National Water-Quality Assessment Program

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Scientific Investigations Report 2006–5059

U.S. Department of the Interior
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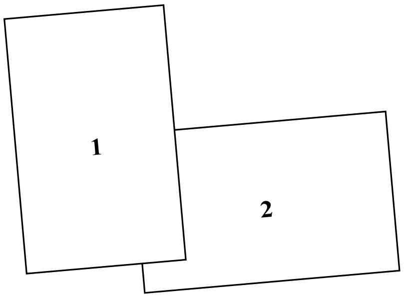

Cover.

1. U.S. Geological Survey scientist seals a glass ampule containing a well-water sample to be used for determining ground-water age.
2. U.S. Geological Survey scientists assemble chambers designed to minimize the likelihood of contamination of ground water during sample collection and preservation at the well site.

Ground-Water Quality in Unmined Areas and Near Reclaimed Surface Coal Mines in the Northern and Central Appalachian Coal Regions, Pennsylvania and West Virginia

By Steven D. McAuley and Mark D. Kozar

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FOREWORD

The U.S. Geological Survey (USGS) is committed to providing the Nation with credible scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, now measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). The NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991-2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html).

In the second decade of the Program (2001-2012), a major focus is on regional assessments of water-quality conditions and trends. These regional assessments are based on major river basins and principal aquifers, which encompass larger regions of the country than the Study Units. Regional assessments extend the findings in the Study Units by filling critical gaps in characterizing the quality of surface water and ground water, and by determining status and trends at sites that have been consistently monitored for more than a decade. In addition, the regional assessments continue to build an understanding of how natural features and human activities affect water quality. Many of the regional assessments employ modeling and other scientific tools, developed on the basis of data collected at individual sites, to help extend knowledge of water quality to unmonitored, yet comparable areas within the regions. The models thereby enhance the value of our existing data and our understanding of the hydrologic system. In addition, the models are useful in evaluating various resource-management scenarios and in predicting how our actions, such as reducing or managing nonpoint and point sources of contamination, land conversion, and altering flow and (or) pumping regimes, are likely to affect water conditions within a region.

Other activities planned during the second decade include continuing national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology; and continuing national topical studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on stream ecosystems, and transport of contaminants to public-supply wells.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA 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.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources, The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)

Temperature in degrees Celsius (˚C) may be converted to degrees Fahrenheit (˚F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (˚F) may be converted to degrees Celsius (˚C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviated water-quality units: Chemical concentration and temperature are given in metric units. Chemical concentration is expressed in milligrams (1×10^{-3} grams) per liter (mg/L), micrograms (1×10^{-6} grams) per liter (µg/L), or picograms (1×10^{-12} grams) per liter (pg/L)

Ground-Water Quality in Unmined Areas and Near Reclaimed Surface Coal Mines in the Northern and Central Appalachian Coal Regions, Pennsylvania and West Virginia

by Steven D. McAuley and Mark D. Kozar

Abstract

Findings are presented from investigations during 1996-1998 by the U.S. Geological Survey National Water-Quality Assessment Program. Ground-water quality in 58 wells downgradient of reclaimed surface coal mines is compared to ground-water quality from 25 wells in unmined areas (background concentrations) in the bituminous coal fields of the northern Appalachian coal region (high-sulfur coal region) in Pennsylvania, Maryland, and West Virginia and the central Appalachian coal region (low-sulfur coal region) in West Virginia. Ground water in the mined high-sulfur coal region has significantly greater median concentrations of sulfate, hardness, calcium, and specific conductance compared to the unmined high-sulfur coal region and to both mined and unmined areas in the low-sulfur coal region. Ground water in mined areas had median values of mine-drainage constituents (sulfate, iron, manganese, aluminum, hardness, calcium, magnesium, turbidity, and specific conductance) that were significantly greater than medians for wells in unmined areas. Mine-drainage constituents include cations such as calcium and magnesium that become elevated compared to levels in unmined areas because of exposure of acidic mine drainage to calcareous materials. The transport of pyrite-oxidation products from the mined site and subsequent neutralization reactions by calcareous materials at the mine site or along the flow path are likely processes that result in greater concentrations of mine-drainage constituents in mined areas compared to unmined areas. Mine-drainage constituents generally exceeded unmined-area background concentrations within about 500 feet of mined sites but were at or below background levels in wells more than 1,000 feet downgradient of mined sites. Concentrations of sulfate, hardness, and total dissolved solids were greatest at well depths of 50 to 150 feet but generally were less than background concentrations in wells deeper than 150 feet. Concentrations of iron, manganese, and aluminum exceeded background concentrations in many wells less than 150 feet deep.

In mined areas, median ground-water ages are nearly as old in hill locations as in valley locations. Older ground-water age correlates with increased distance from mined areas. The lack of significant correlation among mine-drainage-constituent concentrations, ground-water age, distance from mined areas, and topographic locations may be the result of factors such as (1) mixing of ground-water ages in wells open to fractures with variable depths, lengths, and interconnections; (2) disturbance of rock from blasting; and (3) variations in slope and terrain relief in the study area.

Introduction

The overall goal of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program is to describe the status and trends in the quality of the ground-water and surface-water resources of the United States and to link these trends to an understanding of the natural and human factors that affect the quality of these resources (Gilliom and others, 1995). The NAWQA Program integrates water-quality information on both a national and a local scale. Major components of the ground-water portion of the program are to 1) assess the quality of ground water in major ground-water regions throughout the United States and 2) determine the factors that affect the quality of water in these aquifer systems. This goal is achieved primarily by conducting surveys to assess the occurrence and distribution of water-quality constituents within an aquifer and to link data collected as part of the surveys to the natural and human factors that affect the quality of water within the aquifer. A study of ground-water quality near surface coal mines provides data on the effects of mines on ground-water quality.

Sulfur, iron, and manganese are sometimes present in high levels in coal, coal overburden, and rock that underlies the coal (Brady, 1998). Coal-mine drainage can be acidic or alkaline. Oxidation of iron-disulfide minerals, such as pyrite (FeS_2), occurs when the coal and overburden are exposed to oxygen and moisture, resulting in increased levels of sulfuric acid, iron, manganese, and aluminum in ground water. Pyrite oxidation is the principal mechanism for the formation of acidic mine drainage (AMD), in which acidity exceeds alkalinity. Neutral or alkaline mine drainage has alkalinity that equals or exceeds acidity but can still have elevated concentrations of sulfate, iron, and manganese. Because sulfate is conservative in chemical reactions and not normally targeted for removal by treatment, it is generally expected to persevere in mined areas (Rose and Cravotta, 1998).

Surface coal mines (surface mines) have had major effects on the quality of shallow ground water, especially with respect to iron, manganese, sulfate, and turbidity levels (Rauch, 1987; Williams and McElroy, 1995). The effects of blasting during surface mining also can have negative effects on ground-water supplies by causing turbidity levels in wells to increase and by causing a loss of water to wells and springs (McCurry and Rauch, 1986). Other problems commonly reported as a result of surface mining include changes in ground-water quality due to increased levels of methane and (or) hydrogen sulfide gas. These problems are significant because the vast majority of rural homeowners in the study area obtain their water from ground-water sources. In some instances, the effects of mining on ground water have caused rural homeowners to abandon their wells or springs, to purchase bottled water, or to haul water from other locations.

In 1977, Congress passed the Surface Mining Control and Reclamation Act (SMCRA). Some provisions of SMCRA include (1) regrading benches formed during the mining process to approximate original contour of the land prior to mining; (2) installing sedimentation ponds prior to and during mining to reduce sediment loads to receiving streams; (3) revegetating reclaimed strip benches upon completion of mining; (4) stabilizing and protecting surfaced-mined areas including spoil piles to control erosion and reduce the potential for surface and ground-water contamination; and (5) managing debris, toxic or acid-forming materials by burying, compacting, or disposing of the material in such a manner so as to prevent ground- or surface-water contamination (U.S. Office of Surface Mining Reclamation and Enforcement, 1993). In concept, changes in mining practice as a result of SMCRA should result in an improvement in surface- and ground-water quality.

In the Pennsylvania Code, Title 25, Subsection 87.102, regulations require monitoring of surface-mine sites during mining and, in some cases, after reclamation. The monitoring is normally focused on mine-drainage discharges to streams and springs. Regulations for mine drainage from surface mines in Pennsylvania are complex and exact limitations vary based on weather conditions (“dry” weather compared to 10-year, 24-hour precipitation events as listed in the Pennsylvania Code) and time period over which the limitations apply (30-day average, daily maximum, or instantaneous maximum) (Commonwealth of Pennsylvania, 2004). However, the most stringent limitation is that under “dry” weather conditions, the 30-day average effluent concentrations cannot exceed 3.0 mg/L for total iron, 2.0 mg/L for total manganese, and 35 mg/L for suspended solids, pH must be in the range of 6.0 to 9.0, and alkalinity must be greater than acidity.

In the Pennsylvania Code, Title 25, Subsection 87.116, regulations also state that ground-water quality, levels, infiltration rates, subsurface flows, and storage characteristics are to be monitored in a manner approved by the Pennsylvania Department of Environmental Protection (PaDEP) to determine effects of surface-mining activities on the quality and quantity of ground water, as well as on recharge capacity on reclaimed land, in the permitted mining area and adjacent areas (Commonwealth of Pennsylvania, 2004). The adjacent areas that are monitored usually are decided on a case-by-case basis. Several constituents are to be monitored for changes and must include specific conductance or total dissolved solids, pH, alkalinity, acidity, total iron, total manganese, sulfate, and water levels, but exact limitations for the constituents are not given in the regulations (Commonwealth of Pennsylvania, 2004). The limitations would have to be at least as stringent as the U.S. Environmental Protection Agency (USEPA) drinking-water standards (U.S. Environmental Protection Agency, 2004) if the affected aquifer or stream or spring were a source for a public water supply. However, in most cases, residents near surface mines use a well or spring for private domestic supply and these are not regulated.

Within the State of West Virginia, discharge of mine-related contaminants is governed by separate sets of regulations. For effluent discharged directly from pipes and other point sources, such as those commonly found draining tailings or treatment ponds, effluent concentrations are regulated by antidegradation standards established as part of recently enacted legislation (West Virginia Code 22-11-7b, Title 60 - Series 5, Antidegradation Implementation Procedures, established in 2001 [West Virginia Department of Environmental Protection, 2002]). Prior in-stream water-quality standards also apply and are designed to protect human health and animals, birds, fish, and other aquatic organisms and plant life. In-stream water-quality standards apply more to nonpoint sources of contamination and are governed by West Virginia Code 22-11-2, Title 46 - Series 1, Requirements Governing Water-Quality Standards (West Virginia Environmental Quality Board, 2005). The water-quality standards and the antidegradation standards vary depending on (1) drainage basin (stream) location and state-designated level of protection, and (2) conditions of weather, type of surface-water body, and time period over which standards apply. In general, the West Virginia in-stream standard for pH is similar to Pennsylvania (must be in 6.0 to 9.0 range), the iron maximum is 1.5 mg/L, and the manganese maximum is 1.0 mg/L. For ground-water quality in mining areas, a plan to monitor changes to ground-water baseline quality is required during mining operations and these regulations are described in the West Virginia Code 22-1-3, Title 38 - Series 3 (West Virginia Department of Environmental Protection, 2001).

Although the regulations state that contamination of ground-water quality is to be prevented, few studies (Rose and Cravotta, 1998; Williams and McElroy, 1995; McElroy, 1988; Friel and others, 1967; are examples) have examined whether ground water has been affected by surface coal mining near surface mining sites that have been reclaimed. Specifically, it has not been previously determined whether constituents that are indicative of mine drainage are present at concentrations greater than those for ground-water quality observed in unmined areas of the bituminous coal mining region of Pennsylvania and West

Virginia. Rose and Cravotta (1998) showed that in unmined areas, spring water and ground water typically were slightly acidic and contained much lower concentrations of dissolved solutes than water from mined areas. In mined areas, ground water ranged from alkaline to acidic and included elevated concentrations of sulfate, iron, manganese, and aluminum. In a study of water resources of Indiana County, Pa. (Williams and McElroy, 1995), ground water from the heavily mined geologic strata had higher median concentrations of iron, manganese, hardness, and total dissolved solids compared to that from the sparsely mined geologic strata. McElroy (1988), in a study of the ground-water resources of Fayette County, Pa., reported that wells near mining areas had statistically higher concentrations of sulfate, magnesium, and total dissolved solids than wells that did not penetrate a coal seam and that were more than 0.25 mi from mining sites. Friel and others (1967, p. 108) indicated that in the Monongahela Basin of West Virginia, median sulfate concentrations were greater in ground water from coal-bearing aquifers of Pennsylvanian age than from those aquifers that were in non-coal-bearing strata of Mississippian age. Ground water circulating through mined areas had increased acidity, total dissolved solids, and hardness, and often had dissolved metals carried in solution.

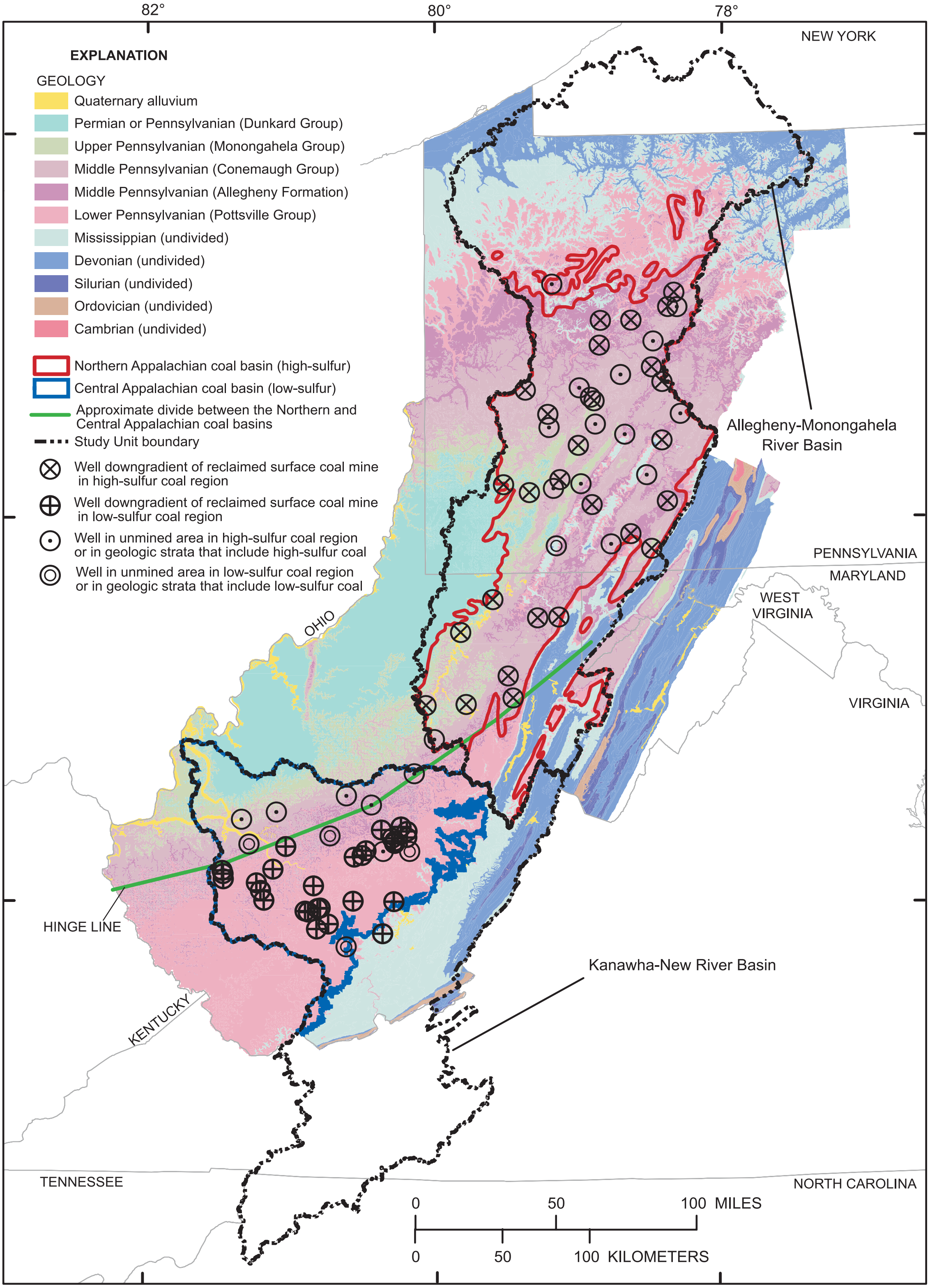
Purpose and Scope

This report summarizes major findings of a study of ground-water quality in surface coal-mining land-use areas. This study was conducted by the Kanawha-New River (KANA) NAWQA Program in the central Appalachian coal region of southern West Virginia (referred to as the low-sulfur coal region) and by the Allegheny-Monongahela River (ALMN) NAWQA Program in the northern Appalachian coal region in northern West Virginia, western Maryland, and southwestern Pennsylvania (referred to as the high-sulfur coal region) (fig. 1). The primary objective of the study was to compare and contrast ground-water quality from domestic-supply wells near reclaimed surface mines with water quality from equivalent wells in unmined areas. The report summarizes the (1) quality of ground water from unmined areas, (2) quality of water from aquifers immediately downgradient of reclaimed surface coal mines, (3) difference in quality of ground water from mined and unmined regions, (4) spatial extent of mine-drainage constituents in ground water from wells near reclaimed surface coal mines, (5) difference in quality of ground water between the high-sulfur and low-sulfur coal regions (in mined and unmined areas), and (6) difference in apparent age of ground water from mined and unmined areas and relation between apparent age and water quality in mined areas. The target population for sites to be sampled as part of this study was private wells (less than about 250 ft deep) downgradient (within about 2,000 ft) of surface mines that had been reclaimed (bond released) during 1985-1996. In 1997 to 1998, 58 such wells were sampled as part of this study, including 30 in the high-sulfur coal region and 28 in the low-sulfur coal region. In 1996 to 1998, 25 additional wells in unmined areas were sampled for comparison. All data used in this study were collected as part of the NAWQA Program. Data from previous studies were not used.

Description of the Study Area

This investigation considers ground-water resources in two adjoining drainage basins (fig. 1) of the Appalachian Plateaus Physiographic Province in New York, Pennsylvania, Maryland, West Virginia, Virginia, and North Carolina. The Appalachian Plateaus study area consists of rugged, deeply incised hilly terrain with uplifted plateaus capped by resistant layers of relatively flat-lying sandstone and shale (Fenneman, 1938; Fenneman and Johnson, 1946; U.S. Geological Survey, 1970). Geologic nomenclature used in this report is that of the Pennsylvania Topographic and Geologic Survey and the West Virginia Geological and Economic Survey. The study area is underlain by gently dipping, relatively flat lying, slightly folded sandstone, siltstone, shale, limestone, and coal of Devonian, Mississippian, Pennsylvanian, and Permian ages (fig. 1). Approximately 80 mineable coal seams are in the study area (Keystone Coal Industry Manual, 1994). The drainage basin in the northern part of the study area is the 8,778-mi^2 Allegheny-Monongahela River Basin in northern West Virginia, western Pennsylvania, and western Maryland. The basin is within the “northern Appalachian coal region” or the “high-sulfur coal region.” Many researchers (Cecil and others, 1985; Donaldson and others, 1985; Maksimovic and Mowrey, 1993; Tully, 1996a, 1996b) have found that the bituminous coal, overburden rock, and underlying rock in much of the northern Appalachian coal region of western Pennsylvania and northern West Virginia generally has a high sulfur content. Cecil and others (1985) indicates that the high-sulfur coals are the group of coals with a median sulfur content greater than 1.0 percent in the northern Appalachian coal region. Tully (1996a) characterizes the sulfur content as greater than 1.5 percent. The drainage basin in the southern part of the study area is the 4,395-mi^2 Kanawha–New River Basin of southern West Virginia. Most of the southern basin is within the “central Appalachian coal region” or the “low-sulfur coal region.” Cecil and others (1985) indicate that the low-sulfur coals are the group of coals with median sulfur content of less than 1.0 percent in the central Appalachian coal region. Tully (1996a) characterizes the sulfur content as less than 1.5 percent. Some of the northwestern Kanawha-New River drainage basin is within the high-sulfur coal region. In West Virginia, the high-sulfur and low-sulfur coal regions commonly are referred to as the northern and southern coal fields, respectively.

The differences in coal (and adjacent rock) sulfur content are due to depositional environments. The older rocks received more paleo-rainfall and paleo-recharge and thus the sulfur content was diluted compared to the younger rocks formed in a drier paleoclimate with higher ash, nutrient, and dissolved solids content that combine to result in higher sulfur content (Cecil and others, 1985). The younger rocks were deposited in marine



Geology from Berg and others (1980) and Cardwell and others (1968)

Figure 1. Study area, geology, and locations of wells sampled.
[The boundary between high-sulfur and low-sulfur coal regions coincides with that dividing the Northern and Central Appalachian Basins, respectively. The Pottsville Group in Pennsylvania (Berg and others, 1980) is recognized as the Kanawha, New River, and Pocahontas Formations in southern West Virginia (Cardwell and others, 1968).]

environments that had higher contents of sulfur and calcium carbonate. In contrast, the older rocks formed in areas that were marginally brackish, and so had lower content of sulfur and calcium carbonate. However, within most of the rocks of both ages, there are formations that represent marine, brackish, and marginally brackish paleoenvironments and each of these has high and low sulfur contents.

Cecil and others (1985) have indicated that the dividing line between the high-sulfur coal region and the low-sulfur coal region lies generally along the contact between the younger Pennsylvanian-aged rocks of the Allegheny, Conemaugh, and Monongahela Groups and the older Pennsylvanian-aged rocks of the Pottsville Group (Kanawha, New River, and Pocahontas Formations of West Virginia) in southern West Virginia (fig. 1). The dividing line between the high-sulfur coal region and the low-sulfur coal region commonly is referred to as the “hinge line.” The “hinge line” is the same as the divide between the northern and central Appalachian coal basins shown in figure 1.

Average annual precipitation is about 42 in. for the central and northern Appalachian coal regions, although it is distributed unevenly with respect to topography and climatological regions (National Oceanic and Atmospheric Administration, 1997a, 1997b). Areas at higher elevations typically receive higher average amounts of precipitation than areas at lower elevations. Surface water is the principal source of water used in the region, accounting for 92 percent (2,340 Mgal/d) of all freshwater withdrawals (Pennsylvania and West Virginia Departments of Environmental Protection, written commun., 2000). Ground water accounts for only 8 percent (193 Mgal/d) of freshwater withdrawals. However, 12 percent of all water used for public water supply (51.9 Mgal/d) and 99.8 percent of self-supplied water used by rural homeowners (45.1 Mgal/d) is obtained from ground water. Land cover for the mining area is dominated by forested, agricultural, and rural residential uses (U.S. Geological Survey, 1992).

Geohydrologic Framework and Ground-Water Flow

The generalized hydrogeologic framework of the study area is based on regional topography, stratigraphy, and structure, with upland plateaus formed by resistant clastic rocks and valleys developed in zones of structural weakness. Structurally, the rocks in the Appalachian Plateaus study area are nearly flat to gently folded and commonly fractured. Pennsylvanian-age clastic rocks form the predominant outcropping units in the uplands and valley walls of southern and central West Virginia (Cardwell and others, 1968). Pennsylvanian and Permian stratigraphic units consist of sandstone, conglomerate, siltstone, shale, and coal, with local beds of limestone and dolomite. Where these bedrock units are not exposed at land surface, they commonly are overlain by a relatively thin layer of regolith or alluvium and, in northwestern Pennsylvania, by areally restricted, unconsolidated deposits of glacial origin (Berg and others, 1980).

Ground-water flow paths are relatively short and limited to two principal types of aquifer systems: (1) unconsolidated alluvial aquifers made up of sand, silt, clay, and gravel; and (2) fractured-bedrock aquifers made up of sedimentary and carbonate rocks (Puente, 1985). Because they tend to be shallow and thin, the alluvial aquifers present within the study area typically are not used as water supplies but can combine with soil and regolith to provide shallow storage for recent recharge. Fractured-bedrock aquifers are the primary aquifers in the study area. Locally, regolith, where alluvium is not present, is commonly thin with low permeability, providing little ground-water storage. Ground-water storage and flow in bedrock occurs through joints, fractures, and bedding-plane separations (Kozar and Mathes, 2001, p. 11). In the study area, secondary permeability due to jointing and stress-release fracturing accounts for most of the porosity and permeability in the bedrock, because original intergranular porosity commonly has been filled by calcium carbonate or silica cementation (Wyrick and Borchers, 1981).

Recharge to fractured-bedrock aquifers in the region occurs primarily as rainfall; snowmelt is only an important source of recharge in areas at elevations above 3,000 ft. Once precipitation falls on the surface, that part that does not run off to streams percolates into and through shallow soils and regolith and eventually recharges fractured-bedrock or alluvial aquifers.

A decrease in hydraulic conductivity with depth has been documented by several researchers. For a mine site in West Virginia, average hydraulic conductivity of an aquifer decreased from 10^{-5} m/sec at a depth of 150 ft to 10^{-9} m/sec at depths greater than 300 ft (Bruhn, 1985). For a site in Greene County, Pa., hydraulic conductivity decreased by an order of magnitude per 100 ft of depth to a depth of approximately 500 ft (Stoner, 1982). According to Callaghan and others (1998), the vast majority of ground-water circulation occurs at moderate depths of less than 300 ft.

In the Appalachian Plateaus, local fractured-bedrock aquifers generally of less than 5.0 mi^2 in area are defined by topographic valleys and boundary ridges. Each small valley may contain a locally distinct aquifer from which ground water discharges to a nearby stream or to deeper subregional or regional aquifers. The ridges surrounding the valley define the lateral boundaries of the local aquifer and its principal recharge area. Subregional aquifers (generally from 100 to 500 ft below land surface) occur at intermediate depths between the shallow local aquifer (less than 100 ft below land surface) and deeper regional aquifers. Subregional aquifers are larger than local aquifers and may include several smaller local aquifers. Discharge of ground water from subregional aquifers is primarily to tributary streams with drainage areas typically much larger than 5.0 mi^2. A small component of recharge to these aquifers is from deeper regional aquifers. These intermediate aquifers can extend beneath local topographic divides and discharge to regional aquifers. Depth to saline water (brines) has been used to infer the depth of regional aquifers (Callaghan and others, 1998). In the study area, the depth to brackish water ranges from a maximum in excess of 2,000 ft near the southern part of the study area in West Virginia and to a minimum of less than 50 ft in the northwestern part of the study area in Pennsylvania (Foster, 1980). Regional aquifers may contain saline or brackish water and typically discharge to large rivers.

Within the local aquifers, ground water typically flows from hilltops to valleys, perpendicular to local tributary streams, through an intricate network of stress-relief fractures and interconnected bedding-plane separations, commonly in a stair-step pattern (fig. 2) (Harlow and LeCain, 1993). Vertical hydraulic conductivity can be negligible, resulting in horizontal ground-water flow (especially within coal seams) that discharges as springs or seeps in hillsides and valleys (Harlow and LeCain, 1993). A small proportion of the ground water flows deeper within the central core of the mountain or ridge, especially within coal seams and along bedding-plane separations, and likely reaches the valley to discharge locally to surface water or it may recharge subregional and regional aquifers. Ground-water flow in valleys occurs primarily in bedding-plane separations beneath valley floors and in vertical and horizontal slump fractures along valley walls (Wyrick and Borchers, 1981). Enhanced permeability of bedrock in valleys may result in ground-water flow parallel to and beneath local tributary streams before ultimately discharging to surface-water bodies.

The age of water in the subregional aquifer systems of the study area is not well documented. Based on ages of water in deeper wells sampled in West Virginia (Kozar, 1998), subregional ground water is at least 57 years old but may be much older, perhaps even centuries old. Deep saline brines in regional aquifers may be thousands of years old.

Surface coal mines can substantially change surface-water and ground-water flow patterns by altering recharge areas, recharge rates, and the porosity and permeability of aquifers.

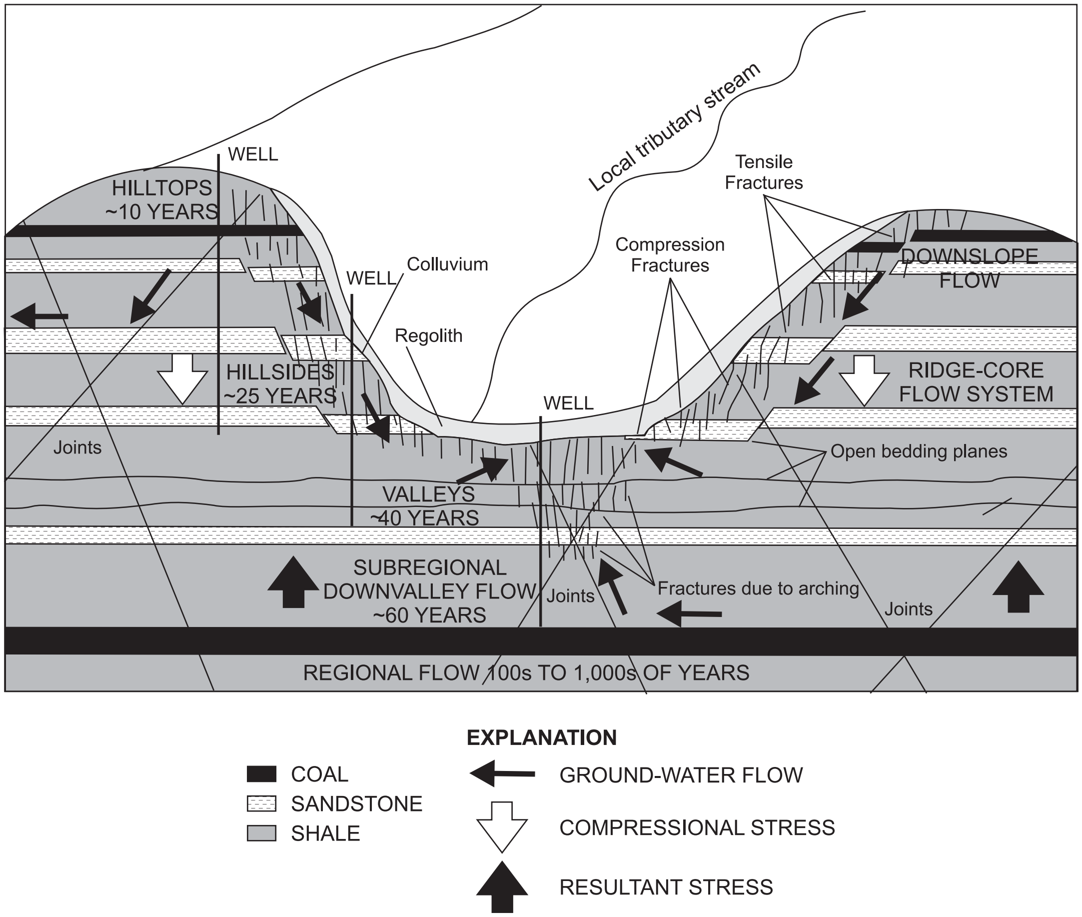


Figure 2. Conceptual model of ground-water flow in a fractured-bedrock aquifer in the Appalachian Plateaus, including apparent age of ground water (modified from Wyrick and Borchers, fig. 3.2-1, 1981 and Kozar, 1998). [Ground-water-age data presented in this figure are typical of ground water in the central Appalachian coal region but should not be considered characteristic of ground-water age in the northern Appalachian coal region.]

Surface coal mines can be reclaimed to mimic the original contours of the land surface before mining (surface contour-surface mines). Ground-water flow in and through reclaimed contour-surface mines depends on many factors including the dip of bedrock at a mine, the composition and permeability of material within spoil, the age of spoil, and engineering controls such as ditches, terraces, sediment retention basins, ponds, and flumes or chutes. Each reclaimed surface mine has its own local ground- and surface-water flow system. There are, however, aspects common to most reclaimed contour-surface mines (Hawkins, 1998a, 1998b).

Typically, ground water will pool at the base of the surface-mine bench. Recharge to the ground water at a mine can originate as surface drainage through spoil and unmined areas upgradient of the backfilled contour bench (Hawkins, 1998a). If the coal seam dips away from the highwall, there may be little water stored within the spoil because ground water will freely flow down-dip through spoil. Where a coal seam dips towards a highwall, however, ground water commonly will accumulate and flow laterally along the base of the highwall until emerging to the surface as springs or seeps. Water emerging in seeps and springs may be conveyed away from a reclaimed contour-surface mine by ditches or drains to a nearby tributary stream and may be lost as a potential source of recharge. Mine spoil typically exhibits dual porosity, especially when more than one type of bedrock makes up the spoil (for example, sandstone, which usually consists of coarse-grained deposits such as sand, gravel, and boulders, and shale, which typically consists of fine-grained deposits within the spoil). Even where only one type of bedrock (for example, sandstone) is present within the spoil, differential settling of coarser-grained deposits (boulders and cobbles) is typical at the base of a cast spoil pile with finer-grained deposits (sand, dust, and gravel) near the surface during the backfilling process. Ground-water flow within the spoil is therefore highly variable because of interspersed fine- and coarse-grained deposits within the backfill.

Methods

Although a comparison of ground-water quality in mined areas or mined strata to sparsely mined areas or strata has been studied by other researchers as previously mentioned, this study collected data to examine ground-water quality in unmined areas and areas downgradient of only reclaimed surface coal mines. During June 1997-September 1998, ground water was sampled from 58 wells downgradient from reclaimed surface mines. In the low-sulfur coal region, 28 wells were sampled, and in the high-sulfur coal region, 30 wells were sampled (fig. 1). The wells sampled (Ward and others, 1998, 1999; Coll and Siwicki, 1997, 1999) are considered to be in the low-sulfur coal region if they are within the outcrop area of the Pocahontas, Kanawha, or New River Formation. All others are in the high-sulfur coal region. All wells were sampled using parts per billion, clean-hands protocols developed by the USGS NAWQA Program (Koterba and others, 1995). The downgradient wells were generally within about 2,000 ft from reclaimed surface mines, which were generally contour strip mines whose bond had been released during 1985 to 1996. The 2- to 12-year bond-release criteria were selected because 2 years generally is considered to be the minimum time required for ground water to return to steady-state equilibrium after the reclamation process has been completed and 1985 was considered to be the year when provisions of SMCRA were fully implemented within the study area. Two of the downgradient wells were further than 2,000 ft from a mine. Shallow wells, generally less than 250 ft in depth, were also selected for sampling. In concept, the shallow, private, domestic supply wells will be more representative than the deeper wells in terms of intercepting recharge infiltrating from upgradient land surface, thus reflecting effects of the targeted land use (surface mining) on ground-water quality. A few wells were deeper than 250 ft. To identify position relative to mines, the principal direction of ground-water flow is assumed to coincide with the topographic gradient.

During July 1996 through September 1998, ground water also was sampled from 25 wells in areas that had not been mined, to serve as reference sites to the wells sampled near mines. Determination of a lack of coal mining for the wells in the unmined areas was made by examination of land-use geographic information system (GIS) coverages and by conducting well-owner interviews. In addition, a search was conducted for mining permit records near and upgradient of wells selected for sampling. The wells in unmined areas are in flow systems in fractured rock that are similar to the wells sampled near mines. Twenty of the wells sampled in unmined areas are in the high-sulfur coal region and 5 wells are in the low-sulfur coal region. Of the 25 reference sites sampled, 10 were within the Kanawha-New River Basin and 15 were in the Allegheny-Monongahela River Basin. Hereafter, the term “unmined” will be used instead of “reference.”

The water samples from wells were analyzed for a broad range of constituents. Mine-drainage-related constituents included sulfate, pH, alkalinity, acidity, iron, manganese, aluminum, hardness, calcium, magnesium, specific conductance, total dissolved solids, and turbidity. Other constituents collected included physical field measurements (temperature and dissolved oxygen), other common ions (calcium, magnesium, sodium, and chloride), other trace metals, nutrients, dissolved organic carbon (DOC), dissolved gases, chlorofluorocarbons (CFCs), and radon. Calcium and magnesium are included with mine-drainage constituents in this report because the levels commonly are elevated because of alkaline treatment at mine sites. Bacteria samples were collected from the 28 wells sampled in the low-sulfur coal region but were not collected from the 30 wells sampled in the high-sulfur coal region. The wells sampled in the high-sulfur coal region were sampled for selected volatile organic compounds (VOCs) but wells sampled in the low-sulfur coal region were not because VOCs were not normally examined in mining-area studies in southern West Virginia. All samples, except CFCs and field measurements, were analyzed at the USGS National Water Quality Laboratory (NWQL). Results of all laboratory analyses are published in

Ward and others (1998, 1999) and Coll and Siwicki (1997, 1999). References for methods for the analyses performed by the NWQL can be found in the aforementioned reports as well as in publications by researchers at the NWQL (U.S. Geological Survey, 2005). Methods for field measurements are described in the USGS National Field Manual for the Collection of Water Quality Data (U.S. Geological Survey, variously dated).

The acidity data in this report are calculated using the major components of acidity (pH and iron, manganese, and aluminum concentrations) in the method described in Rose and Cravotta (1998). Rose and Cravotta (1998) and Hedin and others (1994) have shown that calculated and measured acidities are comparable. Hedin and others (1994) found differences of less than 10 percent in measured and calculated acidities of mine-drainage samples where pH values were between 3.0 and 4.0. In alkaline samples, calculated acidity may exceed measured acidity because as the sample pH increases, iron and other metal ions form hydroxide complexes that have less capacity than the uncomplexed ions to consume bases (so there is less acidity contribution).

Ground-water age data may be used to (1) estimate average ground-water flow velocity, (2) determine relative ground-water flow directions, (3) better understand the ground-water flow processes within an aquifer, (4) assess when or if past and present land-use activities may affect an aquifer, and (5) develop strategies for protecting valuable ground-water reservoirs.

Estimates of ground-water age referred to within this report were determined by collecting ground-water samples and analyzing them for CFCs using analytical and interpretive methods of Busenburg and Plummer (1991, 1992) and Szabo and others (1996). CFCs are stable synthetic organic compounds that were first manufactured in the 1930s. CFCs, also known as Freons, are detectable at very low concentrations (one part in 10^{15} by weight or 1 pg/L in water) and are commonly used as ground-water tracers (Busenburg and Plummer, 1991). Concentrations of CFCs in ground water depend on their atmospheric partial pressures and the equilibrium temperature (recharge temperature) of the water at the base of the unsaturated zone during recharge (Busenburg and Plummer, 1992). Concentrations of CFC-11, CFC-12, and CFC-113 in the atmosphere have steadily increased since their development in the 1930s. Curves of atmospheric concentrations of CFC-11 and CFC-12 were reconstructed on the basis of production records (Chemical Manufacturer's Association, 1990) and rates of release to the atmosphere (McCarthy and others, 1977; Gamlen and others, 1986). Similar techniques were used to reconstruct atmospheric concentration curves for CFC-113 (Szabo and others, 1996). Assuming that CFC concentrations in recharge are proportional to atmospheric concentrations at a particular time and location, apparent ground-water age can be estimated to within 2 years from these curves by knowing the concentration of CFCs and the temperature of recharged water.

The estimation of apparent ground-water age with respect to mined and unmined areas and with respect to the high-sulfur northern and low-sulfur central coal regions is based on the assumption of piston flow. In a simple piston-flow system, water enters the aquifer in an upland area and flows downgradient to a discharge area with little or no mixing with water from areas other than the upland recharge area.

Quality-assurance (QA) samples were collected in addition to the environmental samples. Blanks were collected to assure that sampling procedures were not introducing bias into the data, and replicate and spiked samples were collected to verify that laboratory measurements were acceptable. Blank samples generally did not reveal problems with sampling procedures except for low levels of a few constituents (table 1). Analyses of replicates and field spike data did not indicate potential problems in analytical determinations at the laboratory.

Iron, aluminum, zinc, ammonia, and DOC were detected in several blank samples at concentrations greater than the minimum reporting limits of 3 µg/L, 1 µg/L, 1 µg/L, 0.015 mg/L, and 0.10 mg/L, respectively. Nevertheless, most detections of iron, zinc, and ammonia concentrations in the well samples were at concentrations greater than the level of contamination detected in the quality-assurance field blanks and thus are considered to represent valid data. However, concentrations of aluminum below 4.8 µg/L may have been affected by sampling or analytical bias. In addition, concentrations of DOC less than 16 mg/L that were reported for blanks may also have been affected by sampling or analytical bias. Because of the high concentration of DOC in blanks, DOC was included in tabular summaries of the data but not discussed further in the interpretation of water-quality data. Sampling and analytical bias were considered during statistical analyses of the available data. No VOCs analyzed in this study had field or trip blanks showing concentrations greater than an estimated 0.07 µg/L; therefore, censoring of VOC data was not warranted (table 1).

All instruments used for monitoring pH, specific conductance, water temperature, and dissolved oxygen were calibrated daily in the field. Review of log sheets for instrument calibration did not indicate any problems with field determinations of these constituents. Comparison of field and laboratory determinations of pH and specific conductance indicated close agreement for the wells sampled.

Concentrations of constituents sampled were compared to USEPA Drinking Water Standards, both primary and secondary. National Primary Drinking Water Regulations (primary standards) are legally enforceable standards that apply to public water supply systems (U.S. Environmental Protection Agency, 2004). Under the Federal Safe Drinking Water Act, a Maximum Contaminant Level (MCL)—the maximum allowable concentration—is set for inorganic and organic contaminants that can adversely affect public health. For comparison purposes, the water quality of private domestic wells near mined and unmined sites evaluated for this study was examined in relation to these standards. National Secondary Drinking Water Regulations (secondary standards) are nonenforceable guidelines established by the USEPA for contaminants such as sulfate, iron, and manganese that may cause water to have poor taste, odor, or color; may cause staining of plumbing fixtures; or may cause

Table 1. Summary of field and trip blank quality-assurance data with detections from ground-water samples collected as part of mining land-use studies in the high-sulfur and low-sulfur coal regions.

[Constituents not detected in blanks are not listed in this table; mg/L, milligrams per liter, µg/L, micrograms per liter; N/A, not applicable; <, less than; E, estimated]

Constituent name	Method detection limit	Unit of measure	Blank samples			Routine samples from mined areas		
			Number of samples	Number of detections	Range of concentrations detected	Number of samples	Number of detections	Range of concentrations
Calcium (dissolved)	0.02	mg/L	4	1	0.05	58	58	1.4–230
Magnesium (dissolved)	.01	mg/L	4	1	0.01	58	58	1.7–57.0
Silica (dissolved)	.01	mg/L	4	2	0.02–0.04	58	58	3.5–20.0
Aluminum (dissolved)	1.0	µg/L	4	3	3.3–4.8	58	58	2.7–971
Iron (dissolved)	3.0	µg/L	4	3	4.5–5.7	58	54	<3.0–31,000
Zinc (dissolved)	1.0	µg/L	4	3	1.2–3.4	58	56	<1.0–472
Ammonia (dissolved as N)	.015	mg/L	3	3	0.016–0.058	58	55	<0.010–1.54
Dissolved organic carbon	.10	mg/L	3	3	0.6–16.0	58	58	<0.10–10.0
Chloroform (total)	.052	µg/L	2	1	E0.01	58	8	0.008–0.119
Toluene (total)	.038	µg/L	2	1	E0.03	30	3	0.009–0.04
1,4 Dichlorobenzene (total)	.050	µg/L	2	1	E0.01	30	0	<0.050
Dichlorodifluoromethane (total)	.140	µg/L	2	1	E0.004	30	0	<0.100
1,2,4 Trimethylbenzene (total)	.056	µg/L	2	1	E0.07	30	18	0.008–0.140
m–p Xylene (total)	.060	µg/L	2	1	E0.01	30	1	E0.008-<0.064

cosmetic effects such as tooth discoloration (U.S. Environmental Protection Agency, 2004).

A Mann-Whitney nonparametric rank-sum test was conducted to compare mine-drainage-related constituents and ground-water ages from samples downgradient of mined sites to those constituents from samples in unmined areas to determine if observed differences are statistically significant (Helsel and Hirsch, 1992, p. 118-124). Results of the tests are reported as significant at the 95-percent confidence level (p value <0.05). A nonparametric Kruskal-Wallis rank-sum test also was conducted to determine if mine-drainage constituents differ significantly based on orientation of sampled wells (in terms of dip and strike) relative to the mined area (Helsel and Hirsch, 1992, p. 159-163). A Spearman's rank correlation test was conducted to compare the age data to the distance and topographic data and to water-quality data, specifically the mine-drainage constituents listed previously (Helsel and Hirsch, 1992, p. 217-219). Multiple-step Kruskal-Wallis tests were conducted on ranks of the data to determine if median concentrations of mine-drainage constituents differ significantly in ground-water samples based on (1) location in coal-sulfur regions and (2) topographic location (Helsel and Hirsch, 1992, p. 159-163 and p. 200-207). For each of the two hypotheses tested, there were four groups including two for mining land use (mined, unmined) and two for either coal-sulfur region (high, low) or topographic location (hill, valley). The Kruskal-Wallis tests were conducted on the four sample groups, then on subsets of the four sample groups as needed to determine which sample group differed from the others. The significance level was alpha = 0.05 for comparison of four groups, and alpha = 0.025 for two groups. Nonparametric procedures were chosen because of unbalanced sample sizes and because of observations of skewness and of outliers in boxplots for many constituents. For purposes of ranking data with multiple minimum reporting levels for use in statistical tests, data were set equal to just less than the highest minimum reporting level. In boxplots, the highest minimum reporting level is shown as the censored level of the data.

Ground-Water Quality in Unmined Areas and Near Reclaimed Surface Coal Mines

Ground-water quality generally is influenced by several factors, such as climate, aquifer type and lithology, geologic structure, topographic setting, and land use. In this report, general comparisons of water quality including water types are presented. Background concentrations of constituents useful in characterizing mine drainage are assigned and discussed. Results of statistical testing to differentiate waters from wells in unmined areas and wells downgradient of areas with reclaimed surface coal mines (hereafter termed “mined areas”) are examined for existence of contamination by mine drainage. The degree of the contamination compared to drinking-water-quality standards is discussed. The influence of hydrogeologic factors (spatial and temporal extents of changes downgradient of mined areas) as well as geological factors (changes in source geochemistry of aquifer rocks) also are examined.

Detailed data, except for CFC data, are not available in this report because they can be found in other publications (Coll and Siwicki, 1997, p. 188-201; 1999, p. 325-344; Ward and others, 1998, p. 342-351; 1999, p. 446-454). Data from USGS water-quality and ground-water databases also may be accessed at web site *http://waterdata.usgs.gov/*. Site identification numbers, local identification name, coal sulfur content region, land-use classification (unmined or mined), topographic location, distance downgradient from mine, and well depth are given in appendix 3.

Comparison of Water Quality Between Mined Areas and Unmined Areas

Surface mining of coal causes the disturbance of great volumes of coal, overburden rock, and pavement rock that underlies the coal. These disturbances may result in changes in hydrology of the area and expose previously buried rocks to oxygen and water that may result in changes in the quality of ground water beneath and downgradient from mined areas. Common effects include increased concentrations of dissolved sulfate, iron, aluminum, manganese, and other ions and metals that contribute to hardness and acidity and increased suspended solids and turbidity (Rose and Cravotta, 1998).

Data collected for this study are summarized in terms of the two most general data groups, ground water from wells in unmined and mined areas. However, to evaluate the data in a regional sense, the wells in unmined and mined groups were further subdivided into low-sulfur coal region and high-sulfur coal-region categories. This was done because characteristics of the coal-bearing rocks that form the aquifers, and thus affect ground-water quality, have been shown to have significantly different characteristics in previous research (Cecil and others, 1985; Donaldson and others, 1985; Maksimovic and Mowrey, 1993; Tully, 1996b). Wells in the northern Appalachian coal region of western Pennsylvania and northern West Virginia are assigned to the high-sulfur coal-region category. Wells in the central Appalachian coal region that includes southern West Virginia are assigned to the low-sulfur coal-region category. Cecil and others (1985) have indicated that the dividing line between the high-sulfur coal region and the low-sulfur coal region lies generally along the contact between the younger Pennsylvanian-aged rocks of the Allegheny, Conemaugh, and Monongahela Groups and the older Pennsylvanian-aged rocks of the Pottsville Group (Kanawha, New River, and Pocahontas Formations of West Virginia) in southern West Virginia (fig. 1).

Summary statistics describing ground-water chemistry for the unmined and the mined groups, including the minimum, maximum, median, and mean values for all constituents discussed in this report, are shown in table 2. The water-quality standards that will be compared to the concentrations in ground-water samples later in this section are listed in table 2.

Variations of Water Quality Related to Regional Differences in Coal Sulfur Content

The regional differences in major-ion composition of ground water in unmined and mined areas are illustrated using Piper diagrams (fig. 3). The principal composition of the ground water in unmined areas of the high-sulfur and low-sulfur coal regions is calcium-magnesium carbonate-bicarbonate type (69 percent of samples). The principal composition of ground water from mined areas in the high-sulfur and low-sulfur coal regions ranges from calcium-magnesium carbonate-bicarbonate type (52 percent of samples) to calcium-magnesium sulfate type (36 percent of samples).

The increased prevalence of sulfate-type waters in mined areas indicated that sulfate and other constituents would occur at different concentrations in mined areas compared to unmined areas. Box plots of several constituents (sulfate, iron, radon, pH, hardness, calcium, and specific conductance) are shown for high-sulfur versus low-sulfur coal regions in figure 4. Multiple stage Kruskal-Wallis tests (Helsel and Hirsch, 1992, p. 159-163, 200-207) on the four data subsets—mined high-sulfur, mined low-sulfur, unmined high-sulfur, and unmined low-sulfur—were conducted on the unbalanced ranks of the data, with results reported at a significance level of alpha = 0.025. Significantly different sample subset medians are denoted by different letters (A, B) on the box plots in figure 4. A subset median denoted AB in figure 4 is statistically the same as the median for code A and code B populations.

For unmined areas, there are no statistically significant differences between median concentrations of most mining-related constituents when high-sulfur and low-sulfur regions are compared. This generalization holds for sulfate, iron, pH, hardness, calcium, and specific conductance (fig. 4).

Medians of some constituents (specific conductance, calcium, radon, and pH) are greater in wells sampled in the high-sulfur mined areas compared to low-sulfur mined areas but not all are significantly greater. Iron and manganese (not shown in

Table 2. Summary statistics and related Federal drinking water standards for constituent concentrations in ground water from wells in mined (58 samples) and unmined areas (25 samples).

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; µS/cm, microsiemens per centimeter; NTU, nephelometric turbidity units; <, less than; NA, not applicable; MCL, maximum contaminant level, enforceable standard; AMCL, alternate maximum contaminant level, enforceable standard; SDWR, secondary drinking water regulation—nonenforceable guideline for cosmetic or aesthetic effects; Advisory, nonenforceable advisory for taste or odor]

Constituent	Units	Samples from mined areas				Samples from unmined areas				U.S. Environmental Protection Agency drinking water standard[1]
		Minimum	Mean	Median	Maximum	Minimum	Mean	Median	Maximum	
Acidity	mg/L	0.03	6.22	1.46	45.7	0.037	10.9	1.74	86.3	NA
Alkalinity	mg/L	0	128	117	357	0	133	114	344	NA
Aluminum	µg/L	2.7	35.5	3.75	971	<1	8.04	3.1	79	50-200 (SDWR)
Ammonia	mg/L as N	<.015	.26	.141	1.54	<.015	.147	.078	.92	30 (Advisory)
Barium	µg/L	7.8	265	122	2,680	20	209	161	1,230	2,000 (MCL)
Beryllium	µg/L	<1.0	<1.0	<1.0	1.4	<1.0	<1.0	<1.0	<1.0	4 (MCL)
Calcium	mg/L	1.4	52.4	35.9	230	1.5	27.2	21	85	NA
Chloride	mg/L	.31	50.1	5.1	1,200	.9	21.6	7.3	240	250 (SDWR)
Chromium	µg/L	<1.0	2.23	1.9	8.3	<1.0	2.23	1.5	6.7	100 total (MCL)
Cobalt	µg/L	<1.0	6.55	<1.0	158	<1.0	1.73	<1.0	17	NA
Copper	µg/L	<1.0	6.25	<1.0	125	1.0	30.4	<1.0	409	1,000 (SDWR)
Dissolved organic carbon	mg/L	<.10	1.54	.8	10	.2	.76	.6	2.5	NA
Dissolved oxygen[2]	mg/L	<.01	2.07	.4	11	<.01	1.98	.2	7.3	NA
Fluoride	mg/L	.1	.21	.14	1.6	.1	.272	.2	1.1	4 (MCL)
Hardness	mg/L	13	188	135	820	3	95.8	70	290	NA
Iron	µg/L	<3.0	4,440	840	31,000	<3.0	733	80	5,170	300 (SDWR)
Lead	µg/L	<1.0	<1.0	<1.0	19	<1.0	<1.0	<1.0	29	15 (USEPA action level)
Magnesium	mg/L	1.7	13.9	9.9	57	1.1	6.78	4.4	19	NA
Manganese	µg/L	<1.0	527	235	2,780	<1.0	249	94	1,530	50 (SDWR)
Net alkalinity	mg/L	-86.3	116	111	355	-9.3	130.6	113	344	NA
Nickel	µg/L	<1.0	8.7	1.3	166	<1.0	2.1	<1.0	11	NA
Nitrate plus nitrite	mg/L as N	<.050	.23	.05	2.9	<.050	1.02	.07	14	10 (MCL)
Nitrite	mg/L as N	<.010	.011	.01	.021	<.010	.054	.01	1.1	1 (MCL)
pH	standard units	3	6.51	6.7	8.8	4.2	6.85	6.9	9.2	6.5-8.5 (SDWR)
Potassium	mg/L	.52	2.17	1.75	7.5	.12	1.62	1.4	4.5	NA
Radon	pCi/L	26	306	181	4,132	43	812	380	4,688	300 (MCL)/4,000 (AMCL)
Silica	mg/L	3.5	11.1	11	20	5.9	9.37	8.8	15	NA
Sodium	mg/L	.52	43.9	9.35	806	.5	35.8	18	270	30-60 (Advisory)
Specific conductance	µS/cm at 25°C	42	559	358	4,210	78	338	285	1,350	NA
Sulfate	mg/L	<.10	97.1	32.5	700	.45	14.75	14	53	250 (SDWR)
Total dissolved solids	mg/L	32	362	218	2,300	34	207	180	773	500 SDWR)
Turbidity	NTU	.25	57.7	6	1,000	<.01	24.9	2	500	NA
Zinc	µg/L	<1.0	33.9	8.1	472	<1.0	12.9	3.4	85	5 (SDWR)

[1] These standards only regulate public supplies and no not apply to private domestic wells.

[2] Only 56 and 24 samples in mined and unmined areas, respectively.

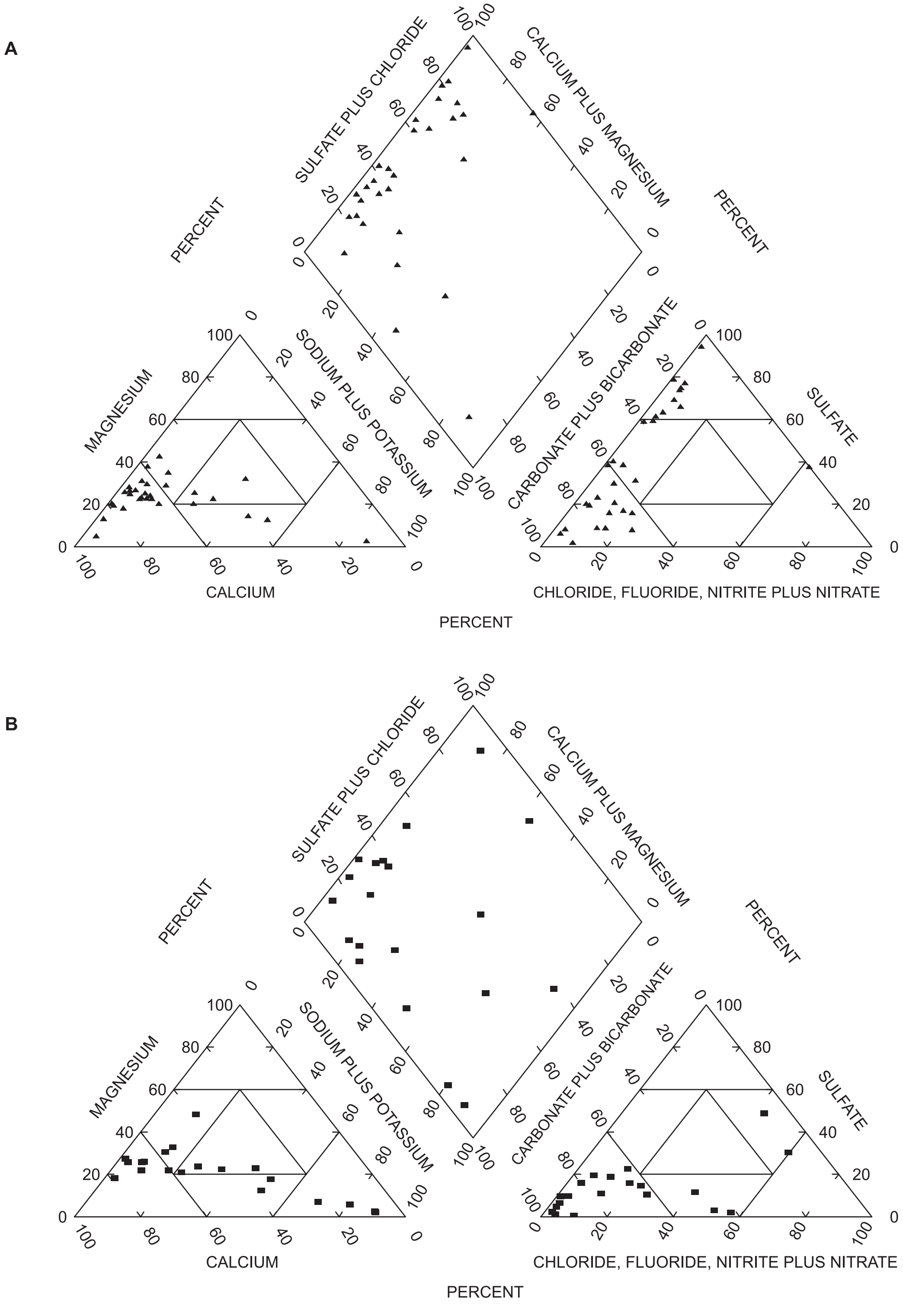


Figure 3. Major-ion composition of ground water (A) downgradient of reclaimed surface coal mines in the high-sulfur coal region, (B) in unmined areas in the high-sulfur coal region, (C) downgradient of reclaimed surface coal mines in the low-sulfur coal region, and (D) in unmined areas in the low-sulfur coal region.

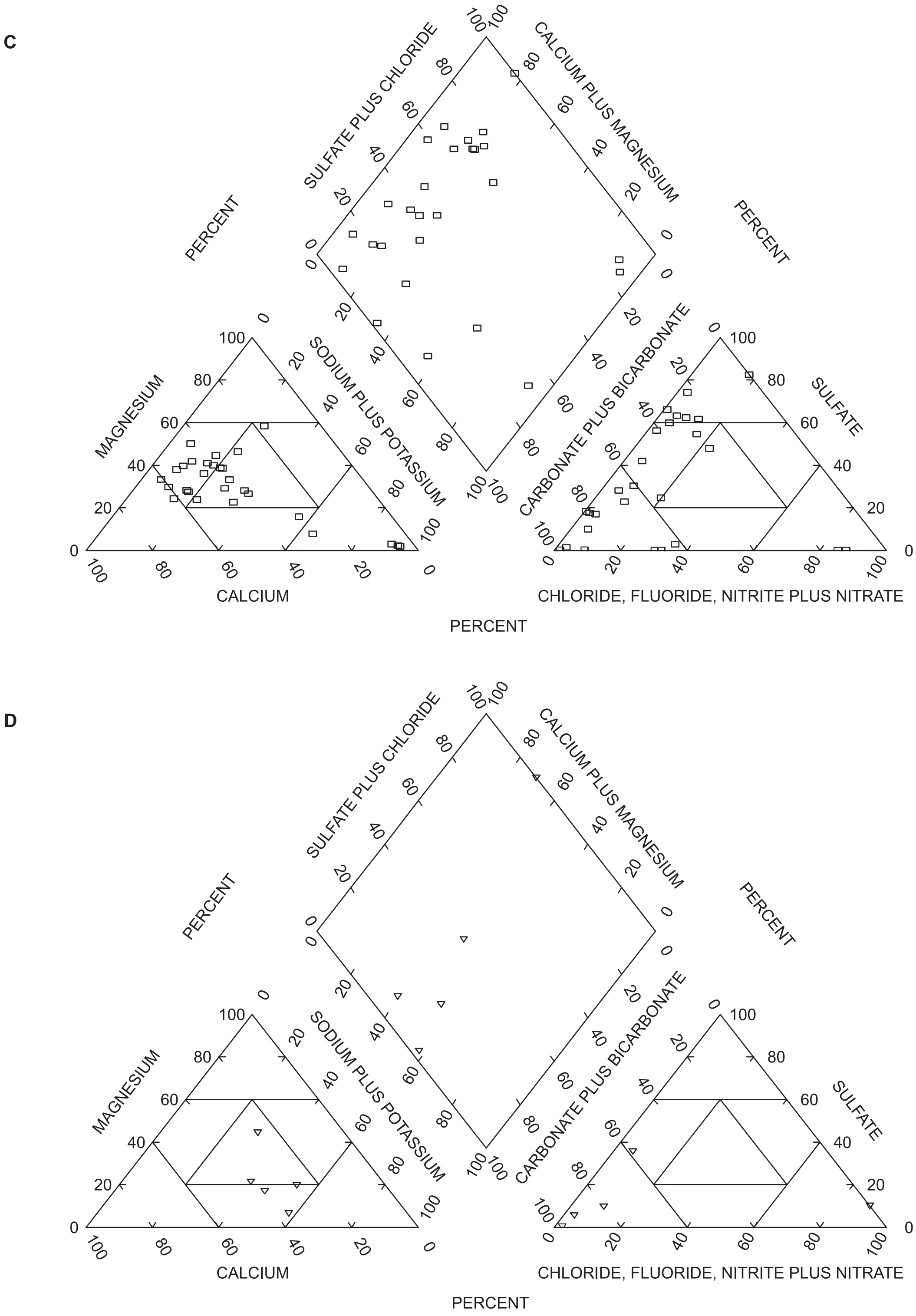


Figure 3. Major-ion composition of ground water (A) downgradient of reclaimed surface coal mines in the high-sulfur coal region, (B) in unmined areas in the high-sulfur coal region, (C) downgradient of reclaimed surface coal mines in the low-sulfur coal region, and (D) in unmined areas in the low-sulfur coal region.—Continued

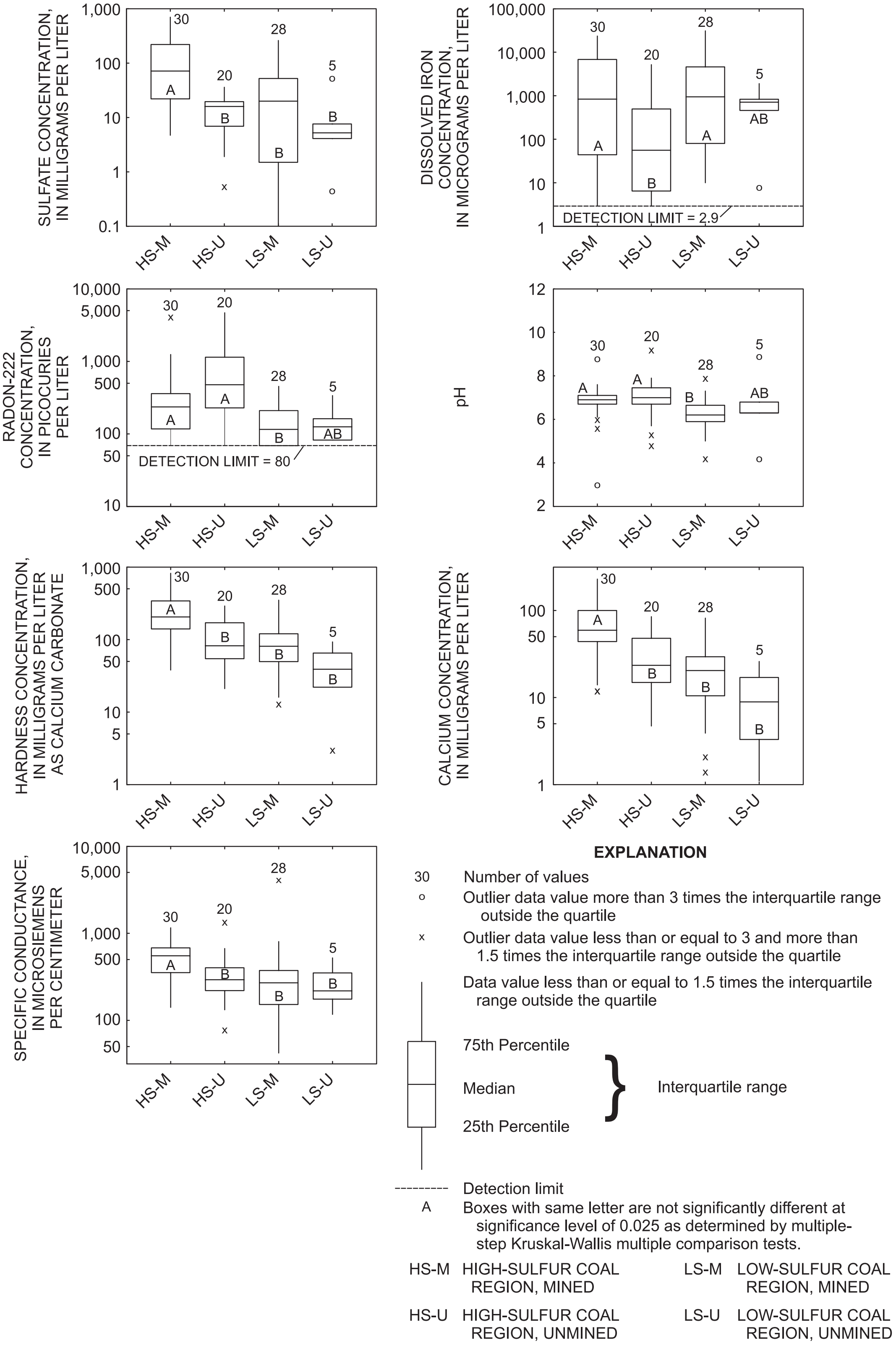


Figure 4. Selected mine-drainage constituents in ground water downgradient of reclaimed surface coal mines and in unmined areas of high-sulfur and low-sulfur coal regions.

figure 4) concentrations are not significantly different between high-sulfur and low-sulfur mined areas. Median concentrations of sulfate, hardness, specific conductance, and calcium are significantly greater for mined areas in the high-sulfur coal region compared to mined areas in the low-sulfur coal region, and to any unmined location. Radon and pH are significantly greater in the high-sulfur coal region for mined areas compared to mined areas in the low-sulfur coal region. The radon and pH in any unmined area was not different from mined areas in the high-sulfur coal region. Iron and other mine-drainage constituents showed no significant difference related to coal-sulfur region.

Curiously, acidity is not significantly greater in any one region or mining condition. This may suggest that reclamation practices are effectively reducing acid concentration. Calcareous materials used as amendments to mine spoil and high-wall fill are likely helping to reduce acid through neutralization reactions that increase the calcium and magnesium levels. Many more mining operations also now employ special handling methods for highly pyritic materials, thus further reducing release of acid into the ground water. Calcareous minerals are also more abundant in general in rocks of the high-sulfur area.

To summarize, there are some significant differences in mine-drainage contaminant levels between high-sulfur and low-sulfur regions but the greatest differences are between mined high-sulfur region sites and all other sites because the combination of source geochemical factors and mining disturbance are maximized. Iron levels are also increased in mined areas regardless of coal-sulfur content. Because of the subtle differences in ground-water quality when evaluated by coal-sulfur region, hereafter, the focus will be on comparing the results from unmined areas with results from mined areas regardless of coal-sulfur content.

Background Water Quality in Unmined Areas

To identify water affected by mine drainage in general and to later estimate the extent of lateral and vertical migration of waters originating from reclaimed surface mines, a background concentration representing unaffected waters was determined for selected mine-drainage constituents—sulfate, iron, manganese, aluminum, zinc, hardness, and total dissolved solids that generally are expected to be increased in mined areas (Rose and Cravotta, 1998). Alkalinity, acidity and pH background concentrations were not calculated because these constituents could be either higher or lower in mined areas compared to unmined areas depending on whether acidic mine drainage or neutral or alkaline mine drainage occurs (Rose and Cravotta, 1998). Data from the wells representing aquifers in unmined areas were used. Concentrations were ranked, and the concentration that was exceeded in 10 percent of the samples (the 90th percentile value) for each constituent was used to represent the background concentration.

Using sulfate as an example, only one sample from an unmined area had a sulfate concentration greater than 50 mg/L. Both the mean and median sulfate concentrations in ground water from wells representing unmined areas are about 14 mg/L. Using the aforementioned procedure, the background concentration (90th percentile value) was determined to be 26 mg/L. This value is low compared to those determined by other researchers. McCurry and Rauch (1986) working in northern West Virginia, Brady (1998) in Pennsylvania, and river assessments across western Pennsylvania by Sams and Beer (2000) have yielded higher background concentrations for sulfate of 50, 40, and 75 mg/L, respectively. Background concentrations for selected constituents are plotted in subsequent illustrations to facilitate identification of concentrations elevated above background levels.

Major Water Characteristics and Mine-Drainage Constituents

Ground water in mined areas appears to have water quality distinct from unmined areas. Ground-water chemistry in mined areas is characterized by elevated specific conductance and total dissolved solids associated with mine-drainage constituents such as sulfate, dissolved iron, dissolved manganese, dissolved aluminum, and hardness (table 2). Median pH values of 6.7 and 6.9 characterize the mined and unmined areas, respectively. Alkalinities were about the same in mined and unmined areas. Box plots of 10 selected constituents illustrate the frequency distributions of data for mined and unmined areas (fig. 5). Background concentrations also are shown in figure 5. To determine if medians of the two sample distributions plotted in figure 5 were significantly different, Mann-Whitney rank-sum tests were conducted. The results of the tests are summarized for 30 constituents in table 3.

Median concentrations of sulfate, iron, manganese, aluminum, zinc, calcium, magnesium, hardness, specific conductance, turbidity, potassium, silica, and ammonia were significantly higher in mined areas compared to unmined areas, whereas radon and fluoride were significantly lower in mined areas compared to unmined areas. The pH is significantly lower in mined areas compared to unmined areas (fig. 5).

Trace Elements

Sixteen trace elements including aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, silver, uranium, and zinc were determined by analysis of ground-water samples. Results were highly censored, with many concentrations reported to be less than reporting limits of the analytical methods. Data for all 16 elements are published elsewhere (Coll and Siwicki, 1997, p. 197-198; 1999, p. 337-340; Ward and others, 1998, 1999) and summary statistics for concentrations of only 9 elements are presented in table 2. Elements related to coal mining, such as selenium, that had no concentrations at or above the method reporting limit of 1 µg/L are not discussed hereafter.

Table 3. Mann-Whitney rank-sum test results comparing median concentrations of constituents in ground water from wells in mined and unmined areas.

[Shaded cells are significantly different with a p value of < 0.05; mg/L, milligrams per liter; µg/L, micrograms per liter; NTU, nephelometric turbidity units; pCi/L, picocuries per liter; µS/cm, microsiemens per centimeter]

Chemical constituent (units)	Median		p value
	Mined (total = 58)	Unmined (total = 25)	
Acidity (mg/L)	1.46	1.74	0.709
Alkalinity (mg/L)	117	114	.551
Aluminum (µg/L)	3.75	3.1	.0236
Ammonia (mg/L)	.141	.078	.043
Barium (µg/L)	122	161	.509
Calcium (mg/L)	35.5	21	.0207
Chloride (mg/L)	5.1	7.3	.321
Chromium (µg/L)	1.9	1.5	.478
Cobalt (µg/L)	<1	<1	.0964
Copper (µg/L)	<1	<1	.961
Dissolved organic carbon (mg/L)	.8	.6	.03
Dissolved oxygen	.4	.2	.56
Fluoride (mg/L)	.14	.2	.0448
Hardness (mg/L)	135	70	.0082
Iron (µg/L)	840	80	.0031
Magnesium (mg/L)	9.9	4.4	.0026
Manganese (µg/L)	235	94	.0221
Net alkalinity (mg/L)	111	113	.785
Nickel (µg/L)	1.3	<1	.146
Nitrate plus nitrite (mg/L as N)	.05	.07	.249
pH (standard units)	6.7	6.9	.0453
Potassium (mg/L)	1.75	1.4	.0419
Radon (pCi/L)	181	380	.0092
Silica (mg/L)	11	8.8	.0494
Sodium (mg/L)	9.35	18	.297
Specific conductance (µS/cm at 25°C)	358	285	.028
Sulfate (mg/L)	32.5	14	.0024
Total dissolved solids (mg/L)	218	180	.115
Turbidity (NTU)	6	2	.0047
Zinc (µg/L)	8.1	3.4	.0393

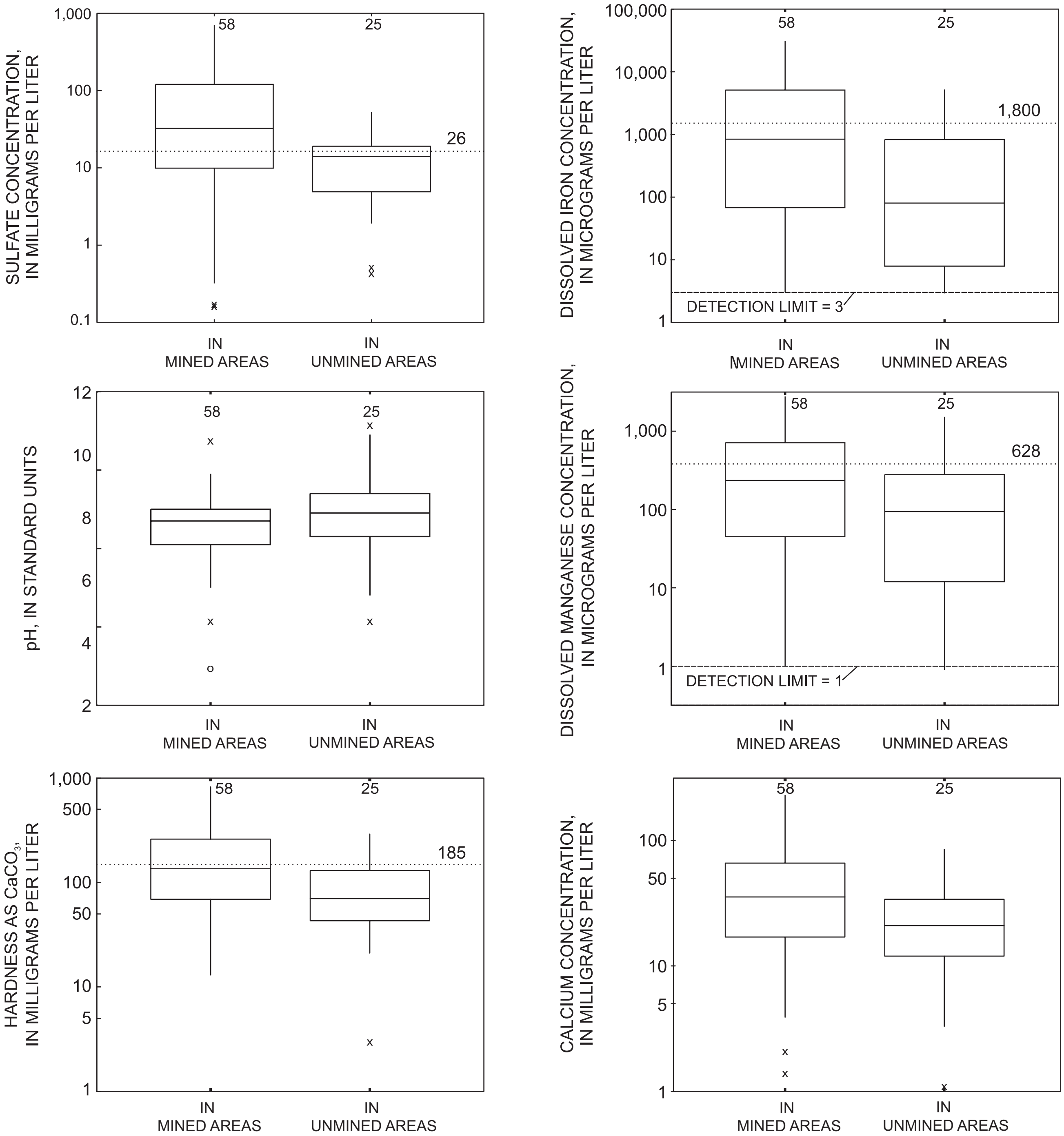


Figure 5. Concentration distribution of mine-drainage constituents downgradient of reclaimed surface coal mines and in unmined areas.

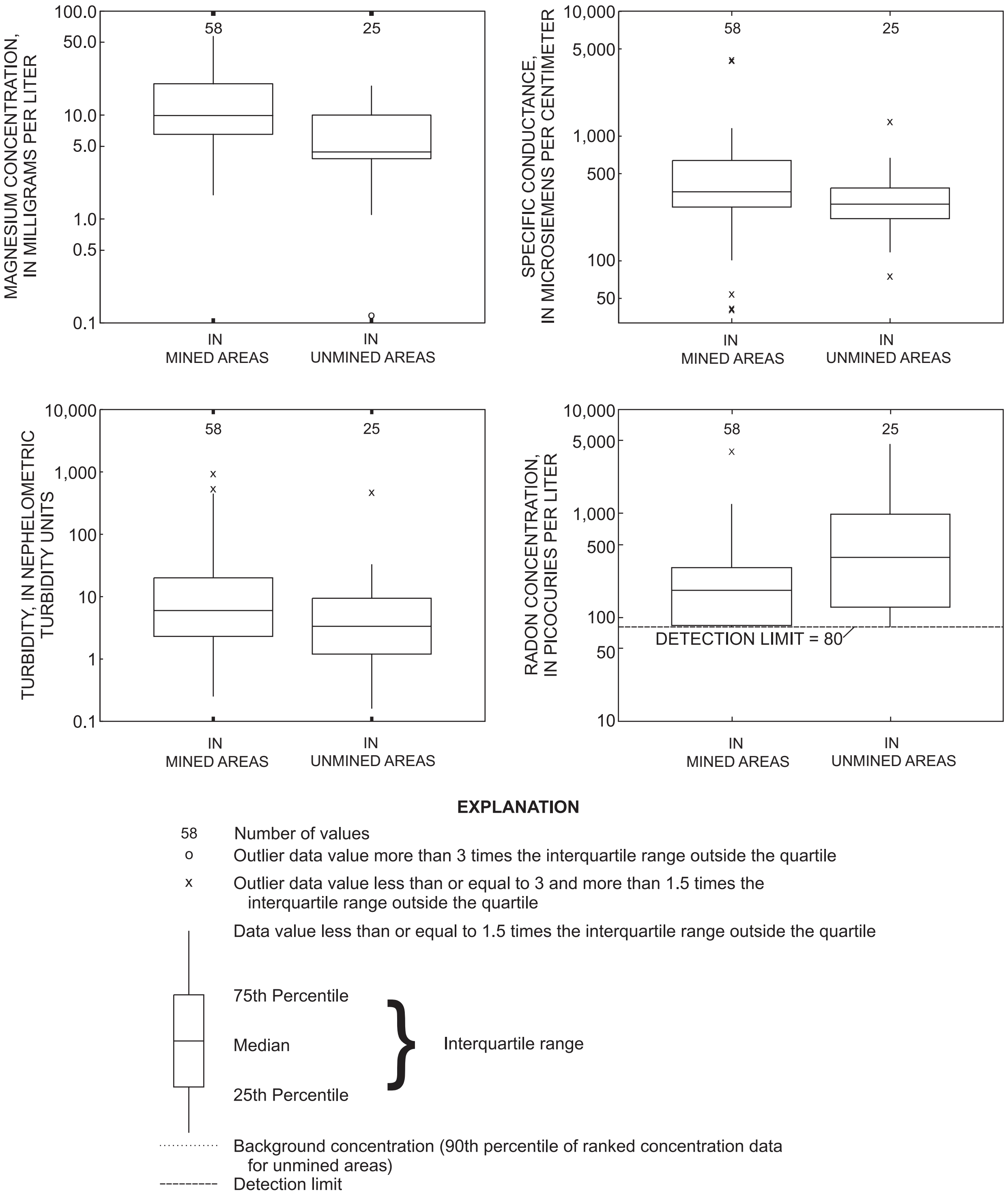


Figure 5. Concentration distribution of mine-drainage constituents downgradient of reclaimed surface coal mines and in unmined areas.—Continued

Six elements for which there was at least one concentration above the minimum reporting limit were analyzed for significant differences between mined and unmined areas. Medians of aluminum, chromium, and zinc are higher for mined areas than in unmined areas (table 2). Also, greater concentrations for outlier values and greater numbers of outlier points for aluminum and zinc were measured in mined areas compared to unmined areas (fig. 6). Results of Mann-Whitney rank-sum tests indicate that only zinc is significantly greater in mined areas (median of 8.1 µg/L) than in unmined areas (median of 3.4 µg/L) (fig. 6 and table 3). The results for aluminum indicate a significantly greater median of 3.75 µg/L in mined areas compared to a median of 3.1 µg/L in unmined areas; however, these results (table 3 and fig. 6) are inconclusive due to the bias resulting from low-concentration detections of aluminum in analyses of three of four blank samples. Medians for other trace elements were not significantly different between mined and unmined areas.

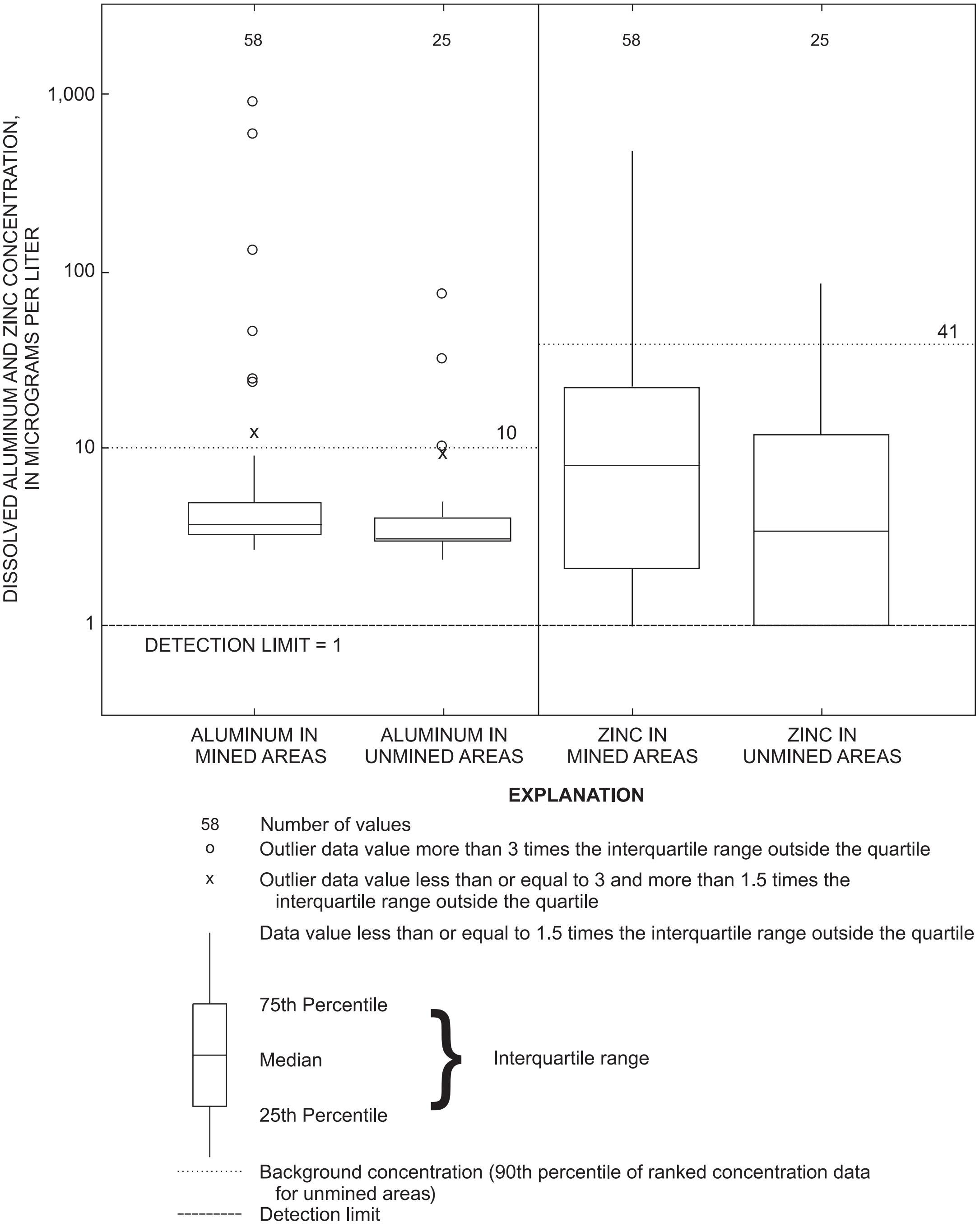


Figure 6. Concentration distribution of trace elements that are significantly different between mined and unmined areas.

Volatile Organic Compounds

Samples for analysis of volatile organic compounds (VOCs) were collected from 30 wells in mined areas and from 15 wells in unmined areas in the northern Appalachian coal region. Analytical reporting limits (detection limits) varied widely among the compounds. Twenty-seven of the 30 samples from mined areas and each of the 15 samples from unmined areas had at least one VOC concentration above the minimum reporting limits. Of the 86 compounds analyzed, at least 1 detection was reported for 23 compounds. Seven compounds were detected in samples collected in mined areas only, and eight compounds were detected in samples collected from unmined areas. The compounds detected, the maximum concentrations reported, and the MCLs are listed in table 4.

Of the 23 detected compounds, 7 are compounds that include benzene, toluene, and xylene (BTEX compounds), 11 are halogenated straight chain compounds (alkanes and alkenes), 2 are ketones, 1 is an ether, and the remaining 2 compounds (tetrahydrofuran and carbon disulfide) are unrelated by functional group. In samples collected from mined areas, there were 33 detects for BTEX compounds (1.10 detects per sample) and 17 detects for halogenated straight chain compounds (0.57 detects per sample). In samples collected from unmined areas,

Table 4. Maximum concentration detected and number of samples with detections of volatile organic compounds (VOCs) for mined and unmined areas in the northern Appalachian coal region.

[E, estimated; <, less than; —, no MCL has been set; *, Total for trihalomethanes is 0.08 mg/L; P, Regulation is pending]

Compound name	Minimum reporting limit (micrograms per liter)	U.S. Environmental Protection Agency maximum contaminant level[1] (micrograms per liter)	Samples from wells in mined areas		Samples from wells in unmined areas	
			Maximum concentration (micrograms per liter)	Number of detections (total = 30)	Maximum concentration (micrograms per liter)	Number of detections (total = 15)
Bromodichloromethane	0.048	80P*	< 0.048	0	0.05	1
Tetrachloromethane	.088	—	E .01	1	< .088	0
Dibromochloromethane	.18	80P*	< .18	0	E .03	1
Chloroform	.052	80P*	.12	8	.20	6
Toluene	.05	1,000	E .04	3	.067	1
Benzene	.10	5	.598	6	E .02	1
Ethylbenzene	.030	700	E .01	1	< .030	0
Chloromethane	.25	—	E .10	3	E .029	2
Dichloromethane	.38	5	< .38	0	.382	7
Tetrachloroethylene	.10	5	< .10	0	E .04	1
1,1,1-Trichloroethane	.032	200	E .02	1	.06	1
Trichloroethylene	.038	5	< .038	0	.17	1
Carbon disulfide	.37	—	E .318	7	E .01	2
cis-1,2 Dichloroethylene	.038	70	< .038	0	.10	1
Styrene	.042	100	E .040	1	E .005	1
1,2,3-Trimethylbenzene	.12	—	< .12	0	E .002	1
1,2,4-Trimethylbenzene	.056	—	.140	18	E .041	10
Methyl iodide	.021	—	.080	3	< .021	0
Methyl *tert*-butyl ether	.17	—	E .030	1	< .17	0
4-Methyl-2-pentanone	.37	—	E .10	1	< .37	0
2-Butanone	1.6	—	< 1.6	0	E 1.1	1
Tetrahydrofuran	9.0	—	E 3.0	7	< 9.0	0
m- and p-Xylene	.06	10,000	E .008	1	< .06	0

[1] These maximum contaminant levels only regulate public supplies and do not apply to private domestic wells.

there were 14 detects of BTEX compounds (0.93 detects per sample) and 21 detects of the straight chain compounds (1.4 detects per sample). Detection frequencies of benzene and toluene are greater in mined areas (20 and 10 percent) than in unmined areas (7 and 7 percent) (fig. 7).

The greater frequency of detection of VOCs in mined areas could be related to accidental releases of petroleum products from machinery used during mining; however, it also is possible that atmospheric deposition is a pathway by which VOCs reach ground water at the low concentration levels measured in this study (U.S. Environmental Protection Agency, 1999). The occurrence of VOCs at low levels in the atmosphere can be widespread because of emissions from automobiles, industries, heating, power generating plants, and other sources (National Science and Technology Council, 1997).

Relation to Drinking Water Standards

USEPA primary standards for barium and lead were exceeded at one site each in mined areas. USEPA primary standards for nitrate, nitrite, and lead were exceeded at one site each in unmined areas. However, because none of these constituents are commonly related to coal mining, they are not further discussed.

USEPA Secondary Maximum Contaminant Levels (SMCL) for aluminum, chloride, iron, manganese, pH, sulfate, and total dissolved solids were exceeded at two or more sites in mined areas (table 5). None of the samples from unmined areas exceeded the aluminum, chloride, or sulfate SMCLs. Generally, the constituents related to mining (sulfate, aluminum, iron, manganese, pH, and total dissolved solids) exceeded SMCLs more frequently in mined areas compared to unmined areas. The concentration of sulfate exceeded the SMCL of 250 mg/L in six samples from mined areas. Concentrations of chloride exceeded the SMCL of 250 mg/L in only two samples from mined areas. The SMCL of 300 µg/L for iron was exceeded in samples from 64 percent (37 of 58) of sites in mined areas and 36 percent (9 of 25) of sites in unmined areas. The SMCL of 50 µg/L for manganese was exceeded in samples from 71 percent (41 of 58) of sites in mined areas and 56 percent (14 of 25) of sites in unmined areas. The pH of samples from 38 percent (22 of 58) of sites in mined areas and 36 percent (9 of 25) of sites in unmined areas was outside of the Secondary Drinking Water Standard range of 6.5 to 8.5. The concentration of aluminum exceeded the SMCL range maximum value of 200 µg/L in only three samples from mined areas. The concentration of total dissolved solids exceeded the SMCL of 500 mg/L in samples from 16 percent (9 of 58) of sites in mined areas and 4 percent (1 of 25) of sites in unmined areas. All VOC concentrations reported were below the USEPA MCL values for drinking-water supplies.

The ground water in mined areas has concentrations of constituents indicative of pyrite oxidation and treatment of mine drainage with calcareous amendments. Higher concentrations of calcium, magnesium, and hardness can result from leaching of minerals from rocks due to reactions with sulfuric acid, from excavation of calcareous overburden to obtain more calcareous materials to use in filling high wall areas to neutralize AMD (Hawkins, 1998b, p. 17-1–17-6, Brady, 1998, p. 9-7–9-8), or from calcareous amendments introduced at the site to neutralize AMD in the mine spoil and at locations below seeps (Brady, 1998, p. 10-6–10-8). The calcareous materials used at surface-mine areas would also increase pH and decrease acidity and may explain why acidity was not significantly different and why the pH difference, though statistically significant, was small between ground water in mined and unmined areas. Total dissolved solids, specific conductance, and turbidity usually will increase as rocks are disturbed and broken and more minerals dissolved through exposure and weathering. Radon usually will decrease (resulting in less radon available for dissolution into the ground water) because it is released to the atmosphere by increased fracturing of rocks above and below the surface.

Table 5. Maximum values reported and number of samples exceeding the U.S. Environmental Protection Agency Secondary Maximum Contaminant Level for aluminum, chloride, iron, manganese, pH, sulfate, and total dissolved solids in ground water downgradient of reclaimed surface coal mines and wells in unmined areas.

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

Contaminant (units)	SMCL	Samples from wells in mined areas		Samples from wells in unmined areas	
		Maximum concentration	Number of samples exceeding SMCL (total = 58)	Maximum concentration	Number of samples exceeding SMCL (total = 25)
Aluminum (µg/L)	200	971	3	79	0
Chloride (mg/L)	250	1,200	2	240	0
Iron (µg/L)	300	31,000	37	5,170	9
Manganese (µg/L)	50	2,780	41	1,530	14
pH (standard units)	6.5-8.5	3.0-8.8	22	4.2-9.2	9
Sulfate (mg/L)	250	700	6	53	0
Total dissolved solids (mg/L)	500	2,300	9	773	1

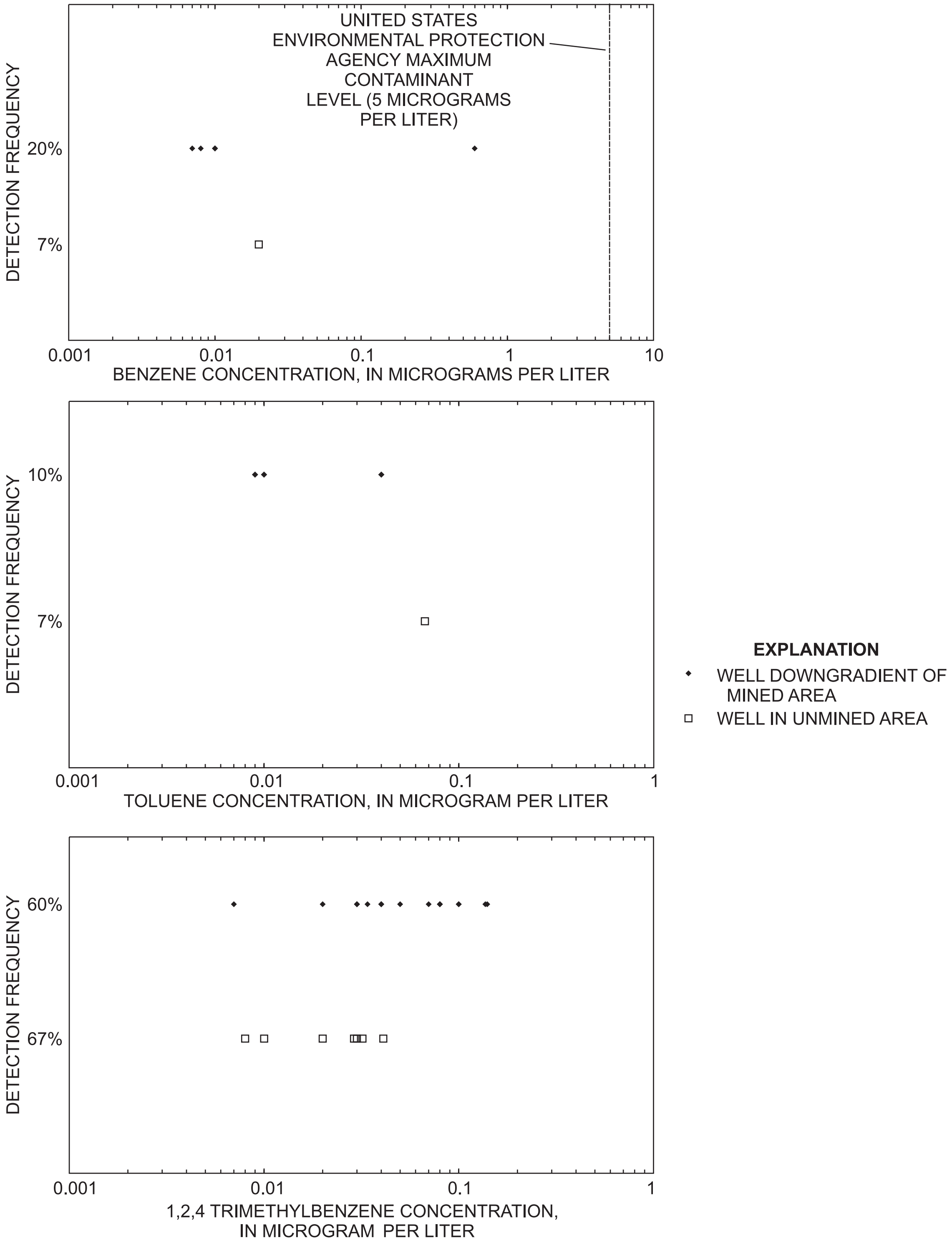


Figure 7. Concentration distribution of selected volatile organic compounds related to petroleum compounds in ground water downgradient of reclaimed surface coal mines and in unmined areas.

Spatial and Temporal Relations and Local Extent of Mine-Drainage Constituents in Mined Areas

Ground-water quality is affected by mine drainage to various degrees at various distances from reclaimed surface mines. There also are changes in the quality of ground water as a function of depth, topography, coal-sulfur content, and time, assuming that 1) movement of ground water is by piston flow, 2) flow paths coincide with topographic downgradient directions, 3) the primary discharge areas are surface-water bodies, and 4) springs do not intercept a significant amount of ground-water flow through hills and hillsides.

Lateral Distance from Mined Area

Among the 38 samples from wells less than 500 ft from mined areas, the 9 samples from wells more than 500 ft but less than 1,000 ft from mined areas, and the 11 samples from wells more than 1,000 ft from mined areas, concentrations of several mine-drainage constituents are higher than background. Sulfate, manganese, acidity, aluminum, zinc, and hardness concentrations are highest in samples collected at distances less than 500 ft downgradient of mined sites. At distances greater than 1,000 ft from mined sites, the concentrations typically are at or below background concentrations. In general, highest concentrations were detected within 1,000 ft from the mined sites (fig. 8). Sulfate and iron concentrations not only exceeded background near mined sites but also at distances more than 1,000 ft downgradient of the mined site. The relation between pH and distance is not as clear as for other constituents, but there is only one pH value below 6.0 at distance greater than 1,000 ft, compared to nine pH values at sites sampled less than 1,000 ft, and eight of the nine pH values less than 6.0 are at sites

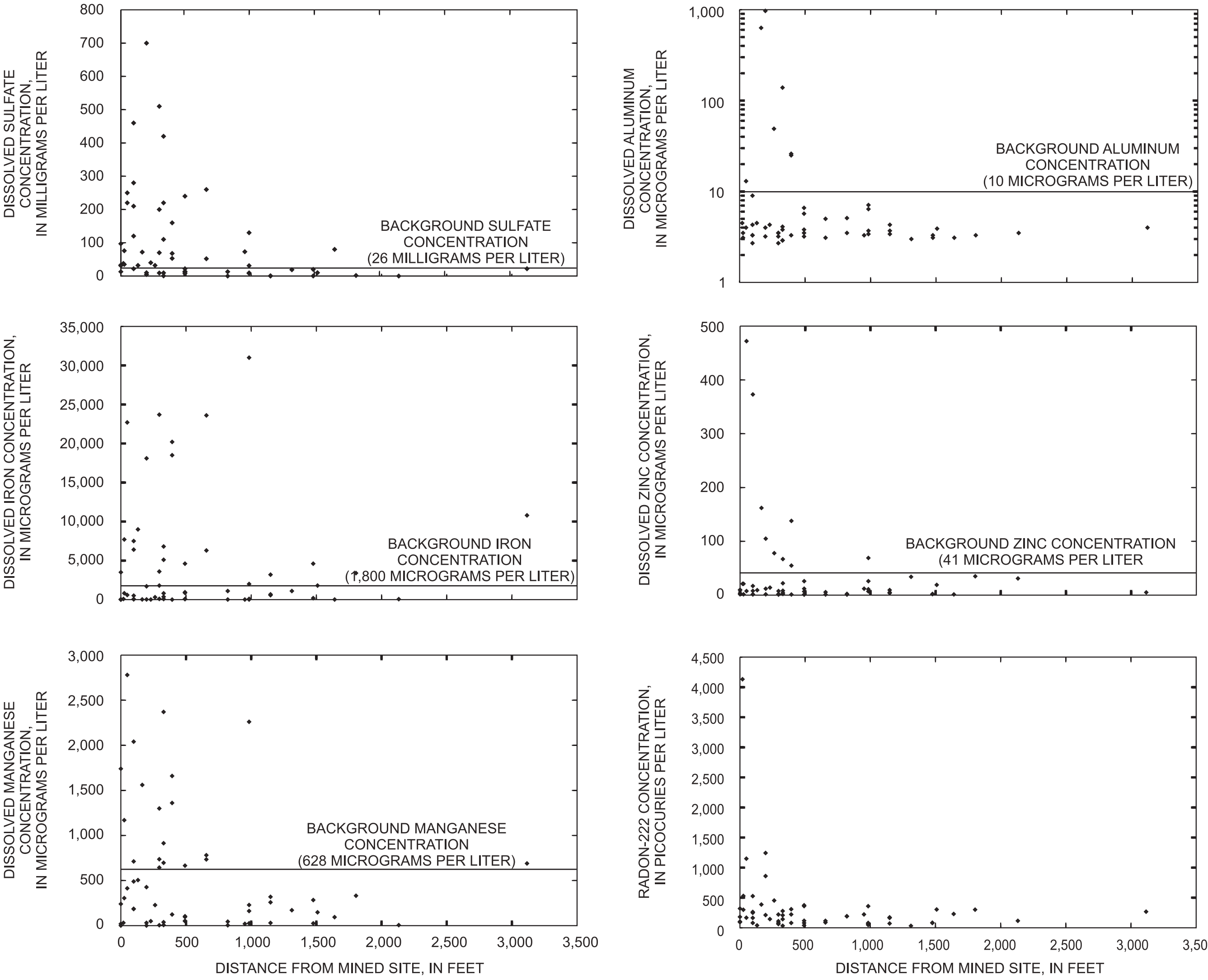


Figure 8. Concentrations of selected mine-drainage constituents downgradient of reclaimed surface coal mines.

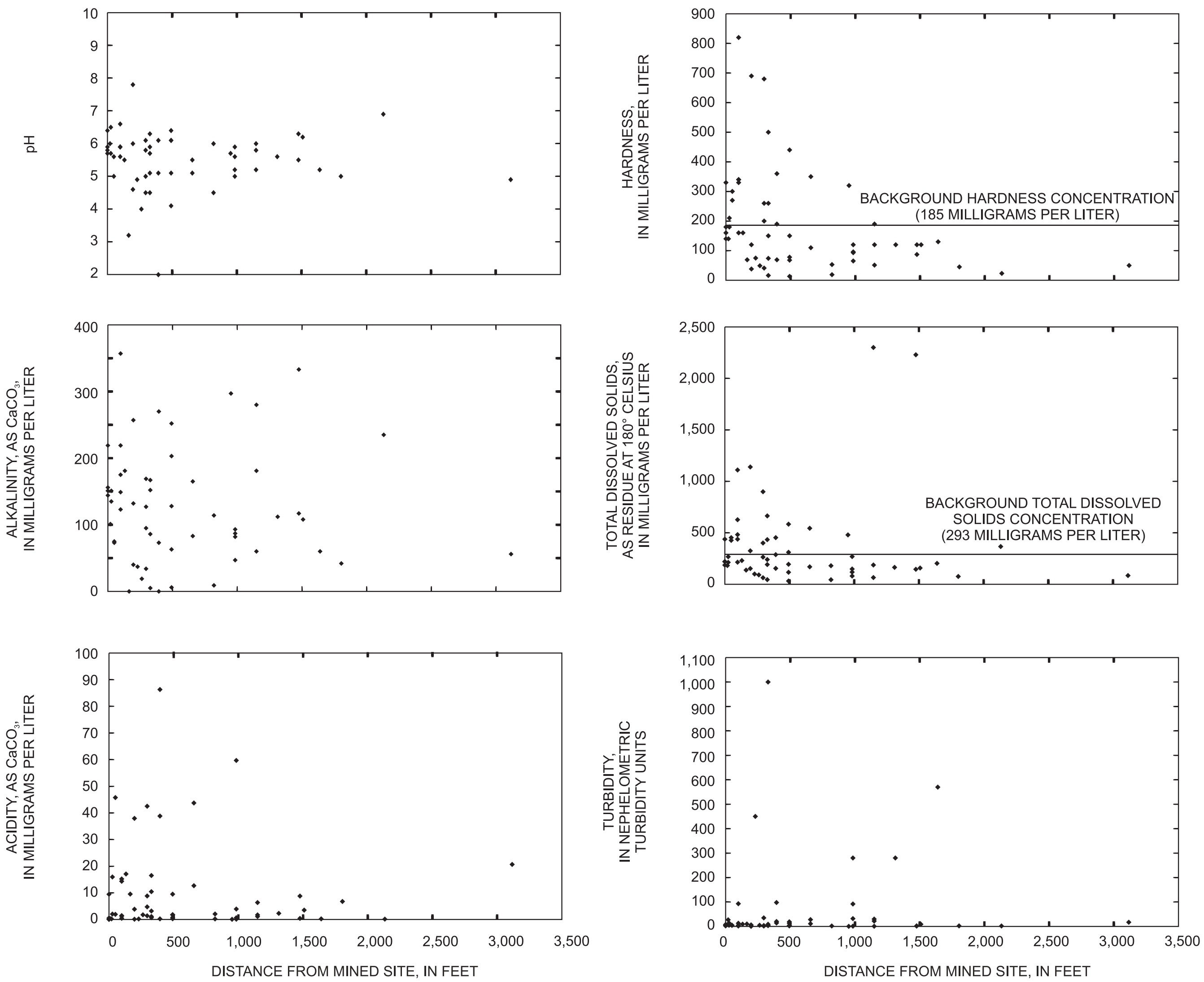


Figure 8. Concentrations of selected mine-drainage constituents downgradient of reclaimed surface coal mines.—Continued

sampled less than 500 ft downgradient of mined sites. Alkalinity showed no patterns related to distance.

The decline of constituent concentrations with increasing distance from the mined site is generally due to dispersion, dilution, adsorption, neutralization, and sulfate reduction, as well as decreased rates of oxidation of pyritic material at the source as rock surfaces weather and become armored with precipitates. The highest concentrations of sulfate and other mine-drainage constituents listed above generally occur at less than 500 ft downgradient from mined sites and are likely due to accelerated rates of oxidation of pyritic materials at the mined site as noted by Rose and Cravotta (1998) in previous research. The lower constituent concentrations at distances less than about 500 ft from mined sites may indicate sites where oxidation rates have not peaked yet and flow paths through mine spoil are not fully established. The lower concentrations also may indicate that comparatively less pyritic materials exist at the mined site, or that the sampled well intercepts ground water from other recharge areas in addition to the mined site. The elevated concentrations of hardness are likely due to reactions of the acid with calcareous rocks either placed in the mine spoil to neutralize acid production, or existing along the flow path.

The relation of well location on the geologic structure nearby the mined area was examined. Fifty-five of the 58 sampled wells were characterized as being downdip (26 wells), updip (16 wells), or along strike (13 wells) from mines. All wells considered for this analysis were topographically downgradient of nearby mines. In this study, mine-drainage constituent concentrations at wells downdip of mines are not significantly greater than those updip or along strike. A Kruskal-Wallis rank-sum test for nonparametric distributions of data show that there is no difference in mine-drainage constituent concentrations based on structural locations of wells relative to the mines. Nevertheless, other researchers (McCurry and Rauch, 1986; O'Steen and Rauch, 1983) found that mine-drainage constituents, notably sulfate, were present in greater concentrations in wells downdip from mines than in water from wells updip or along strike. The higher concentrations of mine-drainage constituents downdip are likely because of preferential flow directions of ground water along bedding-plane separations and down the elevation gradient when downdip and downhill directions coincide. At many of the areas examined during this study, perhaps disturbances of rock, by blasting and rock removal, have resulted in creation of new vertical joints and fractures so that ground water in the shallow (generally less than 250 ft deep) wells flows primarily downgradient from the mined area, and not just preferentially downdip.

Vertical Extent and Relation to Depth of Wells

Of 58 wells sampled downgradient of reclaimed surface coal mines, 16 have depths from 21 to 50 ft, 38 have depths from 51 to 150 ft, and 4 have depths of 200 to 375 ft (appendix 3). With so few deep wells sampled (more than 200 ft deep), it is difficult to assess conditions of deep parts of the aquifers. Some mine-drainage constituents are present at the highest concentrations at well depths between 50 and 150 ft but others show high concentrations in shallow wells less than 50 ft deep. Concentrations of sulfate, hardness, and total dissolved

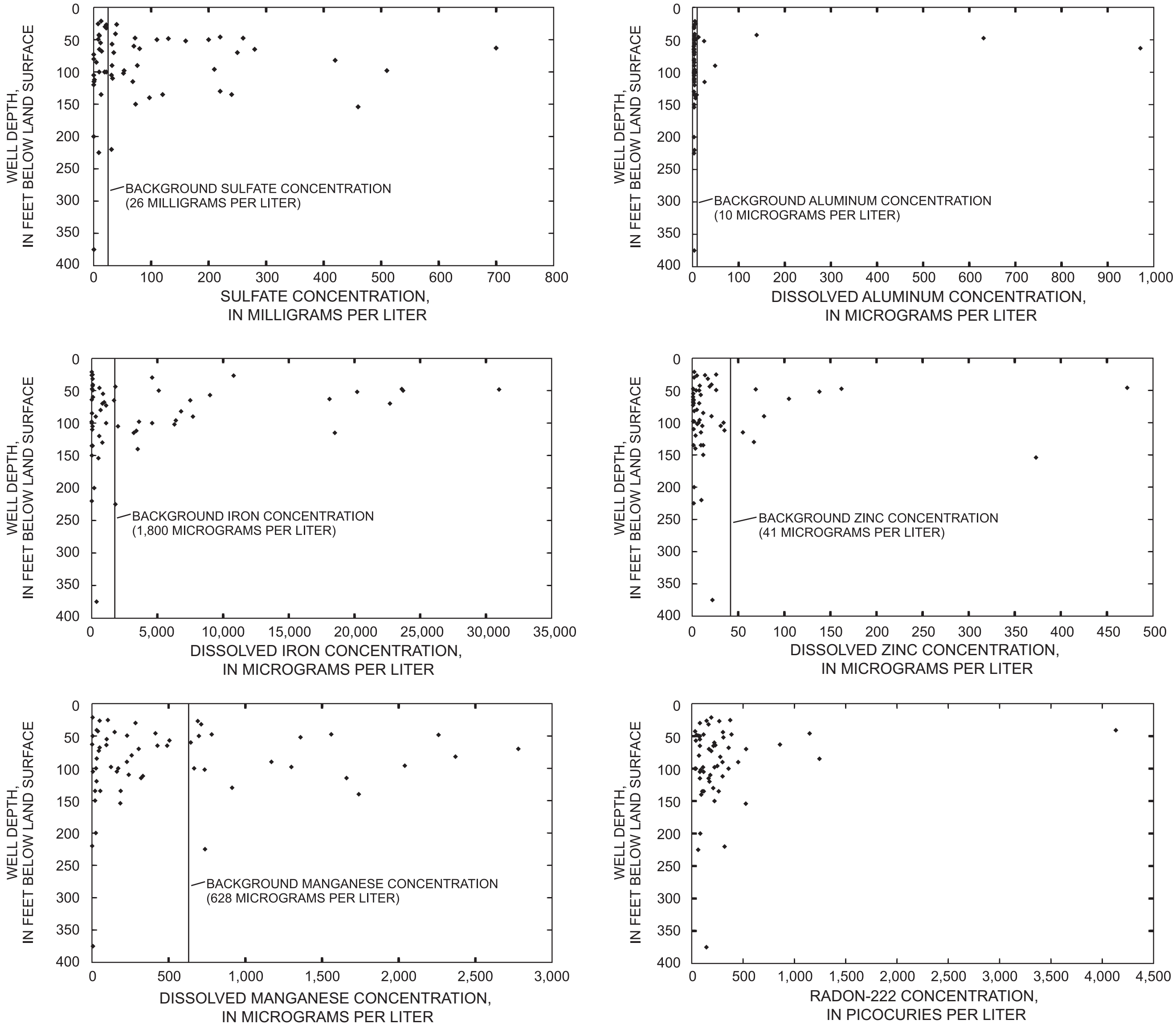


Figure 9. Vertical extent of mine-drainage constituents in ground water downgradient of reclaimed surface coal mines.

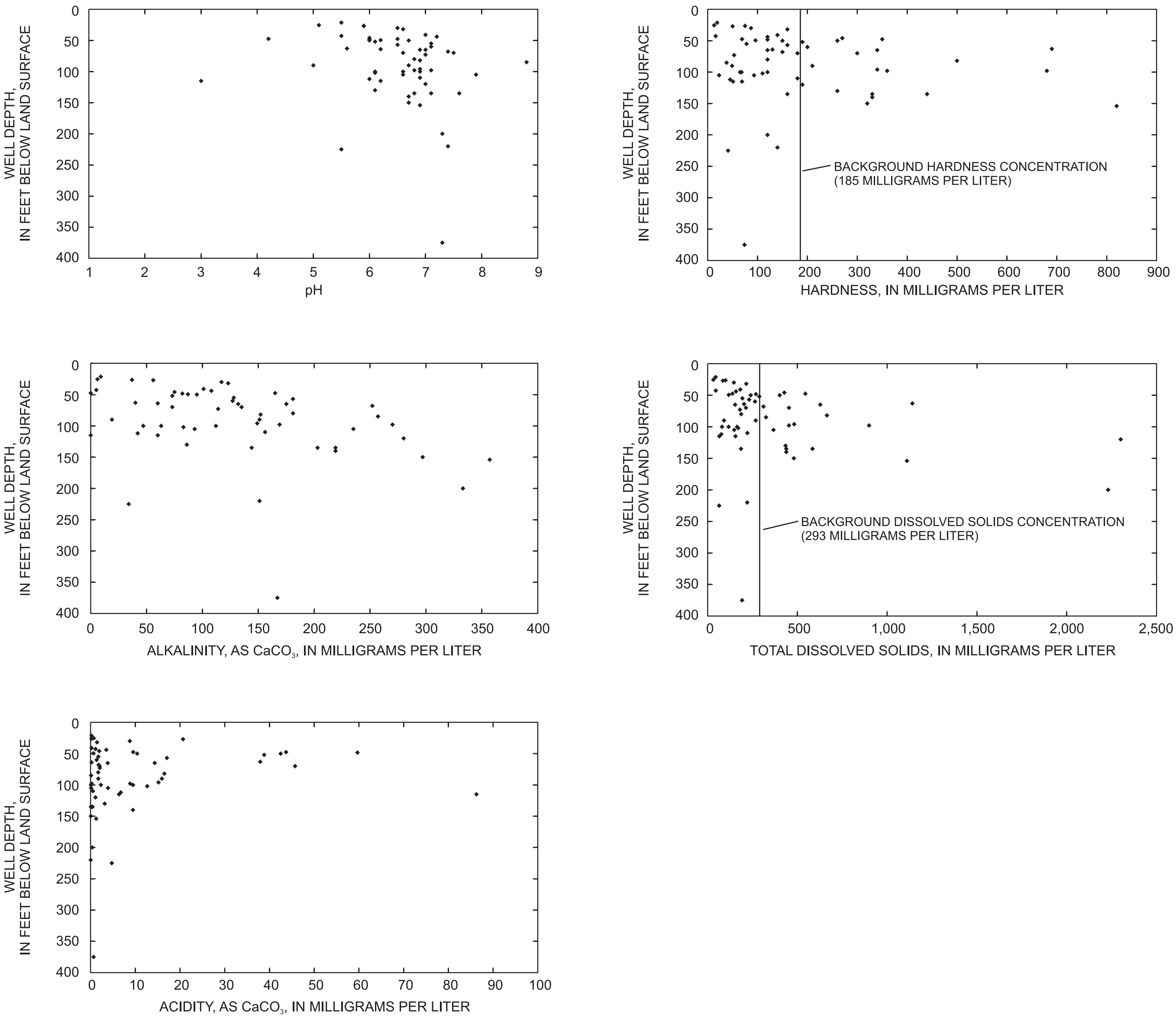


Figure 9. Vertical extent of mine-drainage constituents in ground water downgradient of reclaimed surface coal mines.—Continued

solids are greatest in wells in mined areas with well depths between about 50 and 150 ft (fig. 9). Concentrations of sulfate, iron, manganese, aluminum, and zinc are greater than background both in shallow wells (20 to 50 ft of depth) and in wells more than 50 to 150 ft deep. Acidity concentrations are also greatest at well depths less than 150 ft. Concentrations of zinc and radon are greatest at depths of less than 50 ft. Few concentrations of total dissolved solids and hardness exceed background at depths less than 50 ft and patterns on figure 9 indicate that these constituents' concentrations and alkalinity increase with increased well depth. The pH can be less than 6.0 at any depth, but several wells had less than 6.0 pH at depths less than 50 ft. In this study, the depth of the interception of the mine-drainage constituents is not known, only the well depth, but the mine-drainage constituents may flow through the aquifer at depths less than 50 ft according to other researchers who have shown that shallow wells and springs typically show higher concentrations of mine-drainage contaminants than deeper wells (McCurry and Rauch, 1986).

The increased concentrations of mine-drainage constituents from wells 20 to 150 ft deep compared to wells more than 150 ft deep likely coincide with the greater density of fractures available to transport mine-drainage constituents in the first 150 ft of strata. Fewer fractures at depths greater than 150 ft may result in less flow of ground water transporting mine-drainage constituents from the surface to greater depths. Of the 16 shallowest wells (less than 50 ft deep), 9 are in valleys, and water in these wells may have lower concentrations of mine-drainage constituents due to dilution of ground water as it intercepts and mixes with ground water from deeper regional or subregional flow paths.

Relation to Topographic Location

Topographic location has been reported to be a significant factor for both well yield and ground-water quality (McElroy, 1988). The effects of topographic location, such as hilltop, hillside, or valley locations, on ground-water quality downgradient from reclaimed surface mines are examined. Because only one downgradient well is on a hilltop, the hilltop and hillside locations were combined in evaluating water quality. Figure 10 shows box plots of sulfate, iron, and turbidity concentrations in unmined and mined areas in hilltop/hillside locations (referred to as hill locations) versus valley locations.

Results of multiple comparison tests using a multiple-step Kruskal-Wallis test (Helsel and Hirsch, 1992, p. 200-207; Ott, 1993) on ranks of the data indicate that very few mine-drainage contaminants in this study are shown to differ significantly based on topographic location. The tests indicate that turbidity was significantly greater at mined hill locations (median of 7.8 NTU) compared to unmined hill locations (median of 2.0 NTU). Sulfate concentrations were not significantly different among topographic locations. The median iron concentration of 2,000 µg/L at mined valley locations is significantly

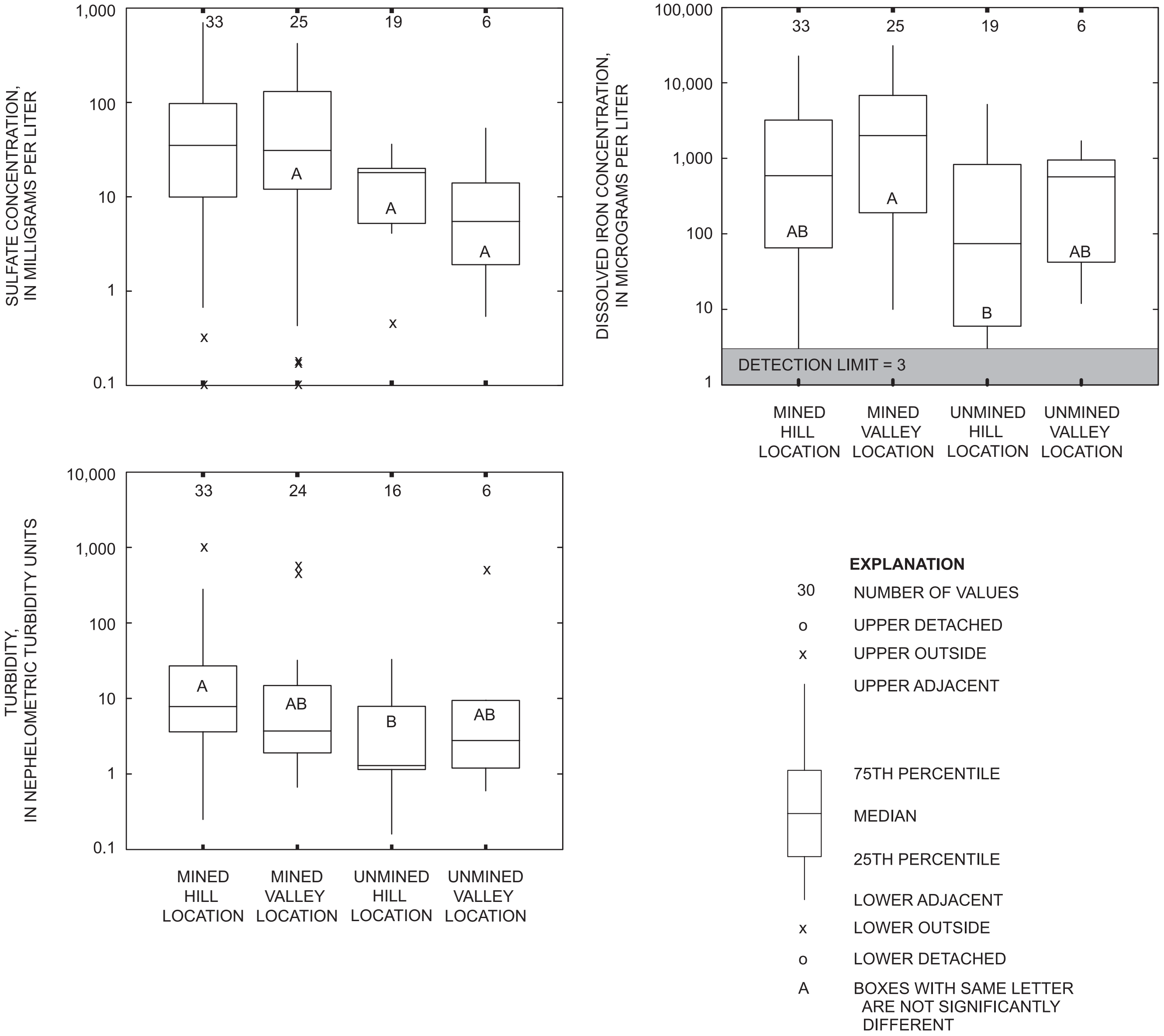


Figure 10. Distribution of constituent concentrations in ground-water samples from wells in hill and valley locations downgradient of reclaimed surface coal mines.

greater than the median iron concentrations of 74 µg/L at unmined hill locations. The median iron concentration for the mined hill location (590 µg/L) is greater, although not statistically significant, by nearly an order of magnitude than median iron concentration for the unmined hill location (74 µg/L).

The general trends (that are not statistically significant) relating topographic location to concentrations of mine-drainage constituents in well water are that the constituents downgradient of mined locations occur at higher concentrations than constituents in unmined areas, for both hill and valley locations. The downgradient hill locations have higher concentrations than the valley locations, except for iron. The higher concentrations of some mine drainage contaminants at hill locations is likely due to the fact that most mines are on hill slopes, and so the hill locations are closer to the mined areas.

Relation to Ground-Water Age

The residence time of water in the rock can affect concentrations of mine-drainage constituents. Ground-water age was measured in an attempt to estimate residence time in the rock. For samples collected from wells downgradient of reclaimed surface coal mines, 54 of 58 have age data (30 in the high-sulfur coal region and 24 in the low-sulfur coal region). Thirteen wells in unmined areas have age data for ground water. Ground-water age data presented within this report are characteristic of ground water from wells completed in fractured-bedrock aquifers and should not be assumed to be characteristic of ground-water flow in near-surface regolith or the unsaturated zone. The age data presented in this report represent the portion of ground water typically used by domestic homeowners and smaller public supplies as a source of drinking water and mixing of older and younger waters is likely. Obviously, younger water occurs in near-surface regolith, the unsaturated zone, and very shallow bedrock. Such shallow water (less than 50 ft in depth) typically has a chemical composition more characteristic of precipitation than of deeper ground water (Kozar, 1996). Methane and hydrogen sulfide can cause degradation or stripping of CFC compounds, especially for CFC-11 and CFC-113. Methane and hydrogen-sulfide compounds commonly are present in ground water near coal-bearing rock and near coal mines. Hydrogen sulfide was not analyzed in this study, but methane data are listed in appendix 1. The CFC compound data used to estimate ages are given in appendix 2 (G. Casile, U.S. Geological Survey, written commun., 2004).

Other researchers have indicated that because of increased residence time, specific conductance and dissolved solids increase with depth in hillside wells (Hawkins and others, 1996). Wells in valleys are reported to receive mixtures of various aged waters (Brady and others, 1996) and have greater yields (Clark and others, 1976).

A Spearman's rank correlation was conducted to compare the age data to the significant water-quality data, specifically the mine-drainage constituents listed previously. Spearman's rank correlation was also used to compare the age data to the distance data by topographic location (hill and valley). No significant correlations were shown between any mine-drainage constituent and age. The only mine-drainage constituents correlative with age (indicated by a correlation coefficient greater than 0.50) were pH and alkalinity, and then only in the low-sulfur coal region, and acidity, only in the high-sulfur region, where correlation coefficients were 0.55, 0.52, and 0.53, respectively, indicating an increase with increased age, but the relation is not statistically significant (fig. 11). No significant

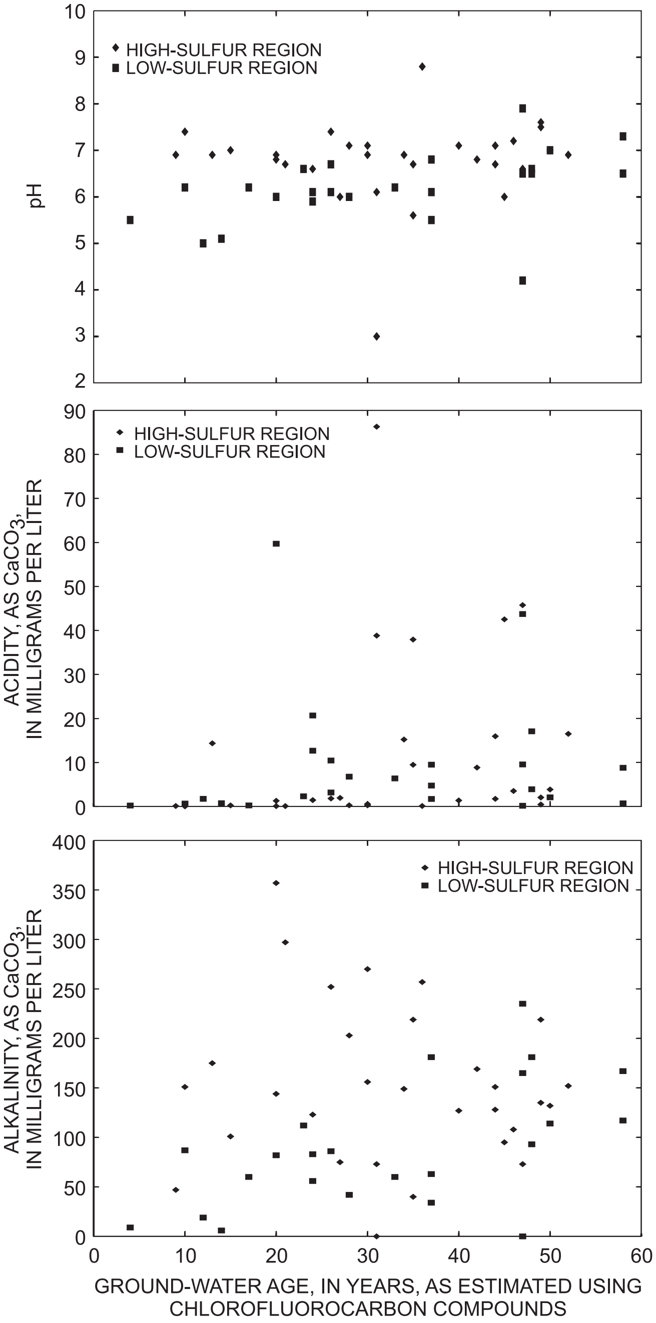


Figure 11. Comparison of selected mine-drainage constituents and ground-water age downgradient of reclaimed surface coal mines in high-sulfur and low-sulfur coal regions.

correlation exists between the distance data and the age data for well waters downgradient from mines, by topographic-location group (hill and valley) (fig. 12). However, at distances greater than 1,000 ft from the mined area, age of water from wells on hills shows an increase with increased distance from the mine (fig. 12). At other distances, any age of well water between 4 and 58 years is reported for both hill and valley topographic locations (fig. 12).

The lack of significant correlation among mine-drainage constituents, age, distance from mined areas, and topographic location may be the result of several factors. These factors include mixing of ground-water ages in water intercepted by the wells, hydraulic impacts of mining (disturbance of rock from blasting), configuration of land surface (slope and relief), and rock orientation relative to mined areas and wells sampled.

Several conditions may result in wells in mined areas intercepting ground water of mixed ages (or residence times): (1) strong indications of mixed residence times were seen in 10 of 54 wells (19 percent) for which CFC data were used to estimate ground-water residence time as shown in appendix 2 and figure 12 (G. Casile, U.S. Geological Survey, written commun., 2004), (2) some samples have old ages (46->58 years) determined from CFC data but are very near (350 ft or less) to the mined area (fig. 12), which would require an extremely small hydraulic conductivity to move the ground water only a short distance over decades (assuming that the hydraulic gradient is 0.1 or greater), and that is unlikely, and (3) the wells are open hole completions into the fractured bedrock and the fractures may supply ground water of differing residence times based on fracture lengths, fracture depths, and interconnection of multiple fractures of variable lengths and depths.

A significant hydraulic impact from mining is rock disturbance, such as caused by blasting at the mine site. Blasting can cause increased fracture density and open more interconnected pathways for a greater volume of mine-drainage constituents to flow downgradient of the mined site, perhaps at a more rapid rate than that prior to the disturbance from mining. The effects

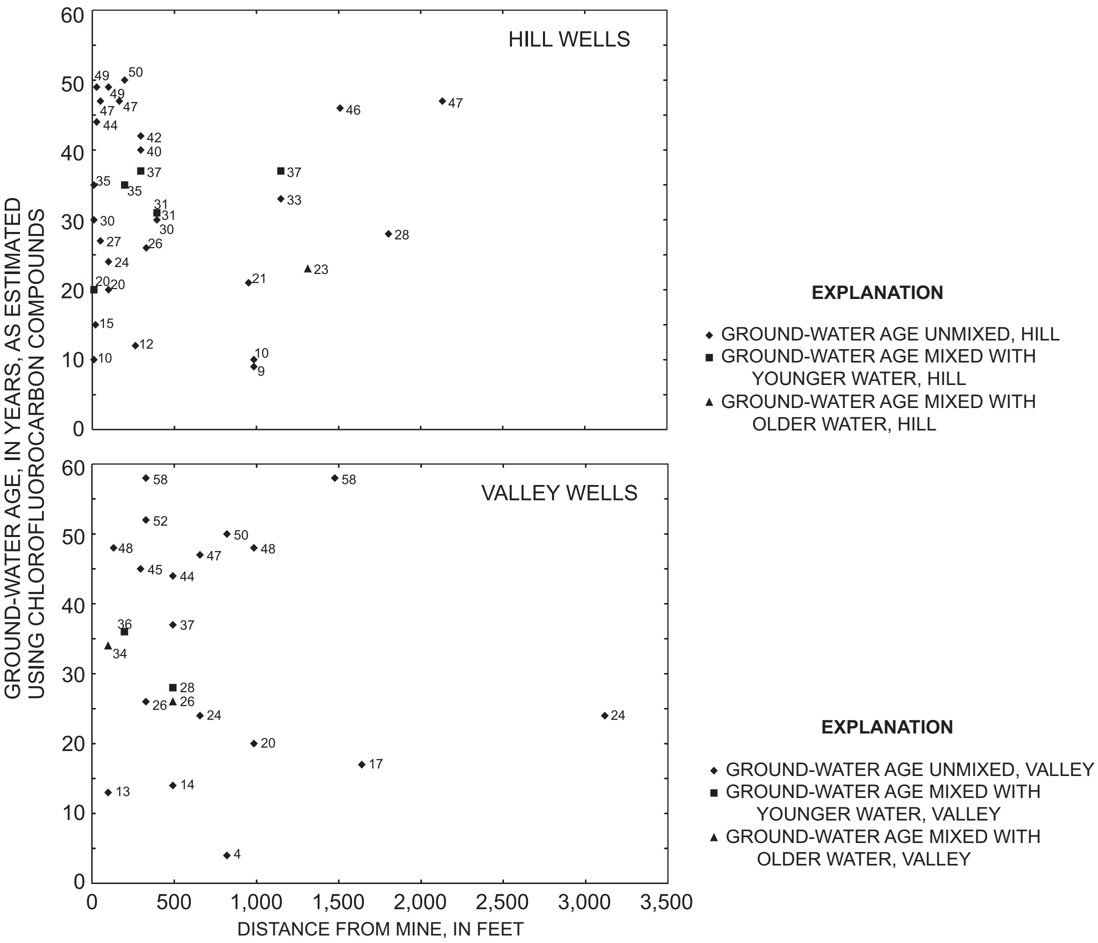


Figure 12. Age of well water at various distances and hill and valley topographic locations downgradient of reclaimed surface coal mines. (Samples listed with mixed ages are estimated by interpretation of chlorofluorocarbon data by G. Casile, U.S. Geological Survey, written commun., 2004).

would vary from site to site dependent on amount of overburden removal and blasting done.

Configuration of land surface and rock orientation and the variability of these factors within the study area may be related to ground-water residence times. For example, wells in hilltop settings in mined areas with steep slopes and terrain may have “younger” aged ground water and higher concentrations of mine-drainage constituents than wells in mined areas with less steep slopes and terrain. Orientation of bedrock with downgradient directions of ground-water flow could result in younger ground-water ages, but orientation (downdip, updip, or along strike relative to the location of the mine) did not correlate with high concentrations of mine-drainage constituents in this study. Also, mixing of older and younger ground water is more likely in valley settings than in hilltop or hillside settings.

A comparison of mine-drainage constituents in “young” ground water (age of water less than or equal to time elapsed since the reclamation was completed) to representative mine-drainage constituent concentrations in unmined area ground-water samples could not be conducted because the age of most ground waters sampled exceeded the time elapsed since reclamation completion. Twelve years is the maximum elapsed time since reclamation completion in the sample population. Yet, of all samples with ages exceeding 12 years, most samples had at least one mine-drainage constituent concentration exceeding background levels.

The median apparent age of ground water from 24 wells (table 6) sampled in mined areas of the low-sulfur coal region was 30 years. Samples from four wells in unmined areas of the low-sulfur coal region indicated a similar median apparent ground-water age of 25 years. No statistically significant difference in apparent ground-water age could be determined between mined and unmined areas in the low-sulfur coal region. In the high-sulfur coal region, the median apparent age of ground water from 9 wells in unmined areas was 44 years and the median apparent age of ground water from 30 wells in mined areas was 33 years. Although the median apparent ground-water age for unmined areas in the high-sulfur coal region was approximately 11 years older than mined areas, no statistical difference in the age of mined and unmined areas could be established.

Table 6. Statistical summaries of ground-water age comparing mined and unmined areas and topographic location of wells in the high-sulfur and low-sulfur coal regions.

[>, greater than]

Coal region	Sample size	Ground-water age, in years		
		Median	Maximum	Minimum
High-sulfur coal region				
Mined areas	30	33	52	9
Unmined areas	9	44	50	10
Low-sulfur coal region				
Mined areas	24	30	>58	4
Unmined areas	4	25	27	11
High-sulfur coal region (All wells sampled)				
Hilltop wells	3	44	50	35
Hillside wells	26	31	50	9
Valley wells	10	35	52	10
Low-sulfur coal region (All wells sampled)				
Hilltop wells	2	18	25	11
Hillside wells	11	28	47	10
Valley wells	15	26	>58	4
High-sulfur coal region (Mined areas only)				
Hilltop wells	1	35	35	35
Hillside wells	21	31	50	9
Hilltop and hillside wells	22	31	50	9
Valley wells	8	34	52	13
Low-sulfur coal region (Mined areas only)				
Hilltop and hillside wells	10	30	47	10
Valley wells	14	32	58	4

Ground water in mined areas in the high-sulfur coal region is typically older and has less variability in age than that in the low-sulfur coal region (table 6 and appendix 2). Major factors likely responsible for differences in ground-water age between the two coal regions are topographic relief and slope. Typical basin slopes are 60 percent greater and relief is about 20 percent greater in the low-sulfur coal region than in the high-sulfur coal region, which may result in less residence time, or younger ground-water age in general, in the low-sulfur coal region. Topographic location was the only factor that has a discernible pattern (though not statistically significant) with apparent ground-water age, and only in the low-sulfur coal region (table 6). Within the low-sulfur coal region, ground water from wells on hilltops (median age of 18 years) was younger than water from wells in valley settings (median age of 26 years). Ground-water age data indicate ground-water flow from ridges or hillsides to streams or subregional aquifers in valley bottoms. Within the high-sulfur coal region, median age of ground water for hilltop, hillside, and valley wells was 44, 31, and 35 years, respectively.

Although data from this study do not show a statistically significant relation between topographic setting and ground-water age, in a previous investigation, 25 wells were sampled randomly within the low-sulfur central coal region as part of an areal assessment of ground-water age within the Appalachian Plateaus Physiographic Province in the Kanawha–New River Basin. The study did not specifically sample wells downgradient from reclaimed surface mines; the wells selected for sampling were randomly chosen. For these 25 wells, the median age of ground water was estimated to be 30 years (Kozar, 1998), and median ground-water age for wells sampled in hilltop, hillside, and valley settings were 13, 29, and 42 years, respectively (Kozar, 1998). This finding is similar to age estimates determined as part of this investigation where well sampling yielded median age estimates of 18, 28, and 26 years for wells sampled within the low-sulfur coal province from hilltop, hillside, and valley settings, respectively (table 6). The major difference being that ground water in valley settings in primarily mined areas (median age of 26 years) appears to be significantly younger than that documented in valley settings in the earlier investigation (median age of 42 years) where wells were selected randomly. Younger waters in valley settings in mined areas may indicate a faster ground-water transit time in valley settings because of the enhanced fracturing of rock that is common as a result of both surface and underground coal mining.

Summary and Conclusions

Surface coal mines have historically had major impacts on the quality of shallow ground water. Since about 1977, changes in mining practice have been mandated to result in reclamation of surface-mined areas. Although current programs in Pennsylvania and West Virginia monitor water quality in and near surface coal mines, this study examines whether post-reclamation ground-water quality near coal mines is similar to ground-water quality observed in unmined areas in the bituminous coal fields of the northern Appalachian coal region (high-sulfur coal region) and the central Appalachian coal region (low-sulfur coal region). This study also examines the spatial and temporal extent of chemical constituents derived from mine drainage in ground water downgradient of reclaimed surface-coal-mined areas. This effort is part of the USGS NAWQA Program assessment of factors that affect ground-water quality, such as mining land use.

Samples collected from 58 wells (30 in the high-sulfur coal region and 28 in the low-sulfur coal region) about 2,500 ft or less downgradient of surface coal mines that were reclaimed during 1985-96 were compared to 25 samples from wells (20 in the high-sulfur and 5 in the low-sulfur coal region) in unmined areas. Samples from mined areas also were compared to background concentrations (estimated from the 90th percentile of concentrations in unmined areas) of selected constituents (sulfate, iron, manganese, aluminum, zinc, hardness, and dissolved solids). The wells were all private domestic supply wells of depths generally less than 250 ft. Ground water in these wells flows into open-hole sections in the gently dipping, relatively flat-lying fractured units of Pennsylvanian age, which may include sandstone, siltstone, shale, limestone, and coal.

Constituents examined include common inorganics (particularly constituents related to mine drainage such as sulfate, iron, manganese, aluminum, pH, acidity, alkalinity, hardness, and total dissolved solids), various trace elements (radon, lead, nickel, and zinc), and VOCs. Ground-water age was calculated from CFC compounds.

The mine-drainage constituents in ground water downgradient of the mined areas result from the transport of pyrite-oxidation products from the mined site and from neutralization reactions by the dissolution of calcareous materials introduced at the mine site or along the ground-water-flow path. The disturbance of the rock during blasting, drilling, or excavating causes fracturing of rocks and exposes rocks to additional recharge, mechanical weathering, and geochemical reactions.

Ground water downgradient of surface coal mines has significantly higher concentrations of sulfate, iron, manganese, aluminum, pH, hardness (calcium and magnesium), turbidity, and specific conductance compared to ground water in unmined areas. In addition, concentrations of zinc and detections of BTEX compounds (in the high-sulfur region only) were greater downgradient of surface coal mines compared to unmined areas. High concentrations of iron and manganese were ubiquitous throughout the study area. Sixty-four percent of samples downgradient of surface mines and 36 percent of samples from unmined areas exceeded the USEPA SMCL of 300 μg/L for iron, and 71 percent of samples downgradient from surface mines and 56 percent of samples from unmined areas exceeded the USEPA SMCL of 50 μg/L for manganese.

Sulfate, hardness, calcium, and magnesium concentrations were significantly greater in the high-sulfur coal region downgradient of reclaimed surface coal mines compared to downgradient of reclaimed surface coal mines in the low-sulfur coal region and unmined locations in either region. Specific conductance, pH, and radon downgradient of reclaimed surface coal mines were significantly greater in samples from the high-sulfur region compared to samples from the low-sulfur region sites.

Concentrations of several mine-drainage constituents (sulfate, manganese, aluminum, zinc, and hardness) were greatest and generally exceeded background less than 500 ft downgradient of surface-coal-mine sites but decreased to less than background concentrations at distances more than 1,000 ft downgradient. Concentrations of sulfate, hardness, and total dissolved solids were greatest in wells with depths between 50 and 150 ft but generally were less than background concentrations in wells deeper than 150 ft. Iron, manganese, and aluminum concentrations exceeded background in shallow wells (less than 50 ft deep) and in wells 50 to 150 ft deep. Alkalinity concentrations and pH were variable at all well depths. Radon and zinc concentrations were highest in shallow wells compared to wells more than 50 ft deep. Although turbidity levels were significantly greater at hill locations downgradient from surface-coal-mined sites compared to hill locations in unmined areas, mine-drainage constituents did not vary significantly by topographic location (hill as compared to valley).

The median age of ground water sampled in the low-sulfur coal region in mined and unmined areas was 30 and 25 years, respectively. The median ground-water age sampled in the high-sulfur coal region in mined and unmined areas was 33 and 44 years, respectively.

In mined areas, ground water in the high-sulfur coal region typically was older than ground water in the low-sulfur coal region, though not significantly. Ground-water age in mined areas typically was greater than time elapsed since mining completion and did not significantly correlate with concentrations of any mine-drainage constituent.

In comparing ground-water age to distance from mined areas and to topographic location, no significant correlations were found but a few observations are noteworthy. In mined areas, median ground-water ages increased from hill to valley locations for wells sampled in the low-sulfur and high-sulfur coal regions. In samples from wells in hill locations more than 1,000 ft from a mined area, a pattern was observed that ground-water age increased with increased distance from the mined area.

The lack of significant correlation among mine-drainage constituents, age, distance from mined areas, and topographic location may be the result of several factors. These factors include mixing of ground-water ages in water intercepted by the wells, hydraulic impacts of mining (disturbance of rock from blasting), configuration of land surface (slope and relief), and rock orientation (dip and strike) relative to mined areas and wells sampled. The mixing is likely related to the open-hole completion wells that intersect fractures of varying numbers, depths, lengths, and are interconnected with other fractures. In addition, the effects of blasting vary with the amount of overburden removed, and slope, relief, and structural orientation vary across the study area.

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Appendixes 1-3

Appendix 1a—Dissolved gas and recharge temperature data for 24 wells sampled downgradient from reclaimed surface coal mines in the low-sulfur coal region

Appendix 1b—Dissolved gas and recharge temperature data for 9 wells sampled downgradient from reclaimed surface coal mines in the high-sulfur coal region

Appendix 1c—Dissolved gas and recharge temperature data for 5 wells sampled in unmined areas in the low-sulfur coal region

Appendix 1d—Dissolved gas and recharge temperature data for 8 wells sampled in unmined areas in the high-sulfur coal region

Appendix 2a—Chlorofluorocarbon data and apparent ground-water-recharge dates for 24 wells sampled in the low-sulfur coal region downgradient from reclaimed surface coal mines

Appendix 2b—Chlorofluorocarbon data and apparent ground-water-recharge dates for 30 wells sampled in the high-sulfur coal region downgradient from reclaimed surface coal mines

Appendix 2c—Chlorofluorocarbon data and apparent ground-water-recharge dates for 5 wells sampled in unmined areas of the low-sulfur coal region

Appendix 2d—Chlorofluorocarbon data and apparent ground-water-recharge dates for 9 wells sampled in unmined areas in the high-sulfur coal region

Appendix 3—Site identification numbers, local well names, coal-sulfur-content region, land-use classification, topographic location, distance from mine, and well depth for wells sampled

Appendix 1a. Dissolved gas and recharge-temperature data for 24 wells sampled downgradient from reclaimed surface coal mines in the low-sulfur coal region.

[°C, degrees Celsius; mg/L, milligrams per liter; *, possible methane degradation of CFCs; ND, no data available]

Local identifier	Field water temper-ature (°C)	N_2 (mg/L)	Ar (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	Recharge elevation	Recharge temper-ature (°C)	Excess air (mg/L)
Ral-0211	14.9	15.848	0.5764	0.07	76.73	0.0000	2,584	14.7	0.8
	14.9	16.013	.5760	.06	78.32	.0000	2,584	15.2	1.1
Fay-0274	15.0	16.456	.6142	6.99	65.56	.0000	2,000	12.0	.3
	15.0	16.450	.6146	7.39	62.86	.0000	2,000	12.0	.2
Fay-0275	11.5	17.398	.6527	3.86	16.85	.0000	2,440	8.8	.3
	11.5	17.594	.6532	4.03	16.79	.0000	2,440	9.1	.6
Fay-0276	13.4	17.975	.6384	.69	70.41	.0000	2,400	11.6	1.9
	13.4	18.220	.6422	.48	70.45	.0000	2,400	11.7	2.2
Fay-0279	11.3	28.490	.8502	.20	46.87	.0072	2,240	8.2	11.0
	11.3	19.645	.6845	.57	37.84	.8104	2,240	9.8	2.8
Grb-0284	12.3	26.485	.8180	1.13	46.46	.0017	3,320	6.4	9.0
Fay-0272	12.6	19.406	.6869	.07	78.42	.0021	2,480	8.7	2.3
	12.6	19.334	.6848	.08	76.83	.0028	2,480	8.8	2.3
Boo-0260	13.2	20.728	.7528	.00	14.69	*7.8175	1,760	5.3	1.8
	13.2	20.860	.7589	.00	14.99	*7.6909	1,760	4.9	1.7
Boo-0258	13.6	18.446	.6697	.61	37.97	.0000	1,640	10.0	1.3
	13.6	18.132	.6618	1.34	37.52	.0000	1,640	10.3	1.1
Fay-0270	13.7	21.286	.6966	.10	50.45	.0402	2,000	12.0	5.1
	13.7	21.745	.7095	.09	50.66	.0234	2,000	11.4	5.3
Boo-0259	14.2	24.680	.8839	.00	5.73	*8.4649	1,560	ND	3.0
	14.2	24.689	.8904	.00	5.82	*8.0106	1,560	ND	2.7
Boo-0256	13.4	19.963	.6870	.23	73.32	.2458	1,160	11.8	3.2
	13.4	20.409	.6944	.27	82.90	.3121	1,160	11.8	3.6
Boo-0257	15.0	7.361	.2674	.00	102.81	*13.3136	1,180	ND	-1.3
	15.0	8.546	.3149	.00	123.63	*11.0795	1,180	ND	-1.2
Kan-0935	13.8	20.369	.6990	.08	24.48	.0042	1,440	10.7	3.4
Nic-0212	13.0	19.171	.6865	2.04	51.92	.0000	1,680	9.5	1.9
	13.0	19.168	.6896	1.64	52.68	.0000	1,680	9.1	1.7

Appendix 1a. Dissolved gas and recharge-temperature data for 24 wells sampled downgradient from reclaimed surface coal mines in the low-sulfur coal region.—Continued

[°C, degrees Celsius; mg/L, milligrams per liter; *, possible methane degradation of CFCs; ND, no data available]

Local identifier	Field water temperature (°C)	N_2 (mg/L)	Ar (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	Recharge elevation	Recharge temperature (°C)	Excess air (mg/L)
Nic-0209	11.8	21.143	0.7334	0.13	24.83	0.0713	1,880	7.8	3.3
	11.8	21.169	.7385	.11	28.64	.0721	1,880	7.3	3.1
Nic-0213	13.8	20.882	.7045	.20	75.18	.2022	2,200	10.0	4.1
	13.8	29.378	.8527	.23	80.83	.1896	2,200	9.6	12.5
Kan-0938	14.4	19.398	.6751	.29	17.24	.3522	1,580	11.4	2.7
	14.4	19.507	.6780	.30	16.08	.3997	1,580	11.3	2.8
Nic-0214	12.8	20.219	.6638	.31	83.38	.3837	2,440	13.2	4.7
	12.8	19.857	.6576	.30	82.85	.3826	2,440	13.2	4.3
Nic-0215	12.4	22.711	.7994	.00	11.61	*6.3042	2,440	3.2	3.2
	12.4	25.044	.8377	.00	11.61	*6.1873	2,440	3.3	5.6
Nic-0211	12.5	16.233	.6225	.00	36.32	*5.2565	2,480	9.9	-.4
	12.5	15.919	.6182	.00	38.59	*5.5752	2,480	9.7	-.8
Nic-0219	12.5	21.044	.7220	.22	59.44	.2434	2,800	7.5	3.7
	12.5	20.500	.7134	.23	58.51	.2621	2,800	7.4	3.1
Nic-0217	12.5	23.409	.7518	.60	59.81	.6122	2,520	9.0	6.5
Nic-0218	12.1	18.126	.6303	3.12	198.76	.0000	2,560	12.8	2.5

Appendix 1b. Dissolved gas and recharge temperature data for 9 wells sampled downgradient from reclaimed surface coal mines in the high-sulfur coal region.

[°C, degrees Celsius; mg/L, milligrams per liter; *, possible methane degradation of CFCs]

Local identifier	Field water temperature (°C)	N_2 (mg/L)	Ar (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	Recharge elevation	Recharge temperature (°C)	Excess air (mg/L)
LE411	16.7	20.504	0.7017	0.05	0.92	*16.1643	1,070	11.3	3.5
WS973	14.5	21.462	.7436	.29	39.05	.0047	1,090	8.4	3.4
	14.5	27.119	.8468	2.00	39.35	.0042	1,090	7.7	8.7
MN612	14.1	21.350	.6608	.12	142.84	.0000	1,140	18.4	6.6
	14.1	21.496	.6628	.15	138.87	.0004	1,140	18.5	6.8
BA012	14.4	20.968	.7174	.11	81.45	.5526	1,700	9.4	3.7
CR726	13.2	21.725	.7497	.04	59.04	.0283	1,270	8.0	3.6
	13.2	22.557	.7642	.07	61.79	.0283	1,270	8.0	4.4
AR106	12.8	13.095	.4944	.00	32.26	*25.5844	980	22.8	-.6
	12.8	14.473	.5417	.03	32.77	*25.7054	980	19.0	-.2
SO853	11.8	20.217	.7103	.02	116.01	.0624	2,380	7.8	2.7
	11.8	20.510	.7224	.01	115.41	.0661	2,380	7.1	2.7
JE423	11.9	23.231	.7974	.06	61.55	.0090	1,460	5.5	4.2
	11.9	22.854	.7897	.14	60.91	.0093	1,460	5.7	3.8
JE424	11.6	23.479	.7240	.07	257.99	.0533	1,670	13.8	7.7

Appendix 1c. Dissolved gas and recharge temperature data for 5 wells sampled in unmined areas in the low-sulfur coal region.

[°C, degrees Celsius; mg/L, milligrams per liter; *, possible methane degradation of CFCs; INT, sample could not be analyzed for oxygen content due to unforeseen interference effects]

Local identifier	Field water temperature (°C)	N_2 (mg/L)	Ar (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	Recharge elevation	Recharge temperature (°C)	Excess air (mg/L)
Ral-0220	11.3	17.881	0.6525	0.10	34.09	0.0000	2,850	9.1	1.18
Kan-0927	13.3	20.625	.7217	.04	47.98	.0000	1,000	9.4	2.83
Cla-0141	12.9	16.271	.6255	.07	23.51	*6.7144	1,400	11.2	-.58
FA509	13.0	16.913	.6335	4.91	48.54	.0000	2,385	10.1	.3
	13.0	16.523	.6246	5.18	47.45	.0000	2,385	10.3	.0
LE412	19.3	13.598	.5085	INT	12.44	*8.7633	1,100	21.7	-.3
	19.3	13.344	.4987	INT	12.43	*8.5065	1,100	22.6	-.4

Appendix 1d. Dissolved gas and recharge temperature data for 8 wells sampled in unmined areas in the high-sulfur coal region.

[°C, degrees Celsius; mg/L, milligrams per liter; *, possible methane degradation of CFCs]

Local identifier	Field water temper-ature (°C)	N_2 (mg/L)	Ar (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	Recharge elevation	Recharge temper-ature (°C)	Excess air (mg/L)
Nic-0208	12.5	20.953	0.7389	0.03	32.31	*1.9742	3,000	5.3	2.83
SO124	14.7	20.465	.7068	.06	2.37	*1.0421	700	11.2	3.15
SO126	13.4	21.988	.7236	9.03	51.25	.0003	1,120	11.6	5.09
	13.4	22.294	.7337	9.20	51.24	.0000	1,120	11.0	5.19
IN915	13.5	17.732	.6434	3.61	17.75	.0000	1,564	11.8	1.19
Brx-0269	13.4	21.553	.7383	.15	23.12	.0022	1,400	8.7	3.76
CR727	15.1	22.306	.7496	.15	31.93	.1026	1,485	8.7	4.6
	15.1	22.061	.7452	.15	26.63	.1097	1,485	8.7	4.3
AR108	12.8	26.568	.8278	.09	11.58	.0000	1,240	8.5	8.6
	12.8	26.311	.8208	.09	11.29	.0000	1,240	8.8	8.4
WE315	12.0	19.857	.7103	.10	41.44	.0000	1,120	9.0	2.0
	12.0	19.712	.7073	.65	42.17	.0000	1,120	9.1	1.9

Appendix 2a. Chlorofluorocarbon data and apparent ground-water-recharge dates for 24 wells sampled in the low-sulfur coal region downgradient from reclaimed surface coal mines.

[ft, feet; pg/kg, picograms per kilogram; pptv, parts per trillion per volume; <, less than date or age; >, greater than date or age. CFC sample collected for well Boo-0257; however, no data tabulated here due to sample degredation and inconclusive results.]

Local county identifier	Date	Time	Well depth (ft below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chloro-fluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
Sum-0105	06181998	1200	115	34.1	45.7	0.0	13.6	78.9	0.0	11.0	1965	33
				12.7	42.5	.0	5.1	73.5	.0	11.0		
				11.2	58.9	2.6	4.5	101.8	2.5	11.0		
Ral-0221	05271998	900	49.5	479.3	227.9	60.1	236.4	479.2	72.1	14.7	1988	10
				442.6	216.8	57.1	218.3	455.9	68.5	14.7		
				467.9	225.5	59.4	230.8	474.0	71.3	14.7		
Fay-0274	05211998	1100	47.5	489.4	304.4	209.4	205.1	552.0	210.5	12.0	1951	47
				490.7	299.1	219.3	205.6	542.3	220.4	12.0		
				493.6	293.4	227.6	206.8	531.9	228.7	12.0		
Fay-0275	05121998	1100	21.25	684.3	324.1	101.9	247.0	515.2	86.8	9.0	1994	4
				686.2	334.0	96.1	247.7	530.9	81.9	9.0		
				686.9	325.4	101.4	248.0	517.1	86.4	9.0		
Fay-0276	05081998	1300	102	209.6	122.7	122.2	87.7	222.6	122.4	11.7	1974	24
				190.5	118.0	129.5	79.7	214.1	129.8	11.7		
				193.4	112.8	114.3	80.9	204.7	114.6	11.7		
Fay-0279	05261998	1400	30	.0	.0	.0	.0	.0	.0	9.0	<1940	>58
				.0	.0	.0	.0	.0	.0	9.0		
				2.5	1.8	.0	.9	2.9	.0	9.0		
Grb-0284	06161998	1100	112	14,684.4	110.3	30.0	4,708.5	158.2	22.4	6.4	1970	28
				2,104.9	53.1	12.9	674.9	76.2	9.6	6.4		
				1,888.1	51.5	13.0	605.4	73.9	9.7	6.4		

Appendix 2a. Chlorofluorocarbon data and apparent ground-water-recharge dates for 24 wells sampled in the low-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[ft, feet; pg/kg, picograms per kilogram; pptv, parts per trillion per volume; <, less than date or age; >, greater than date or age. CFC sample collected for well Boo-0257; however, no data tabulated here due to sample degredation and inconclusive results.]

Local county identifier	Date	Time	Well depth (ft below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temperature	Chlorofluorocarbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
Fay-0272	05131998	1200	225	39.1	37.4	10.4	13.9	58.6	8.7	8.7	1961 with younger water	37
				35.2	32.3	7.0	12.5	50.6	5.9	8.7		
				37.0	36.1	8.2	13.1	56.6	6.9	8.7		
Boo-0260	05151998	1000	73	1.4	3.8	.0	.4	4.8	.0	5.1	1948	50
				.9	1.7	.0	.3	2.2	.0	5.1		
				.0	.0	.0	.0	.0	.0	5.1		
Boo-0258	05061998	1000	64	333.9	176.5	61.2	124.4	287.7	54.2	10.1	1981	17
				354.8	193.0	67.9	132.2	314.6	60.1	10.1		
				352.4	188.8	63.4	131.3	307.9	56.1	10.1		
Fay-0270	05221998	1200	27	4.1	109.3	4.8	1.7	195.3	4.8	11.7	1974	24
				154.1	266.7	17.2	63.5	476.6	17.0	11.7		
				4.9	114.4	5.1	2.0	204.4	5.1	11.7		
Boo-0259	06231998	1000	105	3.6	2.9	.0	1.4	5.0	.0	11.0	1951	47
				6.2	4.4	.0	2.4	7.5	.0	11.0		
				11.9	11.4	.0	4.7	19.4	.0	11.0		
Boo-0256	05041998	1300	130	76.2	96.4	13.8	30.6	167.8	13.3	11.8	1972	26
				69.7	101.0	15.5	28.0	175.8	14.9	11.8		
				67.9	102.2	13.8	27.3	177.9	13.3	11.8		

Appendix 2a. Chlorofluorocarbon data and apparent ground-water-recharge dates for 24 wells sampled in the low-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[ft, feet; pg/kg, picograms per kilogram; pptv, parts per trillion per volume; <, less than date or age; >, greater than date or age. CFC sample collected for well Boo-0257; however, no data tabulated here due to sample degredation and inconclusive results.]

Local county identifier	**Date**	**Time**	**Well depth (ft below land surface)**	**Chlorofluorocarbon concentration in water (pg/kg)**			**Chlorofluorocarbon partial pressure (pptv)**			**Recharge temper-ature**	**Chloro-fluoro-carbon apparent CFC recharge date**	**Estimated age of ground water (years)**
				CFC-11	**CFC-12**	**CFC-113**	**CFC-11**	**CFC-12**	**CFC-113**			
Kan-0935	05051998	1100	100	130.9	86.0	13.4	50.1	143.4	12.2	10.7	1975 with older water	23
				169.2	108.5	22.2	64.7	180.9	20.2	10.7		
				183.8	116.0	20.6	70.3	193.4	18.7	10.7		
Nic-0212	05191998	1400	25.5	268.2	194.2	74.1	95.7	304.6	62.5	9.3	1984	14
				249.3	191.0	74.3	89.0	299.7	62.7	9.3		
				6,581.6	923.1	68.5	2,349.2	1,448.0	57.8	9.3		
Nic-0209	07081998	900	50	4.2	95.2	.0	1.4	137.9	.0	7.6	1972	26
				3.9	122.5	.0	1.3	177.4	.0	7.6		
				2.6	120.2	.0	.8	174.1	.0	7.6		
Nic-0213	05281998	1400	48.38	122.6	186.3	.0	45.9	305.5	.0	9.8	1978	20
				12.1	149.2	.0	4.5	244.7	.0	9.8		
				3.2	175.5	.0	1.2	287.8	.0	9.8		
Kan-0938	06221998	1000	105	2.7	.8	.0	1.1	1.4	.0	11.3	1950	48
				18.4	2.6	.0	7.3	4.4	.0	11.3		
				6.4	1.9	.0	2.6	3.3	.0	11.3		
Nic-0214	06031998	900	47.6	38.2	56.7	36.6	17.3	110.7	40.1	13.2	1951	47
				6.9	2.0	29.2	3.1	3.9	31.9	13.2		
				6.1	2.3	30.0	2.8	4.4	32.9	13.2		
Nic-0215	06021998	1200	375	.0	.0	.0	.0	.0	.0	11.0	<1940	>58
				.0	.0	.0	.0	.0	.0	11.0		
				880.4	341.8	66.6	355.3	600.2	64.1	11.0		

Appendix 2a. Chlorofluorocarbon data and apparent ground-water-recharge dates for 24 wells sampled in the low-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[ft, feet; pg/kg, picograms per kilogram; pptv, parts per trillion per volume; <, less than date or age; >, greater than date or age. CFC sample collected for well Boo-0257; however, no data tabulated here due to sample degredation and inconclusive results.]

Local county identifier	Date	Time	Well depth (ft below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temperature	Chlorofluorocarbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
Nic-0211	06101998	900	80	28.7	27.2	2.6	10.9	45.1	2.4	9.8	1961 with younger water	37
				26.0	22.5	2.7	9.8	37.3	2.4	9.8		
				19.4	21.8	.0	7.3	36.2	.0	9.8		
Nic-0219	06041998	900	57	4.4	3.2	.0	1.5	4.8	.0	7.5	1950	48
				4.1	2.4	.0	1.4	3.6	.0	7.5		
				9.5	4.2	.0	3.2	6.3	.0	7.5		
Nic-0217	06121998	1000	100	37.0	23.3	.0	13.4	37.1	.0	9.0	1961	37
				36.7	24.8	2.3	13.3	39.5	2.0	9.0		
				41.4	22.1	.0	15.0	35.2	.0	9.0		
Nic-0218	06171998	1100	90	292.4	226.0	38.3	130.6	434.6	41.2	12.8	1986	12
				273.5	226.2	35.4	122.1	435.0	38.1	12.8		
				277.8	230.9	33.7	124.1	444.0	36.2	12.8		

Appendix 2b. Chlorofluorocarbon data and apparent ground-water-recharge dates for 30 wells sampled in the high-sulfur coal region downgradient from reclaimed surface coal mines.

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chloro-fluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
SO851	09171997	800	44	3.0	4.3	0.0	1.1	7.0	0.0	9.6	1951	46
				.1	3.3	.0	.0	5.3	.0	9.6		
				1.4	4.6	.0	.5	7.5	.0	9.6		
BT407	10161997	800	65	527.4	256.5	128.7	171.7	369.8	98.3	8.0	1984	13
				534.8	260.0	119.2	174.1	374.8	91.1	8.0		
				555.9	254.3	111.3	180.9	366.6	85.1	8.0		
JE422	08261997	800	60	40.1	12.9	.0	13.1	18.6	.0	8.0	1957	40
				41.5	15.1	.0	13.5	21.8	.0	8.0		
				37.2	14.7	.0	12.1	21.2	.0	8.0		
SO853	09161997	800	115	78.9	88.9	67.6	26.1	130.5	52.3	7.5	1966 with younger water	31
				69.7	79.1	18.1	23.0	116.1	14.0	7.5		
				71.9	83.9	40.7	23.8	123.2	31.5	7.5		
BA012	10081997	800	90	3.6	8,402.2	.0	1.3	13,256.9	.0	9.4	1953	44
				4.4	8,358.4	.0	1.6	13,187.9	.0	9.4		
				4.9	3,257.8	.0	1.8	5,140.1	.0	9.4		
PR773	09241997	800	41	440.3	571.3	47.1	155.1	886.3	39.2	9.0	1982	15
				442.2	513.4	39.7	155.8	796.5	33.0	9.0		
				432.2	482.5	45.6	152.3	748.6	37.9	9.0		
CA457	09151997	800	100	592.6	290.4	103.3	197.9	429.8	81.0	7.9	1988	9
				549.3	262.1	70.0	183.4	387.9	54.8	7.9		
				603.5	311.0	75.7	201.5	460.4	59.3	7.9		

Appendix 2b. Chlorofluorocarbon data and apparent ground-water-recharge dates for 30 wells sampled in the high-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chloro-fluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
WE313	08201997	800	135	0.0	0.0	0.0	0.0	0.0	0.0	8.5	1948	49
				1.9	2.6	.0	.6	3.8	.0	8.5		
SO852	08141997	800	70	.0	.0	.0	.0	.0	.0	9.8	1948	49
				10.2	80.3	5.0	3.8	130.6	4.4	9.8		
				.0	.0	.0	.0	.0	.0	9.8		
MN612	09231997	800	40.7	100.1	443.3	.0	40.6	778.4	.0	12.0	1970	27
				101.1	362.9	.0	41.0	637.1	.0	12.0		
				110.7	373.0	.0	44.9	654.9	.0	12.0		
JE424	09101997	800	50	3.6	1,529.5	.0	1.2	2,338.4	.0	8.8	1952	45
				.6	1,506.4	.0	.2	2,303.1	.0	8.8		
				1.1	1,502.0	.0	.4	2,296.4	.0	8.8		
IN917	09031997	800	82	.0	.0	9.5	.0	.0	7.4	8.3	1945	52
				.0	.0	10.3	.0	.0	8.0	8.3		
				.0	1.4	.0	.0	2.0	.0	8.3		
BT406	08191997	800	68	384.5	528.2	5.8	112.3	690.6	4.0	6.3	1973	24
				346.7	432.1	7.5	101.3	564.9	5.1	6.3		
				338.1	387.4	6.9	98.8	506.4	4.7	6.3		
IN918	09021997	800	65	4.6	3.7	.0	1.5	5.4	.0	8.2	1947	50
				.0	.0	.0	.0	.0	.0	8.2		
				.2	.0	.0	.1	.0	.0	8.2		

Appendix 2b. Chlorofluorocarbon data and apparent ground-water-recharge dates for 30 wells sampled in the high-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chloro-fluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
AR107	08271997	800	154	5,810.1	3,101.5	17.6	1,953.9	4,608.8	13.9	8.4	1977	20
				4,915.1	6,354.5	18.8	1,953.0	9,442.9	14.9	8.4		
				5 891.1	2 902.3	16.9	1 981.2	4 312.9	13.4	8.4		
WS973	09181997	800	98	109.0	67.2	.0	35.5	97.0	.0	8.1	1967	30
				84.0	63.8	.0	27.4	92.1	.0	8.1		
				85.3	64.1	8.4	27.8	92.5	6.4	8.1		
UP972	10201997	800	68	131.5	63.2	.0	48.9	102.7	.0	10.2	1971 with older water	26
				137.4	72.4	.0	51.1	117.7	.0	10.2		
				150.5	66.1	.0	56.0	107.4	.0	10.2		
IN861	10011997	800	85	98.0	92.0	28.6	32.4	134.5	22.2	8.0	1969 with younger water	28
				92.1	89.8	25.6	30.4	131.4	19.9	8.0		
				154.3	90.5	19.2	51.0	132.4	14.9	8.0		
BA011	10211997	800	52	52.4	40.9	.0	19.5	66.5	.0	10.2	1966	31
				75.4	55.1	.0	28.1	89.7	.0	10.2		
				81.2	56.5	34.3	230.2	92.0	30.3	10.2		
WE311	09251997	800	220	510.6	284.8	75.4	166.7	411.9	57.8	8.0	1987	10
				507.9	275.6	68.1	165.9	398.5	52.2	8.0		
				519.6	265.9	87.2	169.6	384.5	66.9	8.0		
FA508	08211997	800	135	415.4	562.2	52.9	138.8	831.3	41.5	8.2	1977 with younger water	20
				416.3	571.3	50.7	139.2	844.8	39.8	8.2		
				404.1	551.0	43.5	135.1	814.8	34.2	8.2		

Appendix 2b. Chlorofluorocarbon data and apparent ground-water-recharge dates for 30 wells sampled in the high-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chloro-fluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
HR332	09301997	800	96	47.5	57.8	5.6	19.6	102.8	5.5	12.4	1963 with older water	34
				6.0	36.5	.0	2.5	64.9	.0	12.4		
				26.0	31.0	.0	10.7	55.2	.0	12.4		
PR774	09291997	800	110	28.7	36.7	7.2	10.9	60.9	6.5	10.7	1967	30
				30.7	39.4	3.2	11.7	65.4	2.9	10.7		
				36.6	54.5	8.3	13.9	90.3	7.5	10.7		
AR106	08281997	800	55	2.7	.0	.0	.9	.0	.0	9.0	1953	44
				4.9	6.0	.0	1.7	9.0	.0	9.0		
				4.4	1.0	.0	1.5	1.5	.0	9.0		
WE314	10021997	800	140	4.6	29.7	.0	1.6	44.9	.0	9.0	1962	35
				4.0	27.1	.0	1.4	40.9	.0	9.0		
				4.4	27.5	.0	1.5	41.6	.0	9.0		
LE411	10091997	800	85	33.9	22.0	6.8	13.2	37.2	6.4	11.3	1961 with younger water	36
				34.6	41.7	8.8	13.5	70.6	8.2	11.3		
				17.6	10.3	11.7	6.9	17.4	10.9	11.3		
WE312	08071997	800	150	154.2	116.9	6.3	51.6	172.6	4.9	8.5	1976	21
				154.8	113.7	25.9	51.8	167.9	20.4	8.5		
				150.9	122.2	24.2	50.5	180.5	19.0	8.5		
VE058	09081997	800	63	43.6	549.4	30.4	14.9	827.7	24.5	8.7	1962 with younger water	35
				37.8	519.7	25.1	12.9	782.9	20.2	8.7		
				41.5	570.1	28.1	14.2	858.8	22.6	8.7		

Appendix 2b. Chlorofluorocarbon data and apparent ground-water-recharge dates for 30 wells sampled in the high-sulfur coal region downgradient from reclaimed surface coal mines.—Continued

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface)	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temperature	Chlorofluorocarbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
JE423	09111997	800	98	2.5	21.7	0.0	0.7	27.8	0.0	5.6	1954	42
				2.4	20.0	.0	.7	25.7	.0	5.6		
				2.5	21.8	.0	.7	27.9	.0	5.6		
CR726	08251997	800	70	1.6	5.5	.0	.5	8.0	.0	8.0	1950	47
				1.5	5.1	.0	.5	7.4	.0	8.0		
				1.4	.0	.0	.4	.0	.0	8.0		

Appendix 2c. Chlorofluorocarbon data and apparent ground-water-recharge dates for 5 wells sampled in unmined areas of the low-sulfur coal region.

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chlorofluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
Ral-0220	05131997	900	226	8,417.8	269.5	59.2	3,063.7	431.6	51.5	9.1	1986	11
				8,426.5	260.1	51.0	3,066.9	416.6	44.4	9.1		
				8,252.8	235.5	47.3	3,003.7	377.2	41.1	9.1		
Kan-0927	05281997	1100	65	100.5	80.8	17.3	34.7	122.7	14.4	9.4	1970 with younger water	27
				114.1	91.5	20.8	39.5	139.0	17.2	9.4		
				151.6	118.0	28.1	52.4	179.2	23.3	9.4		
Cla-0141	05081997	1100	50	65.7	88.3	24.8	25.4	148.6	23.2	11.2	1972	25
				51.5	69.4	8.4	19.9	116.7	7.9	11.2		
FA509	07221998	800	200	238.2	487.1	34.3	88.2	788.0	30.2	10.2	1973	25
				244.5	445.9	32.6	90.5	721.4	28.6	10.2		
				240.2	485.0	32.7	88.9	784.6	28.7	10.2		
LE412	08271998	800	112	27.4	208.5	40.9	10.8	356.1	38.4	11.3	Unknown	Unknown
				11.4	165.7	57.1	4.5	282.9	53.7	11.3		
				47.6	142.0	57.8	18.7	242.4	54.3	11.3		

Appendix 2d. Chlorofluorocarbon data and apparent ground-water-recharge dates for 9 wells sampled in unmined areas in the high-sulfur coal region.

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temperature	Chlorofluorocarbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
Nic-0208	06161997	1100	208	7.9	14.9	0.0	2.2	19.1	0.0	5.3	1955	42
				9.1	11.5	.0	2.6	14.8	.0	5.3		
				45.7	36.2	.0	13.0	46.6	.0	5.3		
SO124	07111996	800	75	2.7	48,255.0	.0	1.0	79,112.1	.0	11.2	1947	50
				.6	43,737.4	.0	.2	71,705.8	.0	11.2		
				.7	45,188.7	.0	.3	74,085.0	.0	11.2		
SO126	07031996	800	114	295.4	253.4	59.4	115.6	429.9	56.4	11.6	1987	10
				297.0	252.2	60.4	116.2	428.0	57.3	11.6		
				309.3	266.4	69.6	121.0	452.1	66.1	11.6		
IN915	08011996	800	95	339.8	201.6	47.5	136.6	351.0	46.4	11.8	1983	14
CA456	08201996	800	72	1.0	.0	.0	.3	.0	.0	10.0	1947	50
				.7	2.3	.0	.2	3.6	.0	10.0		
				1.2	1.8	4.3	.4	2.8	3.7	10.0		
Brx-0269	06101997	1100	90	1.7	4.9	.0	.6	7.3	.0	8.7	1950	47
				2.3	3.8	.0	.8	5.7	.0	8.7		
				2.2	2.0	.0	.7	3.0	.0	8.7		
CR727	07161998	800	178	9.8	10.0	.0	3.4	15.1	.0	8.7	1954	44
				7.6	12.1	.0	2.6	18.3	.0	8.7		
				9.4	6.9	.0	3.2	10.4	.0	8.7		

Appendix 2d. Chlorofluorocarbon data and apparent ground-water-recharge dates for 9 wells sampled in unmined areas in the high-sulfur coal region.—Continued

[pg/kg, picograms per kilogram; pptv, parts per trillion per volume]

Local county identifier	Date	Time	Well depth, in feet below land surface	Chlorofluorocarbon concentration in water (pg/kg)			Chlorofluorocarbon partial pressure (pptv)			Recharge temper-ature	Chloro-fluoro-carbon apparent CFC recharge date	Estimated age of ground water (years)
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
AR108	07291998	800	100	11.4	4.9	0.0	3.9	7.3	0.0	8.7	1952	46
				13.7	10.6	.0	4.6	15.9	.0	8.7		
				10.0	6.2	.0	3.4	9.3	.0	8.7		
WE315	09081998	800	30	478.6	292.1	43.0	166.6	447.3	35.3	9.1	1986	12
				504.1	265.1	47.2	175.4	405.9	38.8	9.1		
				507.1	307.1	44.3	176.5	470.2	36.4	9.1		

Appendix 3. Site identification numbers, local well names, coal-sulfur-content region, land-use classification, topographic location, distance from mine, and well depth for wells sampled.

[NA, not applicable]

Site identification number	Local well name	Coal sulfur content region H = High L = Low	Land-use classification	Topographic location	Distance from mine, in feet[1]	Well depth, in feet below land surface
390201080311301	LE411	H	downgradient from mine	Valley	197	85
390227080145801	UP972	H	downgradient from mine	Valley	492	68
390353079555601	BA012	H	downgradient from mine	Hillside	26	90
391103079582901	BA011	H	downgradient from mine	Hillside	394	52
392458080165301	HR332	H	downgradient from mine	Valley	98	96
392917079460501	PR773	H	downgradient from mine	Hillside	20	41
392924079374601	PR774	H	downgradient from mine	Hillside	0	110
393533080035501	MN612	H	downgradient from mine	Hillside	49	46
395040078595401	SO851	H	downgradient from mine	Hillside	1,509	44
395520079080301	SO852	H	downgradient from mine	Hillside	26	70
400434079235201	FA508	H	downgradient from mine	Hillside	0	135
400455078532101	SO853	H	downgradient from mine	Hillside	394	115
400846079485701	WE312	H	downgradient from mine	Hillside	951	150
401053079590001	WS973	H	downgradient from mine	Hillside	394	98
401225079361501	WE313	H	downgradient from mine	Hillside	98	135
402319079283001	WE314	H	downgradient from mine	Hilltop	0	140
402415078544301	CA457	H	downgradient from mine	Hillside	984	100
403253079410701	WE311	H	downgradient from mine	Hillside	0	220
403650079220201	IN917	H	downgradient from mine	Valley	328	82
403756079234001	AR106	H	downgradient from mine	Valley	492	55
404050079494001	BT406	H	downgradient from mine	Hillside	98	32
404230078540901	IN861	H	downgradient from mine	Valley	492	135
404712078575501	IN918	H	downgradient from mine	Hillside	197	65
405449079193901	AR107	H	downgradient from mine	Hillside	98	154
405642079455601	BT407	H	downgradient from mine	Valley	98	65
410156079183801	CR726	H	downgradient from mine	Hillside	49	70
410205079061101	JE422	H	downgradient from mine	Hillside	295	60
410609078505701	JE423	H	downgradient from mine	Hillside	295	98
411026078484301	JE424	H	downgradient from mine	Valley	295	50
411336079574901	VE058	H	downgradient from mine	Hillside	197	63
385131080272501	LE412	H	in unmined area	Hillside	NA	112
395200079160101	SO124	H	in unmined area	Hilltop	NA	75
395201079383601	FA509	L	in unmined area	Hilltop	NA	200
400953079382101	WE309	H	in unmined area	Hillside	NA	55
401102079273801	WE310	H	in unmined area	Hillside	NA	250
401337079005201	SO126	H	in unmined area	Valley	NA	114
402629079092301	IN915	H	in unmined area	Hillside	NA	95
402905079400001	WE315	H	in unmined area	Hillside	NA	30
402934079211401	IN914	H	in unmined area	Hillside	NA	160
403237078463101	CA456	H	in unmined area	Hillside	NA	72

Appendix 3. Site identification numbers, local well names, coal-sulfur-content region, land-use classification, topographic location, distance from mine, and well depth for wells sampled.—Continued

[NA, not applicable]

Site identification number	Local well name	Coal sulfur content region H = High L = Low	Land-use classification	Topographic location	Distance from mine, in feet[1]	Well depth, in feet below land surface
404108079273001	AR105	H	in unmined area	Hillside	NA	110
404510079104101	IN913	H	in unmined area	Hillside	NA	123
404924079155201	AR108	H	in unmined area	Hillside	NA	100
410557078465901	CF320	H	in unmined area	Hillside	NA	110
411335079375301	CR727	H	in unmined area	Hilltop	NA	178
375115080474901	Sum-0105	L	downgradient from mine	Hillside	1,148	115
375246081133401	Ral-0221	L	downgradient from mine	Hillside	984	49.5
375420081091301	Fay-0274	L	downgradient from mine	Hillside	164	47.5
375739081171801	Fay-0275	L	downgradient from mine	Valley	820	21.3
375829081180801	Fay-0276	L	downgradient from mine	Valley	656	102
375914081121501	Fay-0278	L	downgradient from mine	Hillside	328	42.7
375915081132501	Fay-0279	L	downgradient from mine	Valley	1,476	30
380106080432801	Grb-0284	L	downgradient from mine	Hillside	1,804	112
380131080591301	Fay-0272	L	downgradient from mine	Hillside	295	225
380153081341101	Boo-0260	L	downgradient from mine	Valley	820	73
380444081351401	Boo-0258	L	downgradient from mine	Valley	1,640	64
380607081145801	Fay-0270	L	downgradient from mine	Valley	3,117	27
380708081370201	Boo-0259	L	downgradient from mine	Hillside	2,133	105
380818081502301	Boo-0255	L	downgradient from mine	Valley	1,476	200
380939081504801	Boo-0256	L	downgradient from mine	Hillside	328	130
381048081504801	Boo-0257	L	downgradient from mine	Valley	1,148	120
381125081304701	Kan-0935	L	downgradient from mine	Hillside	1,312	100
381513080584401	Nic-0212	L	downgradient from mine	Valley	492	25.5
381539080560201	Nic-0209	L	downgradient from mine	Valley	328	50
381656080543301	Nic-0213	L	downgradient from mine	Valley	984	48.4
381847081254201	Kan-0938	L	downgradient from mine	Valley	984	105
381931080425401	Nic-0214	L	downgradient from mine	Valley	656	47.6
382011080424501	Nic-0215	L	downgradient from mine	Valley	328	375
382113080442701	Nic-0211	L	downgradient from mine	Hillside	1,148	80
382123080381701	Nic-0219	L	downgradient from mine	Valley	131	57
382307080381201	Web-0238	L	downgradient from mine	Valley	230	26.5
382340080481301	Nic-0217	L	downgradient from mine	Valley	492	100
382434080401401	Nic-0218	L	downgradient from mine	Hillside	262	90
374645081030701	Ral-0220	L	in unmined area	Hilltop	NA	226
381639080380101	Nic-0206	L	in unmined area	Valley	NA	115
381652080473501	Nic-0208	H	in unmined area	Hillside	NA	208
381852081404401	Kan-0927	L	in unmined area	Hillside	NA	65
382131081091501	Cla-0141	L	in unmined area	Valley	NA	50
382636081432801	Kan-0928	H	in unmined area	Valley	NA	73
382845081300301	Kan-0932	H	in unmined area	Hillside	NA	75

Appendix 3. Site identification numbers, local well names, coal-sulfur-content region, land-use classification, topographic location, distance from mine, and well depth for wells sampled.—Continued

[NA, not applicable]

Site identification number	Local well name	Coal sulfur content region H = High L = Low	Land-use classification	Topographic location	Distance from mine, in feet[1]	Well depth, in feet below land surface
383101080525401	Brx-0270	H	in unmined area	Hilltop	NA	172
383405081022701	Cla-0142	H	in unmined area	Valley	NA	46
384057080354101	Brx-0269	H	in unmined area	Valley	NA	90

[1] Wells with distances from mine of zero were within the mine-boundary area and were assigned a value of zero when used in analysis.