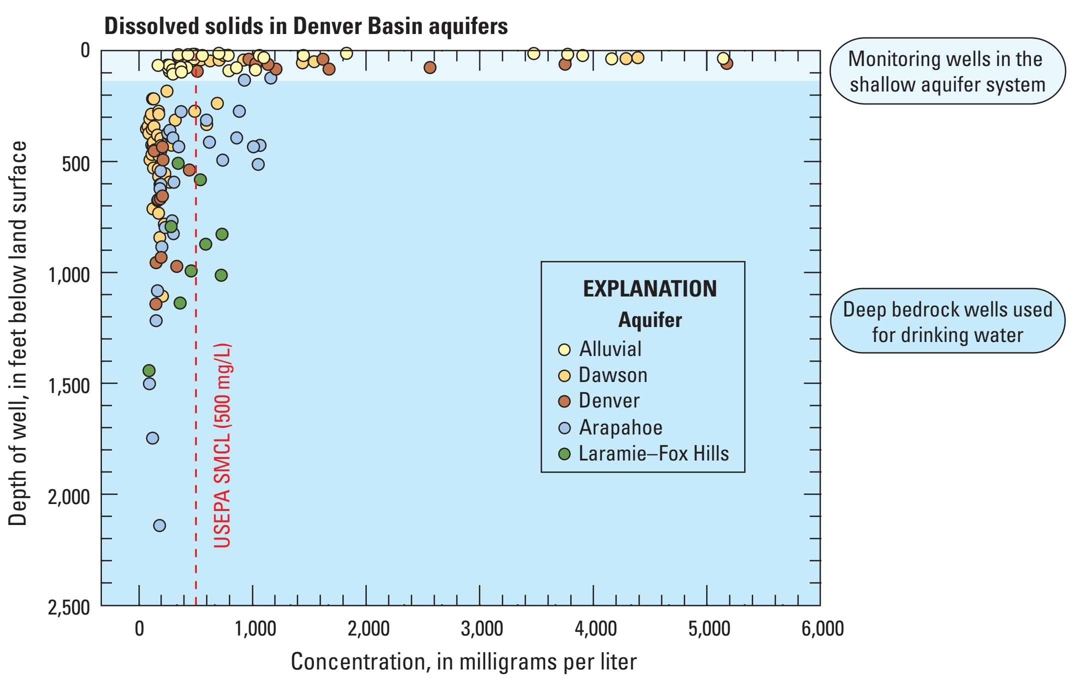
Dissolution and evaporative concentration are two natural processes that can cause the dissolved-solids concentrations in shallow groundwater of the Denver Basin to increase. Precipitation dissolves minerals and other materials in the soil. When some of that water evaporates, the dissolved solids are concentrated in the water that remains. Under natural conditions, further evaporation in the unsaturated zone results in the formation of soluble salts that can eventually be flushed down to the water table during wet periods. In the Denver Basin, irrigation water applied to the land surface in agricultural and urban areas increases the dissolution of soluble salts that have been accumulated from evaporation in the unsaturated zone under natural, semiarid conditions. The amount of soluble salts in the unsaturated zone increases when excess recharge water from irrigation evaporates. Movement of accumulated salts to the water table occurs over time in response to repeated irrigation cycles or periods of above normal precipitation; however, the rate of downward movement is substantially greater in irrigated parts of the basin relative to natural processes.

Concentrations of dissolved solids in Denver Basin groundwater were greatest in samples from the alluvial and shallow parts of bedrock and decreased with depth below the water table (fig. 6–8). Concentrations in samples of groundwater from alluvial and shallow bedrock aquifers were as high as 5,200 mg/L, whereas the maximum concentration in samples from drinking-water wells in deeper parts of bedrock aquifers was about 1,200 mg/L. Exceedances of the dissolved solids SMCL mirror the difference in concentrations—66 percent exceedance for shallow aquifer system samples and 20 percent exceedance for the deep aquifer system samples. In a national context, shallow groundwater in the Denver Basin was of poorer quality than was shallow groundwater underlying other agricultural and urban areas across the Nation; only about one in three samples from shallow aquifers nationally had dissolved-solids concentrations that were greater than the SMCL. For the bedrock aquifers, the frequency of exceedances of the SMCL was the same as that for similar settings nationwide.

Figure 6–8. Concentrations of dissolved solids were greatest in samples from the alluvial and shallow bedrock aquifers of the Denver Basin and decreased as well depth increased. There were fewer exceedances of the SMCL in samples from deeper parts of bedrock aquifers than in samples from the shallow aquifer system.



The use of brackish water to meet supply needs can be costly

To address overuse of Denver Basin groundwater and fill future gaps in water supply, water providers in the Denver Basin area are increasingly looking to use poor-quality alluvial groundwater to meet supply needs. The East Cherry Creek Valley Water and Sanitation District (ECCV), working with the United Water and Sanitation District, developed alluvial wells in Beebe Draw (a paleochannel of the South Platte River in the northern reaches of the Denver Basin) for withdrawal of brackish groundwater to develop additional supply. In order to meet water-quality goals, concentrations of dissolved solids and other constituents in the groundwater need to be reduced. The ECCV has constructed a 10-million-gallon per day Reverse Osmosis (RO) treatment plant for treating the brackish water. Estimated cost for the RO treatment system, and deep well/brine handling facilities is $35 million (Chris Douglass, East Cherry Creek Valley Water and Sanitation District, written commun., 2013; estimated costs as of January 2013).

Photographs from East Cherry Creek Valley Water and Sanitation District

Irrigation in agricultural areas and landscape watering in urban areas has increased dissolved-solids concentrations in the underlying groundwater. Dissolved-solids concentrations in all samples from the alluvial aquifer underlying areas of irrigated agriculture in the South Platte River Basin exceeded the SMCL, as did most samples from urban areas (fig. 6–9). The occurrence of dissolved-solids concentrations greater than the SMCL was greatest for samples of young (recharged since the 1950s) groundwater collected from shallow aquifers. Leaching of chemicals applied to the land surface, such as fertilizers and road deicing salts in agricultural and urban areas, and reaction between some applied chemicals and minerals in the subsurface also contribute to increased concentrations of dissolved solids near the water table.[2, 40, 41]

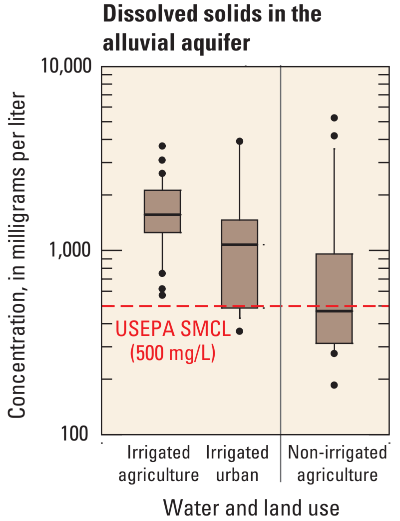


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Figure 6–9. Concentrations of dissolved solids in groundwater underlying irrigated agricultural and urban areas exceeded the SMCL of 500 mg/L in almost every sample, because excess recharge water from crop and landscape irrigation increased the movement of dissolved solids to the water table. In contrast, about half of the samples from non-irrigated agricultural areas exceeded the SMCL level.

Contaminants Derived Primarily from Human Activities: Nitrate

Concentrations of nitrate exceeded the MCL of 10 mg/L as nitrogen in one of every five samples collected from the alluvial and shallow bedrock wells but rarely exceeded the MCL in samples of groundwater from deep bedrock wells. At high concentrations, nitrate in drinking water can cause health problems. The presence of nitrate is controlled by the presence or absence of sources of nitrogen, irrigation practices, and groundwater redox conditions. In a given area, nitrate is most prevalent and is detected at higher concentrations when more nitrogen and water are applied to the land surface and when groundwater is oxic.

Nitrate is a form of nitrogen, an essential nutrient for human health and plant and animal growth. Of the different chemical forms of nitrogen in groundwater, only nitrate typically is found at concentrations that can be harmful to human health and impair aquatic systems. Excess nitrate in drinking water is associated with adverse human-health effects, including methemoglobinemia ("blue-baby syndrome"), which can cause infants to become severely ill or die.[42]

Only 1 of the 90 drinking-water wells sampled in the Denver Basin had a nitrate concentration greater than the MCL of 10 mg/L as nitrogen. The highest concentrations of nitrate were detected in samples of shallow groundwater underlying agricultural and urban areas in the basin (fig. 6–10): concentrations in about 18 percent of samples from the alluvial aquifer and shallow parts of the Dawson and Denver aquifers in these areas were greater than the MCL. The discharge of nitrogen-enriched groundwater to surface water increases the likelihood of eutrophication, including harmful algal blooms. Too much algal growth can adversely affect water quality and human, aquatic-biota, and ecosystem health.

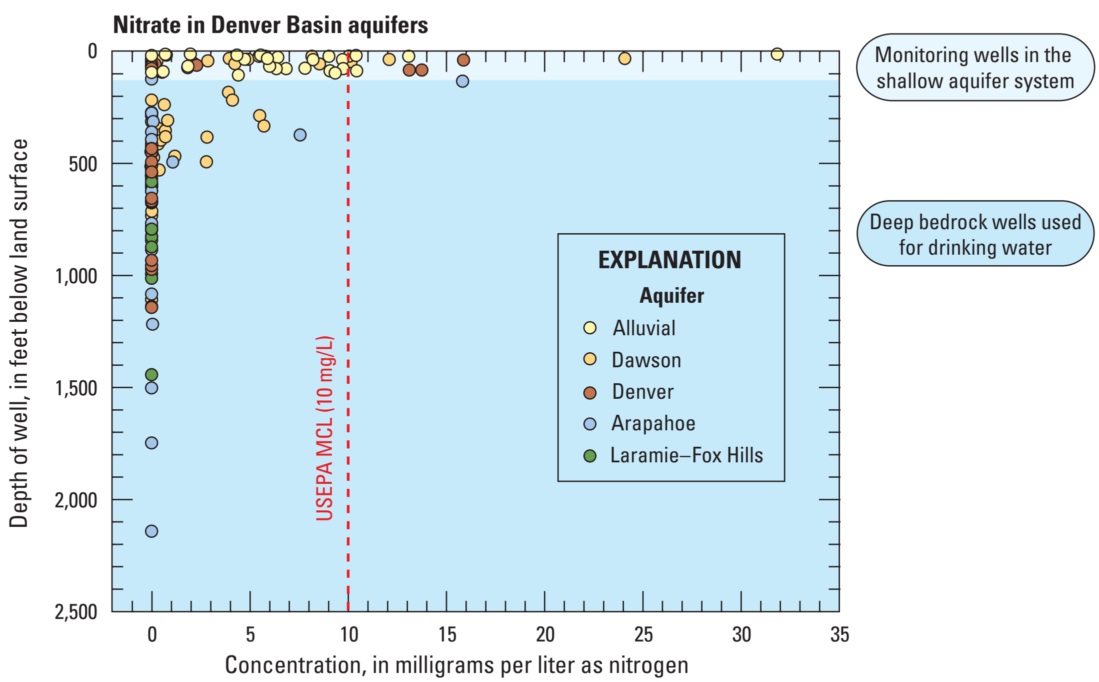
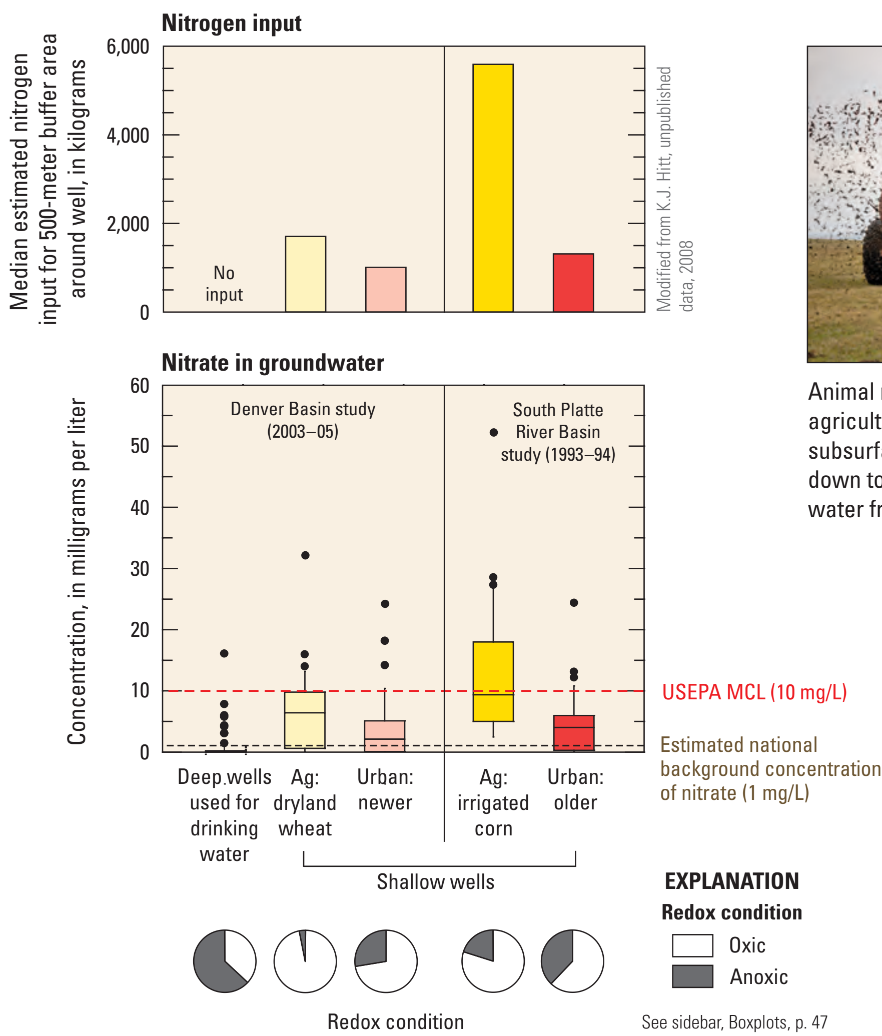


Figure 6–10. Concentrations of nitrate were greatest in samples from the shallow aquifer system and decreased with increasing well depth. Only one sample from a drinking-water well had a nitrate concentration that exceeded the MCL of 10 mg/L as nitrogen. At 140 feet deep, that well, in the Arapahoe aquifer near Brighton, Colo. (an area prone to high nitrate concentrations in groundwater), is one of the shallowest drinking-water wells sampled for this study. About two-thirds of the shallow groundwater samples had nitrate concentrations greater than 1 mg/L, generally considered the threshold for contamination from human activities.[46] The threshold was exceeded in 10 percent of the wells used for drinking water, at depths of as much as 500 feet.

Importance of nitrogen sources and excess irrigation to nitrate concentration in shallow groundwater

Nitrogen is found naturally in plants, animals, soils, the atmosphere, and in some rocks and minerals. Human activity and sources, however, are the primary cause of elevated concentrations of nitrate in groundwater, including application of chemical fertilizers and manure, feedlots, animal waste, biosolids disposal, urban runoff, wastewater-treatment effluent, leaky sewer lines, and septic systems.

When grassland and rangeland are first converted to agriculture, excess recharge water from irrigation can flush nitrate that has accumulated naturally in the unsaturated zone down to the water table.[25] Once agricultural land is established, nitrogen-containing fertilizers routinely applied to the land surface are an additional source of nitrate to shallow groundwater. The amount of nitrogen applied depends on crop type: recommended application rates range from 75 pounds of nitrogen per acre for dryland winter wheat (expected yield, 50 bushels per acre) to 210 pounds of nitrogen per acre for irrigated corn (expected yield, 175 bushels per acre), assuming similar soil nitrogen organic matter content.[43, 44] The effect of nitrogen applications rates and irrigation practices on nitrate concentrations in shallow groundwater is illustrated by results for the Denver Basin and South Platte River Basin studies (fig. 6–11). The median concentration of nitrate in shallow groundwater underlying irrigated areas where corn is grown and fertilizer application rates are high was about 50 percent more than in shallow groundwater underlying non-irrigated areas where dryland wheat is grown and fertilizer application rates generally are low. Thus, application rates of nitrogen and the intensity of irrigation are important controls on the occurrence of nitrate in shallow groundwater.



Photograph by Mike Dabell, copyright istockphoto.com

Animal manure applied as a fertilizer to agricultural fields is a source of nitrogen to the subsurface. Nitrate, a form of nitrogen, moves down to the water table with excess recharge water from irrigation.

Figure 6–11. Nitrate concentrations are highest where application rates of nitrogen are high and groundwater primarily is oxic, for example in shallow groundwater underlying irrigated agricultural areas (Ag). As water moves deeper into the aquifer system where water is anoxic, nitrate concentrations decrease through oxidation/reduction processes.

Fertilization and watering of landscaping in urban areas also can deliver nitrogen to shallow groundwater. Fertilizers are commonly applied to turf grass and other landscaping, and these areas are irrigated in the sense that they are watered regularly—outdoor watering, mostly of lawns, accounts for about 50 percent of the water used by urban residents along the Front Range. Most nitrate concentrations in shallow groundwater underlying urban areas of metropolitan Denver were greater than 1 mg/L, indicating contamination from human activities. Although estimated nitrogen inputs for older developed areas and more recently developed areas were similar, the median concentration of nitrate in shallow groundwater was about twice as high for older parts of the Denver metropolitan area than for areas of newer suburban development (fig. 6–11). This difference probably reflects the relatively long time—years to decades—it takes for water and contaminants to move from the land surface down to the water table. As a result, nitrate associated with recent urban development likely has not yet reached the groundwater sampled for this assessment.(45, 46) Many of the communities in the south Denver metropolitan area with recent development, such as Castle Rock and Parker, have landscape and irrigation standards or recommendations to reduce water use, including planting drought-tolerant plants, which need less fertilization than lawns (fig. 6–12). Reducing the use of irrigation water and fertilizers could decrease the amount of nitrate that reaches the water table.

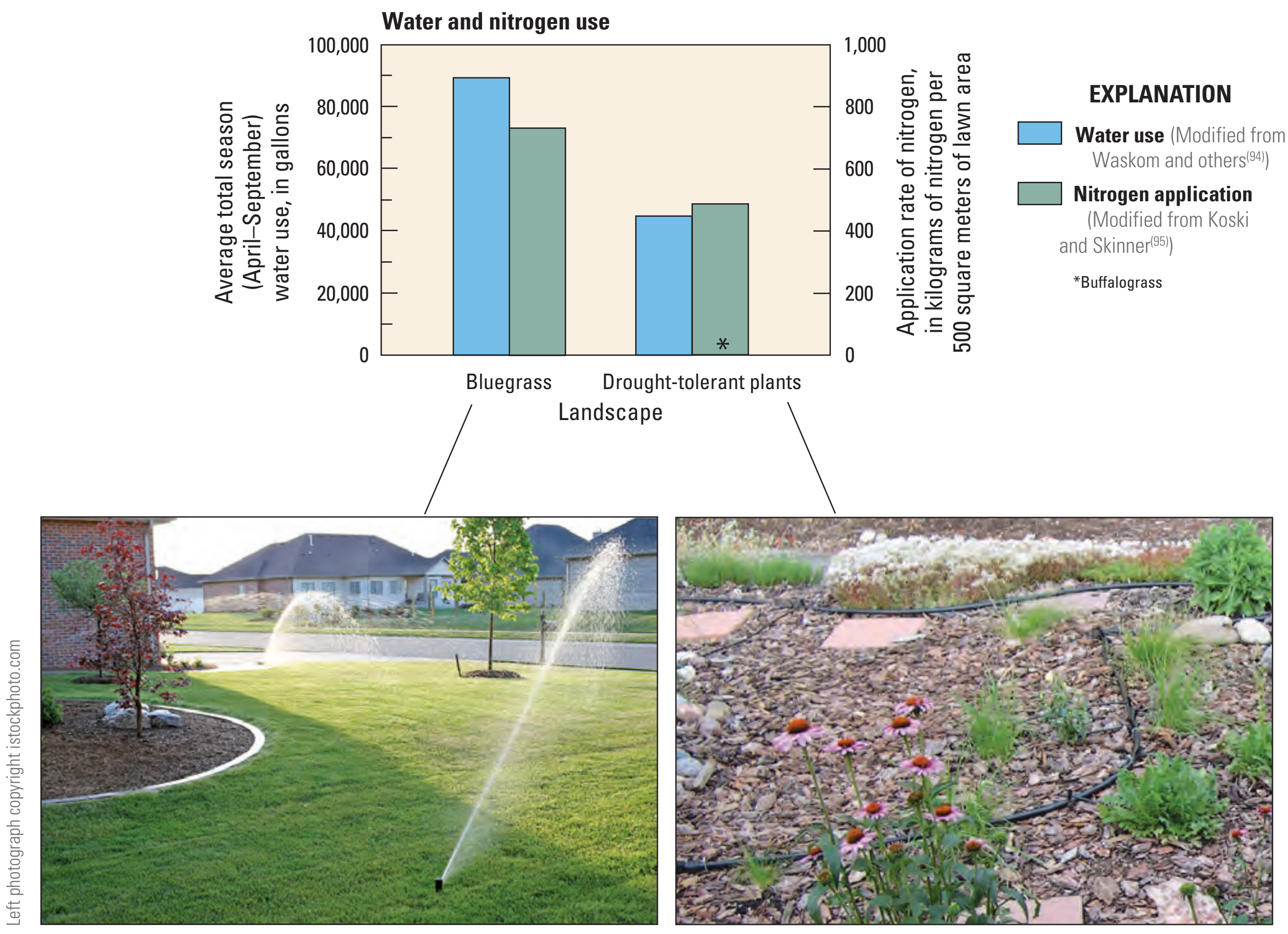


Figure 6–12. About half of the water used in urban residential areas of the Front Range is for outdoor watering, primarily of lawns.[15] Depending on the type of grass grown, some lawns require large amounts of water and fertilization to grow properly. Communities throughout the Denver metropolitan area stress the importance of using water efficiently for landscaping—the choice of plants and irrigation system can greatly reduce water use. Traditional lawns (left) require more water and fertilizer applications than do drought-tolerant plants (right) on drip irrigations systems.

Denitrification decreases nitrate concentrations in groundwater

Input of nitrogen is one factor that controls concentrations of nitrate in groundwater, but redox conditions also are important for nitrate occurrence. Once nitrate is in groundwater, the only way that it can be removed naturally is by denitrification, a process that reduces nitrate to harmless nitrogen gas (see sidebar, How do redox reactions work?, p. 36). Denitrification occurs only when conditions are anoxic—it does not occur in oxic groundwater. As a result, for areas where amounts of nitrogen inputs are similar, nitrate concentrations are lower in anoxic groundwater than in oxic groundwater; where there are no nitrogen inputs, nitrate concentrations in groundwater are negligible regardless of redox condition (fig. 6–13).

Nitrate concentrations in samples from drinking-water wells decreased as well depth and the percentage of wells with anoxic water increased (fig. 6–14). The long amount of time required for water to travel from the water table to deeper parts of the aquifer system provides more time for nitrate to be transformed to nitrogen gas by denitrification reactions. In samples from the deepest wells, where anoxic conditions were most common, nitrate was rarely detected. In addition to redox processes and denitrification, the decrease in nitrate with well depth might also reflect older groundwater (centuries to millennia old) that recharged the aquifer before extensive agricultural or urban development occurred in the Denver Basin.[18]

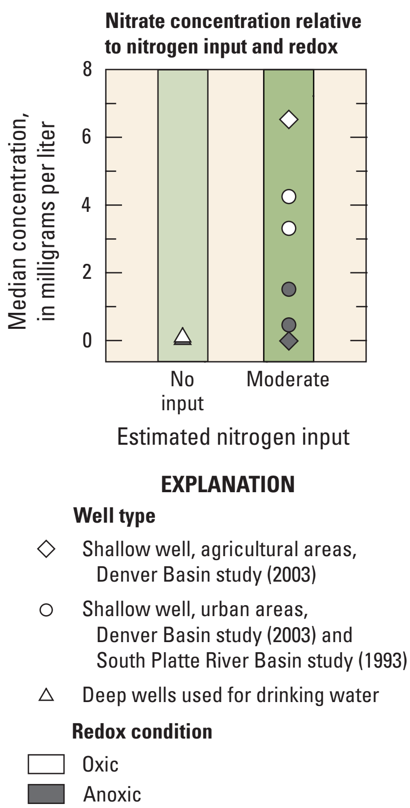


Figure 6–13. Nitrate concentrations are controlled by nitrogen inputs and redox condition. Where there are no nitrogen inputs, such as in deep groundwater used for drinking, nitrate concentrations are negligible, in both oxic and anoxic groundwater. Where nitrogen inputs are similar, such as in shallow groundwater, nitrate concentrations are consistently greater when conditions are oxic and decrease when conditions are anoxic. (Moderate nitrate input: 1,000–2,000 kilograms for 500-meter buffer area around well [K.J. Hitt, unpub. data, 2008].)

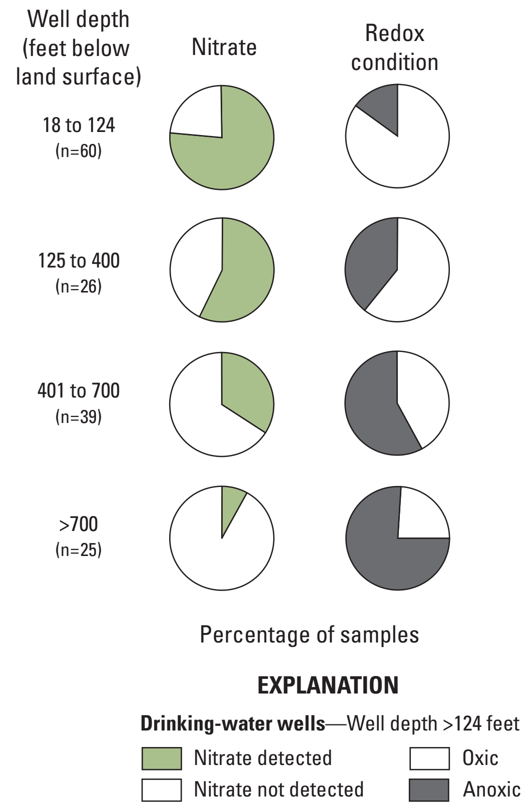


Figure 6–14. Nitrate was most commonly detected in monitoring wells that tap groundwater at the shallowest depths, where oxic conditions were most dominant. Detections of nitrate decreased as well depth and the occurrence of anoxic conditions increased. Only 8 percent of samples from the deepest drinking-water wells, most of which had anoxic water, contained detectable concentrations of nitrate. [n=number of samples]

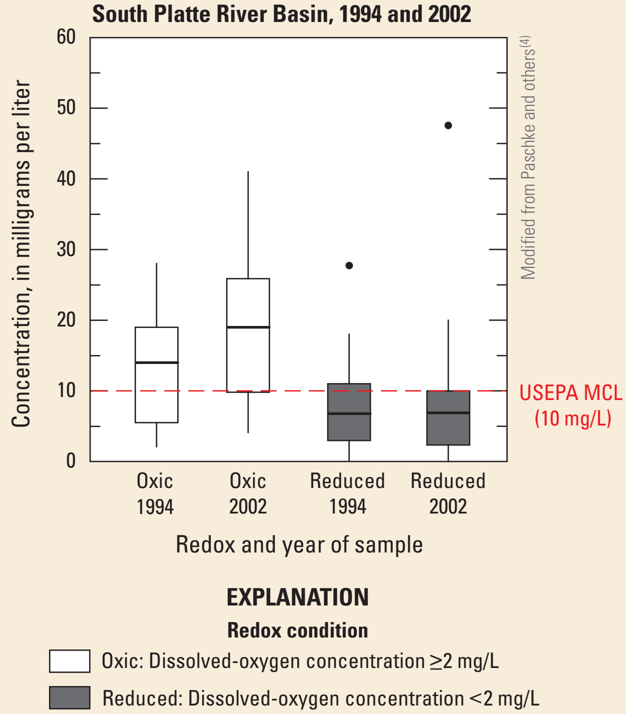
Chapter 6

Trends in nitrate concentrations

Twenty-nine agricultural land-use monitoring wells and 15 groundwater flow-path study wells that tap the South Platte alluvial aquifer were sampled in the early 1990s and again in the early 2000s to investigate near-decadal changes in groundwater quality in this irrigated agricultural area, some of which overlies the Denver Basin aquifer system.[4] Results of groundwater flow-path studies in 1993 and 2004 indicate that dissolved-oxygen concentrations decreased and groundwater age increased with distance along groundwater flow paths and with depth of wells. Every flow-path well had a detectable concentration of nitrate.

Because denitrification has been identified as an important mechanism for mitigating nitrate concentrations in the alluvial aquifer,[4, 82] samples from the 1994 and 2002 agricultural land-use monitoring wells were categorized by dissolved-oxygen content before nitrate concentrations from the same wells were compared for temporal differences. Nitrate concentrations in oxic samples (defined in the study as dissolved-oxygen concentration greater than or equal to 2 mg/L) from the alluvial aquifer were substantially greater in 2002 than in 1994, but there was no substantial difference in nitrate concentrations in reduced samples (dissolved-oxygen concentration less than 2 mg/L) (see figure at right; note different definition of oxic and reducing conditions than in the Denver Basin study, which used a breakpoint of 0.5 mg/L for defining oxic and anoxic samples). This near-decadal increase in nitrate concentrations in oxic groundwater that underlies the agricultural area is attributed to the increased use of synthetic fertilizers and manure since the 1950s.[4]

Nitrate concentrations in the alluvial aquifer underlying agricultural land use in the South Platte River Basin, 1994 and 2002



See sidebar, Boxplots, p. 47

Will nitrate concentrations in Denver Basin shallow groundwater underlying urban areas and deeper groundwater used for drinking water be different in the future? The answer will depend on changes in water and fertilizer use and movement of oxic groundwater. In response to the onset of drought conditions in 2001 and an increased emphasis on water conservation, water use for municipal, domestic, and other purposes has decreased throughout the Front Range. Since the drought, customers of Denver Water, for example, have used about 20 percent less water,[83] and outdoor use of water decreased by more than 50 percent between 1994 and 2004.[84] More and more homeowners and communities are planting drought-tolerant plants with a lower need for nitrogen in place of lawn grasses with higher nitrogen requirements. In contrast to increased water and fertilizer use and higher nitrate concentrations in irrigated agricultural areas, a reduction in water and fertilizer use in urban areas could decrease future nitrate concentrations in urban shallow groundwater. As observed in the near-decadal agricultural land-use studies, though, redox conditions also need to be considered in assessing trends in nitrate concentrations. Concentrations in groundwater used for drinking were highest (1 mg/L or greater) in oxic samples collected at well depths of less than 500 ft below land surface (fig. 6–10). Nitrate concentrations in all anoxic drinking-water samples were at least 10 times lower than in the oxic samples. If nitrate-laden oxic groundwater was to move into parts of the aquifer system that currently are anoxic, the groundwater would lose its capacity to assimilate nitrate by denitrification, and nitrate concentrations in some drinking-water supplies could increase.

Contaminants Derived Primarily from Human Activities: Pesticides and Volatile Organic Compounds

Eight pesticide compounds and 17 VOCs were detected in at least one sample from shallow monitoring wells and drinking-water wells in the Denver Basin, but almost all concentrations were 10 or more times lower than human-health benchmarks. Similar to nitrate and other constituents, pesticides and VOCs were more common in the shallow groundwater system than in the deeper system used for drinking water. Pesticides and VOCs are tracers of the movement of groundwater from shallow to deeper depths in the aquifer system—their occurrence and distribution in groundwater, even at low concentrations, indicates that Denver Basin groundwater is vulnerable to contamination from human activities.

Detections of pesticide compounds and VOCs in well samples, even though at concentrations well below human-health benchmarks, indicate vulnerability of Denver Basin groundwater to contamination.

Pesticides and VOCs are organic chemicals that can be present in groundwater because of their release at or near the land surface. As a result, pesticides and VOCs were detected more frequently in samples of shallow groundwater than in samples of deeper groundwater used for drinking. Pesticides are chemicals used to prevent or control unwanted plants, insects, fungi, and other pests. VOCs are carbon-based compounds that can move between air and water (hence the word "volatile") and are used or produced in a variety of industrial, commercial, and domestic applications. The occurrence of pesticide compounds and VOCs in groundwater can be of concern because of potential human-health effects. Effects of exposure can be short term, such as irritation to skin, eyes, and respiratory system, and (or) long term, such as impairment to the reproductive, immune, and nervous systems and increased risk of cancer. Human-health benchmarks have been established for some but not all pesticides and VOCs. No standards or benchmarks have been established for mixtures or degradates of these compounds in water—the effects of such mixtures or degradates on human health are not well known.

Left, Pesticide applications are common in Denver Basin agricultural areas—here, a helicopter sprays pesticides on a corn field. Detections of atrazine and other pesticide compounds were greatest in shallow groundwater underlying agricultural and urban areas, particularly irrigated agricultural areas where pesticide use is extensive. Concentrations of pesticides in Denver Basin shallow groundwater and deeper groundwater used for drinking were 10 or more times lower than human-health benchmarks. Right, Chloroform, a VOC, is formed by the reaction of chlorine used to disinfect drinking water and organic matter in the water. When treated drinking water is used to water lawns, the chloroform in the water can be carried down to the water table. Leakage from pipes used to deliver treated drinking water is another potential source of chloroform to shallow groundwater.

Assessment levels

The occurrence of pesticide compounds and VOCs in water samples is evaluated in two ways. Detections at any concentration are assessed without regard to differences in reporting levels for individual pesticide compounds or VOCs. Detections are assessed at a common assessment level, greater than 0.1 µg/L for pesticide compounds (fig 6–16, p. 65) and 0.2 µg/L for VOCs (fig 6–18, p. 69), when detection frequencies of two or more compounds with different laboratory reporting levels are being compared. Evaluating detections at a common assessment level facilitates comparison of detection frequencies among compounds with different reporting levels.

Occurrence of pesticide compounds

A total of 130 samples of shallow groundwater underlying agricultural and urban areas and deeper groundwater from wells that tap the Dawson, Denver, and Arapahoe aquifers for drinking-water supply were analyzed for 152 pesticide compounds (pesticides and degradates, table A1–1, appendix 2)—samples from domestic wells in the Denver aquifer and all wells in the Laramie–Fox Hills aquifer were not analyzed for pesticide compounds; these aquifers are not as heavily used for supply as are the Dawson and Arapahoe aquifers. At least one pesticide or pesticide degradate was detected in about one-third of samples from monitoring wells tapping shallow groundwater underlying urban and non-irrigated agricultural areas of the Denver Basin (fig. 6–15). In contrast, only 4 percent of samples (3 of 70 samples) from the deep bedrock aquifers used for drinking water contained a pesticide or a pesticide degradate. All three samples with detections were from the Dawson aquifer at depths of less than 500 ft; in two of these samples more than one pesticide was detected. No pesticides or degradates were detected in samples from the Arapahoe aquifer or from the one sampled public-supply well in the Denver aquifer. Although all concentrations were at least 10 times lower than human-health benchmarks, detections of pesticide compounds in shallow groundwater and deeper groundwater used for drinking indicate the vulnerability of Denver Basin groundwater to contamination from human activities.

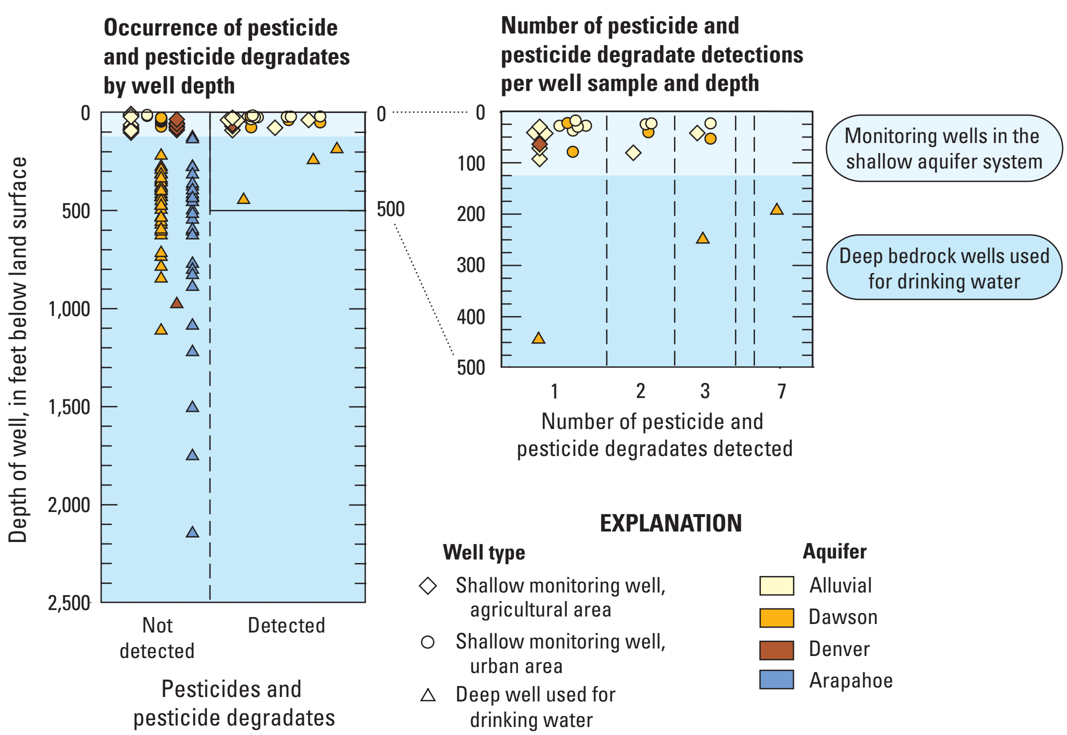


Figure 6–15. Pesticides were detected infrequently in samples from wells used for drinking water but were much more commonly detected in shallow monitoring wells in agricultural and urban areas. Pesticides applied at the land surface are transported with recharge water to shallow groundwater. Detections of pesticides in the drinking-water wells indicate that the bedrock aquifers used for drinking water are vulnerable to the downward movement of contaminants from shallow groundwater. Mixtures of pesticide compounds (two or more pesticides or degradates detected in the same sample) were present in about one-third of the agricultural and urban wells with detections of pesticides and in two drinking-water wells with pesticide detections. The presence of multiple pesticides or degradates in a drinking-water sample, even at low concentrations, is of concern because the health effects of such mixtures are not well understood.[96]

Eight pesticide compounds were detected

Eight pesticide compounds were detected in at least one sample from the study wells: seven herbicides (acetochlor, atrazine, metolachlor, metribuzin, picloram, prometon, and simazine) and one herbicide degradate (deethylatrazine) (fig. 6–16; apendix A2). One or more herbicide compound was detected in 41 percent of samples of shallow groundwater underlying urban areas of the Denver Basin but in only about 26 percent of samples of shallow groundwater underlying agricultural areas (non-irrigated [dryland] winter wheat fields). In the 1994 study of the quality of groundwater in the South Platte River alluvial aquifer underlying irrigated fields of corn and other crops in northeastern Colorado, herbicide compounds were detected in 97 percent of the samples (29 of 30 samples). The large difference in herbicide detections between the two studies likely reflects less intensive use of herbicides on winter wheat fields than on corn and other crops, and less recharge to the water table underlying the wheat fields because of the lack of irrigation. Herbicides also were detected much more frequently (93 percent of samples) in shallow groundwater underlying older, more urbanized areas of the Denver metropolitan area studied during 1993 than in shallow groundwater underlying the newer suburban areas included in the Denver Basin study. Because watering of lawns and other outdoor plants has occurred for decades longer in older urban areas than in areas with newer development, there has been more time in older areas for contaminated water to reach the water table.

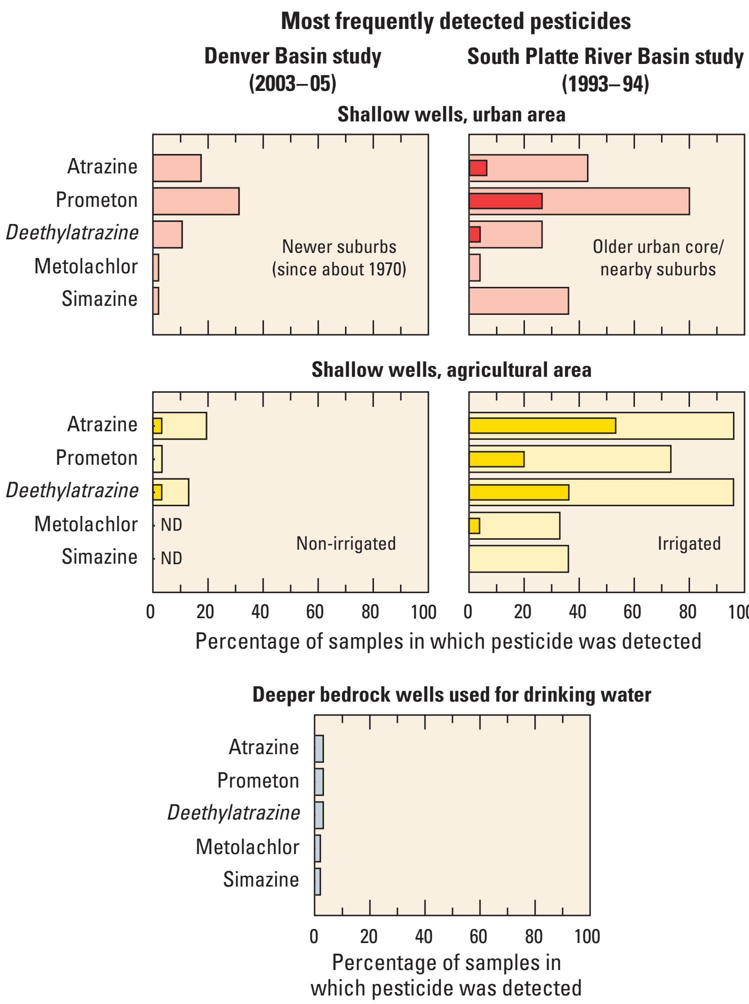
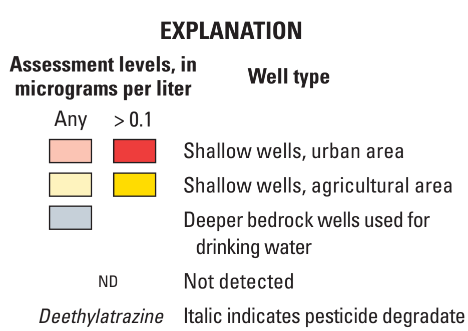


Figure 6–16. Only four herbicides—atrazine, prometon, metolachlor, and simazine—and the herbicide degradate deethylatrazine each were detected in two or more samples of Denver Basin groundwater. These compounds were detected much less frequently in samples of shallow groundwater underlying newer suburban areas in the south Denver metropolitan area and non-irrigated agricultural areas than in shallow groundwater underlying the older urban core of Denver and nearby suburbs and irrigated agricultural areas. Individual pesticide compounds were detected in only three samples (4 percent of wells sampled) of deep groundwater from Denver Basin drinking-water wells.

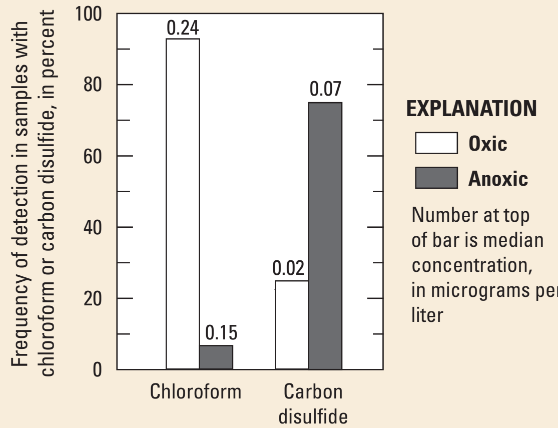


Chemical use and geochemical conditions control chemical occurrence in groundwater

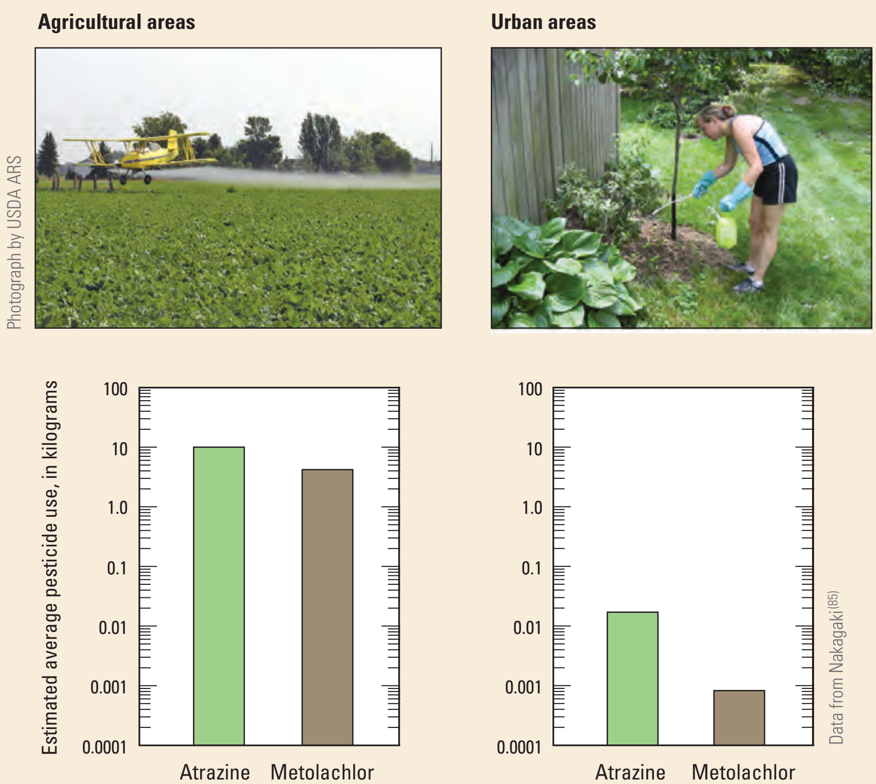
Some chemicals are used more commonly in some land-use settings than others. The herbicides atrazine and metolachlor are used far more heavily in agricultural areas than in urban areas (see figure below), and consequently they were detected more frequently in shallow groundwater underlying agricultural areas than in shallow groundwater underlying urban areas in the South Platte River Basin study (fig. 6–16).

Once a chemical has been applied at the land surface, it can be carried with recharge water down to the water table. Whether or not a chemical persists in soil and groundwater or whether it is broken down by microbial processes depends on the geochemical characteristics of the chemical and of the groundwater. Chloroform, for example, is more readily broken down by the microbial communities that exist in anoxic groundwater, but carbon disulfide is more readily broken down in oxic groundwater and can form naturally in anoxic conditions. These contrasting behaviors are mirrored by the more frequent detection and higher concentrations of chloroform in oxic groundwater and the more frequent detection and higher concentrations of carbon disulfide in anoxic groundwater (see figure at upper right).

Detection frequencies and median concentrations of chloroform and carbon disulfide in Denver Basin groundwater by redox condition



Estimated average pesticide use in 1992 in 500-meter buffer around shallow wells in the South Platte River Basin



Occurrence of VOCs

A total of 99 samples of shallow groundwater underlying urban areas and of deeper groundwater from wells that tap the Dawson, Denver, and Arapahoe aquifers were analyzed for 86 VOCs (tables A1–1, A2–1)—samples from shallow groundwater underlying agricultural areas, domestic wells in the Denver aquifer, and all wells in the Laramie–Fox Hills aquifer were not analyzed for VOCs. At least one VOC was detected in 62 percent of samples from shallow monitoring wells in urban areas and 24 percent of samples from the deeper groundwater used for drinking. All detections for drinking-water samples were from the Dawson and Arapahoe aquifers at well depths from 130 to 1,225 ft (fig. 6–17). The concentrations measured in all samples were very low—only one concentration (for chloroform) exceeded one-tenth its human-health benchmark. The common occurrence of VOCs in shallow groundwater and detections of VOCs in samples of deeper groundwater are additional indicators of the vulnerability of Denver Basin groundwater to contamination.

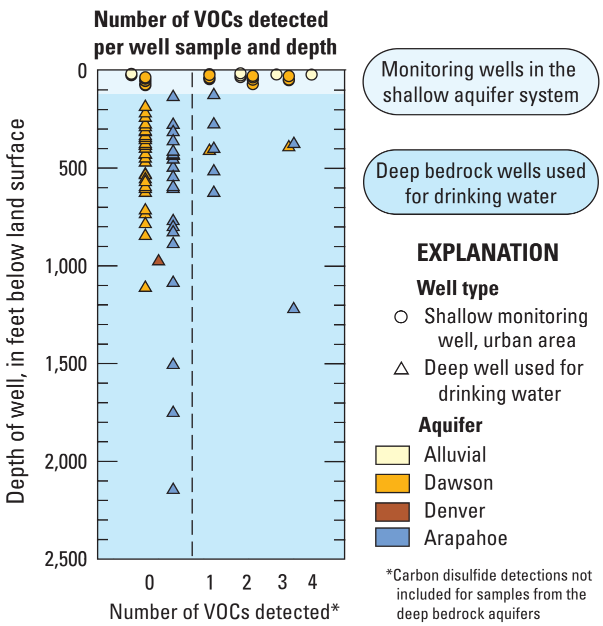


Figure 6–17. Volatile organic compounds (VOCs) were detected in about one-third of Denver Basin groundwater samples, more commonly in samples of shallow groundwater underlying urban areas than in deep groundwater used for drinking. Mixtures of VOCs (two or more VOCs detected in a single sample) were present in 15 percent of the sampled wells. The health effects associated with consuming mixtures of VOCs are not well understood.

Photograph by Stephen S. Anthony, USGS

Because VOCs in air can readily dissolve in water, groundwater samples for VOC analysis are collected from Teflon tubing within a bagged chamber 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 while it is being placed in the sample bottle.

Seventeen VOCs were detected

Seventeen VOCs were detected in at least one sample from the study wells (appendix A2). The VOCs most commonly detected were trihalomethanes (THMs), organic synthesis compounds, and solvents, but gasoline oxygenates, hydrocarbons, and refrigerants also were detected. Trihalomethanes, such as chloroform and bromodichloromethane, are disinfection by-products formed during the chlorination of drinking water. Organic synthesis compounds, such as carbon disulfide, are used to form other organic compounds. Solvents, such as tetrachloroethene (PCE) and methylene chloride, are used to dissolve or disperse other substances and are common in industrial, commercial, and domestic products. Gasoline oxygenates, such as methyl *tert*-butyl ether (MTBE), are added to gasoline to comply with USEPA air-quality regulations; MTBE was banned for use by the State of Colorado in April 2002.[47] Gasoline hydrocarbons, such as toluene, are organic compounds that are common in gasoline and other petroleum products. Refrigerants, such as dichlorodifluoromethane, are used for cooling and air conditioning. Of the 17 VOCs detected in Denver Basin groundwater, the only one with a natural source that is important for this study is carbon disulfide, which forms from the reaction between organic matter and dissolved sulfide under anoxic conditions. In anoxic groundwater, carbon disulfide likely is naturally occurring; in oxic groundwater, it likely is from manmade sources.

Some household products contain VOCs or chemicals that form VOCs when added to water.

Photograph by Joel Beamer, professional photographer

Seven VOCs each were detected in two or more samples from Denver Basin groundwater wells (fig. 6–18); an additional 10 each were detected in a single sample (appendix A2). Chloroform was the VOC most commonly detected in samples of shallow groundwater underlying urban areas, and carbon disulfide was the VOC most commonly detected in samples of deep groundwater from wells used for drinking. Less frequent detections and lower concentrations in newer urban areas than older areas likely result because, in newer areas, there are fewer sources of VOCs, and there has been less time for contaminants in recharge to reach the water table.

In the 1993 South Platte River Basin study of shallow groundwater underlying older, more urbanized areas of the Denver metropolitan area, MTBE was detected in 79 percent of samples, more than twice as frequently as any other VOC (fig. 6–18).[41] In contrast, MTBE was detected in only 7 percent of samples from Denver Basin wells in newer suburban areas. The difference in detection frequency is consistent with a greater abundance of MTBE sources in densely developed urban areas in 1993 and a statewide ban on MTBE use implemented in 2002.

Chloroform was the VOC most frequently detected in groundwater from Denver Basin wells and in groundwater across Principal Aquifers sampled nationwide as part of the NAWQA Program.[35, 48] Chloroform and other THMs can infiltrate to aquifers by the widespread application of chlorinated water to the land surface (for example, by lawn irrigation) and by releases of chlorinated water to the subsurface from leaky water-supply and sewer lines or septic systems. Once in the subsurface, chloroform can be degraded by microorganisms under anoxic conditions. The three samples from drinking-water wells with detectable concentrations of chloroform were oxic.

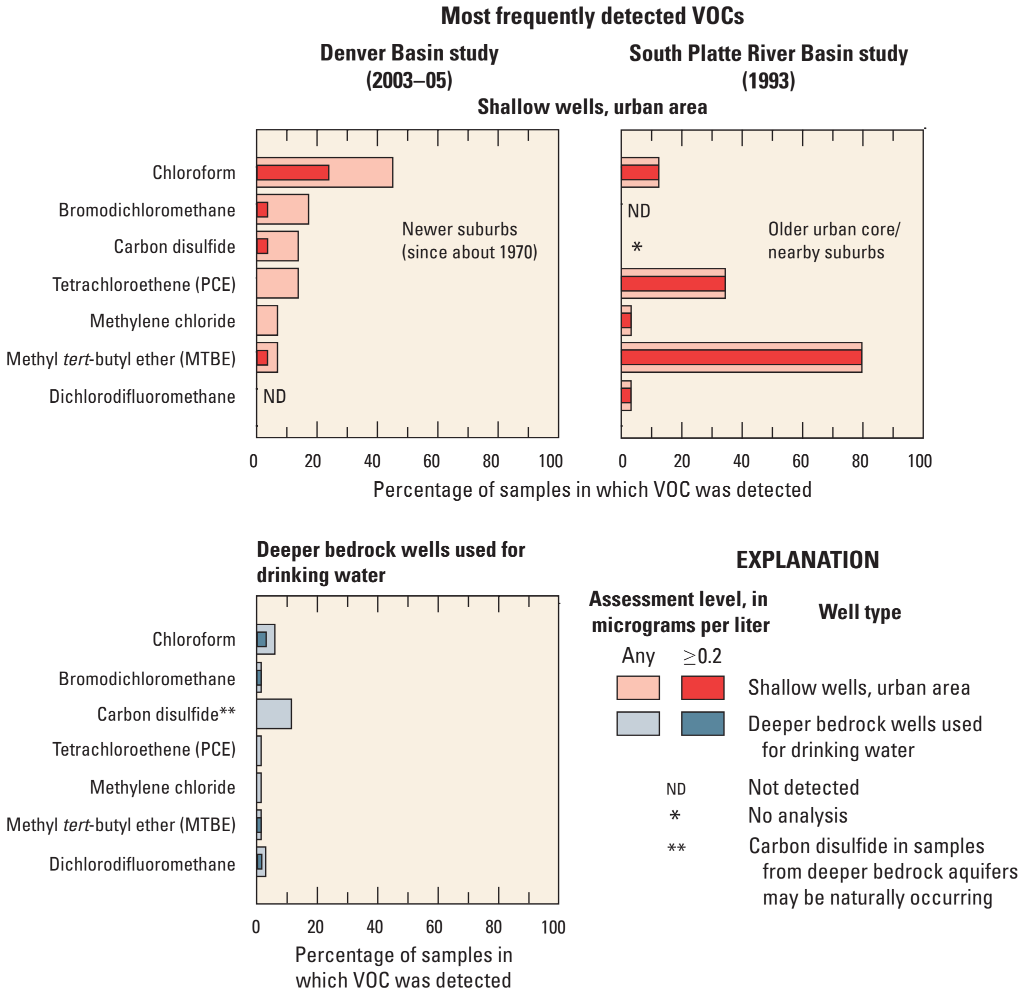


Figure 6–18. Seven volatile organic compounds (VOCs) each were detected in two or more samples of Denver Basin groundwater. Of these, only chloroform and carbon disulfide were detected in more than 10 percent of all samples. Chloroform was detected in 45 percent of samples of shallow groundwater underlying newer suburbs of the south Denver metropolitan area. The most frequently detected VOCs in deeper groundwater were carbon disulfide, chloroform, and dichlorodifluoromethane. Only carbon disulfide was detected in more than 10 percent of the deep groundwater samples—most of these samples were anoxic, which is consistent with a natural source for this compound. MTBE, a gasoline additive, was detected about 10 times less frequently in samples of shallow groundwater collected in newer suburban areas in 2003 than in shallow groundwater samples from older urban areas collected in 1993. The use of MTBE as a gasoline additive was discontinued in 2002.

Monitoring wells that tap the South Platte River alluvial aquifer and shallow parts of bedrock aquifers were sampled to study the effects of land and water resource development on shallow groundwater quality. (Above, the South Platte River near Kersey, Colorado.)

Chapter 7: *Vulnerability of Groundwater to Contamination*

Human activities in the Denver Basin have visibly changed the land surface, as natural grasslands have been converted to rangeland, cropland, small towns, residential developments, and large cities. The related changes to groundwater quality and the vulnerability of groundwater to contamination are less visible, but no less real. Development of the land and of water resources has altered the amount and quality of groundwater recharge, leading to the degradation of water quality in the alluvial aquifer and shallow parts of bedrock aquifers. Deeper groundwater—the groundwater resource—is vulnerable to contamination by downward-migrating shallow groundwater.

This chapter describes the vulnerability of the alluvial aquifer and Denver Basin bedrock aquifers to contamination.

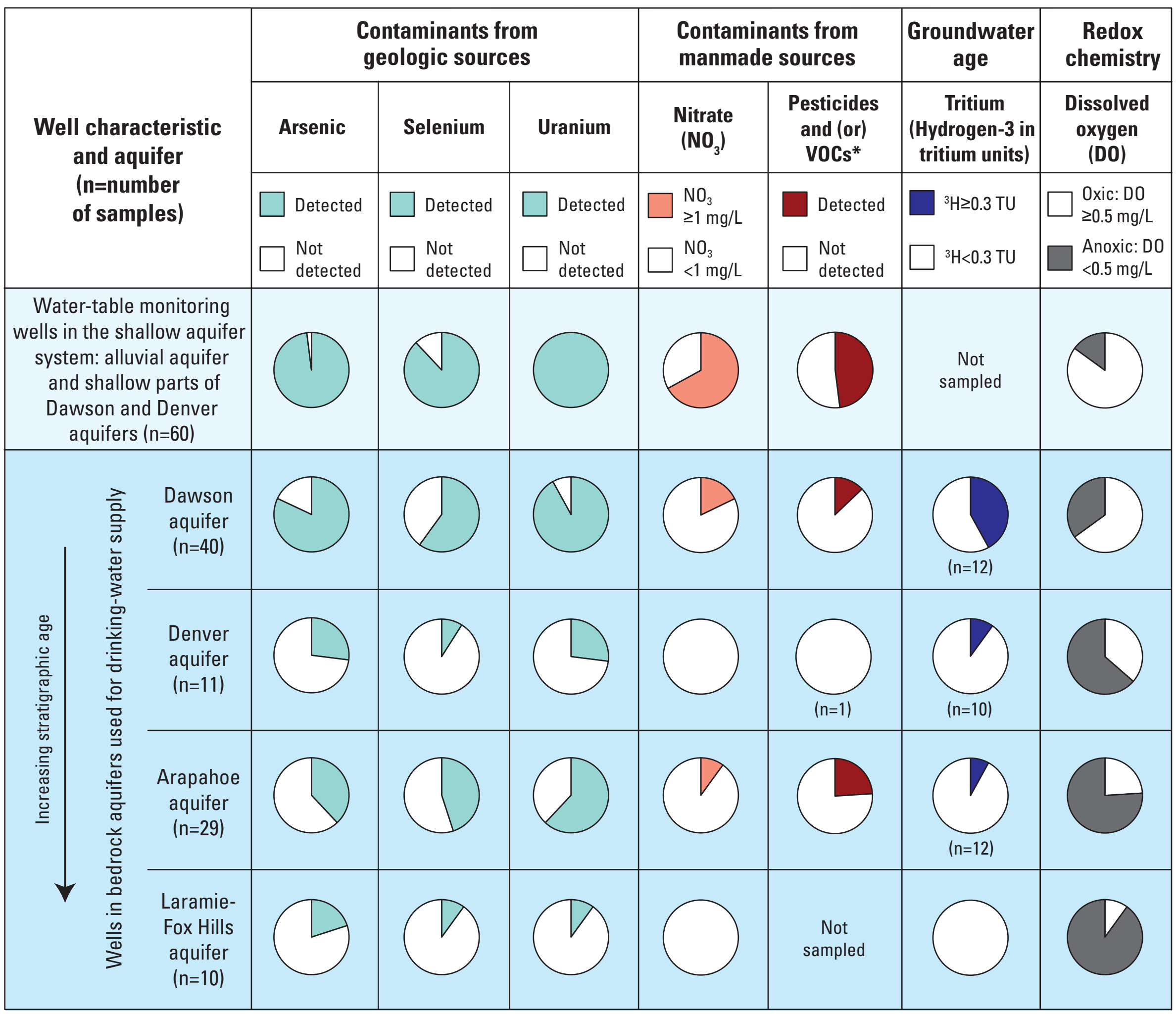
Converting rangeland to residential suburbs and other human activities increases the vulnerability of Denver Basin groundwater to contamination. As other areas along the Front Range are developed, groundwater in those areas may undergo a decrease in quality similar to the changes observed in the Denver Basin.

Photograph by Jon Wark, Wark Photography, Inc.

Human Activities Have Degraded the Quality of Shallow Groundwater—the Source of Recharge to the Deeper Aquifers

The effects of human activities—alteration of groundwater flow by irrigation and pumping and use of chemicals—are evident in the degraded quality of groundwater in the alluvial and shallow bedrock aquifers. The alluvial aquifer and shallow unconfined parts of the bedrock aquifers are most vulnerable to contamination because of proximity to the land surface, shallow depths to water, porous aquifer materials, lack of a confining layer, and increased recharge from excess irrigation water.

In this semiarid climate, the addition of large quantities of recharge water, primarily excess irrigation water, either from agriculture or landscape watering, has markedly changed the hydrology from its natural state. Aquifer sediments in the Denver Basin are naturally rich in minerals that contain the trace elements arsenic, selenium, and uranium, which dissolve when they come into contact with oxic recharge water. As a result, each of these constituents was detected in most or all samples of shallow groundwater (fig. 7–1). More than one-third of the shallow



*Samples from water-table monitoring wells in the agricultural land-use study were not analyzed for VOCs. Carbon disulfide detections not included for samples from the deep bedrock aquifers.

Figure 7–1. Detections of natural and human contaminants and other tracers of shallow, young groundwater indicate vulnerability of the groundwater to contamination. Contamination of groundwater by chemicals from geologic and manmade sources is most evident for the shallow aquifer system, but some contamination is present in the deeper bedrock aquifers used for drinking-water supply. Tracers of shallow, young groundwater (dissolved oxygen and tritium) in the bedrock aquifers were most common in the Dawson aquifer and decreased as aquifer age increased.

groundwater samples (22 of 60 samples) had a detection of arsenic, selenium, and (or) uranium at a concentration of concern for human health if the groundwater were to be used for drinking.

Historically low recharge and high evapotranspiration in the semiarid climate of the Denver Basin resulted in the natural accumulation of soluble salts in the unsaturated zone. The relatively recent introduction of irrigation water, with repeated cycles of application of freshwater to the land surface, has dissolved some of these salts and increased their downward movement to the water table—dissolved-solids concentrations were 10 or more times higher in some shallow groundwater than in deep groundwater. Dissolved-solids concentrations are high enough in some parts of the Denver Basin to preclude use of shallow groundwater even for irrigation.

Nitrate, like trace elements and dissolved solids, has accumulated naturally in the unsaturated zone. As grassland and rangeland were converted to agricultural use and to urban and suburban landscapes, this nitrate was gradually transported down to the water table. Most nitrate in shallow groundwater, however, probably is derived from human sources—septic systems, manure, municipal and industrial wastewater, and fertilizers for crops, lawns, golf courses, and landscaping. Nitrate concentrations greater than 1 mg/L, associated with human contamination, were detected in two-thirds of shallow groundwater samples (fig. 7–1). Concentrations in some samples exceeded the MCL of 10 mg/L as nitrogen by a factor of 2 or more.

Other chemicals that are applied deliberately or released accidentally at the land surface also can be carried down to the water table. Almost half of the samples of shallow groundwater in agricultural and urban areas contained at least one pesticide and (or) VOC (fig. 7–1).

Overall, four of every five monitoring wells sampled in the alluvial aquifer and shallow unconfined parts of bedrock aquifers had a detection of nitrate, a pesticide compound, and (or) a VOC that indicated contamination from human activities (fig. 7–2). These aquifers are used largely to supply irrigation water for agriculture, but are nonetheless potential future sources of drinking water in rapidly growing areas of the Front Range. Further, because shallow groundwater is vulnerable to water-quality changes within relatively short time periods (years to decades), it can indicate how human activities might, in time, affect older (centuries to millennia), deeper groundwater.

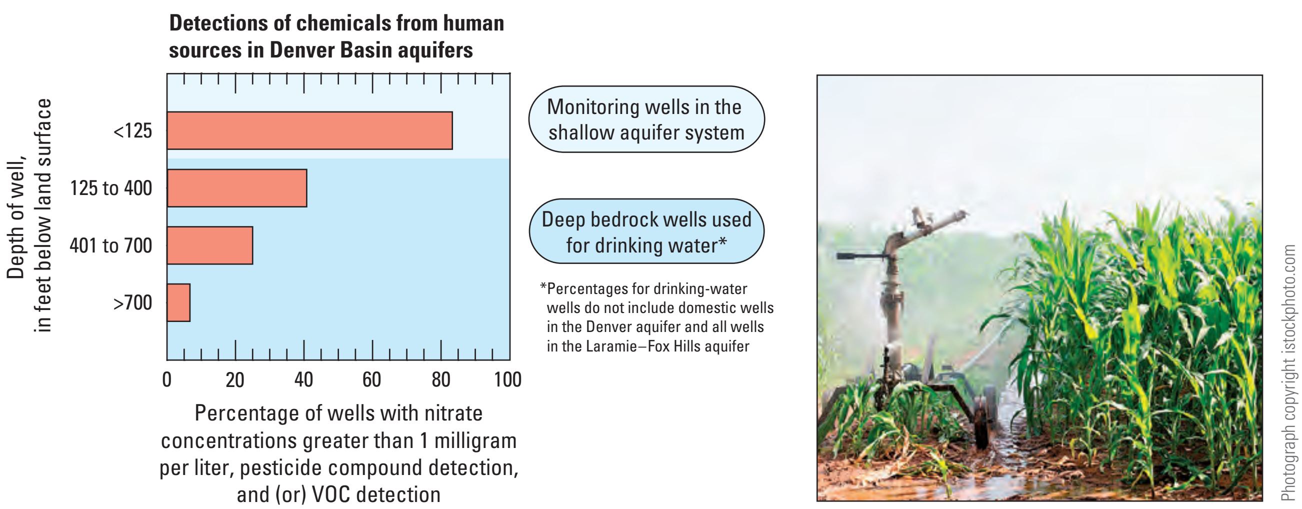


Figure 7–2. Irrigation and pumping have altered the natural groundwater flow system in the Denver Basin, which has brought manmade contaminants down to shallow and deep groundwater.

In other Principal Aquifers in the United States, alteration of the hydrologic system has affected the deep drinking-water resource, sometimes in unexpected ways

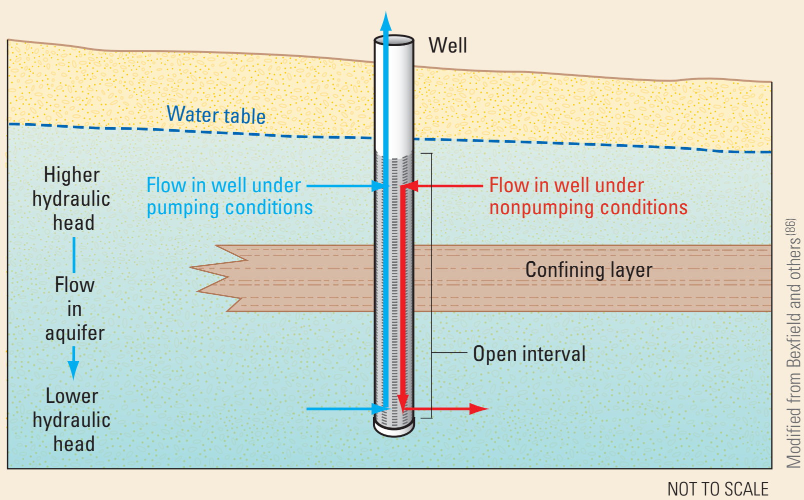
Findings from other Principal Aquifer assessments conducted in similar hydrogeologic and climatic settings provide insights on the vulnerability of Denver Basin groundwater

San Joaquin Valley, California

In the San Joaquin Valley, California, pumping of groundwater from wells for agricultural and urban development and recharge of excess irrigation water have altered the movement of groundwater and contaminants from geologic sources (see sidebar, A cautionary tale: Irrigation and pumping have increased uranium concentrations in groundwater in the Central Valley of California, p. 49). Shallow groundwater with high uranium concentrations has moved downward into parts of the aquifer system used for drinking water that historically have had low uranium concentrations.[49]

More unexpectedly, though, wells not being pumped also can alter groundwater movement by providing pathways for movement of water and contaminants from one part of the aquifer to another.[50] Where hydraulic gradients are downward, shallow groundwater and the contaminants it contains can move down through and along wells into deeper parts of the aquifer commonly used for public supply. In the San Joaquin Valley, natural groundwater flow paths were “short circuited” by a public-supply well and contaminant movement downward increased. During winter, when pumping from the public-supply well was minimal, a substantial volume of shallow water migrated downward through the public-supply well into deep groundwater. VOCs and pesticides that were consistently detected in shallower parts of the aquifer also were detected in water from a deep monitoring well near the public-supply well.

Groundwater flow can be “short circuited” through a well that is open to more than one depth in an aquifer. When the well is not being pumped, if the vertical hydraulic gradient is downward, contaminants can move in and along the well to deeper parts of the aquifer. Downward flow in a well can occur even if there is a confining layer of clay or shale within an aquifer if the well penetrates the confining layer.



High Plains Aquifer, Nebraska

In York, Nebraska, pumping from the High Plains aquifer mixes water from shallow and deep parts of the aquifer, changing redox conditions and mobilizing uranium in the deep aquifer.[50, 87] In this area of east-central Nebraska, the High Plains aquifer is a layered sequence of saturated sands separated by confining layers. The aquifer is heavily pumped to provide water for irrigation, and the pumping wells commonly are screened in more than one aquifer layer. Hydraulic head in the upper aquifer is higher than in the lower aquifer, so that groundwater would flow downward if the confining unit were not present. When wells are not pumping, water can flow from the shallow, unconfined aquifer down through the well and into the deep, confined aquifer. The mixing of oxic, slightly acidic shallow groundwater with anoxic, slightly alkaline deep groundwater causes uranium to be released from deep aquifer sediments. A public-supply well that is screened in the deep aquifer produces water with elevated uranium concentrations.

Data from the Denver Basin study suggest that mixing of groundwater with different ages and redox conditions is present in some parts of the Denver Basin such that contaminants present in poor-quality shallow groundwater have the potential to move to deeper bedrock aquifers used for drinking-water supply.

Geochemistry and Groundwater Ages Suggest Deep Parts of the Denver Basin Might Be Vulnerable to Contamination From Shallow Groundwater

Shallow groundwater is more likely than deeper groundwater to contain fertilizers, pesticides, solvents, gasoline oxygenates, tritium, and other manmade chemicals. As shallow water moves downward by natural and (or) human-influenced flow processes, it can affect the water quality of the deeper groundwater. Historically, groundwater in deep parts of Denver Basin bedrock aquifers was isolated from the effects of human activities at the land surface. In some areas, however, the movement of shallow groundwater into the deeper parts of the aquifer system is now apparent. Manmade contaminants (nitrate, pesticide compounds, and VOCs) were detected in 24 percent of the samples from deep bedrock wells analyzed for these chemicals (figs. 6–10, 6–15, 6–17). The detections primarily were for samples collected at depths of less than 500 ft, but VOCs were present in some samples from depths of more than 500 ft (fig. 6–17).

Tritium, a product of atomic bomb testing, is an indicator of recharge that has occurred since the early 1950s. Detections of tritium in deep groundwater also can provide an indication that shallow, young groundwater has moved downward. In the Denver Basin, tritium was detected in the Dawson, Denver, and Arapahoe aquifers at well depths as great as 500 ft (fig. 7–1).

The presence of dissolved oxygen at depth also can indicate the downward movement of young, shallow groundwater. Dissolved oxygen is brought in from the atmosphere with recharge water. As the groundwater moves through the aquifer along a flow path, the dissolved oxygen in the groundwater commonly is consumed by biological and chemical reactions. Because water in an aquifer is isolated from the atmosphere, the dissolved oxygen, once consumed, is not replenished by natural processes (see sidebar, How do redox reactions work?, p. 36). Oxygen in the deep groundwater, however, can be replenished as a result of human activities. Heavy pumping from deep bedrock wells and the short circuiting of groundwater can cause shallow, oxic groundwater to move downward.[2, 49, 50] Aquifer storage and recovery also can provide a direct pathway for shallow, oxic water to reach deep groundwater (see sidebar, Increased interest in aquifer storage and recovery programs in the Denver Basin, p. 33). Oxic water was present in several deep wells in the Denver Basin (figs. 4–5, 7–3). In addition to indicating the vulnerability of deep groundwater to contamination from the shallow part of the system, the mixing of shallow, oxic water with deeper, anoxic groundwater can cause constituents associated with the aquifer rocks and sediment to dissolve.

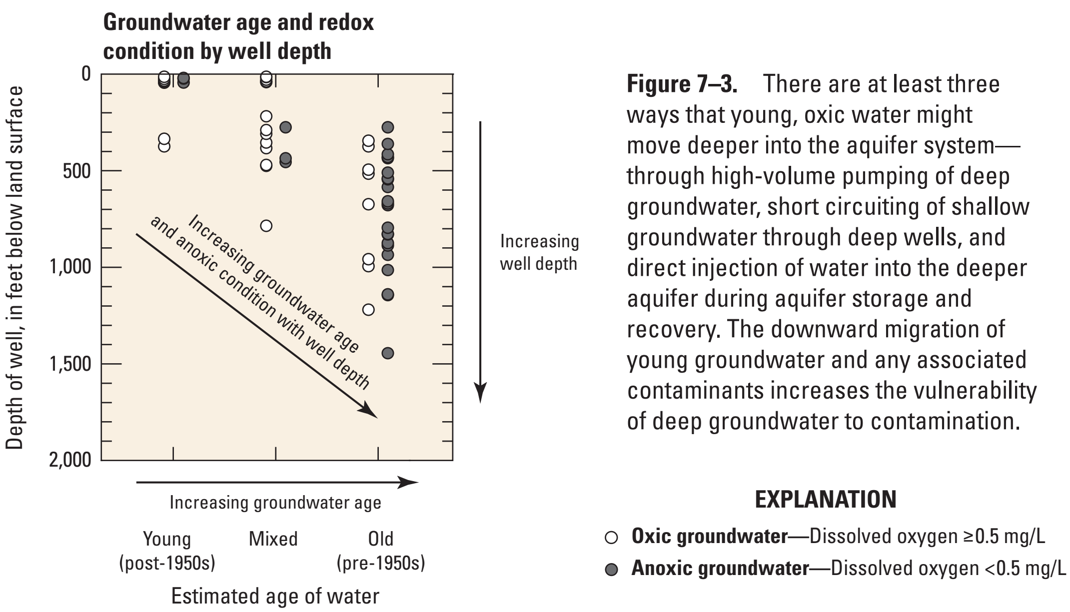


Figure 7–3. There are at least three ways that young, oxic water might move deeper into the aquifer system—through high-volume pumping of deep groundwater, short circuiting of shallow groundwater through deep wells, and direct injection of water into the deeper aquifer during aquifer storage and recovery. The downward migration of young groundwater and any associated contaminants increases the vulnerability of deep groundwater to contamination.

The quality of the deep groundwater of the Denver Basin still is very good—only one drinking-water well contained at least one constituent at a concentration of concern for human health, and that well was relatively shallow. The results of this study indicate, however, that the deep groundwater is vulnerable to contamination from human activities at the land surface, whether from application or releases of chemicals or from increased concentrations of trace elements resulting from downward movement of shallow, oxic groundwater. Of the four bedrock aquifers used as a drinking-water resource, the Dawson aquifer is the most vulnerable to contamination. A plentiful, high-quality source of drinking water is an enormous economic benefit to the Denver Basin area. Understanding the factors that control groundwater quality is essential to managing this vital resource.

Sustainability of Denver Basin groundwater

The sustainability of Denver Basin groundwater depends not only on the quality of water available but also on the quantity of that water. Studies by Paschke[2] and others[57, 88] indicate that high rates of pumping are not sustainable indefinitely. Of concern for many water users and managers is the removal of water from storage in the bedrock aquifers and subsequent decrease in groundwater availability. Changes in land and water uses since the 1950s have altered the groundwater-flow system and groundwater availability. More groundwater is available in some parts of the alluvial aquifer and shallow parts of the hydrologic system, but less water is available in some parts of the bedrock aquifers.[2] Increased pumping has resulted in a decline in water levels, less discharge from bedrock aquifers to streams and to the alluvial aquifer, and a decrease in the amount of water in storage in the bedrock aquifers. One action water managers can consider to address these concerns is to pump less water from bedrock aquifers. To demonstrate the possible effects from such a decrease, Paschke used different predictive simulations in a Denver Basin groundwater-availability model.[2] The first simulation assumed recharge and pumping conditions did not change from 2003 through 2053, and the second simulation assumed recharge did not change but pumping was discontinued from the lowermost part of the Arapahoe aquifer. Results of the first simulation indicated continued water-level declines, continued decrease in discharge from the bedrock aquifers to the surficial system, and continued loss of water from storage. When pumping from the lowermost part of the Arapahoe aquifer was stopped in the second simulation, however, there was an increase in water levels, and the rate of aquifer depletion slowed. A reduction in groundwater pumping, along with other management actions such as water conservation, water reuse, increased use of surface water for supply, and aquifer-storage and recovery projects, might extend the usable life of the Denver Basin aquifer system. Many municipalities that rely on Denver Basin groundwater for supply have instituted these and other management actions to decrease the volume of groundwater withdrawals.

> *Groundwater sustainability can be defined as the achievement of an acceptable tradeoff between groundwater use and the long-term effects of that use.*[89]

For more information about NAWQA Principal Aquifer studies

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

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

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Before the invention of the combustion engine, windmills, such as this antique windmill near Denver, supplied a limited amount of groundwater for people and domestic animals in agricultural areas of the Great Plains, including eastern Colorado.

Glossary

A

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

alluvial fan A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream (especially in a semiarid region) at the place where the rock mass issues from a narrow mountain valley on a plain or broad valley.

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

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

arkosic sandstone A feldspar-rich sandstone that generally forms from the rapid breakdown of granite or granitic rock.

artesian Referring to confined groundwater. If the potentiometric surface in a confined aquifer is higher than the land surface, water discharges spontaneously from a well tapping the aquifer; this is called a "flowing artesian well."

B

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

bedrock aquifer As used in this report, refers to the sandstone aquifers that make up the Denver Basin aquifer system, including the Dawson, Denver, Arapahoe, and Laramie–Fox Hills aquifers. Bedrock is a general term for consolidated (solid) rock that underlies soils or other unconsolidated material.

C

confined aquifer (artesian aquifer) An aquifer in which the groundwater is bounded between layers of relatively impermeable material, such as clay or dense rock. When tapped by a well, water in a confined aquifer is forced up, sometimes above the land surface, by pressure within the aquifer.

confining unit A hydrogeologic unit of impermeable or distinctly less permeable material within an aquifer or bounding one or more aquifers.

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.

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.

drawdown The amount that the level of a reservoir, water level in a well, or head in an aquifer is lowered by the withdrawal of water.

drinking-water well As used in this report, a domestic or public-supply well that produces water used for drinking; the water sample is collected before any treatment.

E

evaporative concentration An increase in the concentration of dissolved solids in solution caused by the removal of water through evapotranspiration.

evapotranspiration Loss of water from soil by evaporation and plant transpiration combined.

excess irrigation water As used in this report, 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. Also known as irrigation return flow.

F

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

Front Range urban corridor Urban and suburban area extending north from Denver to Fort Collins (northwest of Greeley) and south to Colorado Springs along the eastern face of the Rocky Mountains, in Colorado.

G

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

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.

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 source-water-quality assessment A study by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program that characterizes the quality of groundwater from aquifers used as a source of public drinking-water supply in the United States.

H

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.

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.

hydraulic gradient In an aquifer, the rate of change of total head (water-level altitude in a well) per unit of distance of flow at a given point and in a given direction. Water will flow from higher hydraulic head to lower hydraulic head.

hydraulic head The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane.

I

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 hydraulic conditions independent of the chemical characteristics of the contaminant and its sources.

L

laboratory reporting level Concentration determined in the laboratory at which the risk of a false negative (not detecting an analyte when it is present) is not more than 1 percent.

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

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

M

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.

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

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

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

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

N

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

O

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

P

pesticide compounds A term used to refer collectively to parent pesticides, their degradates and, where applicable, their manufacturing by-products.

predevelopment The time prior to substantial groundwater development by humans or effects of agricultural, urban, suburban, or other human-related land uses.

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

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

R

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

S

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 or from chemical precipitation from water. Sandstone and limestone are examples of sedimentary rocks.

shallow aquifer system As used in this report, the alluvial aquifer and parts of the Dawson, and Denver aquifers less than 125 feet below the land surface.

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

susceptibility *See* intrinsic susceptibility.

T

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

tonstein Sedimentary rock composed mainly of the clay mineral kaolinite. Tonsteins are formed by the alteration and leaching of volcanic-ash layers deposited in coal-forming swamps.

U

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

unconsolidated material 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 by-products of chlorine disinfection.

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

W

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

water-table monitoring well As used in this report, a well in the alluvial, Dawson, and Denver aquifers with a depth of less than 125 feet below land surface, constructed for the collection of hydrologic data, such as water levels and water quality, and not used as a source for drinking water.

Appendixes 1–4

Appendix 1. Study Components of the Denver Basin Aquifer System Water-Quality Assessment

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

- Land-use studies sampled water from water-table monitoring wells installed in urban and agricultural areas to assess the effects of these land uses on the quality of the underlying groundwater. Although not usually used for drinking, this shallow groundwater system supplies recharge water to the deeper aquifer system.
- Major aquifer studies provide a broad overview of the quality of the deeper aquifer system used for drinking-water supply. Most of the wells sampled were domestic wells that were distributed across a large area in a mixture of land uses.
- Source-water-quality assessment studies sampled water from public-supply wells to understand occurrence of unregulated manmade chemicals in the groundwater resources that serve large numbers of people.[97]

Each Denver Basin study involved sampling water from a network of 10 to as many as 31 wells. Results of these studies were reinforced by locating some of the studies within the area sampled for the major aquifer studies. This nesting of wells was designed to provide information on how the quality of the recharge water affects that of deeper groundwater.

Table A1–1. Study components of the Denver Basin aquifer system water-quality assessment.

[All wells were sampled once. Samples for radionuclides and (or) stable isotopes were not collected at all wells in a study]

Study component	Study description	Well type	Year sampled	Number of wells sampled	Water-quality parameters*
Land-use study	Characterize the quality of recently recharged water in the alluvial and Denver aquifers underlying non-irrigated wheat fields	Water-table monitoring wells	2003	31	PP, M, N, D, R, TE, P-PD, SI-HO
Land-use study	Characterize the quality of recently recharged water in the alluvial and Dawson aquifers underlying newer (since about 1970) urban setting in the south Denver metropolitan area	Water-table monitoring wells	2003†	29	PP, M, N, D, R, TE, P-PD, SI-HO, V
Major aquifer study	Broadly characterize the regional drinking-water resource of the Dawson aquifer	Domestic	2004–2005	29	PP, M, N, D, R, TE, P-PD, SI-HOC, V
Major aquifer study	Broadly characterize the regional drinking-water resource of the Denver aquifer	Domestic	2005	10	PP, M, N, D, R, TE, SI-HOC
Major aquifer study	Broadly characterize the regional drinking-water resource of the Arapahoe aquifer	Domestic and public supply	2005	29	PP, M, N, D, R, TE, P-PD, V, SI-HOC
Major aquifer study	Broadly characterize the regional drinking-water resource of the Laramie–Fox Hills aquifer	Domestic	2005	10	PP, M, N, D, R, TE, SI-HOC
Groundwater source-water-quality assessment	Characterize the quality of water in the Dawson and Denver aquifers used for public supply	Public supply	2003	12	PP, M, N, D, R, TE, P-PD, V

*Water-quality parameters
D, dissolved organic carbon
M, major ions
N, nutrients
P-PD, pesticides and pesticide degradates
PP, physical properties including water temperature, specific conductance, pH, and dissolved oxygen
R, radiochemical including radon and (or) $carbon^{14}$ and tritium
SI-HO, stable isotopes of hydrogen and oxygen
SI-HOC, stable isotopes of hydrogen, oxygen, and carbon
TE, trace elements
V, volatile organic compounds

†Samples for stable isotopes of hydrogen and oxygen were collected in 2005.

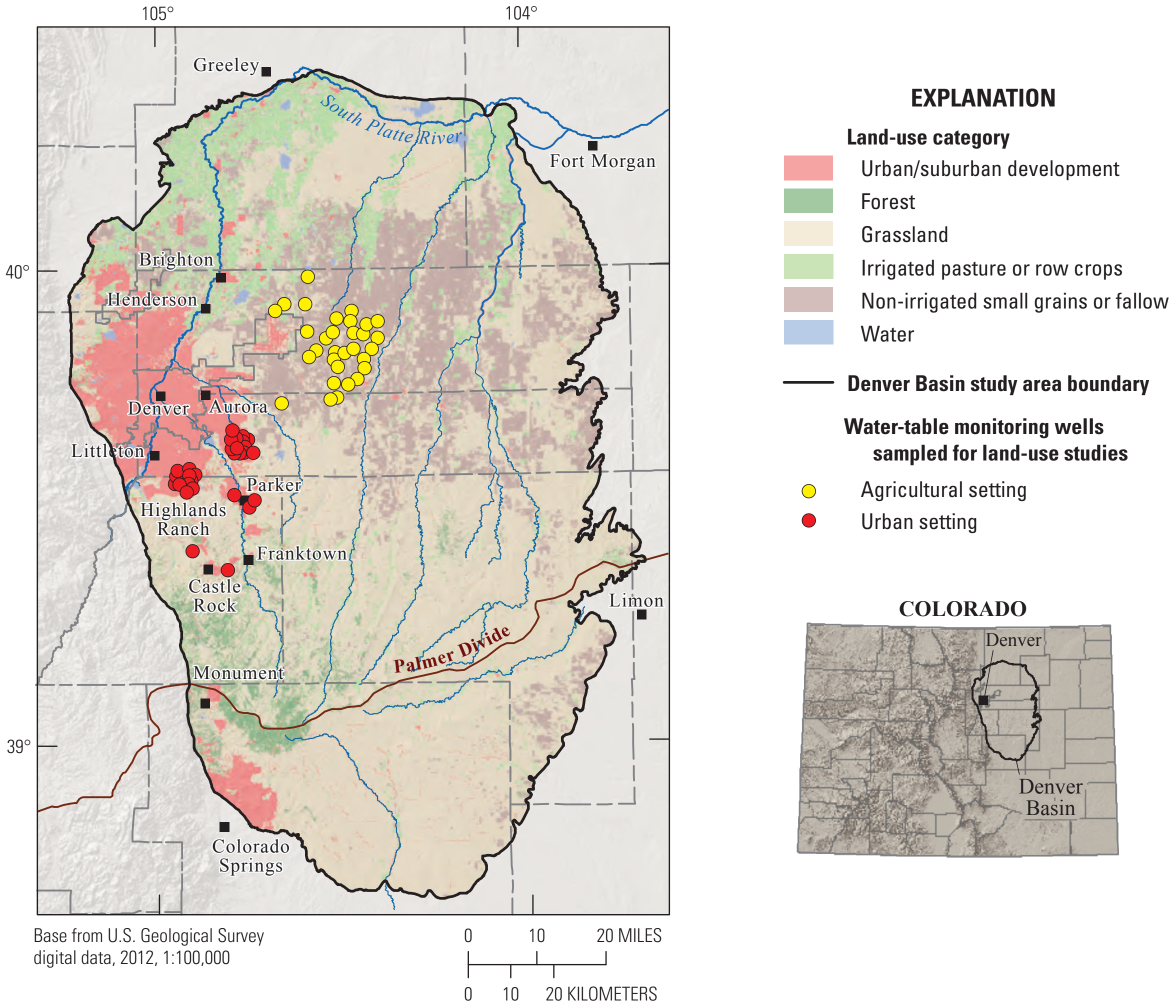


Figure A1–1. Location of water-table monitoring wells in the Denver Basin aquifer system sampled during 2003–05 for land-use studies in agricultural and urban settings.

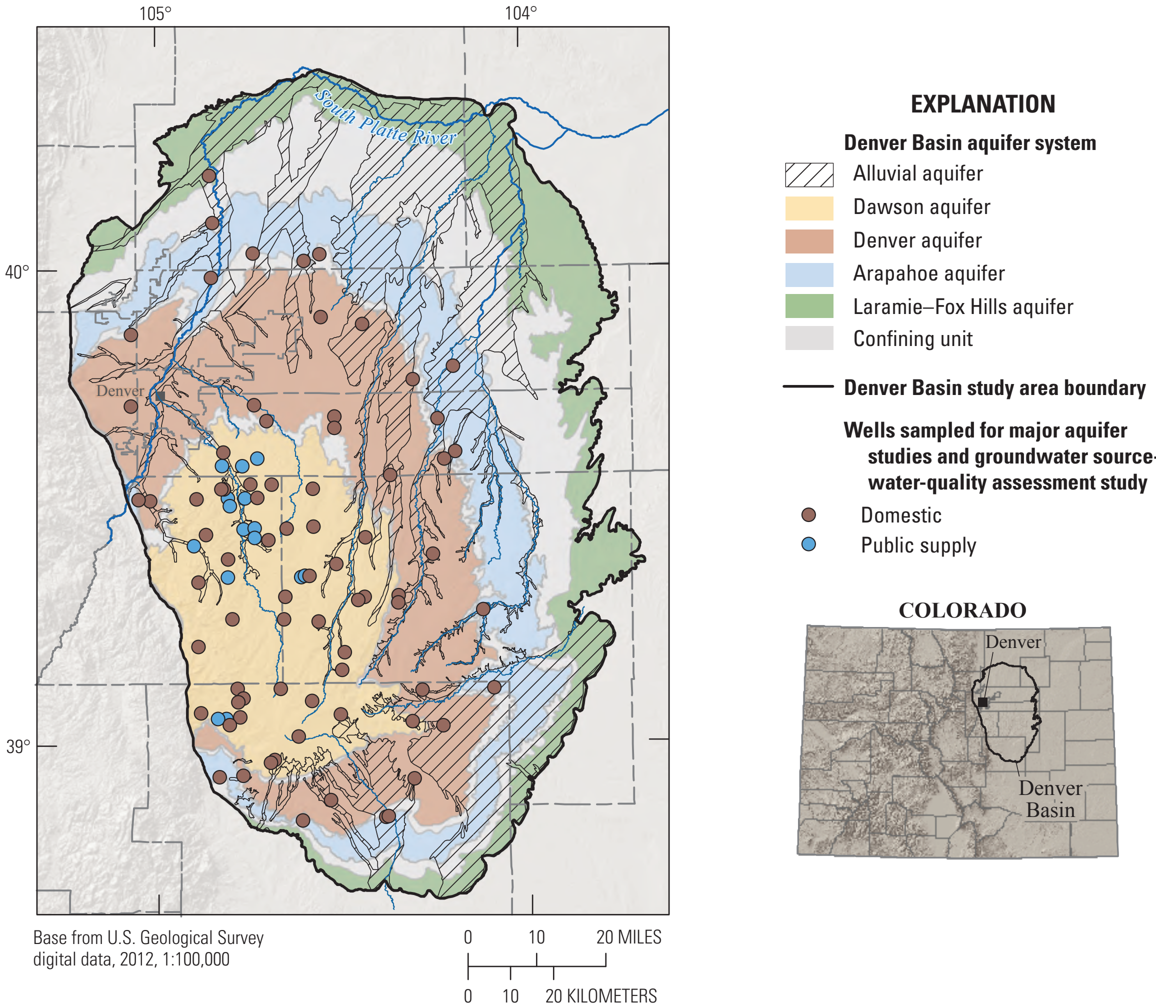


Figure A1–2. Location of domestic and public-supply wells in the Denver Basin aquifer system sampled during 2003–05 to assess the quality of the drinking-water resource.

Appendix 2. Groundwater-Quality Properties and Constituents Measured, a Summary of the Data, and Complete Data Archive for 2003–05

Groundwater-quality properties and constituents measured and a summary of the data for the 2003–05 Denver Basin water-quality assessment, including laboratory reporting levels, human-health benchmarks for drinking water, and non-health guidelines, are presented only online. The data summary and a complete data archive are available for download at *http://pubs.usgs.gov/circ/1357/*.

Appendix 3. Constituents in Sandstone Aquifers and Shallow Groundwater of the Denver Basin and Across the United States

Concentrations of manganese, radon, nitrate, arsenic, selenium, and uranium exceeded human-health benchmarks in samples collected during 2003–05 from drinking-water wells in the Denver Basin bedrock aquifers, none with an exceedance frequency greater than 5 percent (fig. A3–1). Exceedances for the six constituents were less than 8 percent for drinking-water wells in sandstone aquifers sampled throughout the United States by the NAWQA Program from 1991 to 2010.[35] Concentrations of manganese, dissolved solids, iron, fluoride, and sulfate in Denver Basin drinking-water samples exceeded SMCLs. Only the exceedance for fluoride was more common in groundwater from Denver Basin bedrock aquifers than from other sandstone aquifers nationally. The overall quality of water in Denver Basin bedrocks aquifers and in other sandstone aquifers across the United States is mostly suitable for drinking water.

No VOCs or pesticide compounds in Denver Basin drinking-water samples were detected at concentrations greater than human-health benchmarks. Concentrations of only four manmade organic compounds in drinking water from other sandstone aquifers were greater than human-health benchmarks: the insecticides diazinon and dieldrin and the VOC solvents methylene chloride and trichloroethene (TCE). Of these four compounds, only methylene chloride was detected in Denver Basin groundwater from wells used for drinking water.

For both the Denver Basin and other locations in the United States, exceedances of human-health benchmarks for manganese, nitrate, arsenic, selenium, and uranium were more common in samples from shallow groundwater wells in agricultural and urban areas than in groundwater from deeper drinking-water wells (figs. A3–1, A3–2). The major difference in exceedances for wells in agricultural and urban areas in the Denver Basin and across the United States was a much greater frequency of exceedances of the MCL for selenium and uranium in both Denver Basin land-use studies and arsenic and nitrate in the agricultural study (fig. A3–2). Exceedances of SMCLs for sulfate, manganese, dissolved solids, and chloride also were more common for shallow groundwater underlying agricultural and urban areas of the Denver Basin than groundwater underlying similar areas nationally.

The VOC chloroform was detected in 45 percent of samples from shallow groundwater wells in urban areas of the Denver Basin (fig. 6–18) and in about 28 percent of similar samples collected in other urban areas of the United States. The herbicide atrazine and its degradate deethylatrazine were the most common pesticides detected in shallow groundwater wells in agricultural areas of the Denver Basin and nationally; however, detection frequencies varied—about 20 percent (atrazine) and 13 percent (deethylatrazine) in the Denver Basin (fig. 6–16) and 40 percent (atrazine) and 43 percent (deethylatrazine) across the United States. Prometon, the most common herbicide detected in shallow groundwater from urban areas of the Denver Basin (fig. 6–16), was the third most common herbicide detected in groundwater collected in urban areas of the United States.

Differences in exceedances of human-health benchmarks and SMCLs in Denver Basin groundwater, as well as in other sandstone aquifers and in shallow groundwater underlying agricultural and urban areas of the United States, result from differences in geology, recharge rates, and geochemical conditions.[35] Human activities that alter the natural groundwater-flow system can mobilize naturally occurring constituents in shallow parts of aquifers and transport nitrate and other manmade compounds from the land surface to the water table.[35]

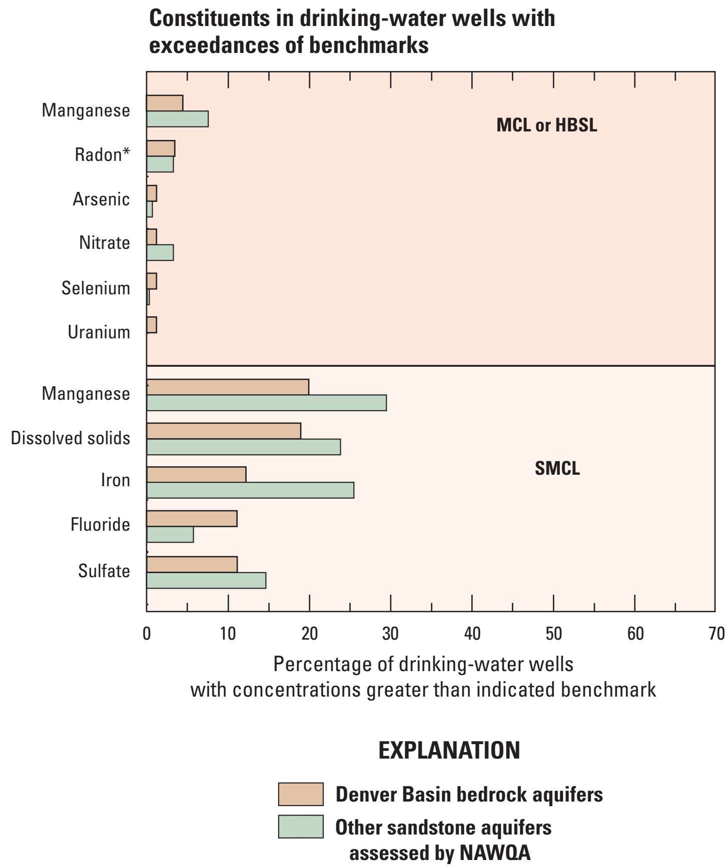


Figure A3–1. Exceedances of human- and non-human health benchmarks for constituents of concern in groundwater wells that tap parts of aquifers used for drinking water in the Denver Basin and other sandstone aquifers across the United States.[35] (*Proposed radon regulation of 4,000 picocuries per liter.)

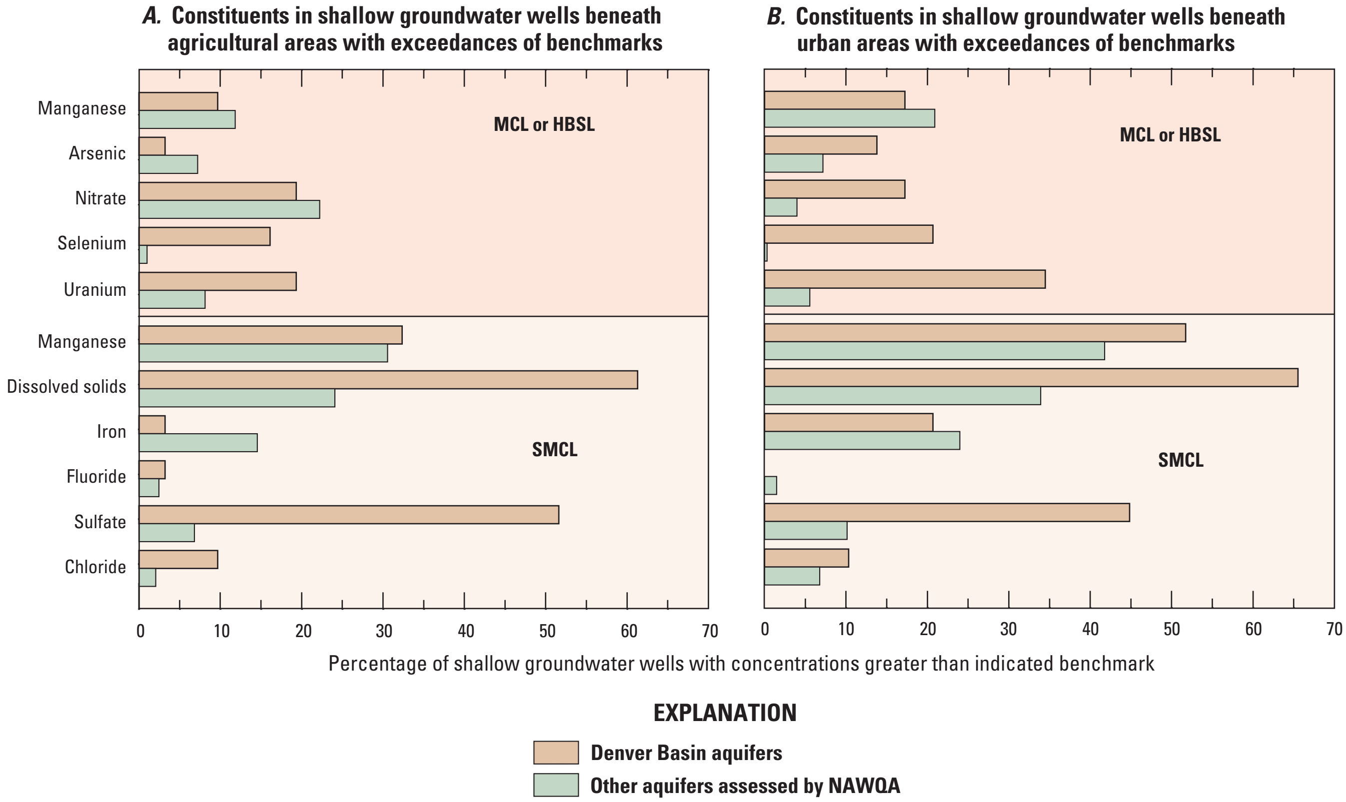


Figure A3–2. Exceedances of human- and non-human health benchmarks for constituents of concern in shallow groundwater wells beneath *(A)* agricultural and *(B)* urban areas of the Denver Basin and similar land-use settings across the United States.[35]

Appendix 4. Groundwater Quality of the Denver Basin Aquifer System in a National Context

Principal Aquifer (number of samples)

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

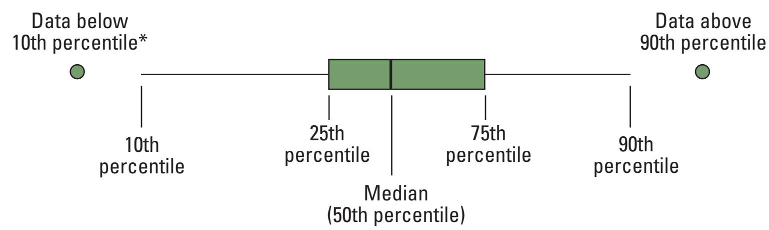
U.S. Environmental Protection Agency contaminant levels for drinking water

- - - - - MCL Maximum Contaminant Level

- - - - - SMCL Secondary Maximum Contaminant Level

- - - - - PMCL Proposed Maximum Contaminant Level

- - - - - AMCL Proposed Alternative Maximum Contaminant Level



* Data below laboratory reporting levels are not shown.

Lithology

Basalt and volcanics**

Crystalline

Carbonate

Sandstone

Semiconsolidated sand and gravel

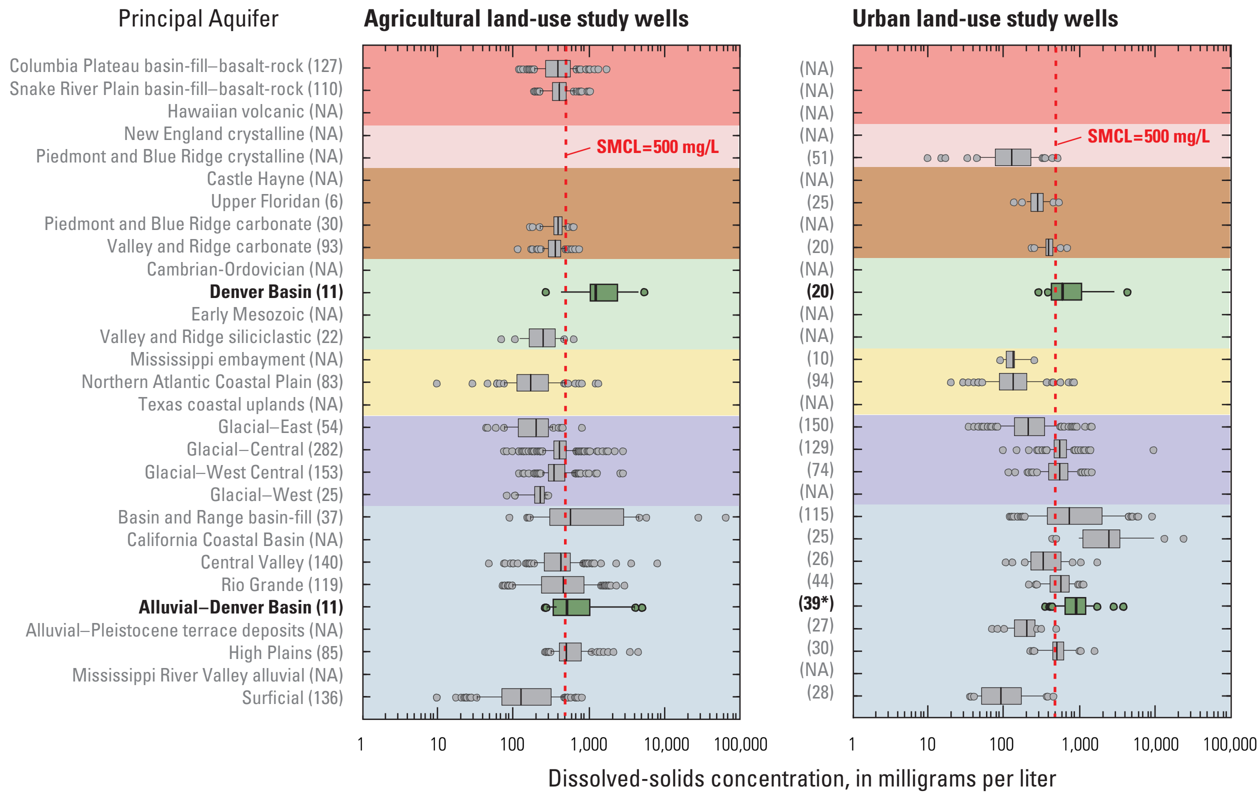
Glacial unconsolidated sand and gravel

Unconsolidated sand and gravel (nonglacial)

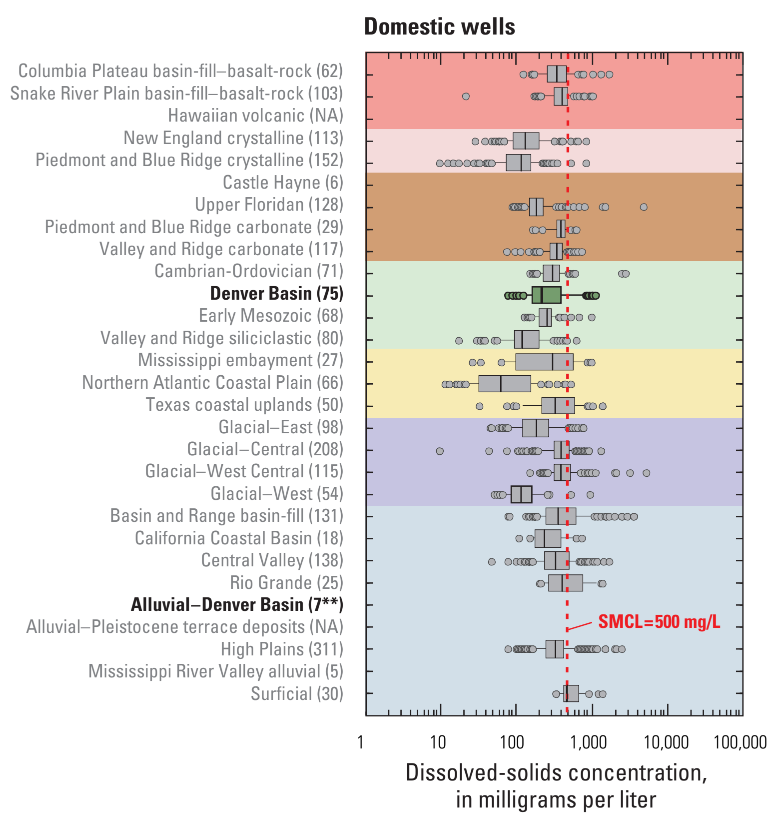
This appendix shows graphical comparisons of chemical concentrations (1991 to 2010) for selected inorganic and organic constituents of potential health or aquatic-life concern in selected Principal Aquifers of the United States. For each constituent, the concentration data are grouped according to five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

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

Dissolved solids

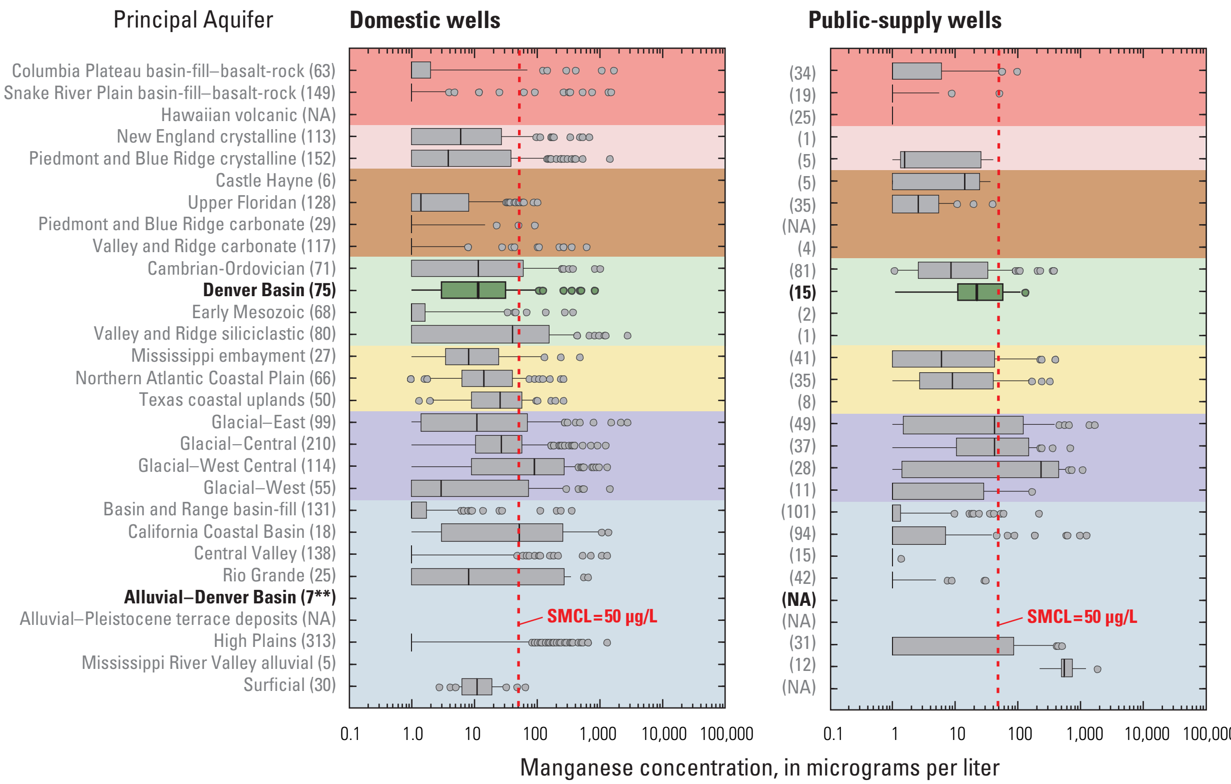


*Includes 30 wells in 1993 South Platte River Basin study located within the Denver Basin boundaries.



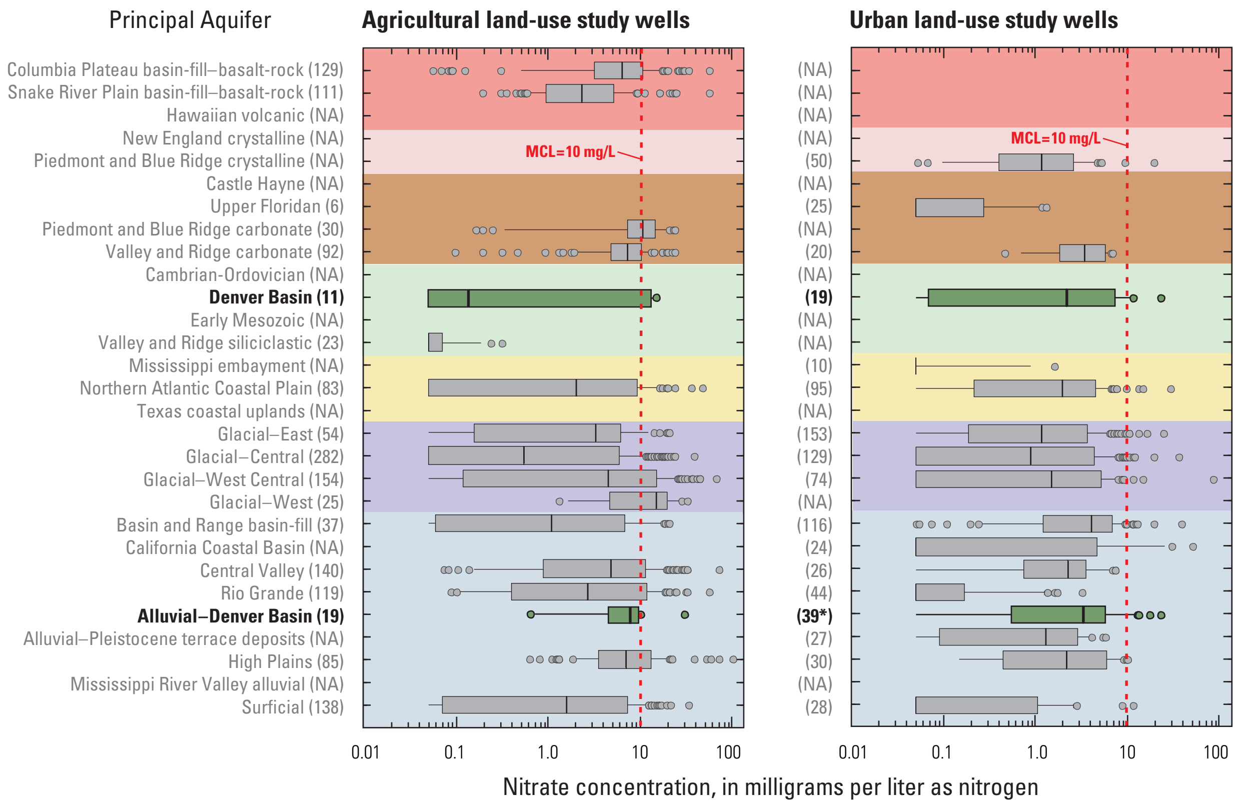
**Wells in 1993 South Platte River Basin study located within the Denver Basin boundaries.

Manganese

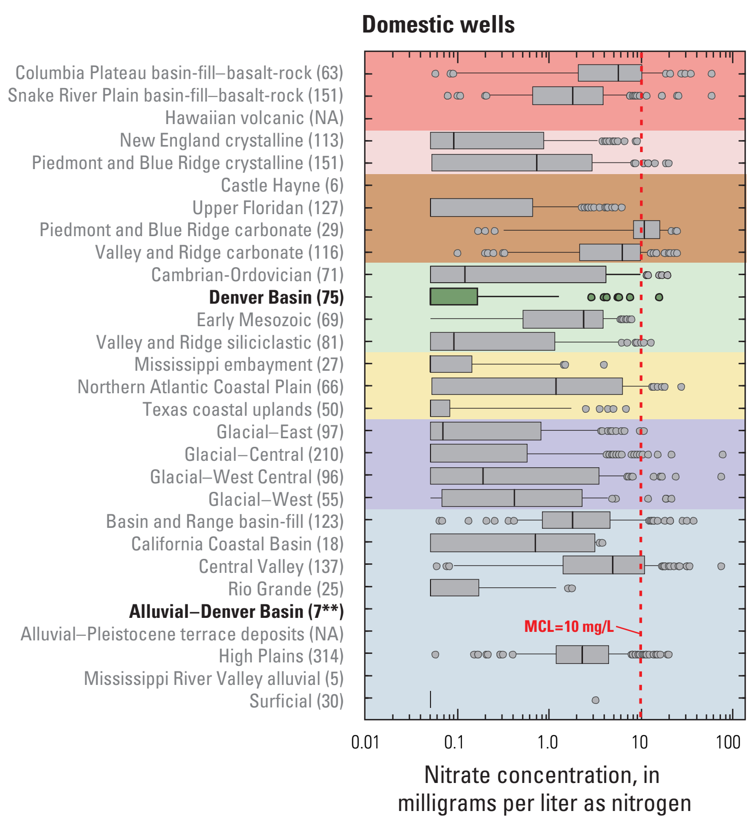


**See footnote, p. 97.

Nitrate plus nitrite (nitrate)

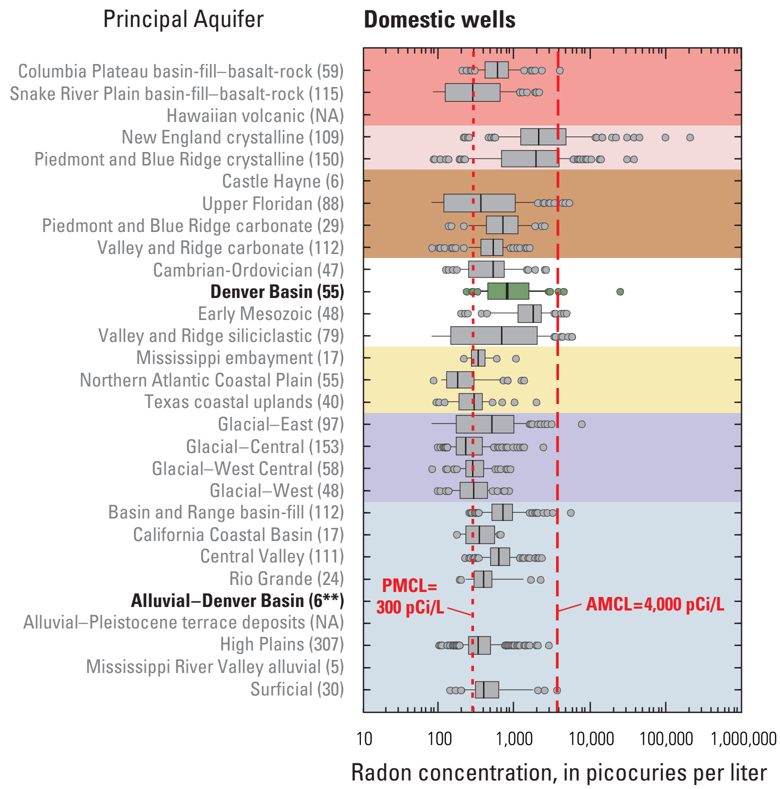


*See footnote, p. 97.



**See footnote, p. 97.

Radon



**See footnote, p. 97.

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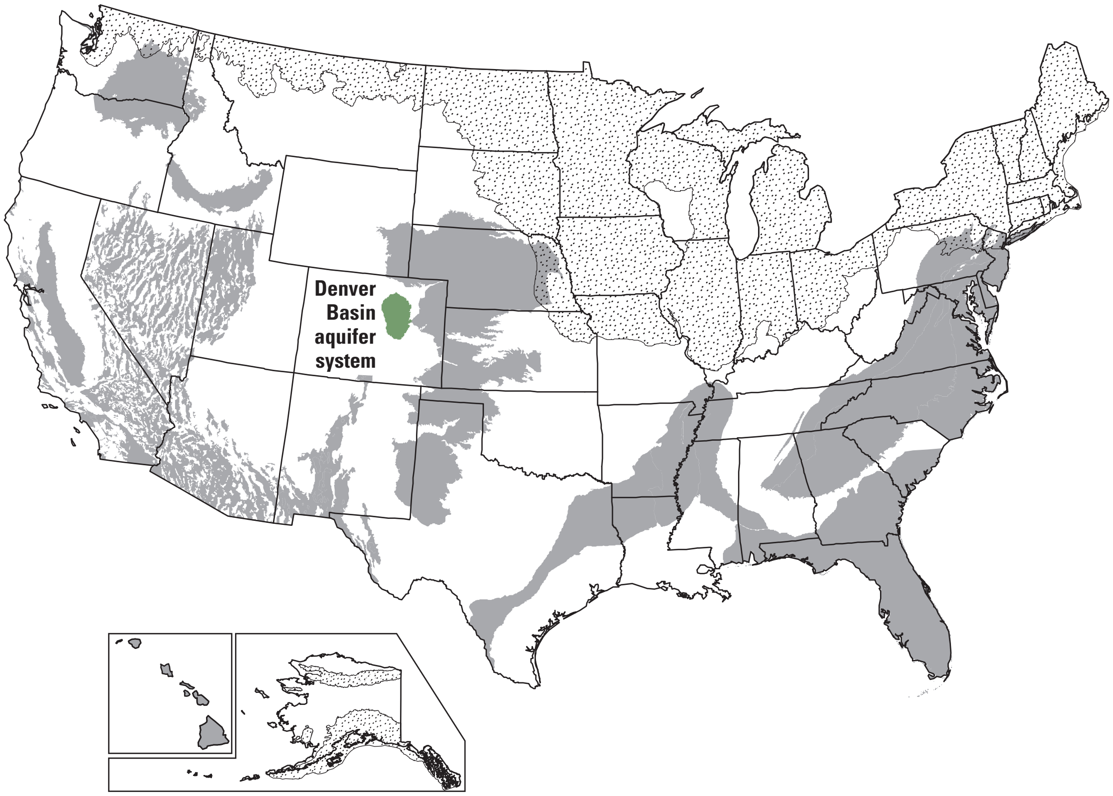
For more information concerning this report, contact:
Chief, National Water-Quality Assessment Program
U.S. Geological Survey
413 National Center
12201 Sunrise Valley Drive
Reston, VA 20192
http://water.usgs.gov/nawqa/



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