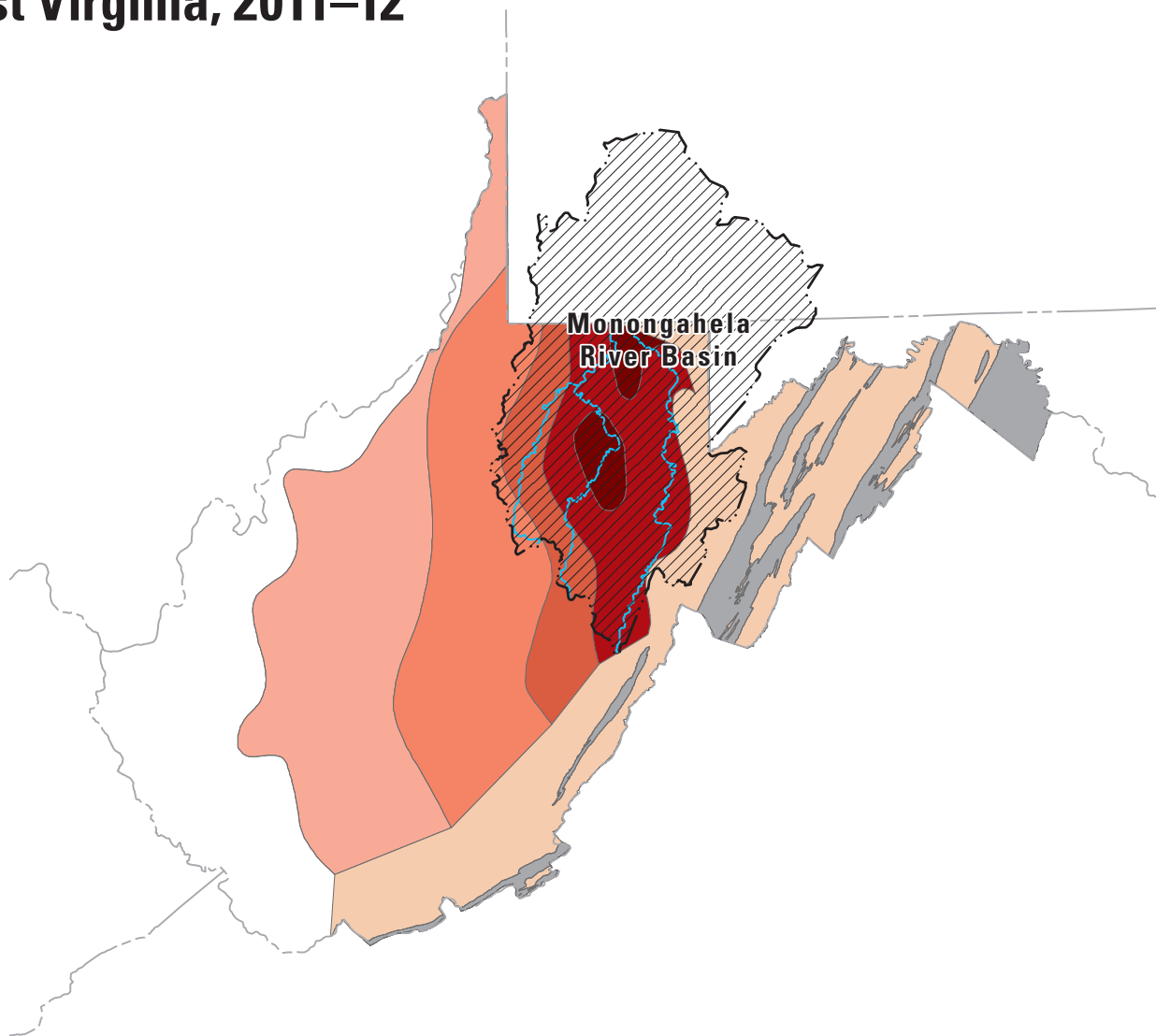


Prepared in cooperation with the  
West Virginia Department of Environmental Protection, Division of Water and Waste Management

# Water Quality of Groundwater and Stream Base Flow in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12



Scientific Investigations Report 2014–5233  
Version 1.1, June 2015

**Cover.** The extent of the Marcellus Shale in West Virginia and the location of the Monongahela River Basin and its major streams. See figure 1 for an explanation of the extent of the Marcellus Shale. Marcellus Shale thickness from Schwietering and Bocan (2011).

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By Douglas B. Chambers, Mark D. Kozar, Terence Messinger, Michon L. Mulder,  
Adam J. Pelak, and Jeremy S. White

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

**U.S. Department of the Interior**  
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**U.S. Geological Survey**  
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U.S. Geological Survey, Reston, Virginia:  
First release: 2015, online and in print  
Revised: June 2015 (ver. 1.1), online and in print

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Suggested citation:

Chambers, D.B., Kozar, M.D., Messinger, Terence, Mulder, M.L., Pelak, A.J., and White, J.S., 2015, Water quality of groundwater and stream base flow in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12 (ver. 1.1, June 25, 2015); U.S. Geological Survey Scientific Investigations Report 2014–5233, 75 p., <http://dx.doi.org/10.3133/sir20145233>.

ISSN 2328-031X (printed)  
ISSN 2328-0328 (online)

## **Acknowledgments**

The authors thank Katherine S. Paybins, Jessica L. Wood, and Hugh E. Bevans of the U.S. Geological Survey (USGS) for helping with the collection of samples during the groundwater survey and base-flow survey. Thanks also go to Jeffrey E. Bailey, West Virginia Department of Environmental Protection, Division of Water and Waste Management, for assistance in understanding land-use patterns in the study area and in surface-water site selection. Lisa Senior and Michael Bradley of the USGS are thanked for their thoughtful reviews that have improved this report.

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## Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi <sup>2</sup> )	259.0	hectare (ha)
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
Volume		
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m <sup>3</sup> )
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m <sup>3</sup> )
gallon (gal)	3.785	cubic decimeter (dm <sup>3</sup> )
million gallons (Mgal)	3,785	cubic meter (m <sup>3</sup> )
cubic foot (ft <sup>3</sup> )	28.32	cubic decimeter (dm <sup>3</sup> )
cubic foot (ft <sup>3</sup> )	0.02832	cubic meter (m <sup>3</sup> )
thousand cubic feet (Mcf)	28.32	cubic meter (m <sup>3</sup> )
Flow rate		
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)
cubic foot per second per square mile [(ft <sup>3</sup> /s)/mi <sup>2</sup> ]	0.01093	cubic meter per second per square kilometer [(m <sup>3</sup> /s)/km <sup>2</sup> ]
Pressure		
atmosphere, standard (atm)	101.3	kilopascal (kPa)
Bar	100	kilopascal (kPa)
inch of mercury at 60°F (in Hg)	3.377	kilopascal (kPa)
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

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

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

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).

Elevation, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Radioactivity of chemical constituents in water are given in picocuries per liter (pCi/L).

# Water quality of groundwater and stream base flow in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12

By Douglas B. Chambers, Mark D. Kozar, Terence Messinger, Michon L. Mulder<sup>1</sup>, Adam J. Pelak<sup>1</sup>, and Jeremy S. White

## Abstract

The Marcellus Shale gas field underlies portions of New York, Pennsylvania, Ohio, Virginia, Maryland, Tennessee, and West Virginia. Development of hydraulic fracturing and horizontal drilling technology led to extensive development of gas from the Marcellus Shale beginning about 2007. The need to identify and monitor changes in water-quality conditions related to development of the Marcellus Shale gas field prompted the U.S. Geological Survey, in cooperation with the West Virginia Department of Environmental Protection, Division of Water and Waste Management, to document water quality for comparison with water quality in samples collected at a future date. The identification of change in water-quality conditions over time is more difficult if baseline water-quality conditions have not been documented.

U.S. Geological Survey personnel sampled groundwater and surface water in West Virginia's Monongahela River Basin during 2011–12. A groundwater survey, in which 39 wells and 2 springs were sampled, was conducted during June through September 2011. A base-flow survey was conducted during July through October 2012; 50 stream sites were sampled under base-flow conditions in this survey.

Because additives to hydraulic fracturing fluids are variable and decrease in flowback water over a relatively short time, water-quality analyses for this study focused on documenting the water-quality characteristics typical of water from shallow aquifers; water derived from contact with the Marcellus Shale (flowback from hydraulic fracturing or formation water); and water with constituents from conventional oil and gas development, sewage effluent, and coal-mine drainage. All samples were analyzed for field properties (water temperature, pH, specific conductance, dissolved oxygen, and turbidity), major ions, trace elements, naturally occurring radioactive materials, and stable isotopes.

In addition to documenting baseline water-quality conditions for an area of shale-gas development, these data were examined for patterns in water quality. Groundwater and base-flow survey data were compared to historical data from the Monongahela River Basin in West Virginia. Additionally, groundwater- and base-flow survey samples were grouped by Marcellus Shale gas production in the subbasin in which that sampling site was located.

The comparisons of data collected as part of this study with historical data identified few differences. No significant difference was found in a comparison of groundwater survey data and historical data. Base-flow survey samples differed significantly from historical data for pH, chloride, and strontium, all of which had higher concentrations in the base-flow survey samples. Differences in pH are likely related to changes in mining regulation beginning in 1977. Concentrations of chloride and strontium elevated above background concentrations may be related to saline groundwater; saline water is within 300 feet of the land surface in parts of the study area.

In the comparison of base-flow survey samples grouped by shale-gas-production setting, significant differences were found for fluoride and barium. Concentrations of fluoride and barium were higher in stream subbasins with active Marcellus Shale production than in subbasins not near active Marcellus Shale production. Elevated fluoride and barium are associated with deep brines.

Generally, naturally occurring radioactive materials were not found in elevated concentrations in either groundwater or base-flow samples. Only 3 samples, 2 from the groundwater survey and one from the base-flow survey, exceeded the U.S. Environmental Protection Agency maximum contaminant level for radium isotopes of 5.0 picocurie per liter for either a single isotope or a combined value of radium-226 and radium-228.

Stable isotope composition indicates broad similarity among surface water, shallow groundwater, and precipitation in the region. Neither shallow groundwater nor surface water

<sup>1</sup>West Virginia University.

showed a marked similarity with the deep brines associated with shale gas. In most of the groundwater survey samples, 38 of 41 samples, dissolved gas profiles were similar to those previously found in samples from shallow, domestic wells in the region.

This study provides a baseline of water-quality conditions in the Monongahela River Basin in West Virginia during the early phases of development of the Marcellus Shale gas field. Although not all inclusive, the results of this study provide a set of reliable water-quality data against which future data sets can be compared and the effects of shale-gas development may be determined.

## Introduction

Natural gas in West Virginia was reported as early as 1774, followed by the first documented industrial use in the State, fueling brine boilers, in 1841 (White, 1904). Since that time, natural gas has been an integral component of West Virginia's and the Nation's energy supply. Since about 2007, the development of hydraulic fracturing and horizontal drilling technology has led to extensive development of gas from the Marcellus Shale in the Monongahela River Basin in West Virginia (figs. 1 and 2).

Much of Nation's historical gas production has been from "conventional" gas fields, geographically discrete accumulations with distinct water-hydrocarbon contacts (Schenk and Pollastro, 2002). The localized nature, high permeability, and high recovery factors of conventional gas accumulations make them amenable to extraction by vertical drilling. In contrast, shale gas resources form within organic-rich shale source rock (U.S. Energy Information Administration, 2012). The low permeability of the shale greatly inhibits the gas from migrating to more permeable reservoir rocks. Although some shale formations have long been known to be rich in gas, little gas could be obtained from them using conventional drilling techniques. Improvements in drilling technologies, specifically horizontal drilling and hydraulic fracturing, have made recovery of shale-gas reserves economically feasible.

The Marcellus Shale is a formation of Devonian age that underlies large parts of New York, Pennsylvania, Ohio, and West Virginia, and smaller parts of Virginia, Maryland, and Tennessee. The Marcellus Shale ranges in depth from about 2,000 feet below mean sea level (MSL) along the western edge of its extent to greater than 6,000 feet below MSL along the eastern edge, with the thicker deposits occurring at greater depths. A recent assessment estimated that 84,198 billion cubic feet of natural gas and 3,379 million barrels of natural gas liquids are technically recoverable from the Marcellus Shale (Coleman and others, 2011). On the basis of the 2009 consumption of 23 trillion cubic feet (ft<sup>3</sup>), this is enough natural gas to meet the needs of the entire Nation for about 15 years (Coleman and others, 2011).

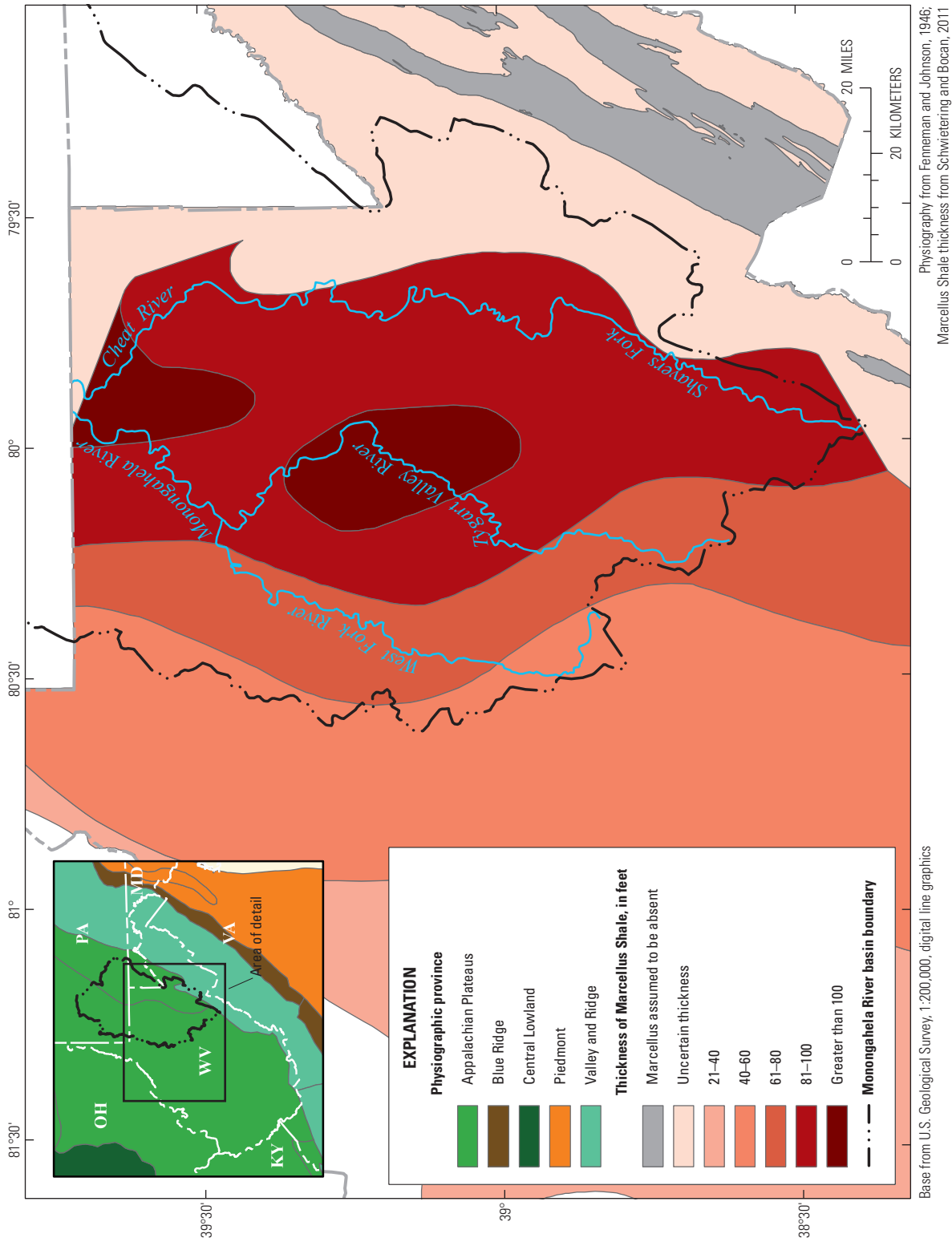
The low permeability and low recovery factors of Marcellus Shale, as with other shale-gas fields, makes extraction with vertical drilling challenging. However, the use of horizontal, or directional drilling, and hydraulic fracturing allow recovery of natural gas from the Marcellus Shale. Directional drilling and hydraulic fracturing capitalize upon and augment naturally occurring fractures, thereby enhancing permeability and gas recovery (U.S. Department of Energy, 2013).

A horizontal well begins with a vertical well drilled to a depth approaching that of the targeted shale bed, 5,000 to 9,000 feet below MSL in the Marcellus Shale in West Virginia (U.S. Department of Energy, 2013). Once the desired depth of vertical well bore is reached, a steerable downhole motor is used to drill the well at an angle. The steerable motor will eventually impart sufficient angular deviation to turn the well bore 90 degrees from the vertical. The well bore is then extended as a lateral well bore, or "lateral," through the shale bed. These laterals can extend for 3,000 to 10,000 feet from the vertical well bore (U.S. Department of Energy, 2013).

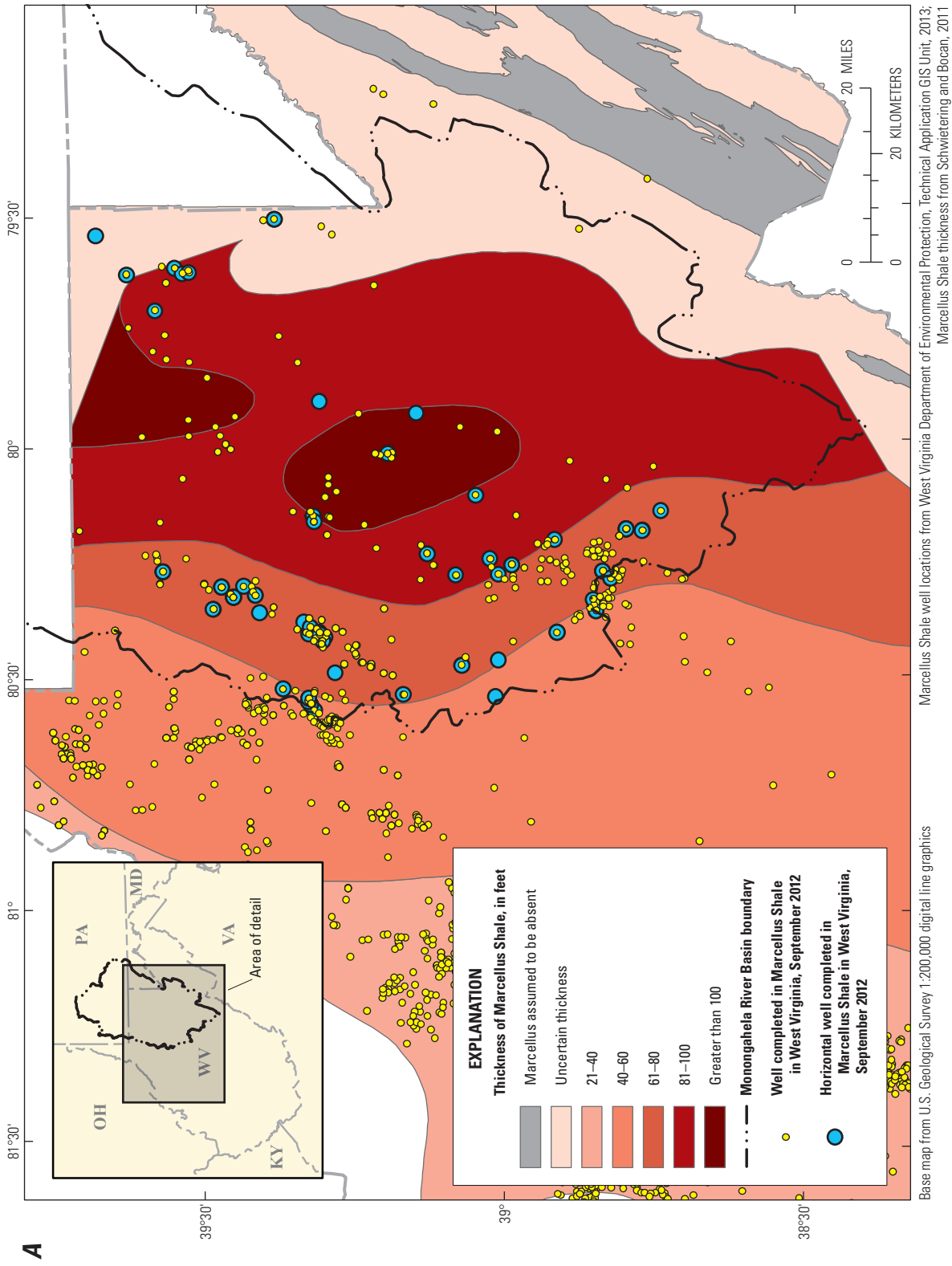
Once the horizontal wells are completed, the recovery of gas from the Marcellus Shale is further enhanced through hydraulic fracturing, commonly referred to as "fracking." Hydraulic fracturing uses fluids under high pressure to create fractures in the rock, increasing gas flow to the well bore. The well casing and cement are perforated with small explosive charges prior to injection of the pressurized fluid. The fluid contains quartz sand or other materials of similar size or shape (proppants) that remain in the newly created fractures to keep them from closing. The hydraulic-fracturing fluid and formation fluid can flow back to land surface as the injection pressure is reduced.

Although natural gas has been promoted as the cleanest-burning fossil fuel, emitting only 53 kilograms (kg) of carbon dioxide (CO<sub>2</sub>) per million British thermal units (Btu); coal emits an average of 95 kg of CO<sub>2</sub> per million Btu (U.S. Energy Information Administration, 1999). Production of natural gas is not without environmental consequences. Kappel and others (2013) presented critical water-resources issues associated with shale-gas development in the Appalachian Basin, grouped into the following categories: water supply, stray gas, radioactivity in shale waste, fluid waste treatment and disposal, deep well injection of fluid waste, solid waste disposal, and construction and transportation.

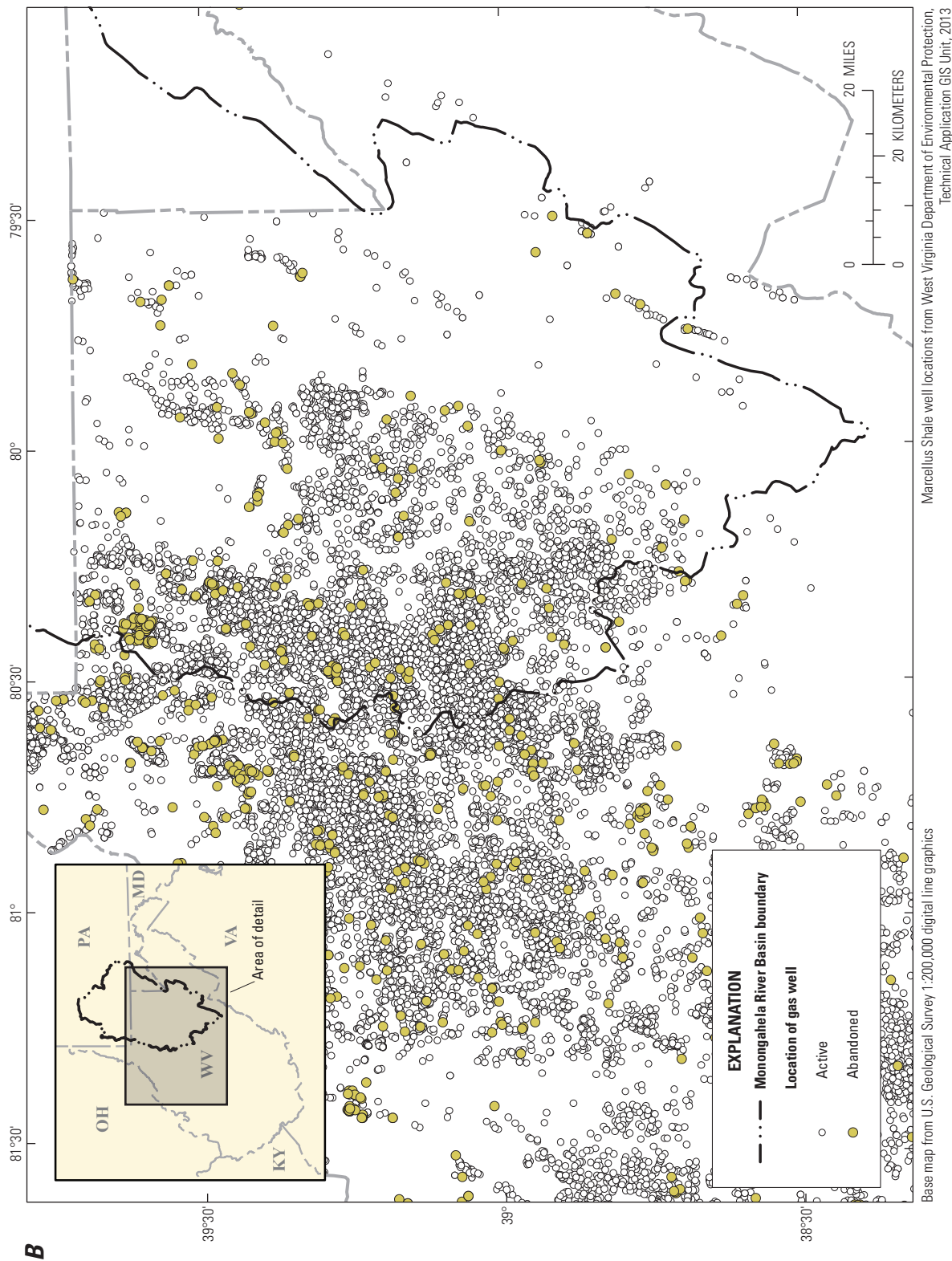
Large quantities of water are used during the hydraulic fracturing, posing potential water-quality issues. As much as 3 million gallons of water can be used for a single hydraulic fracturing treatment. Hydraulic fracturing fluids contain chemicals that increase the viscosity to a gel-like consistency and allow the transport of a proppant, usually sand, into the hydraulically created fractures to keep them open. Other chemicals allow the viscosity of the fluid to break down quickly so that the fluid can be easily removed. In addition to chemical additives in the hydraulic fracturing fluids, the contact of fluids with the rock matrix introduces a variety of formation constituents, including brines, trace elements, and radionuclides.



**Figure 1.** Extent of the Marcellus Shale in the Monongahela River Basin in West Virginia.



**Figure 2.** A, Thickness of the Marcellus Shale, wells completed in the Marcellus Shale, and horizontal wells, and B, locations of all gas wells, including abandoned wells, Monongahela River Basin and vicinity, West Virginia, 2012.



**Figure 2.** A, Thickness of the Marcellus Shale, wells completed in the Marcellus Shale, and horizontal wells, and B, locations of all gas wells, including abandoned wells, Monongahela River Basin and vicinity, West Virginia, 2012. —Continued

Hydraulic fracturing fluids and formation waters are highly contaminated and must be captured and disposed of properly when the fluids flow back to land surface. Initial recovery of hydraulic fracturing fluids in the Marcellus Shale is 20–25 percent (U.S. Department of Energy, 2013). Industry estimates for continued recovery of hydraulic fracturing fluid and formation water, even after the well is on-line, range from 5 to 50 barrels per week. Current regulations in West Virginia require offsite disposal of fracturing fluids and flowback from horizontal wells (West Virginia Department of Environmental Protection, 2010). Fluids are collected in either a sealed tank or a lined open pit and hauled by truck to a disposal site. The preferred method of disposal (as of 2014) for hydraulic fracturing fluids is underground injection into deep formations (West Virginia Department of Environmental Protection, 2010), often former oil- and gas-producing formations. This disposal practice could also be a threat to water quality because of the potential for spills during the fluid handling and transportation process or leakage from natural faults and fractures or from former gas and oil wells that have not been properly constructed or abandoned.

Documentation of the 2011–12 baseline quality of shallow groundwater underlain by the Marcellus Shale in north-central West Virginia can be used for comparison with future water quality to monitor and recognize potential water-quality changes from gas-production activities should they occur. The West Virginia's Monongahela River Basin was identified as an area of rapid Marcellus Shale gas development. Therefore, in 2011 the U.S. Geological Survey (USGS), in cooperation with the West Virginia Department of Environmental Protection (WVDEP), Division of Water and Waste Management, began a study to obtain baseline water-quality information for the Monongahela River Basin in West Virginia. The water-quality properties and constituents documented during this study include those that are naturally occurring in the Marcellus Shale and are likely to be elevated in shallow groundwater through contact with return flows or leakage from hydraulic fracturing activities. Because groundwater discharge to streams forms base flow, potential water-quality changes to groundwater may also affect base-flow quality.

## Purpose and Scope

This report describes the water quality of groundwater and stream base flow in that part of north-central West Virginia drained by the Monongahela River during early development of the Marcellus Shale gas field. Groundwater samples were collected during June–September 2011, and base-flow samples were collected in 2012. The conditions described in this report include those affected by human activities that potentially introduce contaminants into surface water and groundwater similar to those expected from shale-gas development. Concentrations of water-quality constituents are presented in figures and tables.

## Description of Study Area

The study area is the Monongahela River Basin in West Virginia (fig. 1) and encompasses a drainage area of 7,377 square miles (mi<sup>2</sup>) (19,106 square kilometers [km<sup>2</sup>]) in the north-central part of West Virginia. Major tributaries to the Monongahela River are the Cheat River, Tygart Valley River, and the West Fork River. The study area was selected because of the large number of vertical and horizontal gas wells that are proposed for the Marcellus Shale.

## Physiography and Climate

The study area is mostly within the Appalachian Plateaus Physiographic Province, but a small area in the southeastern part of the study area has been mapped as lying within the Valley and Ridge Physiographic Province (Fenneman, 1938). The Appalachian Plateaus are characterized by flat to slightly dipping sedimentary rocks that have been eroded by fluvial processes to form a rolling topography with a dendritic stream drainage pattern.

The boundary between the two provinces is known as the Allegheny Front, an abrupt and complex transition between the two physiographic provinces. To the west of the Allegheny Front, lie the relatively flat to slightly dipping rocks of the Appalachian Plateaus; to the east of the Allegheny Front, lie steeply dipping, long linear ridges and valleys of the Valley and Ridge Physiographic Province.

Within the Valley and Ridge, topography varies and is marked by steep ridges, typically formed by more weather resistant sandstones and limestone, and narrow valleys, which tend to form in areas underlain by less resistant shales and siltstones (West Virginia Geological and Economic Survey, 2014b). Orogenic processes compressed rocks to form the Valley and Ridge Physiographic Province. The compressional stress resulted in significant folding and faulting of the bedrock strata, and resulted in the characteristic alternating long linear valleys and ridges from which the province derived its name. Stream drainages in the Valley and Ridge Physiographic Province commonly exhibit a predominantly trellis drainage pattern.

Elevation in the study area ranges from about 790 ft above the North American Vertical Datum of 1988 (NAVD 88) near the Monongahela River at the border of West Virginia and Pennsylvania to about 4,850 ft in the southern part of the study area. Mean annual precipitation within the Appalachian Plateaus Physiographic Province varies with elevation owing to orographic lifting. Mean annual precipitation (1981–2010) ranged from 44 inches per year (in/yr) to 66 in/yr (PRISM Climate Group, 2012). Maximum precipitation occurs in the mountains in the southern part of the study area, and minimum precipitation occurs near the Monongahela and West Fork Rivers.



## Geologic Setting

Geologic strata in the study area are composed of several formations and groups (fig. 3), ranging in age from Devonian through Permian with Quaternary alluvial deposits along the streams and rivers. The strata include parts of geologic formations of Devonian, Mississippian, and Pennsylvanian age, and all bedrock in the study area is sedimentary in origin. Geologic nomenclature used in this report conforms with that used by the West Virginia Geological and Economic Survey, as depicted on the 1968 State geologic map of West Virginia (Cardwell and others, 1968). Bedrock composition of the formations is described below (Cardwell and others, 1968).

Devonian-age geologic strata exposed at land surface in the study area include parts of the Harrell Shale, Brallier Formation, Chemung Group, and the Hampshire Formation (fig. 3). The Harrell Shale and the Brallier Formation are composed predominantly of dark marine shales with thin interspersed lenses of limestone, siltstone, and sandstone. The Chemung Group is characterized as mostly siltstone and sandstone with shale and conglomerate interbeds. The Hampshire Formation is predominantly shale and fine micaceous sandstone, with siltstone, sandstone, and conglomerate. The oldest rocks that crop out in the study area are in the Harrell Shale Formation. The Mahantango Formation, which is composed predominantly of thick laminated marine shale, siltstone, sandstone, and some limestone (Cardwell and others, 1968), does not crop out within the study area, but immediately underlies the Harrell Shale. The Marcellus Shale, which also does not crop out in the study area but is the primary emphasis of this study, underlies the Mahantango Formation and is composed of predominantly gray black to black thinly laminated pyritic shales (Cardwell and others, 1968).

Mississippian-age strata include parts of the Price Formation, the Greenbrier Group, and the Bluefield, Hinton, Princeton Sandstone, and Bluestone Formations (fig. 3). The Price Formation is composed predominantly of hard massive sandstones with some shale. The Price Formation was previously referred to as the Pocono Group but was later revised as a result of additional stratigraphic studies. Some older geologic maps, as well as the USGS National Water Information System (NWIS) database still refer to the Price Formation as the Pocono Group. The Greenbrier Group is composed of massive marine limestones with associated shales and minor sandstone beds. Outside the study area, the Greenbrier Group is one of the more prominent karst regions in West Virginia. The Bluefield and Hinton Formations are composed of shale and sandstone with minor interbeds of limestone. The Bluestone Formation and Princeton Sandstone are composed predominantly of shale and sandstone. The Bluefield, Hinton, and Bluestone Formations, and the Princeton Sandstone, are thin exposures in the outcrop and are commonly collectively referred to, and shown on the accompanying geologic map (fig. 3), as the Mauch Chunk Group.

Pennsylvanian-age strata within the study area include important coal seams, such as the Pittsburgh, Freeport, Kittanning, and Sewickley seams. Pennsylvanian-age strata in the study area include parts of the New River Formation, Kanawha Formation, Allegheny Formation, Conemaugh Group, Monongahela Group, and the Dunkard Group (fig. 3). In the northeast part of the study area the depositional sequence thins, and the Pocahontas, New River, and Kanawha Formations are collectively referred to as the Pottsville Group (fig. 3). The Pottsville Group is composed of sandstones and some conglomerate with thin shales and coal seams. Where the New River and Kanawha Formations crop out in sufficient area, they are mapped separately from the Pottsville Group (fig. 3). The New River and Kanawha Formations are composed of sandstone with some shale, siltstone, and coal. The Allegheny Formation is composed of cyclic sequences of sandstone, siltstone, shale, limestone, and coal. The more economically relevant coal seams in the Allegheny Formation are the Freeport, Kittanning, and Clarion coal seams. The Conemaugh Group is composed of cyclic sequences of shale, siltstone, sandstone, thin limestones, and coal. Economically important coal seams in the Conemaugh Group are the Bakerstown, Brush Creek, and Mahoning coal seams. The Monongahela Group is also composed predominantly of sandstone, siltstone, shale, limestone, and coal. Economically important coal seams in the Monongahela Group are the Pittsburgh, Sewickley, Uniontown, Waynesburg, and Redstone coal seams.

There is debate about the geologic age of the Dunkard Group, but it occurs either at the top of the stratigraphic sequence of Pennsylvanian strata or at the base of Permian strata. The Dunkard Group is composed of sandstone, siltstone, shale, limestone, and coal similar to that of most of the Pennsylvanian-age strata. Economically important coal seams in the Dunkard Group are the Washington and Waynesburg A coal seams.

Because this report presents baseline water-quality conditions in the Marcellus Shale gas field of the Monongahela River Basin in West Virginia, and because the Marcellus Shale does not crop out in the study area, a discussion of the depth of burial of the Marcellus Shale within the study area is warranted. The USGS recently published geologic cross sections that encompass the study area (Ryder and others, 2008; 2009). On the basis of these cross sections, the depth to the Marcellus Shale may be inferred. The Marcellus Shale ranges in depth from approximately 7,100 feet below land surface (bls) in Marion County, West Virginia, where rocks are slightly dipping, to 4,200 feet bls along the crest of the Deer Park–Leadmine anticline in Preston County, and to only 1,400 feet bls along the crest of the Elkins Valley Anticline in Randolph County, West Virginia, based on the geologic cross sections. The geologic cross sections indicate that thrust faults cut through the Marcellus Shale and extend to the surface.

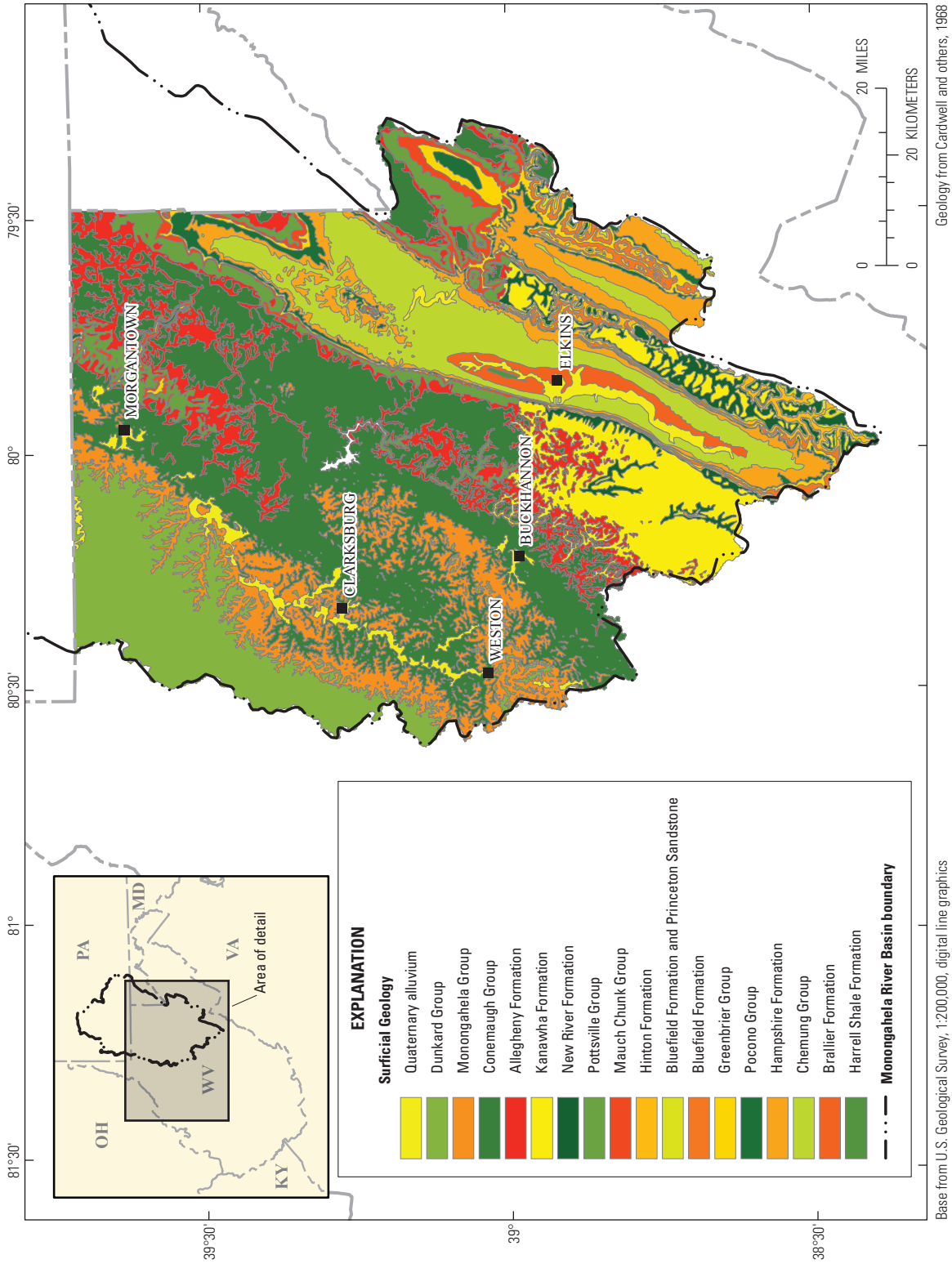


Figure 3. Geologic map of the Monongahela River Basin in West Virginia.

## Land Use

Forest is the most extensive land use in the study area. Agriculture is generally limited and of low intensity (National Agricultural Statistics Service, 2014). The study area includes the cities of Morgantown and Clarksburg, West Virginia, and their suburbs. Morgantown and the surrounding area is among the fastest growing in West Virginia; the population of Morgantown increased 4.5 percent between 2010 and 2012, in contrast to a population growth of 0.2 percent for West Virginia as a whole (U.S. Census Bureau, 2014).

Coal mining was the principal industry in the study area for most of the 20th century. The most important mined coal seams in the study area, underground and surface (fig. 4), are near the western edge, especially within the Dunkard and Monongahela Groups and the Allegheny Formation. The Pittsburgh coal seam is the most historically productive and economically important seam in the study area (Tewalt and others, 2001). The Kittanning, Freeport, Sewickley, Redstone, and Bakerstown coals have also been extensively mined, and at least 15 named coal seams have been mined in the study area. Approximately 16.5 percent of the study area has been mined. Most mines are underground (15.0 % of the study area), and the remainder are either surface mines (2.8 % of the study area) or auger mines (0.02 % of the study area), both of which may overlay underground mines. Many areas have been mined multiple times, using multiple methods, or in more than one seam, so that the two-dimensional footprint of mining is an inadequate measure of mining intensity. Most of the coal mined in the study area has high sulfur concentrations (>2.5 percent), and demand for the high-sulfur coal mined here declined following a mandate in the 1991 Clean Air Act amendments to reduce acid precipitation (Milici and Dennen, 2009).

The hydrologic and water-quality effects of both underground and surface mining in the study area are well documented (Anderson and others, 2000; Cravotta, 2008a–b). Acid mine drainage (AMD) from coal mining has had major effects on the quality of water in streams in the region. A variety of acid mine drainage treatment techniques are being used within the study area, and water quality has improved since in the 1970s (Lambert and others, 2004). Continued treatment is necessary to maintain water quality in many places where mining has ended. Typical water-quality effects of coal mining in the study area include increases in concentrations of iron, manganese, aluminum, and sulfate.

Hydrologic effects of coal mining include several important alterations to the movement of water and the magnitude and timing of flow. In underground coal mines, water flows downdip along the mine floor, even in areas where the dip is slight. If the mined seam is above grade, or higher than the valley floor, water is transferred from the updip side of the mountain to the downdip side (Kozar and others, 2013). If the mined seam is below grade, or if it dips from above grade

on its uphill side to below grade on the downdip side, water collects in a pool in the void space in a mine (McColloch and others, 2012). Where mining is active, the water is pumped to the surface and discharged. Even after mining ends, water from mine pools may reach land surface through openings if hydraulic head is sufficient.

Recent development of the Marcellus Shale by horizontal drilling and hydraulic fracturing has increased interest in natural gas development, but gas has been produced in the study area for decades. Nearly 6,400 gas wells had been completed in the study area through 2012 (fig. 2; West Virginia Department of Environmental Protection, 2013). The earliest recorded completion date for these wells is during 1895, but completion dates are unknown for most wells drilled before permitting began in 1929. At least 29 named formations have been the targets for gas development in the study area, although the target formation for many older wells is not recorded. Beginning about 2002, the targeting of multiple formations in a single well became common. Through September 2012, 147 wells had been completed in the Marcellus Shale within the study area, 75 of which are horizontal wells.

Both current oil and gas extraction and the legacy effects of improperly abandoned oil and gas wells have affected groundwater and surface-water quality in the region. Natural gas in West Virginia is typically associated with sediments of marine origin, so gas typically is found in association with salty water (Price and others, 1937). Salt and other elements of marine origin are among the common constituents that have become elevated in surface or shallow water as a result of gas development (Bain, 1970). Changes to water quality related to gas development may result from initial surface disturbances, such as site, access road, and pipeline construction; from drilling and fracturing activities; and from maintenance or reclamation activities, such as condensate spills. For conventional wells in West Virginia, activities that may affect water quality include onsite disposal of drilling waste, a practice that was banned for horizontal wells by the West Virginia Natural Gas Horizontal Well Control Act (22-6A-2). Improperly sealed gas wells are known to be a pathway for contaminants to migrate upward from deep rock layers (Bain, 1970), although saline groundwater is naturally as close as 300 feet beneath the surface of some river valleys in the study area (Wilmoth, 1975; Foster, 1980). Of the gas wells in the study area, 215 have a regulatory status of “abandoned,” meaning that they are no longer in production but were never sealed and reclaimed.

Underground coal mines and deeper oil and gas reservoirs both produce methane, which has the potential to migrate either by natural processes or potentially as a result of human activities. The isotopic composition, associated ion chemistry, and compositions of associated hydrocarbons can be used to identify the potential source of the gas. Coal-bed methane lacks the associated higher chain hydrocarbons, such as ethane, propane, butane, pentane, and hexane, that may be associated with gases derived from oil and gas reservoirs. Much of

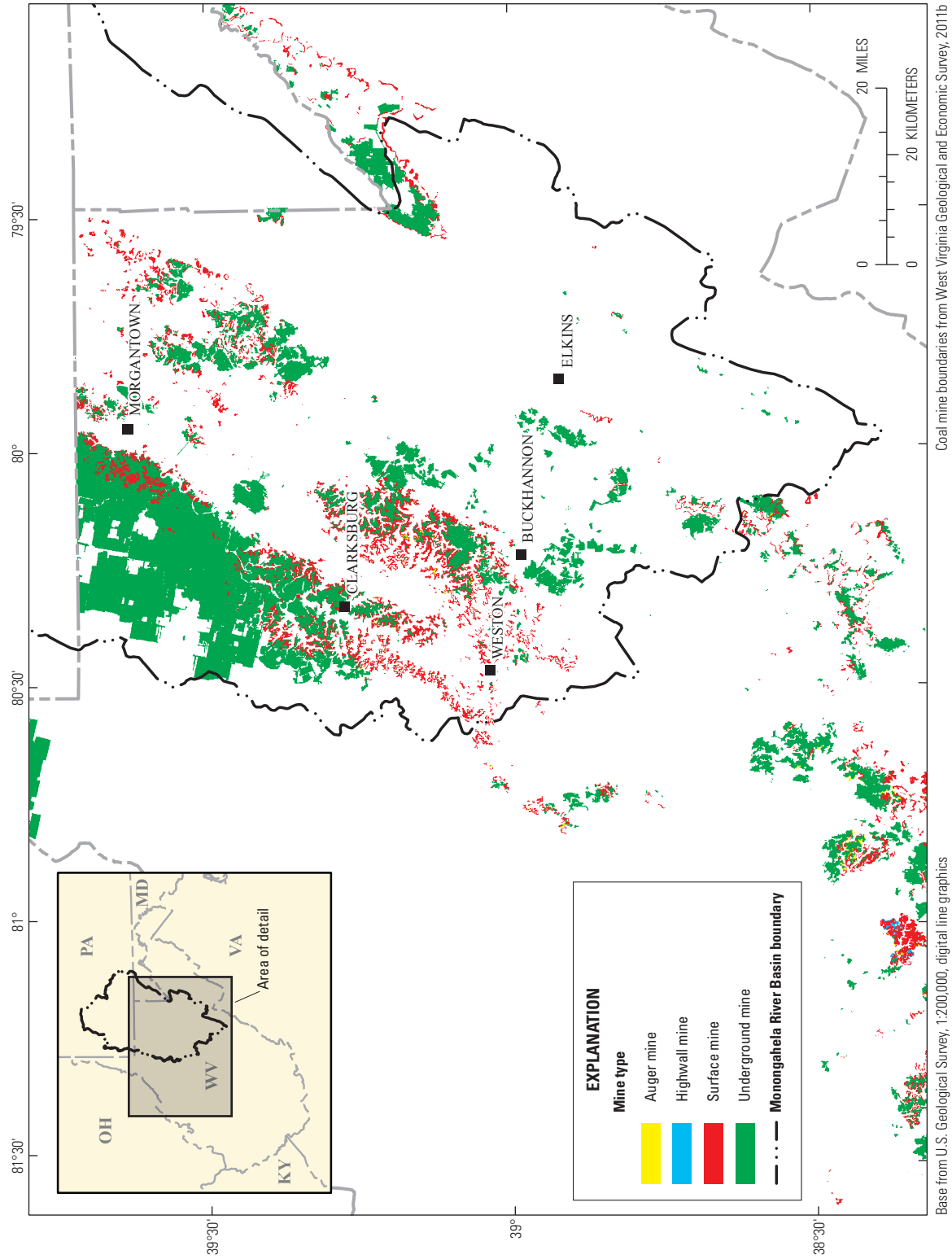


Figure 4. Coal mines in the Monongahela River Basin and adjacent areas in West Virginia.

the most active development of the Marcellus Shale targets “wet” gas, or gas rich in ethane and other higher alkanes. The study area also includes natural gas storage fields (U.S. Energy Information Agency, 2014). Although the gas presently stored in these fields is increasingly from the Marcellus Shale, the storage fields hold mixtures of natural gas from a wide variety of sources and locations (U.S. Energy Information Agency, 2004).

## Methods of Study

Baseline water-quality conditions were documented through sampling a combination of wells, springs, and stream sites. Because additives to hydraulic fracturing fluids are variable and decrease in flowback water over a relatively short time, water-quality analyses for this study documented major ions, trace elements, radionuclides, and isotopes (table 1) that can be used to identify the different sources of water—potable water derived from shallow aquifers, water derived from contact with the Marcellus Shale (flowback from hydraulic fracturing or formation water), and water with constituents from other oil and gas fields, sewage effluent, and coal-mine drainage.

## Site Selection

Groundwater and surface-water base-flow quality in the Monongahela River Basin was investigated in 2011 and 2012 to establish baseline water-quality conditions for the study area. Wells were sampled in summer 2011, and surface water was sampled, under base-flow conditions, in summer and fall 2012.

## Groundwater

Groundwater samples were collected from 39 wells and 2 springs in the Monongahela River Basin in West Virginia (fig. 5, table 2). The sites were selected from a group of wells and springs sampled as part of the West Virginia Ambient Groundwater Monitoring network (Chambers and others, 2012), and information was obtained from a database of production wells maintained by the West Virginia Bureau for Public Health. The groundwater survey sites were selected to provide wide areal distribution throughout the study area. However, the distribution of production wells was not sufficient to provide adequate areal coverage. Therefore, samples were also collected from domestic wells, USGS water-level network wells, other types of wells, or springs to provide additional geographic coverage in areas with few production wells.

The criteria for a well to be considered for sampling were as follows: (1) the well had to be less than 25 years old, (2) the well had to have a minimum reported yield of 5 gallons per minute, and (3) the well had to be plumbed or open to allow sampling of raw water prior to any storage tank or treatment. The minimum information required for each well included

well depth, location (latitude/longitude), and contributing geologic unit (aquifer). Available well-construction information was recorded (age, depth, and casing length). An on-site inspection was conducted to verify well-casing integrity and adequate well-pad construction to prevent surface contaminants from entering the well bore. Existing submersible pumps were most commonly used for water-sample collection, but for a small number of wells, turbine pumps, jet pumps, or a portable submersible pump were used. Well and site characteristics were obtained during a site visit, from drilling logs, and from well-owner records, where available. If both the minimum criteria and the minimum information requirements were met, the well was selected for sampling. The springs were selected for sampling to supplement geographic coverage in areas with few production wells. The springs selected had been previously sampled and documented (Chambers and others, 2012; Kozar and Brown, 1995).

## Surface Water

Surface-water sites were selected using a stratified design on the basis of availability of historical data, basin size and location, Marcellus Shale thickness (Schwietering and Bocan, 2011; West Virginia Geological and Economic Survey, 2011a), and the presence of gas production from wells tapping the Marcellus Shale (West Virginia Geological and Economic Survey, 2014a) in the hydrologic unit in which the stream is located. To be considered for sampling, a site had to have at least one previous sample collected by the USGS that was analyzed for a full set of major ions and had an associated streamflow measurement. The drainage basins for the sites were limited to a range of 10–40 mi<sup>2</sup>. Within the study area, 59 surface-water sites met these criteria. Sites were grouped on the basis of gas production at the 12-digit hydrologic unit code (HUC-12) basin level (U.S. Geological Survey, 2005a). Sites were not necessarily at the outlet of the HUC-12. Gas production data, in thousand cubic feet (Mcf), were downloaded from the West Virginia Geological and Economic Survey (WVGES, 2012) Marcellus Shale webpage (<http://www.wvgs.wvnet.edu/www/datatstat/devshales.htm>) on June 4, 2012, and were complete through 2010 at that time. Production data include information on wells targeting multiple formations, only one of which was the Marcellus Shale. “Marcellus wells,” as used in this section, includes all of these gas wells.

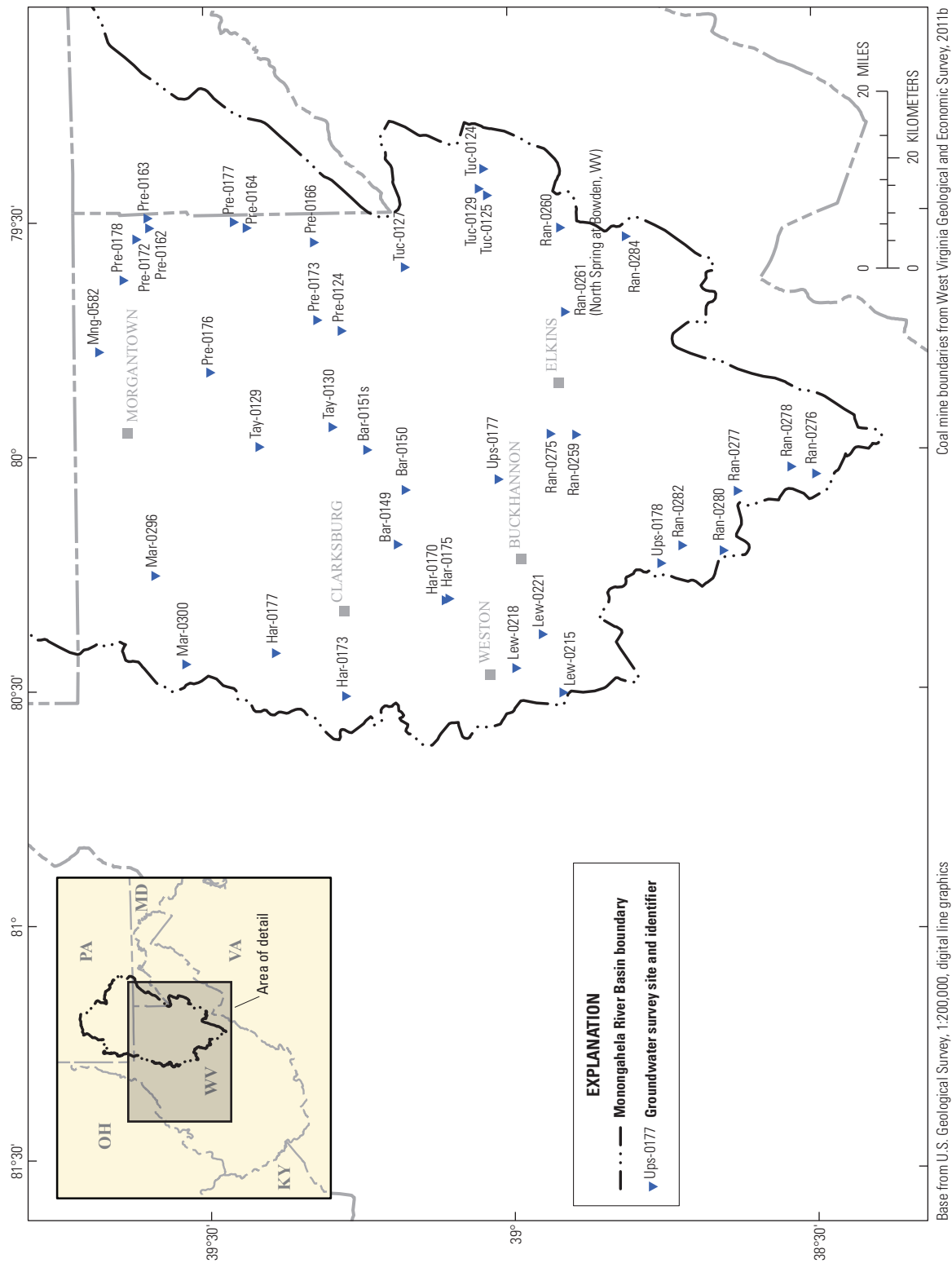
The surface-water sites were grouped into “bins” that were designated as “High Production,” “Low Production,” “Near High Production,” “Near Low Production,” “Underlain by the Marcellus Shale greater than 50 feet thick” (Marcellus >50 ft thick), and “Underlain by Marcellus Shale less than 50 ft thick” (Marcellus <50 ft thick). The break point between high and low production was 1,000 thousand cubic feet per square mile per year (Mcf/mi<sup>2</sup>/year). The Near High Production bin included sites in a 10-digit hydrologic unit code basin (HUC-10) with gas production exceeding 1,000 Mcf/mi<sup>2</sup>/year from Marcellus Shale wells and a site in a HUC-12 with no gas production from Marcellus Shale wells.

**12 Water quality in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12**

**Table 1.** Water-quality properties, major ions, trace elements, naturally occurring radioactive materials, and dissolved gases analyzed for in groundwater and surface-water samples from the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, 2011–12.

[NA, not applicable; °C, degrees Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; FNU, formazin nephelometric units; CaCO<sub>3</sub>, calcium carbonate; wf, filtered water sample; inflect pt, inflection-point titration; μg/L, micrograms per liter; Cs-137, cesium 137; Th-230, thorium 230; pCi/L, picocuries per liter; δ, per mil; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate; --, none; \*, groundwater samples only]

Constituent or property	Reporting limit	Constituent or property	Reporting limit
Temperature, water, °C	NA	Molybdenum, wf, μg/L	0.014
Specific conductance, μS/cm at 25 °C	NA	Nickel, wf, μg/L	0.09
Dissolved oxygen, mg/L	NA	Silver, wf, μg/L	0.005
pH, standard units	NA	Strontium, wf, μg/L	0.2–0.8
Redox potential, mV*	NA	Zinc, wf, μg/L	2.0
Turbidity, FNU	NA	Antimony, wf, μg/L	0.027
Dissolved solids, dry, at 180 °C, mg/L	12	Aluminum, wf, μg/L	1.7–2.2
Alkalinity, wf, inflect, field, mg/L CaCO <sub>3</sub>	1	Selenium, wf, μg/L	0.05
Carbonate, wf, inflect pt, field, mg/L	1	Gross beta, wf, Cs-137, pCi/L	4
Bicarbonate, wf, inflect pt, field, mg/L	1	Alpha activity, wf, Th-230, pCi/L	3
Calcium, wf, mg/L	0.022–0.04	Uranium, wf, μg/L	0.004
Magnesium, wf, mg/L	0.08	Uranium-238, wf, pCi/L	0.1
Sodium, wf, mg/L	0.1–0.24	Uranium-234, wf, pCi/L	0.1
Potassium, wf, mg/L	0.022	Uranium-235, wf, pCi/L	0.1
Bromide, wf, mg/L	0.010	Radium-224, wf, pCi/L	1
Chloride, wf, mg/L	0.02–0.06	Radium-226, wf, pCi/L	1
Sulfate, wf, mg/L	0.07–0.09	Radium-228, wf, pCi/L	1
Fluoride, wf, mg/L	0.04	δ <sup>13</sup> C <sub>CH<sub>4</sub></sub> *	--
Silica, wf, mg/L	0.018–0.029	δ <sup>13</sup> C <sub>DIC</sub> *	--
Arsenic, wf, μg/L	0.02–0.10	δ <sup>18</sup> O <sub>H<sub>2</sub>O</sub> *	--
Barium, wf, μg/L	0.07	δ <sup>18</sup> O <sub>SO<sub>4</sub></sub> *	--
Beryllium, wf, μg/L	0.006	δ <sup>2</sup> H <sub>CH<sub>4</sub></sub> *	--
Boron, wf, μg/L	3.0	δ <sup>2</sup> H <sub>H<sub>2</sub>O</sub> *	--
Cadmium, wf, μg/L	0.016	δ <sup>34</sup> S <sub>SO<sub>4</sub></sub> *	--
Chromium, wf, μg/L	0.06–0.07	Nitrogen, N <sub>2</sub> , dissolved, mg/L	0.001
Cobalt, wf, μg/L	0.02	Oxygen, O <sub>2</sub> , dissolved, mg/L	0.002
Copper, wf, μg/L	0.5–0.8	Argon, dissolved, mg/L	0.003
Iron, wf, μg/L	3.2	Carbon dioxide, dissolved, mg/L	0.04
Lead, wf, μg/L	0.015–0.025	Methane, dissolved, mg/L	0.001
Manganese, wf, μg/L	0.04		



Coal mine boundaries from West Virginia Geological and Economic Survey, 2011b

Base from U.S. Geological Survey, 1:200,000, digital line graphics

Figure 5. Groundwater survey sites in the Monongahela River Basin, West Virginia, June–September 2011.

## 14 Water quality in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12

**Table 2.** Site information for wells and springs sampled for the groundwater survey as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, June–September 2011.

[WV, West Virginia; Marcellus<50, site in basin underlain by a less than 50-foot Marcellus Shale thickness and neither a gas producing basin nor adjacent to a gas producing basin; NA, not applicable]

Local well name	Geologic unit name <sup>1</sup>	Well or spring	Well depth, in feet	Natural gas production bin
Mng-0582	Pottsville Group	Well	190	Near production
Pre-0163	Pottsville Group	Well	179	Marcellus<50
Pre-0162	Pottsville Group	Well	145	Production
Pre-0176	Conemaugh Group	Well	200	Near production
Ran-0276	Hampshire Formation	Well	320	Not near production
Ran-0277	New River Formation	Well	220	Not near production
Ran-0280	Kanawha Formation	Well	80	Production
Ups-0178	Kanawha Formation	Well	158	Production
Ran-0282	Kanawha Formation	Well	105	Production
Mar-0296	Dunkard Group	Well	107	Production
Mar-0300	Dunkard Group	Well	70	Near production
Tay-0129	Conemaugh Group	Well	113	Production
Har-0173	Dunkard Group	Well	70	Production
Lew-0218	Monongahela Group	Well	60	Near production
Har-0170	Conemaugh Group	Well	75	Near production
Ran-0259	Pottsville Group	Well	155	Near production
Ran-0275	Kanawha Formation	Well	500	Production
Ran-0261(North Spring at Bowden, WV)	Greenbrier Group	Spring	NA	Not near production
Ups-0177	Pottsville Group	Well	120	Production
Tuc-0127	Chemung Group	Well	60	Not near production
Tuc-0124	Greenbrier Group	Well	100	Marcellus<50
Tuc-0129	Greenbrier Group	Well	45	Marcellus<50
Ran-0260	Price Formation	Well	222	Production
Tuc-0125	Greenbrier Group	Well	250	Marcellus<50
Pre-0124	Chemung Group	Well	205	Not near production
Pre-0166	Price Formation	Well	100	Marcellus<50
Pre-0173	Conemaugh Group	Well	57	Not near production
Ran-0284	Hampshire Formation	Well	200	Marcellus<50
Ran-0278	Chemung Group	Well	100	Not near production
Lew-0221	Conemaugh Group	Well	100	Production
Lew-0215	Monongahela Group	Well	100	Near production
Har-0175	Conemaugh Group	Well	45	Near production
Bar-0149	Conemaugh Group	Well	180	Production
Pre-0177	Greenbrier Group	Well	145	Marcellus<50
Pre-0164	Greenbrier Group	Well	207	Marcellus<50
Pre-0172	Allegheny Formation	Well	65	Production
Pre-0178	Conemaugh Group	Well	NA	Production
Bar-0150	Conemaugh Group	Well	52	Production
Har-0177	Monongahela Group	Well	150	Production
Tay-0130	Conemaugh Group	Well	160	Not near production
Bar-0151s	Conemaugh Group	Spring	NA	Near production

<sup>1</sup>Geologic nomenclature used in this report conforms with that used by the West Virginia Geological and Economic Survey, as depicted on the 1968 State geologic map of West Virginia (Cardwell and others, 1968).



The number of sampling sites in a bin was made proportional to the ratio of the area of the binned HUC-12s within the study area. For instance, High Production HUC-12s made up 17.2 percent of the basin, so 17.2 percent of the sites had to be from that bin. Since 17.2 percent of 50 is 8.6 and sites could only be selected in increments of integers, the number of sites in that bin was rounded to 9. The category Marcellus <50 ft thick was eliminated from the study because all available sites were underlain by the Marcellus Shale at less than 2 ft thick and judged to be unlikely candidates for future development. The Marcellus <50 ft thick bin made up 10 percent of the overall study area, and the five sites that would have represented this bin were allocated to the Near High Production bin.

After setting up the bins, sites were prioritized by assigning at least one site from each HUC-10 that was represented, then at least one site in each HUC-12 until the bins filled up (fig. 6). If the only available sites for a bin were within the same HUC-12, then multiple sites from that HUC-12 were used. This was done by assigning random numbers to sites within HUC-10s, and then within HUC-12s, and ranking them by the random numbers. Sites were then sorted by (1) bin, (2) HUC-10 rank, (3) HUC-12 rank, and (4) random number, and ordered within bins. Sites with within-bin rank less than or equal to the number of sites per bin were included in the study, and the next site in rank was assigned as the alternate. Using this procedure, two sites were selected in close proximity on the same stream; one site with three samples collected during 1979–80, and the other with an active streamgage, 64 years of flow data, and numerous water-quality measurements (fig. 7). Both sites drain between 10 mi<sup>2</sup> and 20 mi<sup>2</sup>. Although this procedure ranked the un-gaged site higher, the streamgage site was selected for sampling. Finally, during sampling, field crews visited one of the selected sites shortly after limestone sand had been applied to treat acid mine drainage. That site was dropped from the study and replaced by a site in the same bin but with a drainage area of 40.7 mi<sup>2</sup>, which was slightly greater than the original size criterion (table 3, at end of report).

## Sampling Methods

Both groundwater and base-flow samples were collected and processed according to standard USGS operating procedures and protocols. All samples were analyzed for field properties, alkalinity, major ions, trace elements, and uranium (table 1). Field measurements of water temperature, specific conductance, dissolved oxygen concentration, pH, alkalinity, and, for groundwater sites, redox potential were made on site according to standard protocols (U.S. Geological Survey, 2006). Samples were processed according to standard USGS protocol (Wilde and others, 2004). Water samples for cation analysis were filtered through a 0.45-micron ( $\mu\text{m}$ ) filter, collected in an acid-rinsed 250-milliliter (mL) polyethylene bottle, and acidified with 2 mL of nitric acid. Water samples for anion analysis were collected in a 250-mL polyethylene

bottle. Water samples for uranium and radium isotope analysis were collected in a 1-liter (L) polyethylene bottle. If uranium was detected in a sample, that sample was further analyzed for uranium and radium isotopes.

Analyses for major ions, trace elements, and naturally occurring radioactive materials (NORM) were conducted at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. Stable isotope analyses were performed at the West Virginia University Stable Isotope Laboratory in Morgantown, West Virginia, and Isotech Laboratories in Champaign, Illinois. Dissolved gas samples were analyzed at the USGS Dissolved Gas Laboratory in Reston, Virginia.

## Groundwater Sampling

Groundwater samples were collected between June 28 and September 21, 2011. Prior to sampling, wells were purged to remove standing water from the well and ensure that representative water samples were collected. A minimum of one well volume was purged from most wells; high-use production wells that did not require purging or low-yielding wells that would not recover from purging were pumped until field properties stabilized. Field measurements of dissolved oxygen, pH, specific conductance, water temperature, and turbidity were monitored during purging by using a multi-parameter water-quality meter, which was calibrated daily. Water level was also monitored where possible. Sample tubing typically was connected to a  $\frac{3}{4}$ -in. hose bib as close to the wellhead as possible, and pumps were kept on to prevent sample contamination from the plumbing or from backflow from holding tanks. Existing plumbing and well-casing materials included, but were not limited to, steel, galvanized steel, copper, polyvinyl chloride (PVC), and other plastics. The purging procedure prescribed was assumed to have prevented contamination from plumbing materials. Samples were collected after field properties stabilized, according to standard USGS protocols for the collection of water-quality data (U.S. Geological Survey, 2006). Each of the sampled springs discharges into a collection basin, and samples from springs were collected using a peristaltic pump to draw water from the collection basin. Subsurface-dip samples were collected from the spring's collection basin for dissolved gas analyses. Field properties were measured in the collection basin before and during sample collection to monitor the stability of the spring's discharge. To prevent environmental contamination, samples typically were collected and processed inside a mobile field laboratory or a portable chamber assembled near the well or the spring.

## Base-Flow Sampling

Base-flow samples were collected from 50 sites in the Monongahela River Basin during seasonal base-flow conditions between July 31 and October 26, 2012. Samples were collected using methods described in the USGS National Field Manual for the collection of Water-Quality Data (U.S. Geological Survey, 2006). Where possible, depth- and

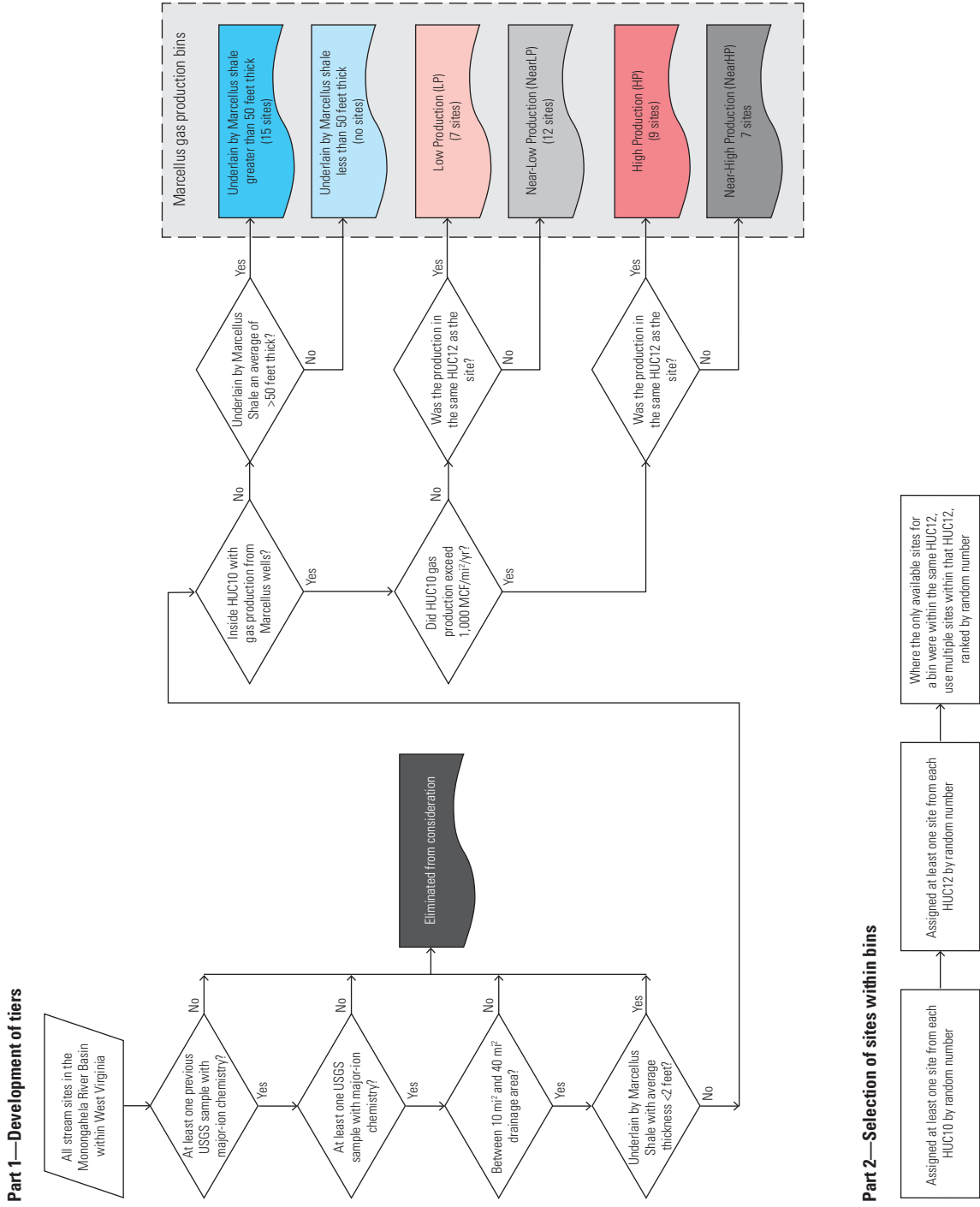
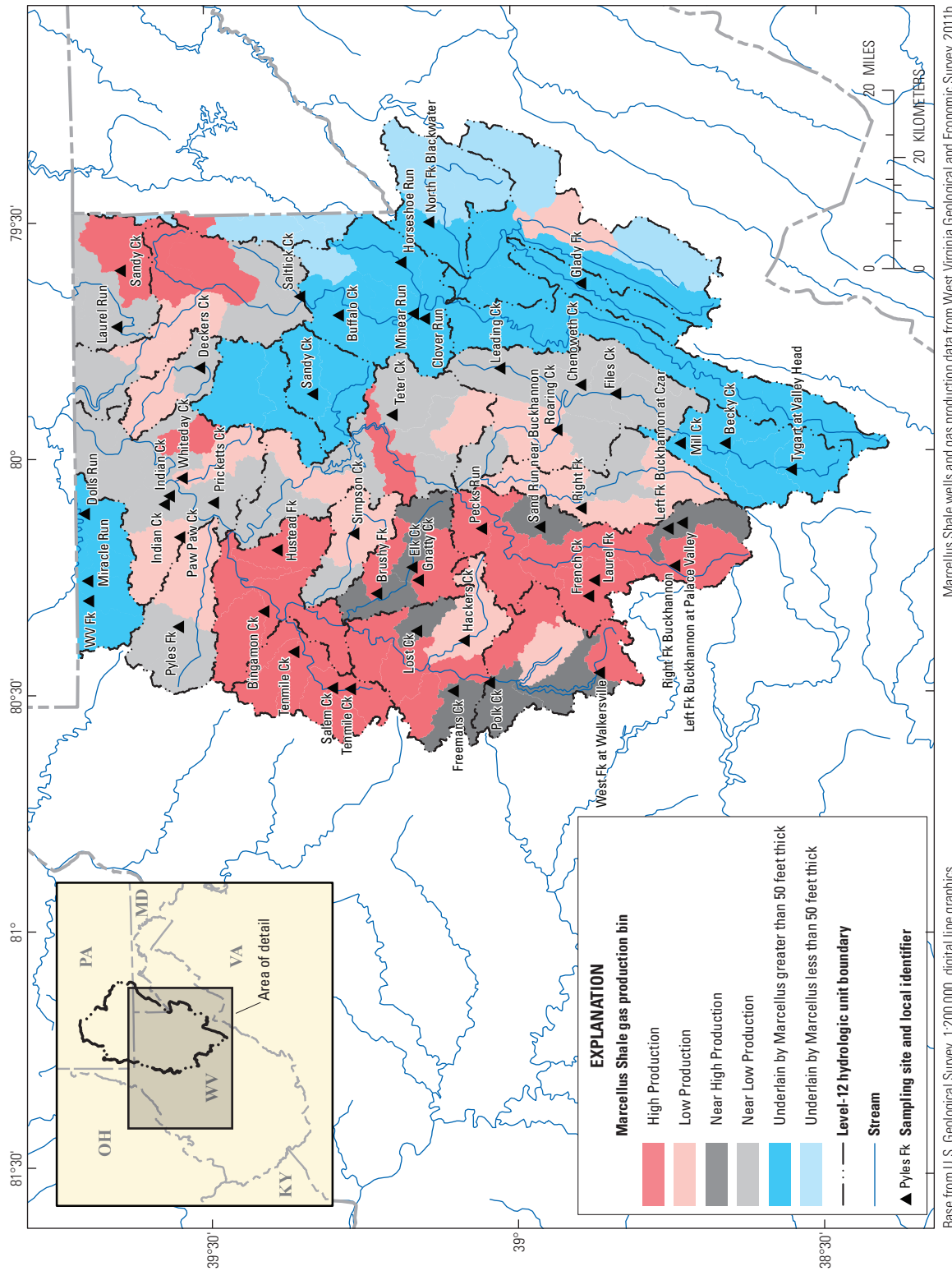


Figure 6. Flow chart showing the process for stratifying stream-water sampling sites.



**Figure 7.** Streams, stream sampling sites, gas wells completed in the Marcellus Shale through 2012 showing gas production through 2010, and average thickness of the Marcellus Shale by HUC-12.

width-integrated samples were collected using a DH-81 isokinetic sampler. Where site conditions did not support the use of a DH-81, such as insufficient stream depth or velocity, samples were collected at multiple points using an open-mouthed bottle. Sample aliquots were composited in a churn splitter and processed according to standard USGS protocols (U.S. Geological Survey, 2006). Field properties of water temperature, specific conductance, dissolved oxygen concentration, pH, alkalinity, and stream discharge were measured at the time of sample collection.

## Methods of Analysis

The results of the groundwater survey and base-flow survey were examined for geospatial and statistical relations. The geospatial and statistical analyses of the water-chemistry results were conducted to discern patterns in these data. Details of these analyses are described in the following two sections.

### Geospatial Analyses

The wells and springs sampled and the associated water-chemistry data were assessed for spatial trends by loading the data into ArcMap, a geographic information system (GIS) tool for analysis of geospatial data. Additional geospatial data were used to assess potential factors that could affect groundwater quality in the region. The geospatial data included (1) location of current and legacy coal mines obtained from the WVGES (West Virginia Geological and Economic Survey, 2011b), (2) location of current active or recently completed Marcellus Shale gas wells (from WVGES, West Virginia Geological and Economic Survey, 2014a), (3) geologic maps of the study area with significant surficial and deeper structural features such as faults and folds (from WVGES), (4) location of current and historical oil and gas wells (from WVGES), (5) elevation data from the USGS National Elevation Dataset, (6) stream coverages from the USGS National Hydrography Dataset (NHD), and (7) basin characteristics derived from the USGS NHD database.

### Statistical Analyses

Descriptive and summary statistics were calculated using Spotfire S-PLUS 8.1 statistical and graphing software (TIBCO Software, Inc., 2008). Descriptive and summary statistics for censored data sets, those with values less than the reporting level, were calculated using the Regression on Order Statistics (ROS) and adjusted maximum likelihood estimation (AMLE) techniques (TIBCO Software Inc., 2008). Statistics were not calculated for sample sets of less than 10 data points. Kruskal-Wallis rank test was used for comparison of medians among groups. A Tukey's Honest-Significant-Difference post hoc test was used for multiple comparisons. Relations among several variables were analyzed through Principal Components Analysis (PCA). Analysis of groundwater-quality data

for geochemical processes was performed using the PCA in Spotfire S-PLUS 8.1 statistical and graphing software.

## Quality Assurance

Quality-assurance samples, blanks, and replicates were collected during both the groundwater sampling and the surface-water base-flow sampling. Blank samples are used to determine the extent to which sampling procedures may contaminate samples, thereby biasing analytical results. Replicate samples are used to determine the variability inherent in the collection and analysis of environmental samples. Together, blank and replicate samples can be used to characterize the accuracy and precision of water-quality data. All quality-assurance samples were collected and processed according to protocols described in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, 2006).

### Blank Samples

A combination of equipment blanks and field blanks was used to identify and quantify potential sources of contamination. An equipment blank consists of a volume of water of known quality that is processed through the sampling equipment in a laboratory environment. A field blank consists of a volume of water processed through the sampling equipment under the same field conditions in which the samples were processed, typically a mobile field laboratory.

### Replicate Samples

Comparison of results among replicate samples can provide insight into the sources of variability that are inherent in sample collection, processing, and analysis. Sample-collection protocols (U.S. Geological Survey, 2006) for groundwater and base-flow samples have been developed to produce a sample that is representative of the sampled well, spring, or stream. If the appropriate sampling procedures have been used, it is assumed that the water being collected is representative of the sampled environment and that any variability among the main and replicate sample is primarily attributable to sample processing and analysis (Koterba and others, 1995).

Variability for a replicate sample pair was quantified by calculating the relative percent difference (RPD) of the samples. The RPD was calculated using the following formula:

$$\left( \frac{|R_1 - R_2|}{\left( \frac{R_1 + R_2}{2} \right)} \right) \times 100,$$

where  $R_1$  is the concentration of the analyte in the first replicate sample and  $R_2$  is the concentration of the analyte in the second replicate sample. Generally, concentrations in replicate sample pairs differed by small amounts, typically less than 15 percent RPD.

## Quality-Assurance Results

### Groundwater Samples

An equipment blank was collected prior to collection of groundwater samples in 2011. The blank sample was analyzed using the same analytical suite as the environmental samples. The only analyte present in this blank at a detectable concentration was cobalt, at 0.052 micrograms per liter ( $\mu\text{g/L}$ ); the detection was confirmed through a re-analysis of the sample. The detection appears anomalous because cobalt concentrations in 15 of the 41 environmental samples processed using this equipment were lower than the concentrations detected in the blank sample.

Replicate samples were collected at two sites, Har-0177 and Ran-0259 (table 2), during the groundwater survey. In general, the replicate samples were in good agreement, with most analyses within 5 percent RPD. All values for the Har-0177 sample pair were within 15 percent RPD. However, the replicate samples from Ran-0259 differed by more than 15 percent RPD for aluminum and arsenic. The aluminum results for the Ran-0259 sample pair were 3.4  $\mu\text{g/L}$  and 2.1  $\mu\text{g/L}$ , a difference of 47 percent RPD. The reporting level for aluminum analysis using this method was 1.7  $\mu\text{g/L}$ . However, the long-term minimum detection level (LTMDL) for this method is 2.2  $\mu\text{g/L}$ , a value calculated using data from the period this sample pair was analyzed. The sample pair results for arsenic were 0.1  $\mu\text{g/L}$  and 0.08  $\mu\text{g/L}$ , a difference of 22 percent RPD with a reporting level of 0.04  $\mu\text{g/L}$ .

### Base-Flow Samples

Field blank samples were collected at the Tygart Valley River at Valley Head and the Elk Creek at Romines Mills sites. Lead was the only analyte detected in the Tygart Valley River blank with a concentration of 0.027  $\mu\text{g/L}$ , 0.002  $\mu\text{g/L}$  greater than the method reporting level of 0.025  $\text{mg/L}$ . Lead was not detected in the environmental sample collected from the Tygart Valley River. Both silica and cobalt were detected in the Elk Creek blank, silica at 0.043 milligrams per liter ( $\text{mg/L}$ ) and cobalt 0.038  $\mu\text{g/L}$ , analytes with laboratory reporting limits of 0.018  $\text{mg/L}$  and 0.021  $\mu\text{g/L}$ , respectively. The silica concentration in the blank is much lower than the minimum environmental concentration of 1.68  $\text{mg/L}$  measured and two orders of magnitude less than the median environmental concentration. It is unlikely silica contamination significantly affected the analysis of any environmental sample or the interpretation of the data. Cobalt concentrations in environmental samples ranged from 0.043 to 20.6  $\mu\text{g/L}$ . The cobalt concentrations in samples collected in the weeks immediately prior to collection of the blank sample were an order of magnitude greater than concentrations for the blank. The Tygart Valley River blank, which had no detectable cobalt, was processed the week following the Elk Creek blank. The presence of

cobalt at a detectable concentration in the Elk Creek blank is unlikely to affect the interpretation of cobalt data.

A replicate sample was collected at Little Sandy Creek at Evansville, W.Va. A replicate sample consists of two samples collected from the same sampling location at the same time. Replicate samples chiefly provide data on variability associated with sampling and analytical methods. The replicate sample pair agreed well; concentrations for 32 of 37 analytes in both samples differed by less than 5 percent RPD. Only one analyte in this sample pair, molybdenum, differed by greater than 15 percent RPD, at 17 percent RPD. The concentrations of molybdenum for the sample pair were 0.019  $\mu\text{g/L}$  and 0.016  $\mu\text{g/L}$ , and the reporting level was 0.014  $\mu\text{g/L}$ .

## Water Quality in the Monongahela River Basin

The baseline water-quality assessment of that part of the Monongahela River Basin underlain by the Marcellus Shale consisted of a groundwater survey and a base-flow survey. The results of both surveys were compared to historical water-quality data for the study area stored in NWIS databases. Historical data used for comparison to the base-flow survey data were restricted to samples collected during the same season, July through October. For the base-flow survey results, further comparisons were made among gas-production bins described in the section “Surface Water” under “Site Selection.” Owing to the small number of sites in some of the bins, a simplified classification structure was used consisting of only three bins—Production, basins with high or low gas production; Near Production, basins without gas production but adjacent to production basins; and Not Near Production, basins underlain by greater than a 50-ft thickness of the Marcellus Shale but neither producing gas nor adjacent to a Marcellus Shale gas-producing basin. Groundwater-survey sites were binned using the same basin designation as that used for the base-flow survey with the addition of a fourth group “Marcellus <50” for groundwater sites not in basins underlain by at least a 50-ft thickness of the Marcellus shale. These comparisons reflect both temporal and current land-use patterns. The results of this study can be found in data tables included in the appendixes for this report; groundwater survey results are in Appendix 1, and the base-flow survey results are in Appendix 2.

### Specific Conductance, Total Dissolved Solids, and pH

Specific conductance and pH of groundwater and surface water provide a general indication of water quality and can affect other chemical constituents present by affecting solubility, partitioning, and valence states. Although much of the variability of specific conductance and pH in groundwater is due to natural factors, human activities, such

as coal mining, also contribute to this variability (McAuley and Kozar, 2006). Total dissolved solids, the concentration of dissolved substances in water, is often highly correlated with specific conductance.

## Specific Conductance

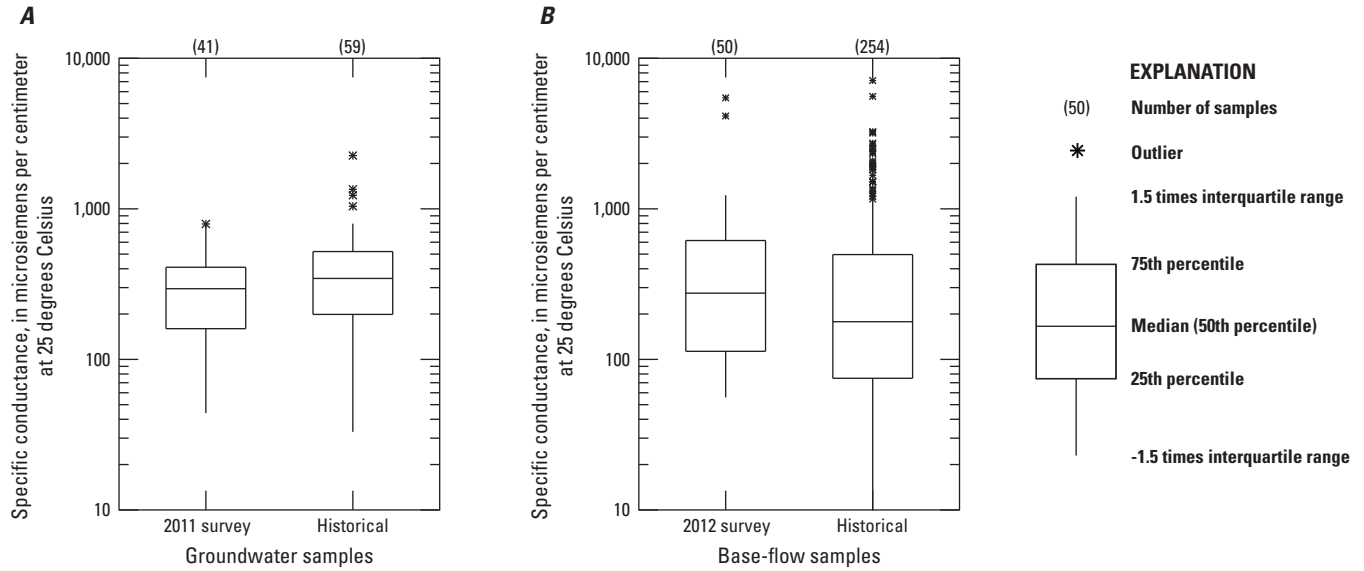
Specific conductance, the ability of water to conduct an electrical current, is dependent upon the amount of dissolved ions present in the water. Specific conductance in groundwater samples ranged from 44 microsiemens per centimeter at 25 degrees Celsius ( $\mu\text{S}/\text{cm}$ ) to 794  $\mu\text{S}/\text{cm}$ , with a median value of 295  $\mu\text{S}/\text{cm}$ . In the base-flow survey samples, specific

conductance ranged from 56  $\mu\text{S}/\text{cm}$  to 5,380  $\mu\text{S}/\text{cm}$  with a median value of 280  $\mu\text{S}/\text{cm}$  (table 4). It is worth noting that although the minimum and median specific conductance values for the groundwater and base-flow surveys are similar, the maximum value for the groundwater survey is an order of magnitude lower than the median value for the base-flow survey. Specific conductance did not differ significantly from historical values in either the groundwater survey or the base-flow survey (fig. 8). Specific conductance varied significantly among the base-flow survey gas-production bins (Kruskal-Wallis test,  $p = 0.011$ ) with the highest values in the Production bin (fig. 9). The groundwater production bins did not differ in regard to specific conductance ( $p = 0.435$ ).

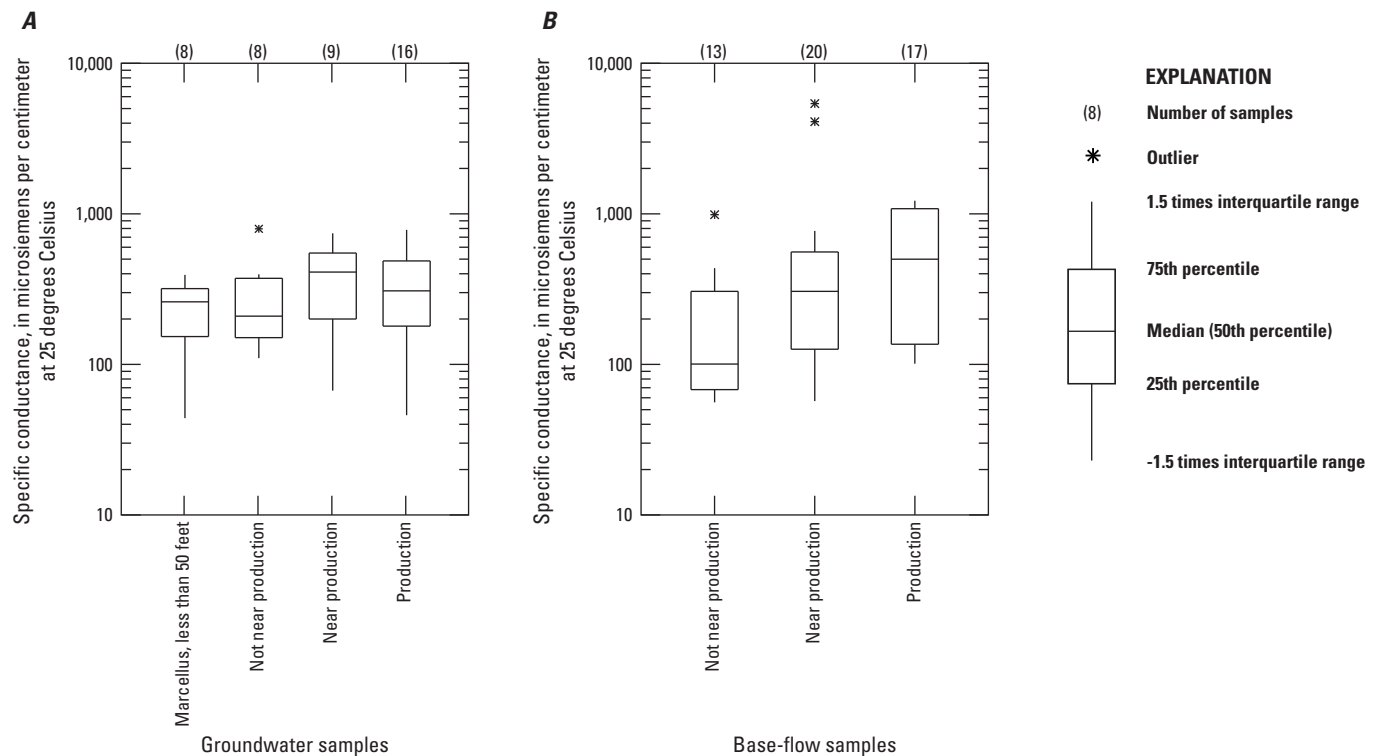
**Table 4.** Statistical summary of water-quality field measurements and major ions in samples collected for the groundwater survey and base-flow survey as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, 2011–12.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; wf, filtered sample; SMCL, secondary maximum contaminant level (U.S. Environmental Protection Agency, 2009); <, less than; NA, not applicable]

Constituent	Reporting unit	Method reporting level	Survey	Minimum value	Maximum value	Median value	SMCL
pH	Standard unit	NA	Groundwater	4.5	9.4	7	6.5–8.5
			Base flow	4.8	8.7	7.7	
Specific conductance	$\mu\text{S}/\text{cm}$	NA	Groundwater	44	794	295	NA
			Base flow	56	5,380	280	
Total dissolved solids	mg/L	12	Groundwater	<12	522	168	NA
			Base flow	37	4,380	171	
Calcium, wf	mg/L	0.022–0.04	Groundwater	0.672	91	16.9	NA
			Base flow	5.51	291	28.3	
Magnesium, wf	mg/L	0.08	Groundwater	0.105	19.1	4.07	NA
			Base flow	1.26	86.3	28.3	
Potassium, wf	mg/L	0.022	Groundwater	0.43	2.9	1.17	NA
			Base flow	0.66	8.85	1.98	
Sodium, wf	mg/L	0.1–0.24	Groundwater	0.46	186	17.2	NA
			Base flow	0.89	949	8.31	
Bicarbonate, wf	mg/L	1.	Groundwater	2.3	382	99.8	NA
			Base flow	<1	401	65	
Chloride, wf	mg/L	0.02–0.06	Groundwater	0.57	67.6	9.42	250
			Base flow	0.87	100	6.94	
Bromide, wf	mg/L	0.010	Groundwater	<0.01	0.598	0.027	NA
			Base flow	0.014	0.692	0.031	
Fluoride, wf	mg/L	0.04	Groundwater	<0.04	1.85	0.1	4
			Base flow	<0.04	0.27	.06	
Sulfate, wf	mg/L	0.07–0.9	Groundwater	<0.09	231	10.18	250
			Base flow	3.42	2,640	9.1	



**Figure 8.** Distribution of specific conductance for samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical specific conductance for samples collected in the Monongahela River Basin, West Virginia: *A*, groundwater samples and *B*, base-flow samples.



**Figure 9.** Distribution of specific conductance for samples collected as part of the Marcellus Shale baseline study, Monongahela River Basin, West Virginia, 2011–12, grouped by gas production type: *A*, groundwater samples and *B*, base-flow samples.

### Total Dissolved Solids

Concentrations of total dissolved solids in groundwater survey samples ranged from less than the reporting level of 12 mg/L to 522 mg/L with a median value of 168 mg/L. Concentrations of total dissolved solids in base-flow survey samples ranged from 37 mg/L to 4,380 mg/L with a median of 171 mg/L (table 4), the same as the median groundwater concentration. As with specific conductance, there are no significant differences between historical data and either groundwater survey or base-flow survey data. Also, as was the case for specific conductance, total dissolved solids concentrations in base-flow survey samples varied significantly by gas-production bin (Kruskal-Wallis test,  $p = 0.019$ ). The highest concentrations were in the Production bin, and there were no significant differences among the groundwater survey gas-production bins.

### pH

The pH of a solution plays an important role in the solubility of metals. The pH of the groundwater survey samples ranged from 4.5 to 9.4 with a median of 7.0. The pH of base-flow survey samples ranged from 4.8 to 8.7 with a median of 7.7 (table 4). The U.S. Environmental Protection Agency (EPA) has established a secondary maximum contaminant level (SMCL) for pH. The SMCL is a recommendation based on aesthetic effects, primarily taste, that ideally pH would fall within the range of 6.5 to 8.5 (U.S. Environmental Protection Agency, 2009). A total of 14 samples fell outside the SMCL

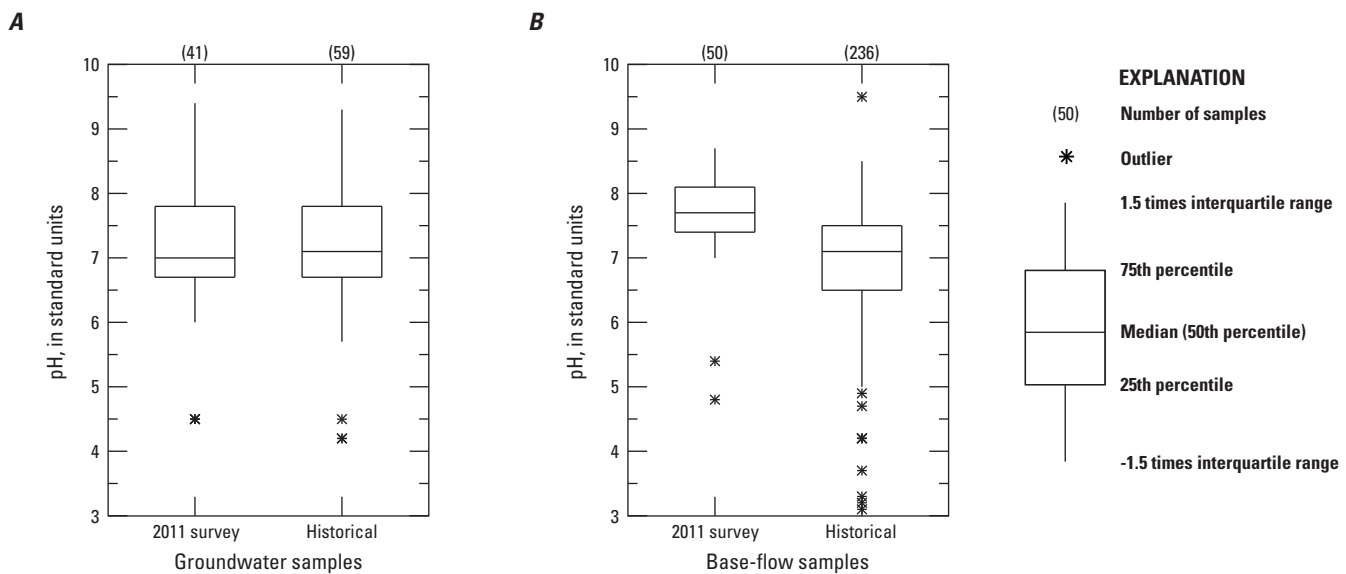
range—9 groundwater samples, (6 samples were less than 6.5 and 3 samples exceeded 8.5) and 5 base-flow samples (2 samples were less than 6.5 and 3 samples exceeded 8.5).

Values of pH in samples collected for the 2011 groundwater survey did not differ significantly from values of the historical data (fig. 10). However, pH measured during the 2012 base-flow survey was significantly higher than historical values (Kruskal-Wallis test,  $p < 0.001$ ). The difference between base-flow survey pH values and historical pH values is most likely attributable to changes in coal-mining practices and acid-mine-drainage treatment that have occurred between the 2012 and historical surveys. Among base-flow survey samples, pH values in the Production bin were higher than those in the Not Near Production bin (Kruskal-Wallis test,  $p = 0.097$ ) (fig. 11A). There was no difference among groundwater survey bins (Kruskal-Wallis test,  $p = 0.252$ ) (fig. 11B).

### Major Ions

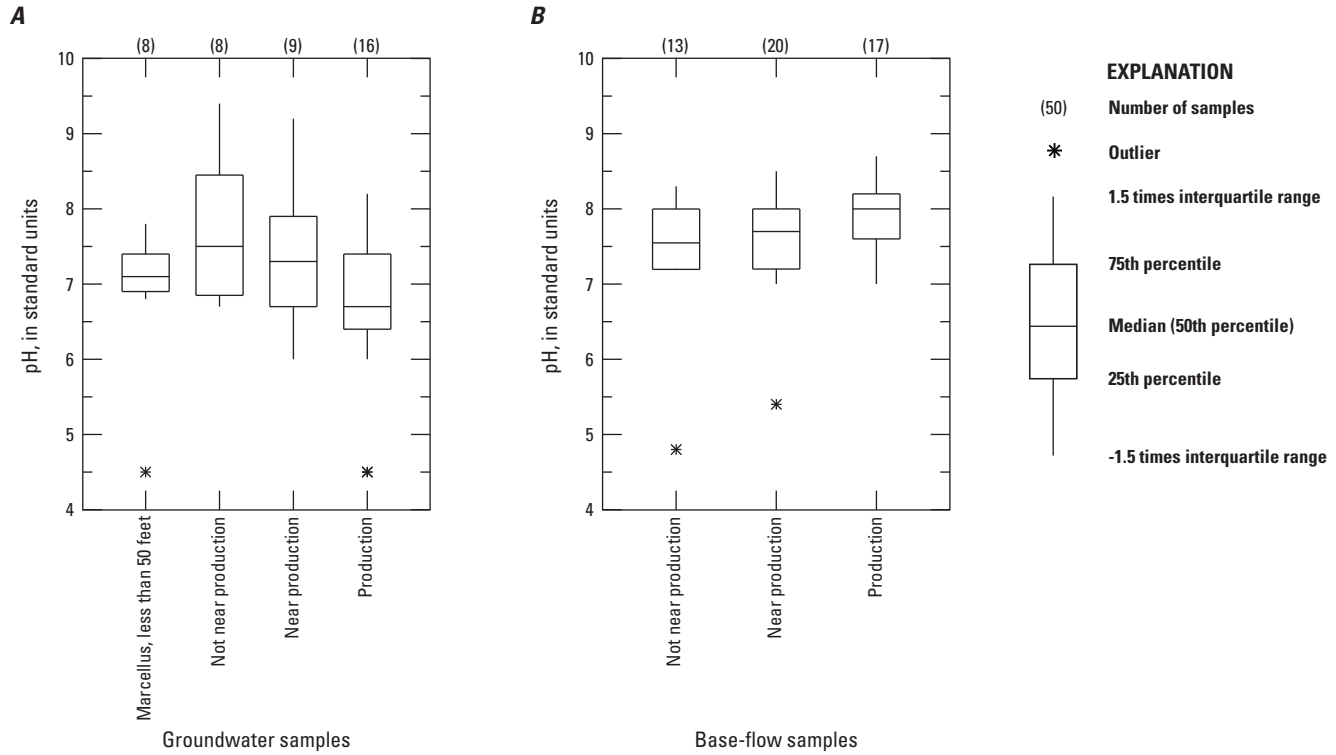
The major ions calcium, magnesium, potassium, sodium, bicarbonate from field alkalinity, chloride, and sulfate exert a strong influence on, and are strongly influenced by, geochemical and anthropogenic processes. Patterns in major ion composition were examined by determination of water type, as well as comparison of historical and 2011–12 survey data. For the base-flow survey samples, further comparisons were made among the gas-production bins.

The relative proportion of major ions in natural waters is the basis for classifying samples by water type. Water



**Figure 10.** Distribution of pH in samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical pH in samples from the Monongahela River Basin, West Virginia: *A*, groundwater samples and *B*, base-flow samples.





**Figure 11.** Distribution of pH in samples collected as part of the Marcellus Shale baseline study in the Monongahela River Basin, West Virginia, 2011–12: *A*, groundwater samples and *B*, base-flow samples.

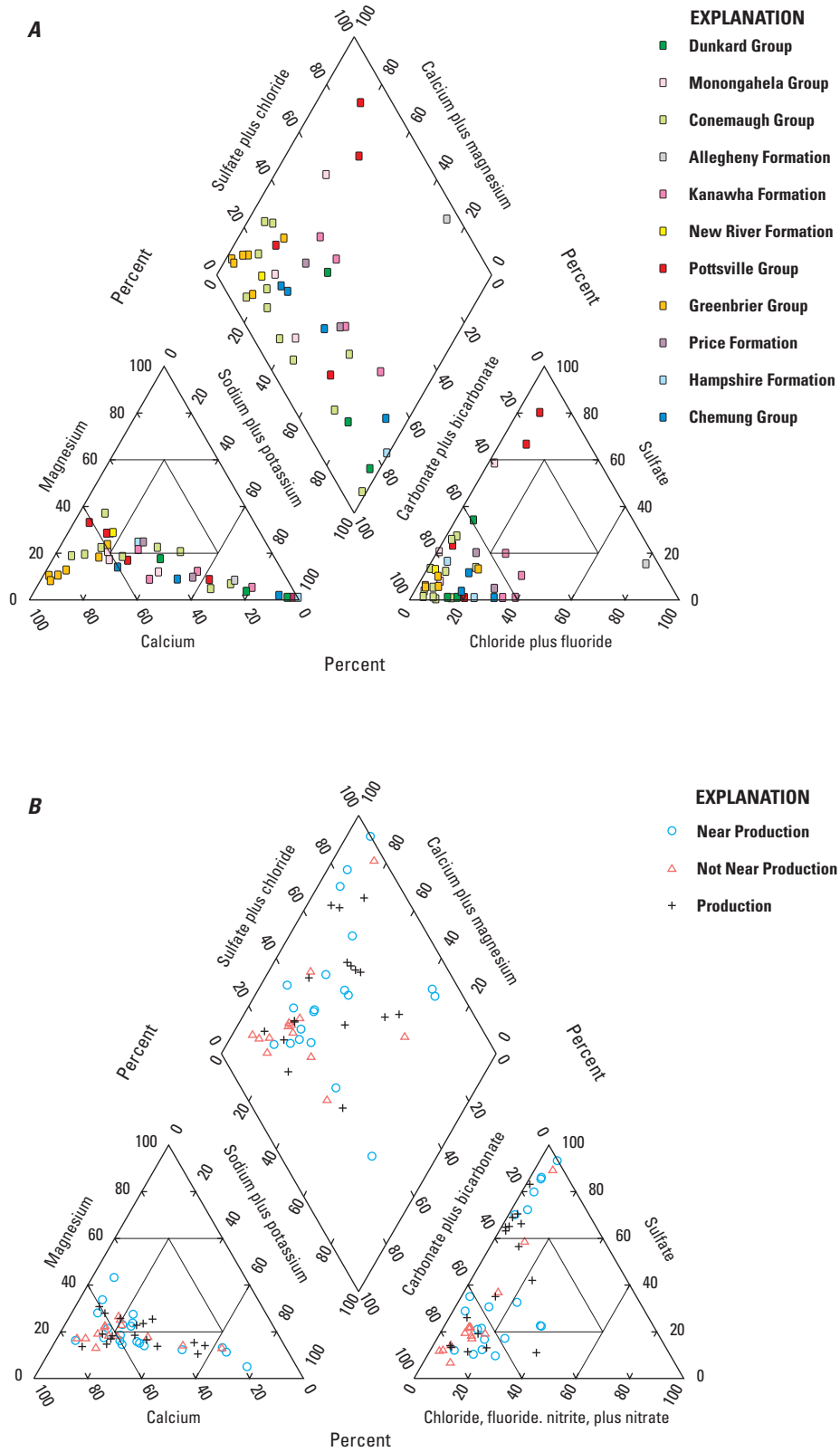
samples with a specific cation or anion constituting more than one-half the total cations or anions can be classified by water type, calcium-carbonate type water for example (Hem, 1985). However, waters in which no single cation or anion constitutes greater than one-half of the total cations or anions are classed as mixed-type waters (Hem, 1985).

Major-ion composition of the water for the 41 groundwater samples was predominantly either a calcium-bicarbonate type or a sodium-bicarbonate type (fig. 12A). A few wells exhibited other signatures, however, including 3 wells (2 completed in the Pottsville Group and one in the Kanawha Formation) that exhibited a calcium-sulfate signature and 1 well (completed in the Allegheny Formation) that exhibited a sodium-sulfate signature. Wells completed in the Greenbrier Group exhibited a strong calcium-bicarbonate signature, which is expected because the Greenbrier Limestone is a significant karst bedrock-forming unit in the study area.

The major ion composition of the groundwater survey samples (fig. 12A) is similar to that found in a study of groundwater downgradient from reclaimed surface mines and in unmined areas in Pennsylvania and West Virginia (McAuley and Kozar, 2006), part of which was conducted in

the Monongahela River Basin. In that study, median chloride concentrations for mined and un-mined areas were 5.1 mg/L and 7.3 mg/L, respectively; median sodium concentrations for mined and unmined areas were 9.35 mg/L and 18.0 mg/L, respectively. Median calcium concentrations for mined and unmined areas were 35.9 mg/L and 21.0 mg/L, respectively, and median magnesium concentrations for mined and unmined areas were 9.9 mg/L and 4.4 mg/L, respectively. Median chloride concentrations for wells sampled as part of the current study were slightly higher (table 4) at 9.42 mg/L.

Salt waters and brines are found as shallow as 300 feet below land surface in certain valleys in Pennsylvanian- and Permian-aged aquifers (Wilmoth, 1975). Chloride and bromide concentrations can be indicative of salt waters and brines. Chloride concentrations in groundwater survey samples ranged from 0.57 mg/L to 67.6 mg/L with a median value of 9.42 mg/L, and bromide ranged from less than the reporting level of 0.010 mg/L to 0.598 mg/L with a median value of 0.027 mg/L. The relative concentrations of chloride and bromide can be used to characterize sources of salt waters and brines because bromide concentrations are greater than chloride concentrations in deep brines (Hem, 1985).



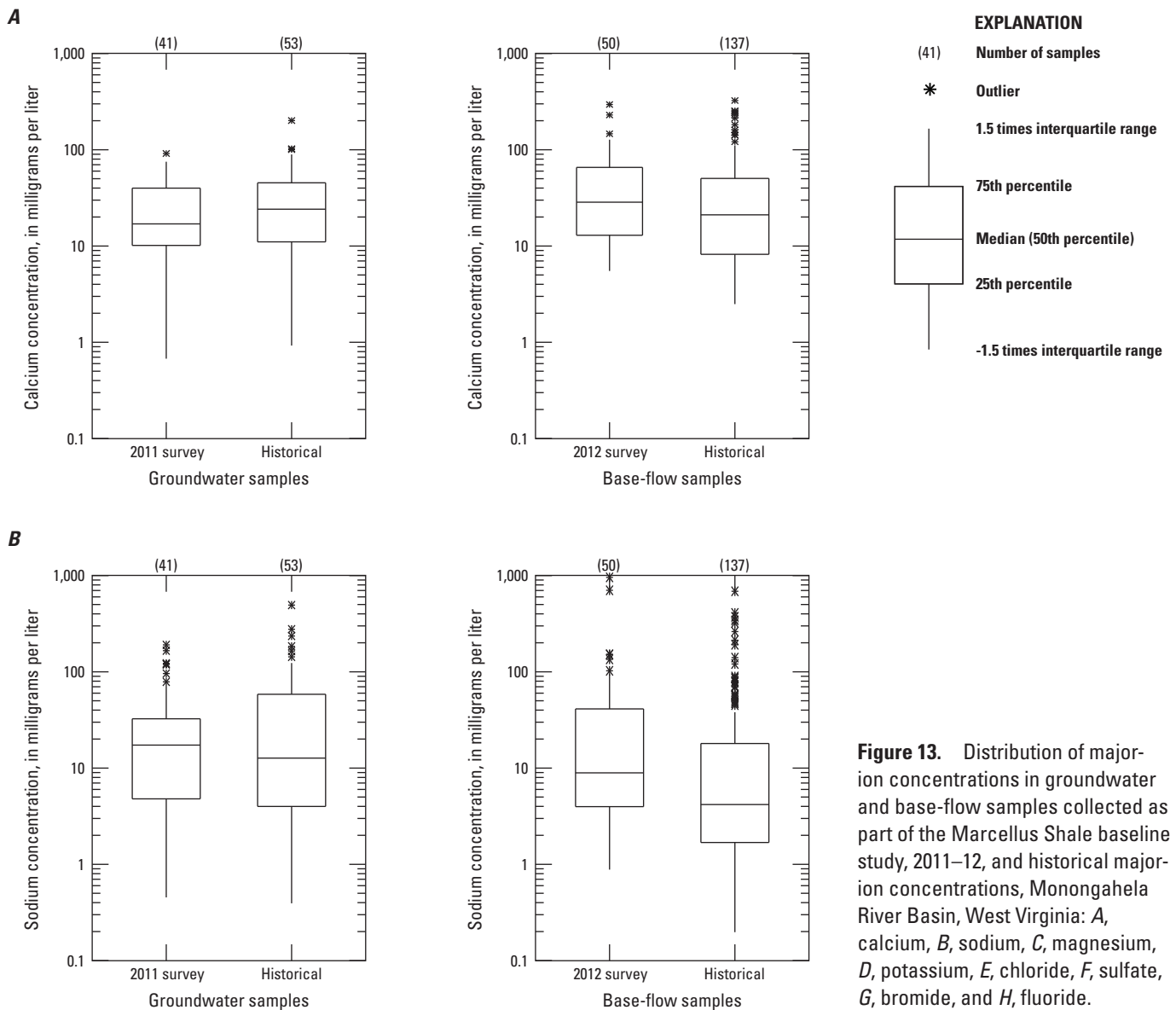
**Figure 12.** Piper diagrams showing major ion composition of samples collected as part of the Marcellus Shale baseline study, 2011–12, from the Monongahela River Basin, West Virginia: *A*, groundwater survey samples classified by geologic formation and *B*, base-flow survey samples.

Chloride concentrations did not vary significantly among the gas-production bins (Kruskal-Wallis test,  $p = 0.169$ ). Bromide concentrations in groundwater survey samples were significantly higher in the Near Production bin than in the other bins (Kruskal-Wallis test,  $p = 0.058$ ). Although the concentrations of the chloride and bromide may indicate potential mixing of shallow groundwater with deeper saline or brine waters, it takes very little saline water or brine to impart a brine signature (Llewellyn, 2014).

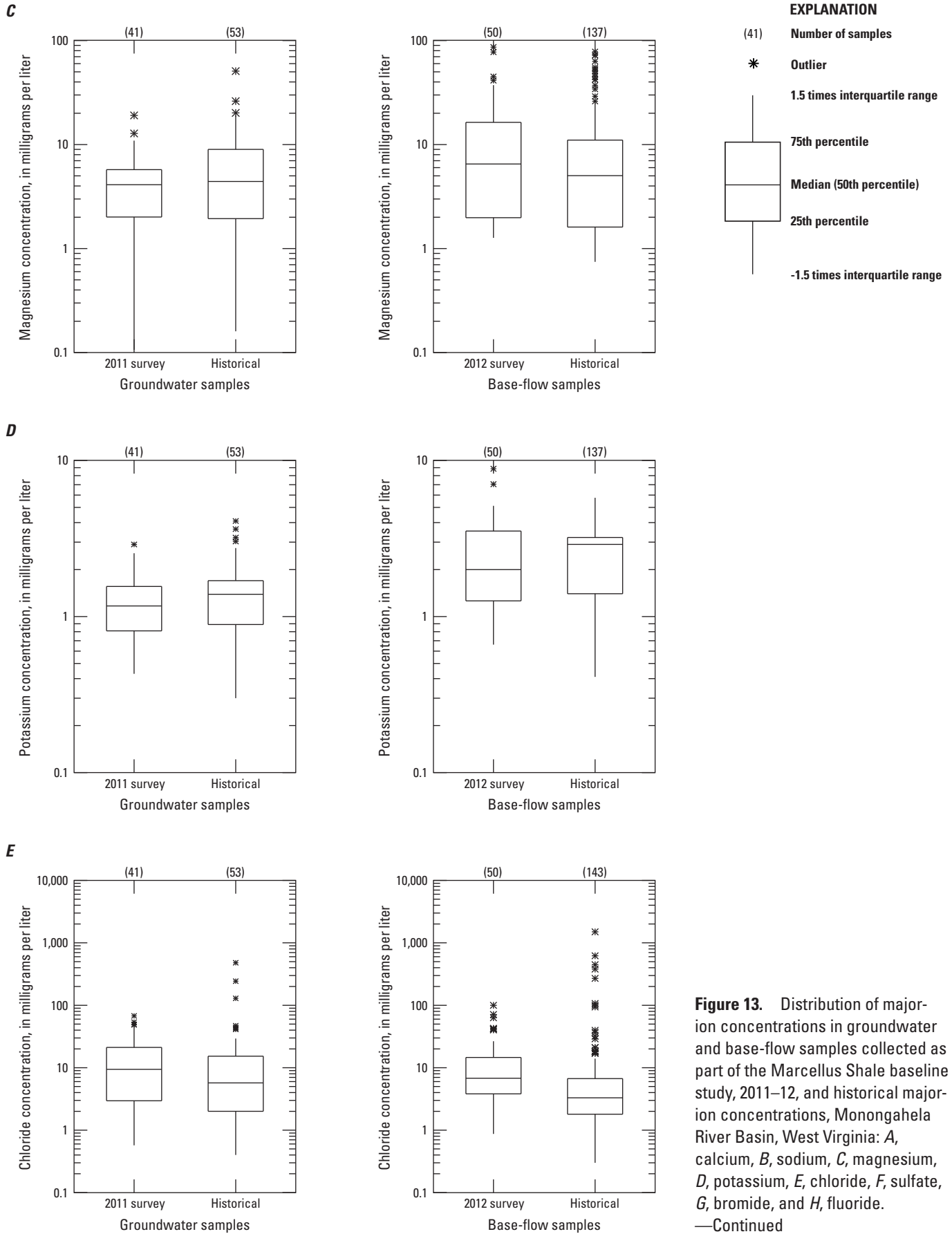
Most of the samples from the 2012 base-flow survey were either calcium-carbonate or calcium-sulfate type waters (fig. 12B). The remainder of samples were mostly either sodium-carbonate or sodium-sulfate type waters. Although samples from Production bins accounted for most of the calcium-sulfate waters, there was no clear pattern of water-type distribution among the bins.

With the exception of chloride in base-flow-survey samples, no significant differences were noted in a comparison of historical data with either groundwater survey or the base-flow survey data (fig. 13). Chloride was significantly higher in the 2012 base-flow survey samples than in the historical data from the Monongahela River Basin (Kruskal-Wallis test,  $p < 0.01$ ). As noted in the discussion of ionic composition of groundwater survey samples, increased chloride concentration may be related to the presence of saline waters or brines from deep aquifers.

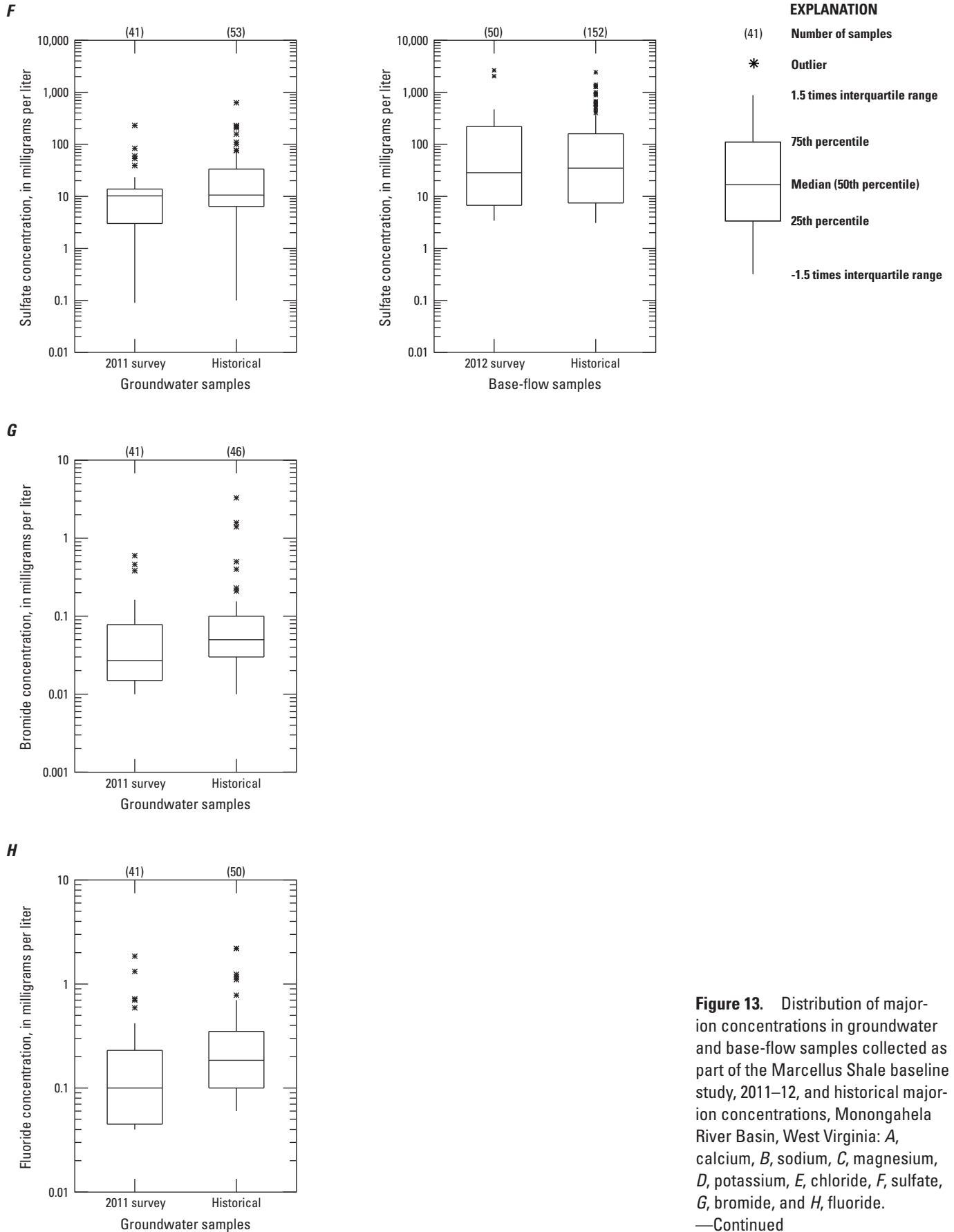
A comparison of major-ion concentrations among the Production, Near Production, and Not Near Production bins revealed no significant differences with the exception of fluoride (fig. 14). Fluoride concentrations in the Production bin were significantly higher than concentrations in either the Near Production or Not Near Production bins (Kruskal-Wallis test,  $p = 0.0416$ , fig. 13H).



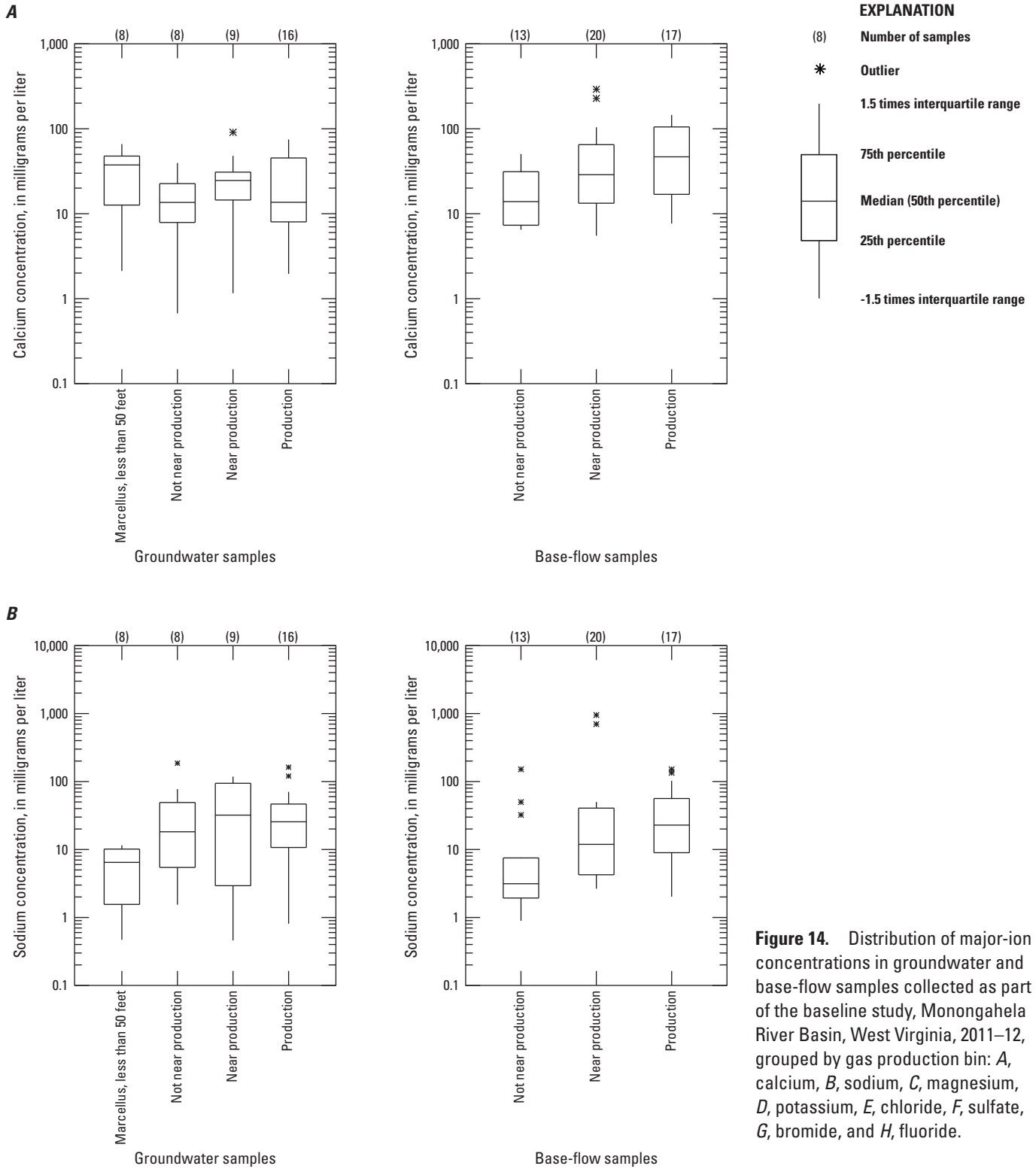
**Figure 13.** Distribution of major-ion concentrations in groundwater and base-flow samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical major-ion concentrations, Monongahela River Basin, West Virginia: *A*, calcium, *B*, sodium, *C*, magnesium, *D*, potassium, *E*, chloride, *F*, sulfate, *G*, bromide, and *H*, fluoride.



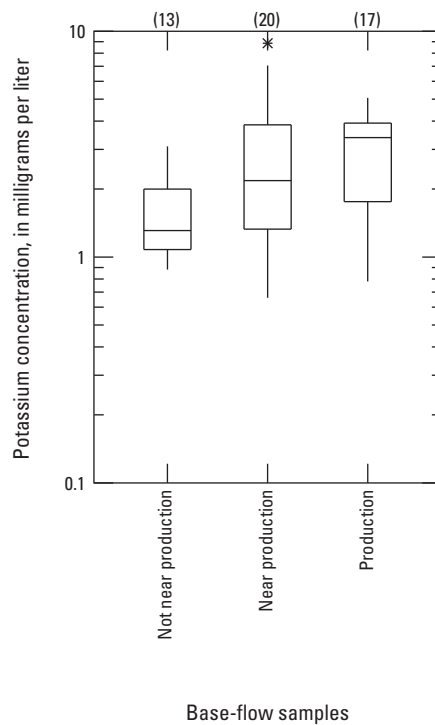
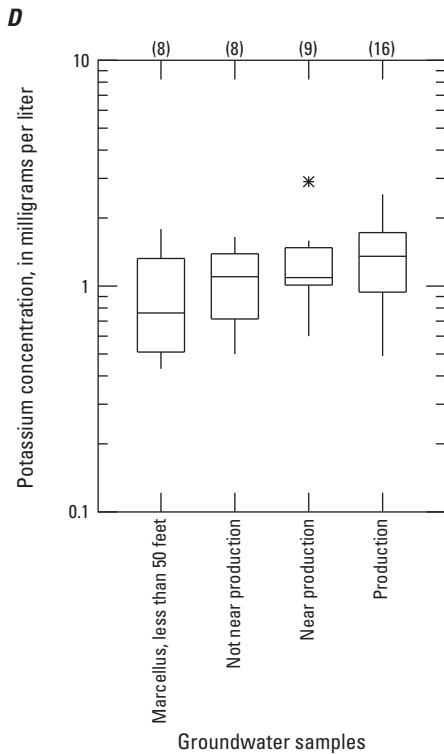
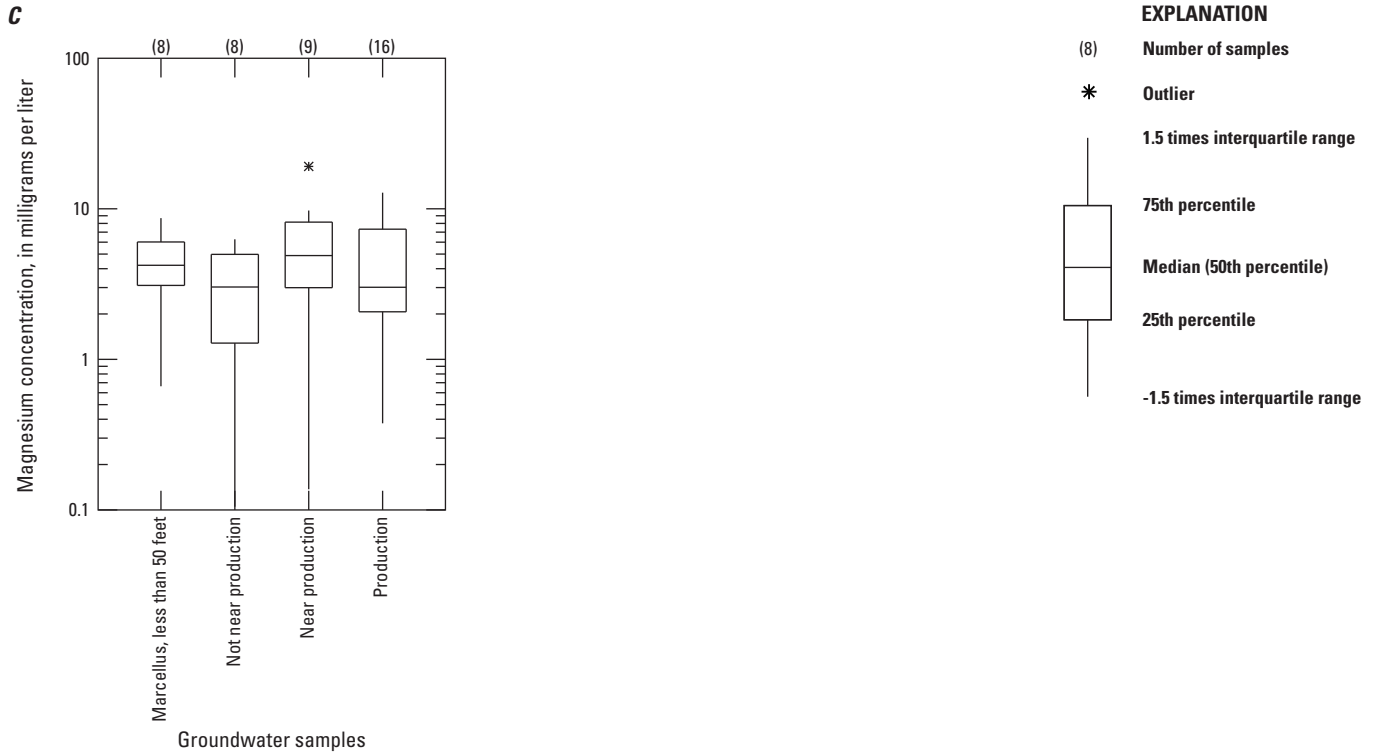
**Figure 13.** Distribution of major-ion concentrations in groundwater and base-flow samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical major-ion concentrations, Monongahela River Basin, West Virginia: *A*, calcium, *B*, sodium, *C*, magnesium, *D*, potassium, *E*, chloride, *F*, sulfate, *G*, bromide, and *H*, fluoride. —Continued



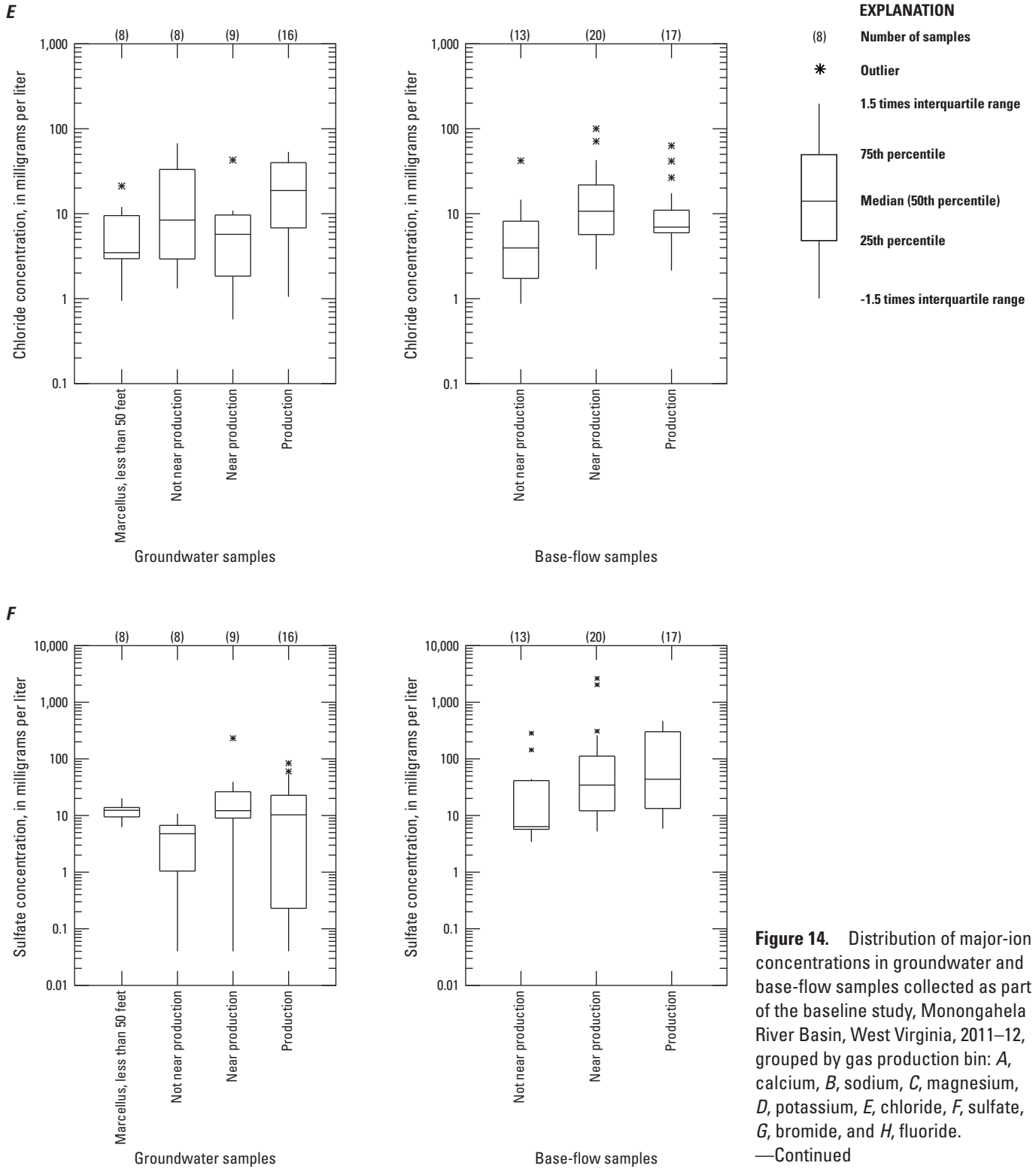
**Figure 13.** Distribution of major-ion concentrations in groundwater and base-flow samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical major-ion concentrations, Monongahela River Basin, West Virginia: *A*, calcium, *B*, sodium, *C*, magnesium, *D*, potassium, *E*, chloride, *F*, sulfate, *G*, bromide, and *H*, fluoride.  
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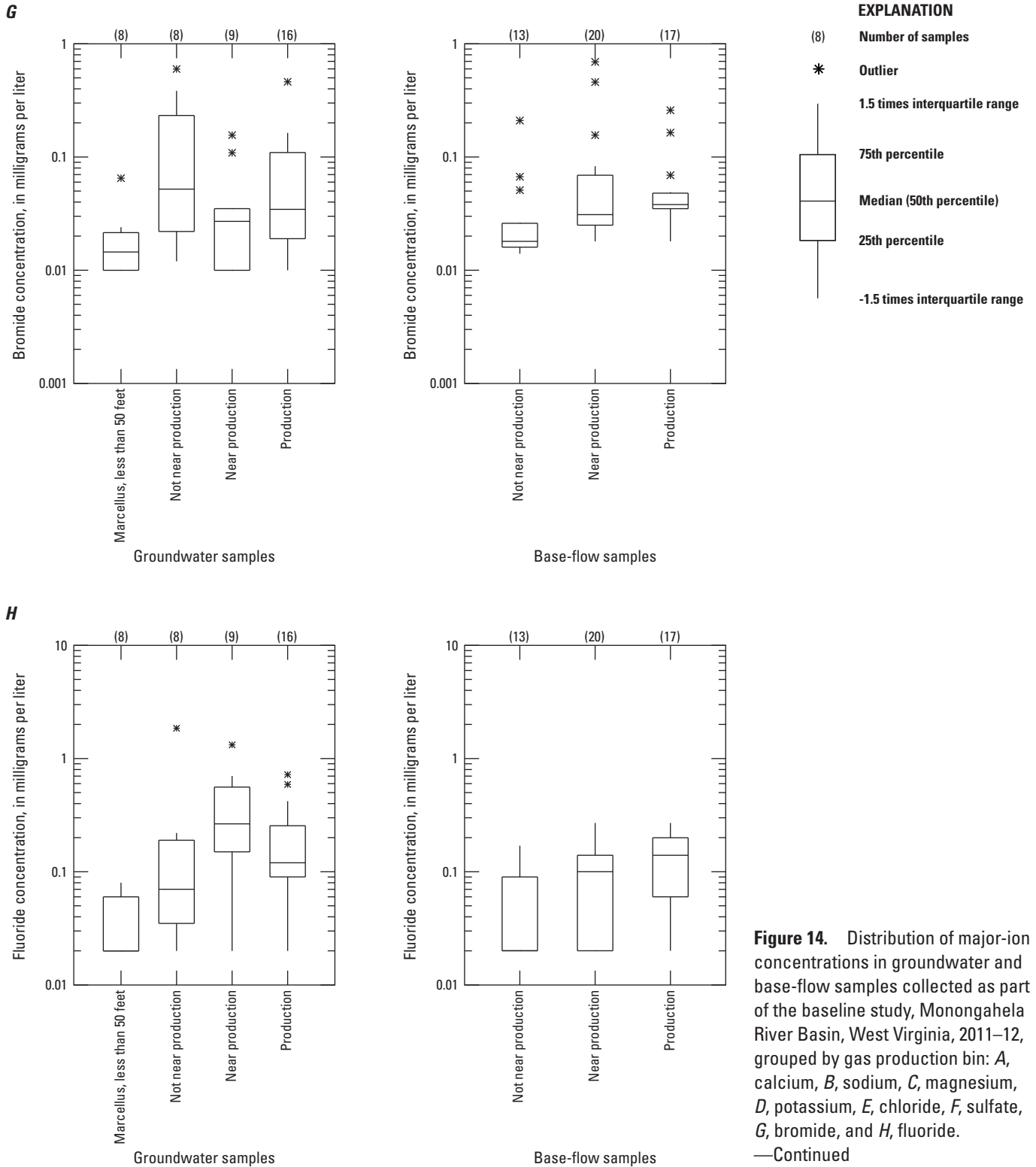
**Figure 14.** Distribution of major-ion concentrations in groundwater and base-flow samples collected as part of the baseline study, Monongahela River Basin, West Virginia, 2011–12, grouped by gas production bin: *A*, calcium, *B*, sodium, *C*, magnesium, *D*, potassium, *E*, chloride, *F*, sulfate, *G*, bromide, and *H*, fluoride.



**Figure 14.** Distribution of major-ion concentrations in groundwater and base-flow samples collected as part of the baseline study, Monongahela River Basin, West Virginia, 2011–12, grouped by gas production bin: *A*, calcium, *B*, sodium, *C*, magnesium, *D*, potassium, *E*, chloride, *F*, sulfate, *G*, bromide, and *H*, fluoride.  
—Continued







## Trace Elements

Trace elements are those constituents that are commonly found in waters at concentrations less than 1.0 mg/L (Hem, 1985). The presence or absence of certain trace elements can provide insight into the origin and composition of sampled waters. In the groundwater survey and the base-flow survey, several of the trace elements (beryllium, cadmium, chromium, copper, lead, nickel, silver, antimony, and selenium) were infrequently detected and, therefore, are not discussed within this report. Aluminum, iron, manganese, barium, strontium, cobalt, molybdenum, and arsenic were more frequently detected in either groundwater or base-flow survey samples (table 5) and are discussed below.

Aluminum, the third most common crustal element, typically occurs in concentrations less than 0.1 mg/L in natural waters (Hem, 1985). The median aluminum value for groundwater survey samples was less than the laboratory reporting level of 1.7  $\mu\text{g/L}$ . However, concentrations of aluminum in base-flow survey samples ranged from less than the 2.2  $\mu\text{g/L}$  reporting level to 4,420  $\mu\text{g/L}$ ; the median concentration of aluminum was 9.1  $\mu\text{g/L}$ . Aluminum concentrations in groundwater survey did not differ from historical data. Historical data were insufficient for a comparison with base-flow survey data. Aluminum concentrations for these samples did not vary significantly among the gas-production bins (figs. 15 and 16).

Iron and manganese are common constituents of groundwater in the study area. Both usually occur in natural waters as a trace element (Hem, 1985). The oxidation of pyrite (iron sulfide) or less commonly siderite (iron carbonate) minerals in bedrock of the region are a major source of iron in West Virginia's waters. Iron concentrations in groundwater survey samples ranged from less than the reporting level of 3.2  $\mu\text{g/L}$  to 11,600  $\mu\text{g/L}$  with a median of 84  $\mu\text{g/L}$ . This median concentration is similar to that found for wells from unmined parts of the Allegheny and Monongahela River Basins sampled as part of a mining land-use assessment (McAuley and Kozar, 2006). Iron concentrations from the groundwater survey did not differ significantly from historical data (fig. 15B). Iron concentrations in base-flow survey samples ranged from less than the reporting level of 3.2  $\mu\text{g/L}$  to 1,040  $\mu\text{g/L}$  with a median concentration of 32.6  $\mu\text{g/L}$ . Results from the 2012 base-flow survey did not differ significantly from historical data for the Monongahela River Basin (fig. 15B), nor did iron concentrations in either groundwater or base-flow survey samples vary significantly among the gas-production bins (fig. 16B).

The presence of manganese in the waters of West Virginia is associated with coal mining. In the groundwater samples, manganese concentrations ranged from less than a reporting level of 0.13  $\mu\text{g/L}$  to 1,670  $\mu\text{g/L}$  with a median concentration of 84.9  $\mu\text{g/L}$ . The median value for manganese compared well with the median concentration for wells in unmined parts of the Allegheny and Monongahela River Basins, 94  $\mu\text{g/L}$  (McAuley and Kozar, 2006), and the groundwater survey

manganese concentrations did not differ significantly from historical data (fig. 15C). Manganese concentrations in the base-flow samples ranged from 1.66  $\mu\text{g/L}$  to 473  $\mu\text{g/L}$  with a median concentration of 26.8  $\mu\text{g/L}$ . Manganese concentrations in samples from the base-flow survey did not differ significantly from historical values (fig. 15C). Among base-flow samples, manganese concentrations were significantly lower in the Not Near Production bin than either the Production or Near Production bins (Kruskal-Wallis test,  $p = 0.006$ ). Groundwater samples did not vary significantly among the gas-production bins (Kruskal-Wallis test,  $p = 0.383$ ) (fig. 16C).

The EPA SMCL, guidelines established on the basis of aesthetic effects, have been developed for iron and manganese in domestic water because they can stain laundry and plumbing fixtures. Iron and manganese concentrations exceeded EPA SMCL drinking water standards of 300  $\mu\text{g/L}$  and 50  $\mu\text{g/L}$ , respectively, in 46 percent (19 of 41) and 59 percent (24 of 41) of the groundwater samples for this study.

Barium is a relatively abundant element; the dissolution of the common mineral barite (barium sulfate) is the chief source of barium in water. Barium is considered to be a common constituent of deeper brines in the study area (Engle and Rowan, 2013). The median concentration in the groundwater-survey samples was 207  $\mu\text{g/L}$  with a concentration range of 22.1–1,400  $\mu\text{g/L}$ . Barium concentrations in the groundwater survey did not differ significantly from historical data (fig. 15D). The median concentration of barium in the base-flow survey samples was 51.7  $\mu\text{g/L}$ , with concentrations ranging from 18.1  $\mu\text{g/L}$  to 98.4  $\mu\text{g/L}$ . The 2012 base-flow survey barium concentrations did not differ significantly from historical concentrations of barium (fig. 15D). Among the gas-production bins, barium concentrations in base-flow samples were significantly higher (Kruskal-Wallis test,  $p = 0.0487$ ) in the Production bin than in either the Near Production bin or the Not Near Production bin (fig. 16D).

Strontium geochemistry is similar to that of calcium (Hem, 1985), and like barium, strontium is considered a common constituent of deeper brines in the study area (Engle and Rowan, 2013). The median concentration of strontium in the groundwater survey samples was 176  $\mu\text{g/L}$ , with a concentration range of 9.6–787  $\mu\text{g/L}$ . Strontium concentrations in base-flow survey samples ranged from 23.6  $\mu\text{g/L}$  to 4,470  $\mu\text{g/L}$  with a median concentration of 117  $\mu\text{g/L}$ . Historical strontium data for groundwater samples were insufficient to make comparisons with samples collected as part of this study. Data were available for the base-flow samples, and concentrations in the base-flow survey samples were significantly higher than concentrations in the historical data for West Virginia's Monongahela River Basin (Kruskal-Wallis test,  $p < 0.01$ ) (fig. 15E). Strontium concentrations did not vary significantly among gas-production bins (fig. 16E).

Median cobalt concentrations in samples from the groundwater survey and the base-flow survey were 0.091  $\mu\text{g/L}$  and 0.420  $\mu\text{g/L}$ , respectively. Historical cobalt data were

**Table 5.** Statistical summary of trace elements in samples collected for the groundwater survey and the base-flow survey as part of the Marcellus Shale baseline survey, West Virginia, 2011–12.

[µg/L, micrograms per liter; wf, filtered water sample; <, less than; MCL, maximum contaminant level (U.S. Environmental Protection Agency, 2009), SMCL, secondary maximum contaminant level (U.S. Environmental Protection Agency, 2009); TT, treatment technique action level (U.S. Environmental Protection Agency, 2009); NA, not applicable]

Trace element	Method reporting level	Survey	Minimum concentration	Maximum concentration	Median concentration	MCL or TT	SMCL
Aluminum, wf, µg/L	1.7–6.6	Groundwater	<1.7	979	<1.7	NA	200
		Base flow	<2.2	4,420	9.1		
Iron, wf, µg/L	3.2	Groundwater	<3.2	11,600	84	NA	300
		Base flow	<3.2	1,040	32.6		
Manganese, wf, µg/L	0.4–0.13	Groundwater	<0.13	1,670	84.9	NA	50
		Base flow	1.66	473	26.8		
Barium, wf, µg/L	0.07	Groundwater	22.1	1,400	207	2,000	NA
		Base flow	18.1	98.4	51.7		
Strontium, wf, µg/L	0.2–0.8	Groundwater	9.6	787	176	NA	NA
		Base flow	23.6	4,470	117		
Cobalt, wf, µg/L	0.02	Groundwater	<0.02	9.48	0.091	NA	NA
		Base flow	<0.02	20.6	0.420		
Molybdenum, wf, µg/L	0.014	Groundwater	<0.014	2.4	0.154	NA	NA
		Base flow	<0.014	2.21	0.232		
Arsenic, wf, µg/L	0.02–0.10	Groundwater	<0.02	6.3	0.35	10	NA
		Base flow	0.06	1.4	0.29		
Beryllium, wf, µg/L	0.006	Groundwater	<0.006	0.495	<0.006	NA	NA
		Base flow	<0.006	1.8	<0.006		
Cadmium, wf, µg/L	0.016	Groundwater	<0.016	0.658	<0.016	5	NA
		Base flow	<0.016	0.21	<0.016		
Chromium, wf, µg/L	0.06–0.07	Groundwater	<0.06	0.75	<0.06	100	NA
		Base flow	<0.07	0.37	<0.07		
Copper, wf, µg/L	0.5–0.8	Groundwater	<0.5	155	<0.5	1,300TT	NA
		Base flow	<0.8	3.7	<0.8		
Lead, wf, µg/L	0.015–0.025	Groundwater	<0.015	3.74	<0.015	15TT	NA
		Base flow	<0.025	1.21	0.034		
Nickel, wf, µg/L	0.09	Groundwater	<0.09	8.1	0.19	NA	NA
		Base flow	0.14	34	0.75		
Silver, wf, µg/L	0.005	Groundwater	<0.005	0.015	<0.005	NA	100
		Base flow	<0.005	0.037	<0.005		
Antimony, wf, µg/L	0.027	Groundwater	<0.027	0.09	<0.027	6	NA
		Base flow	<0.027	0.343	0.077		
Selenium, wf, µg/L	0.03	Groundwater	<0.03	0.3	<0.03	50	NA
		Base flow	<0.03	0.57	0.11		

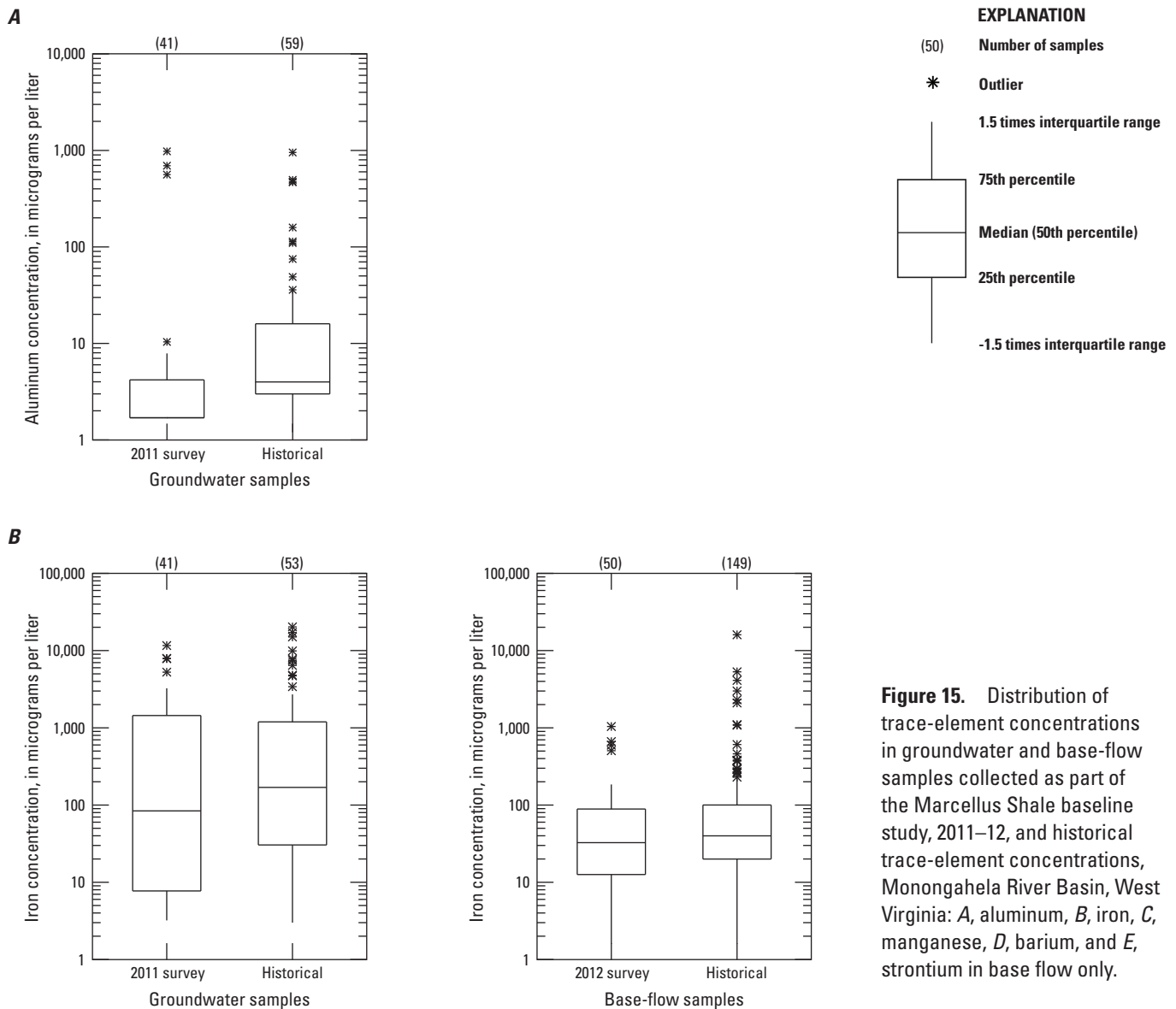
insufficient for comparisons with groundwater and base-flow samples collected as part of this study. Concentrations of cobalt in base-flow survey samples did not vary significantly among gas-production bins (Kruskal-Wallis test,  $p = 0.244$ ) (fig. 16F). However, cobalt concentrations in groundwater survey samples varied significantly among gas-production bins (Kruskal-Wallis test,  $p = 0.033$ ); concentrations were higher in the Production bin than in the other bins.

Molybdenum is a rare trace element and an essential micronutrient (Hem, 1985). Molybdenum concentrations in the groundwater survey samples ranged from less than the laboratory reporting level of 0.014 µg/L to 2.4 µg/L with a median concentration of 0.154 µg/L. The base-flow survey molybdenum concentrations ranged from less than the laboratory reporting level of 0.014 µg/L to 2.21 µg/L with a median concentration of 0.232 µg/L. Historical molybdenum data

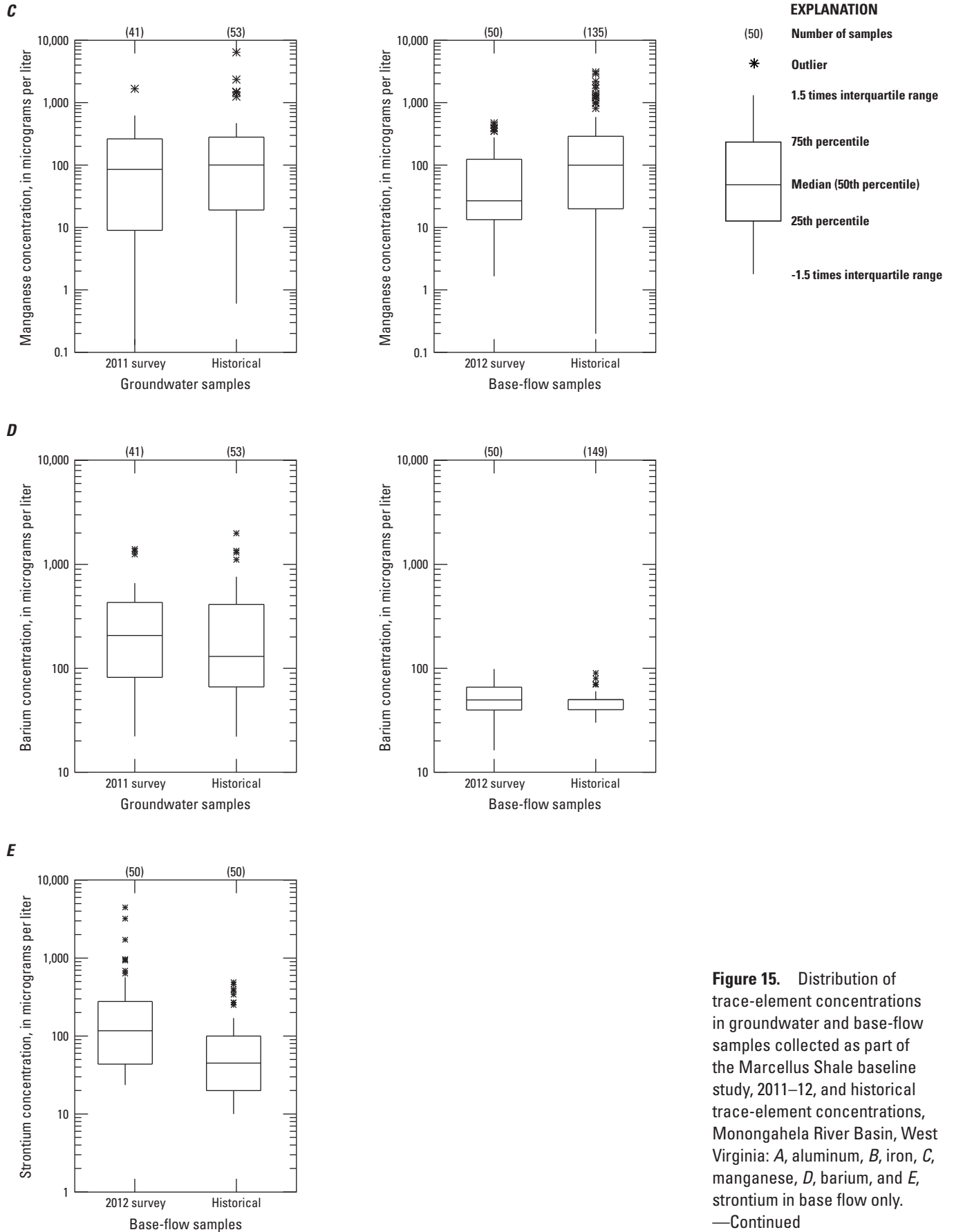
were insufficient for comparisons with groundwater or base-flow samples collected as part of this study. Molybdenum concentrations did not vary significantly among gas-production bins (fig. 16G).

Arsenic, a metalloid element, when consumed in drinking water can cause bladder, lung, and skin cancers, and can also be responsible for neurological and cardiovascular effects (National Research Council, 2001; World Health Organization, 2006). Arsenic concentrations in groundwater samples ranged from less than 0.02 µg/L to 6.3 µg/L. The median concentration of arsenic in groundwater samples was 0.35 µg/L. Arsenic concentrations in the base-flow samples ranged from 0.06 µg/L to 1.4 µg/L. The median arsenic concentration for base-flow survey samples was 0.29 µg/L. Comparisons of

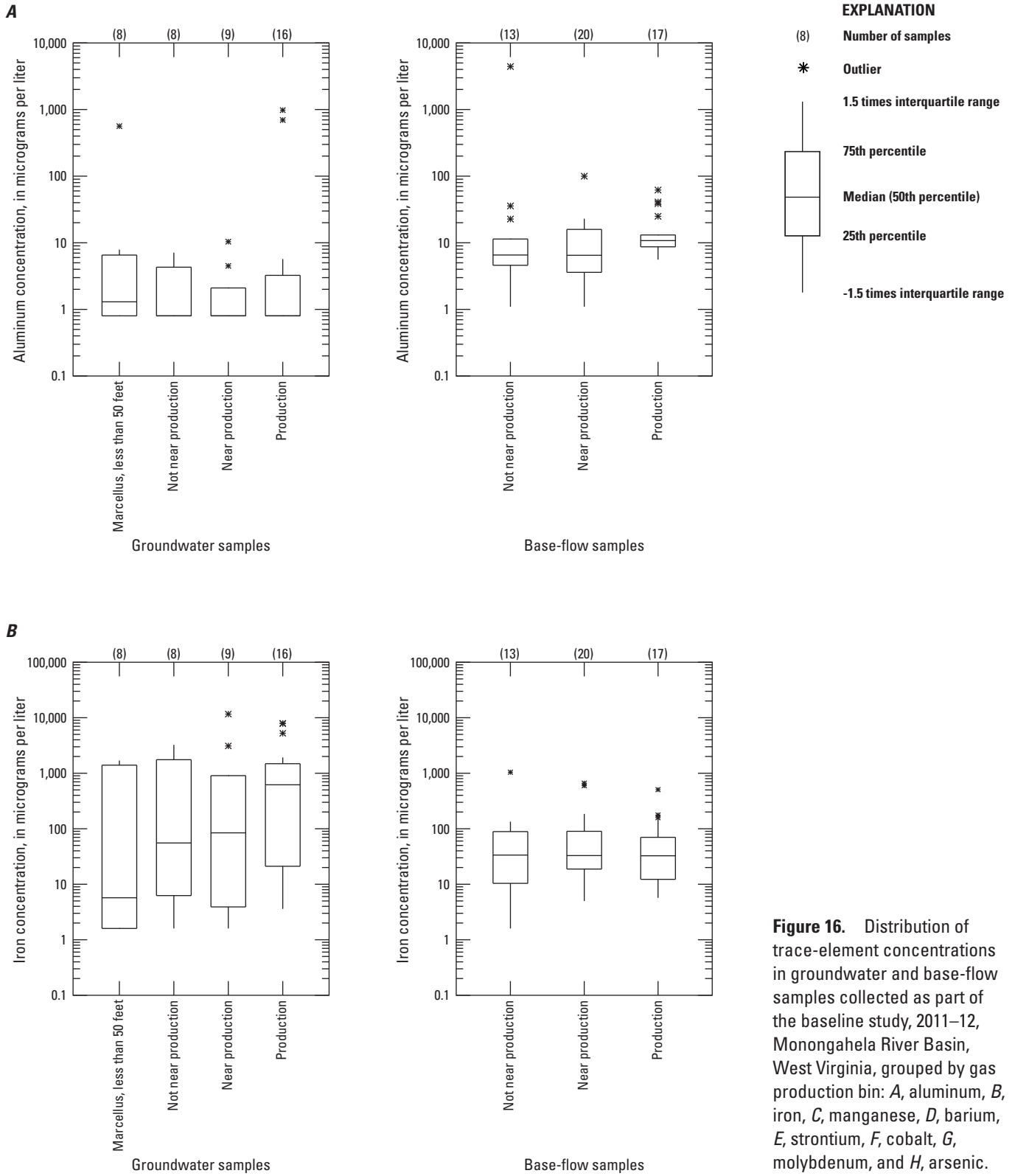
arsenic concentrations from historical data and concentrations in samples from the groundwater and base-flow surveys were complicated by the wide range of reporting levels in the historical data, from 0.18 µg/L to 4.0 µg/L, whereas the analyses for the groundwater and base-flow surveys had a reporting limit of 0.02–0.1 µg/L. No significant difference was observed among the gas-production bins for groundwater (Kruskal-Wallis test,  $p = 0.147$ ) or base-flow samples (Kruskal-Wallis test,  $p = 0.638$ ) (fig. 16H). In 2006, the EPA maximum contaminant level (MCL) for total arsenic was lowered from 50 µg/L to 10 µg/L (Federal Register, 2001); no sample from either the groundwater survey or the base-flow survey exceeded the MCL.

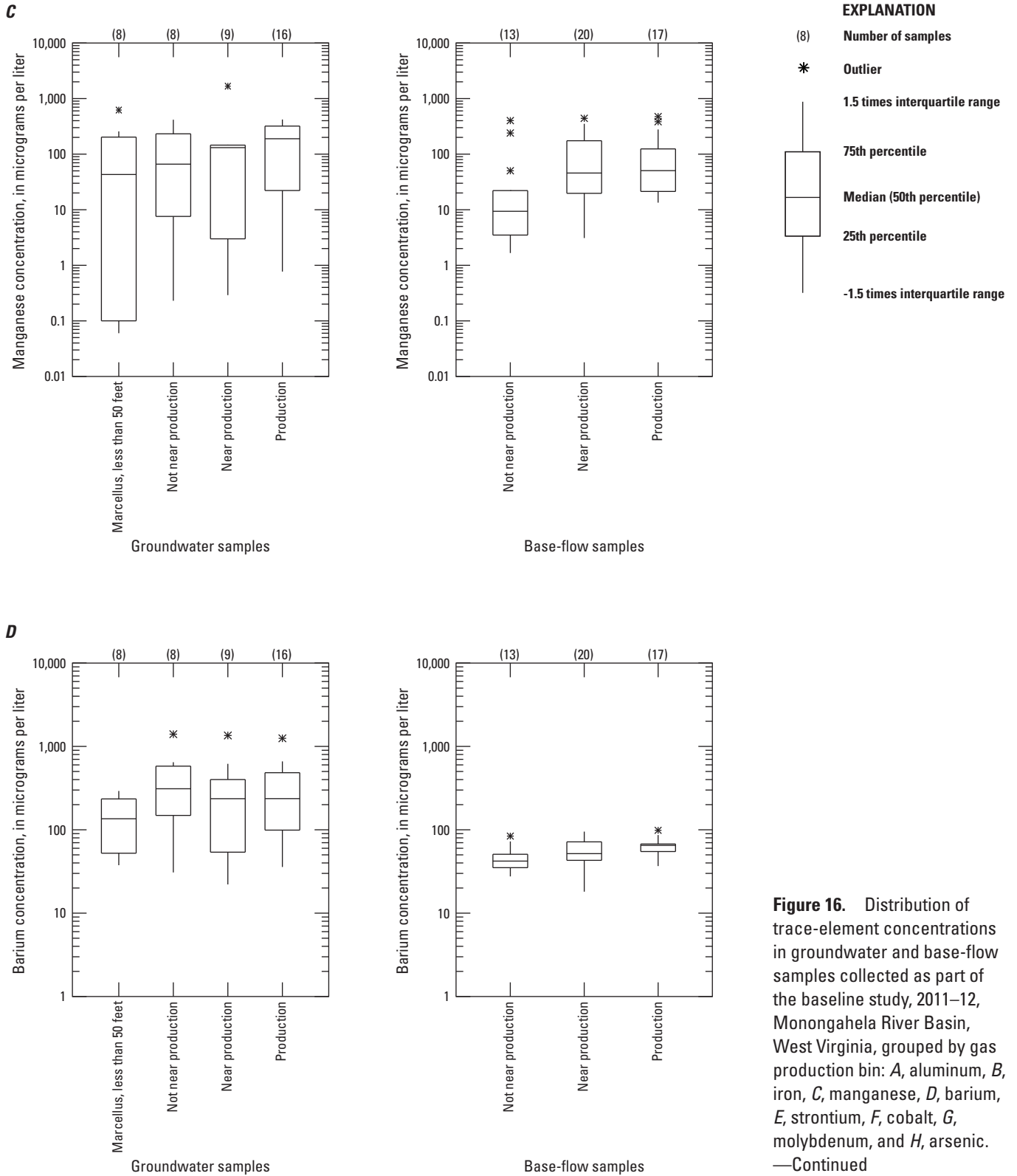


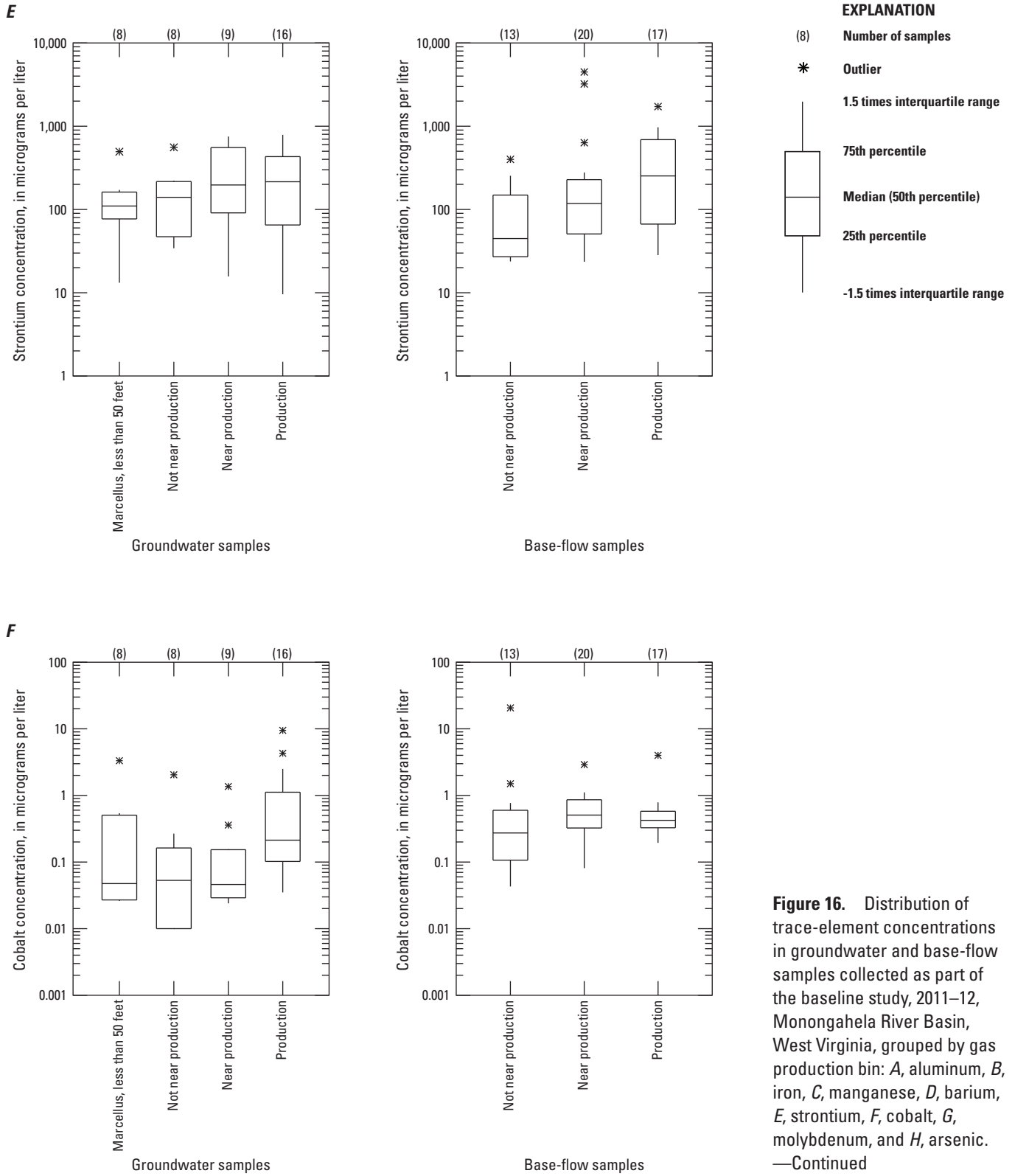
**Figure 15.** Distribution of trace-element concentrations in groundwater and base-flow samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical trace-element concentrations, Monongahela River Basin, West Virginia: *A*, aluminum, *B*, iron, *C*, manganese, *D*, barium, and *E*, strontium in base flow only.



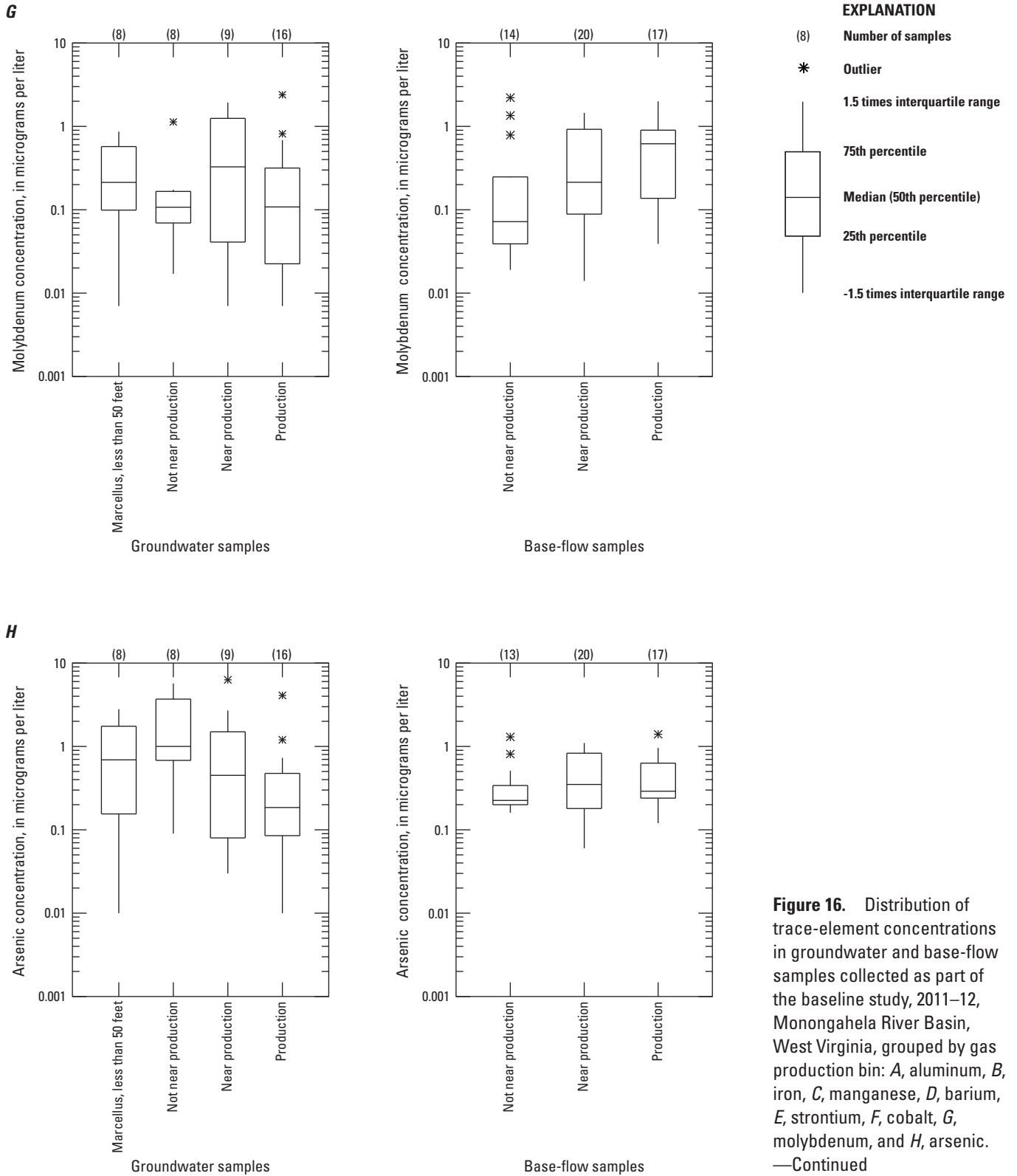
**Figure 15.** Distribution of trace-element concentrations in groundwater and base-flow samples collected as part of the Marcellus Shale baseline study, 2011–12, and historical trace-element concentrations, Monongahela River Basin, West Virginia: *A*, aluminum, *B*, iron, *C*, manganese, *D*, barium, and *E*, strontium in base flow only. —Continued











## Naturally Occurring Radioactive Materials

Numerous sources of naturally occurring radioactive material (NORM), such as uranium and radium, are present in the study area, including sandstone and shale, coal, and the deep formation water associated with oil and gas. Both uranium and thorium, NORMs that radioactively decay to radium isotopes, occur within the deeper shale-gas bearing formations of the Appalachian region (Rowan and others, 2011). Hem (1985) states that the range of uranium concentrations is typically between 0.10 µg/L and 10.0 µg/L.

For this study, only the more common NORMs—uranium (U), uranium isotopes (U-234, U-235, U-238), and radium (Ra) isotopes (Ra-224, Ra-226, Ra-228)—were analyzed (table 1). All samples were analyzed for total uranium. If uranium was detected in a sample, that sample was further analyzed for uranium and radium isotopes. Total uranium is composed of several isotopes including U-234, U-235, and U-238. U-238 is the dominant form and is the starting point in a radioactive decay series that ends with lead-206 (Hem, 1985). Radium has four naturally occurring isotopes (Ra-223, Ra-224, Ra-226, and Ra-228). Ra-228 and Ra-224 are

disintegration products of thorium-232, Ra-223 is a disintegration product of U-235, and Ra-226 is a disintegration product of U-238 (Hem, 1985). Additionally, gross alpha and beta activities were determined for all samples (table 6).

Of the 41 groundwater samples analyzed for uranium, none exceeded the USEPA MCL of 30 µg/L (table 6). Eighteen of 41 samples had concentrations less than the 0.004 µg/L analytical method detection limit, and the median concentration was only 0.007 µg/L. Ra-224, Ra-226, and Ra-228 had similar low activities. None of the samples from the 41 wells that were analyzed for Ra-226, or the samples from 14 wells that were analyzed for Ra-228, had concentrations exceeding 5 picocuries per liter (pCi/L), and only 1 site (Pre-0163) had a concentration of combined Ra-226 and Ra-228 (5.1 pCi/L) greater than 5 pCi/L, which is the EPA MCL drinking water standard for combined Ra-226 and Ra-228. Median activities of Ra-226 and Ra-228 were only 0.27 pCi/L and 0.42 pCi/L, respectively (table 6). Of the 41 wells sampled, only 5 wells—Pre-0163, Pre-0162, Lew-0221, Tay-0130, and Pre-0172—had either a single value or combined value of Ra-226 or Ra-228 exceeding 1.0 pCi/L. The source of radium in these outlier wells is unknown.

**Table 6.** Statistical summary of naturally occurring radioactive materials in groundwater and base-flow samples collected as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, 2011–12.

[µg/L, micrograms per liter; <, less than; U, uranium; Ra, radium; Th, thorium; pCi/L, picoCuries per liter; wf, filtered water sample, SSLC, sample-specific laboratory criteria; MCL, maximum contaminant level (U.S. Environmental Protection Agency, 2009); NA, not applicable]

Trace element in filtered samples	Method reporting level	Survey	Minimum value	Maximum value	Median value	MCL
Uranium, wf, µg/L	0.004	Groundwater	<0.004	0.682	0.007	30
		Base flow	<0.004	1.39	0.066	
U-234, wf, pCi/L	0.1	Groundwater	<SSLC	0.43	0.34	NA
		Base flow	<SSLC	0.590	0.120	
U-235, wf, pCi/L	0.1	Groundwater	<SSLC	0.025	<SSLC	NA
		Base flow	<SSLC	0.03	<SSLC	
U-238, wf, pCi/L	0.1	Groundwater	<SSLC	0.24	0.015	NA
		Base flow	<SSLC	0.44	0.10	
Ra-224, wf, pCi/L	1	Groundwater	<SSLC	3.90	<SSLC	NA
		Base flow	<SSLC	0.80	<SSLC	
Ra-226, wf, pCi/L	1	Groundwater	<SSLC	1.90	0.27	NA
		Base flow	<SSLC	3.00	<SSLC	
Ra-228, wf, pCi/L	1	Groundwater	<SSLC	3.20	0.42	NA
		Base flow	<SSLC	0.41	<SSLC	
Ra-228 + Ra-226, wf, pCi/L	1	Groundwater	<SSLC	5.10	0.42	1 <sup>5</sup> for Ra226 + Ra228
		Base flow	<SSLC	3.00	<SSLC	
Alpha-radioactivity, wf, as Th-230, pCi/L	4	Groundwater	<SSLC	6.80	0.80	15
		Base flow	<SSLC	2.60	<SSLC	
Gross beta-radioactivity, wf, as cesium-137, pCi/L	3	Groundwater	<SSLC	5.10	1.20	NA
		Base flow	<SSLC	7.40	2.20	

<sup>1</sup>One sample exceeded the 5 pCi/L MCL for Ra-226 plus Ra-228, Pre-0163 with an activity of 5.1 pCi/L.

Uranium was detected in 47 of the 50 base-flow survey samples. Concentrations in four samples were less than the laboratory reporting of 0.004 µg/L. The highest uranium concentration was 1.39 µg/L, and the median concentration was 0.066 µg/L (table 6). Uranium concentrations did not vary significantly among the gas-production bins (Kruskal-Wallis test,  $p = 0.0678$ ) (fig. 17). The 47 samples with quantifiable concentrations of uranium were analyzed for uranium isotopes U-234, U-235 and U-238. Uranium-238 was found in the greatest number of samples, 31, with a maximum activity of 0.44 pCi/L.

Radium-226, the most common radium isotope, was found in only 13 of the 50 base-flow survey samples. The highest activity was 3.0 pCi/L (table 6) in the sample from Elk Creek near Romines Mills, W.Va. No base-flow survey sample exceeded the EPA MCL of 5.0 pCi/L. The other radium isotopes analyzed for, radium 224 and radium 228, were detected in 7 and 2 samples, respectively.

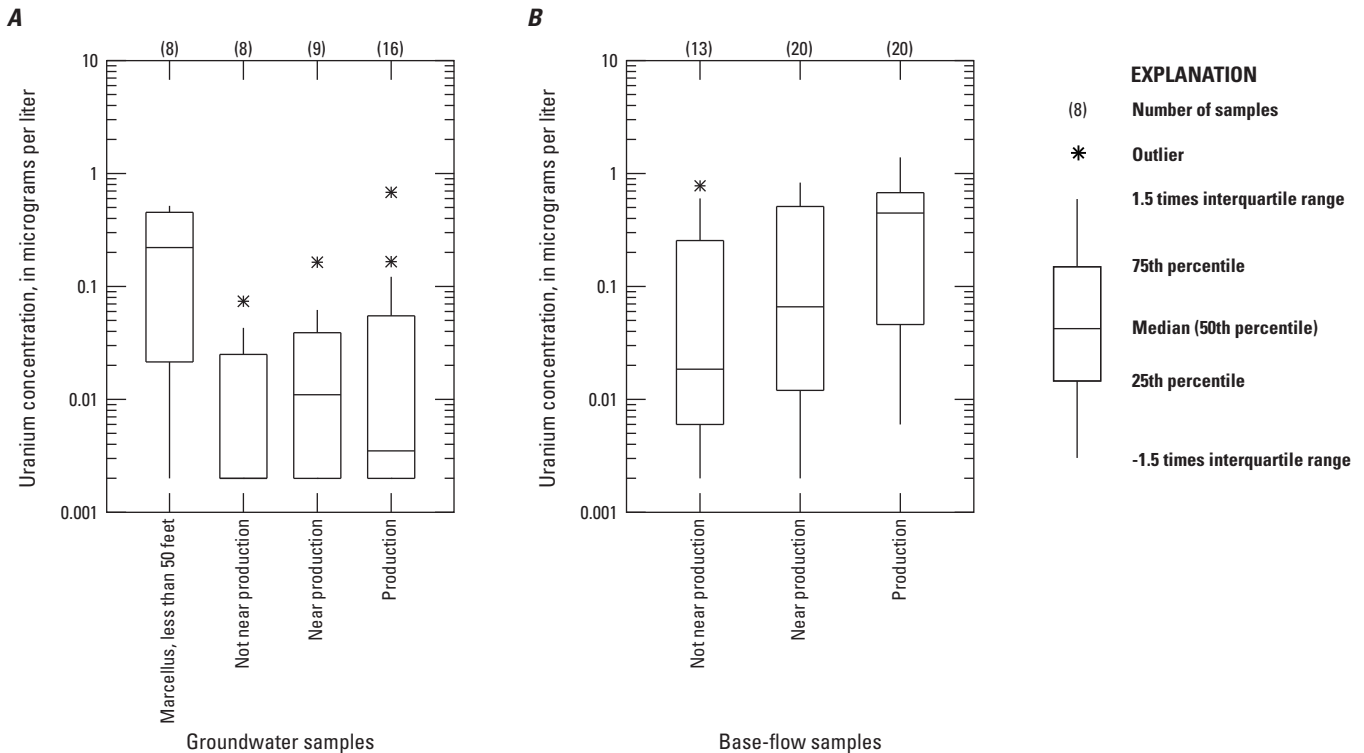
### Isotopes

Isotopic data sampling and analytical methods are discussed in detail by Mulder (2012) and Pelak (2014). The studies by Mulder (2012) and Pelak (2014) included analysis for  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ ,  $\delta^2\text{H}_{\text{H}_2\text{O}}$ ,  $\delta^{13}\text{C}_{\text{DIC}}$ ,  $\delta^{34}\text{S}_{\text{SO}_4}$ ,  $\delta^{18}\text{O}_{\text{SO}_4}$ ,  $\delta^2\text{H}_{\text{CH}_4}$ , and  $\delta^{13}\text{C}_{\text{CH}_4}$ .

These studies also present analysis of the isotopic and supporting major ion data, and interpretation of processes and major findings based on the isotopic analysis.

Numerous studies have been done to analyze national and global trends in oxygen-18 ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta^2\text{H}$ ) in precipitation and rivers. Kendall and Coplen (2001) correlated areas across the United States using  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ ,  $\delta^2\text{H}_{\text{H}_2\text{O}}$ , deuterium excess (*d*-excess), and the corresponding Global Meteoric Water Line (GMWL) slope. Groundwater results for the study area fall within the range of the central east coast data for all mentioned constituents. Topography, latitude, and temperature are shown to affect the composition of  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  on the east coast and, therefore, the study area.

The composition of hydrogen and oxygen isotopes in groundwater samples shows signatures similar to those of precipitation and river water in the study area, which are more depleted on the east coast than on the west coast. The isotopic signatures in the groundwater samples also have corresponding higher *d*-excess values. These higher *d*-excess values are the result of the study area being downwind of air masses originating in the Great Lakes area. The original air masses are subjected to high rates of evaporation over the water bodies, and the evaporative vapor is mixed with atmospheric waters. In conjunction with local processes, such as altitude and latitude, the isotopic signatures of  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  and  $\delta^2\text{H}_{\text{H}_2\text{O}}$  plot above the GMWL in the area of an arid vapor mass.



**Figure 17.** Distribution of uranium concentrations in groundwater and base-flow samples collected as part of the Marcellus Shale baseline study, Monongahela River Basin, West Virginia, 2011–12, grouped by gas production bin: A, groundwater samples and B, base-flow samples.

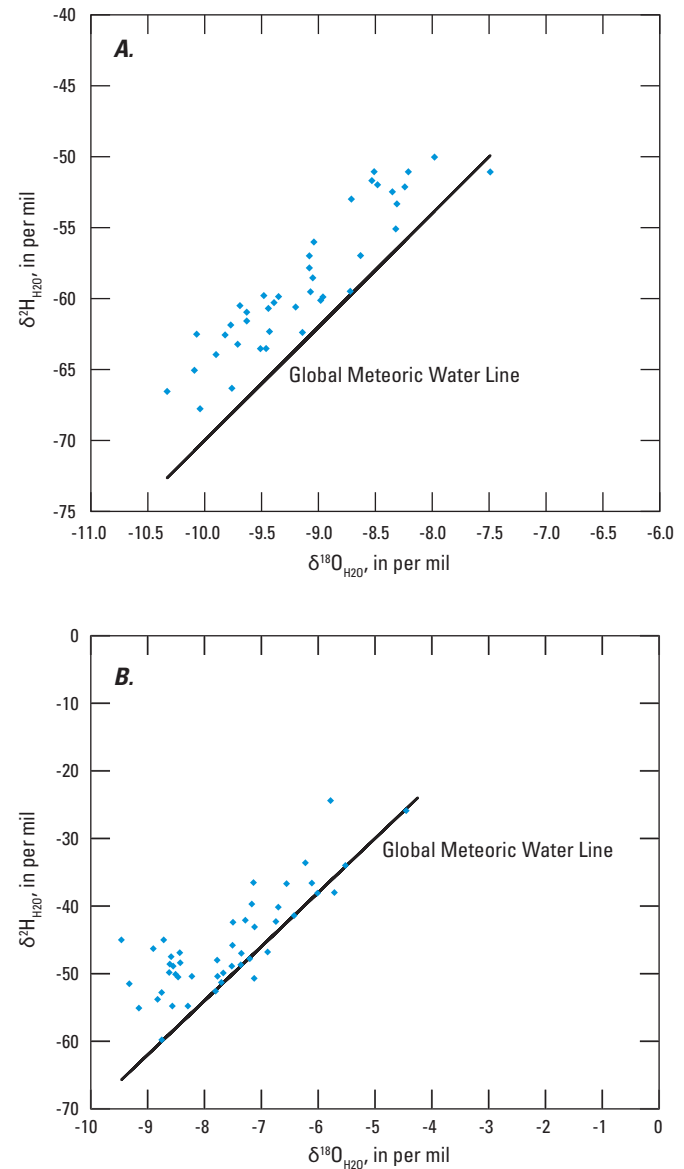
## Groundwater Survey

The overall signatures of the study area groundwater demonstrate a combination of local effects with processes moving downwind from the Great Lakes, affecting precipitation and, therefore, groundwater recharge. The processes may involve elevation, topography, temperature, and humidity levels. The cluster of oxygen and hydrogen isotopic data points along the GMWL indicate steady vapor mass sources (fig. 18). The position of data points on the GMWL indicates a deceptively arid source but is the result of a mixed vapor mass of evaporative and atmospheric moisture originating from the Great Lakes.

Isotope analyses were done for dissolved methane in 11 of the 41 groundwater samples. The isotopic signatures of methane ( $\delta^2\text{H}_{\text{CH}_4}$  and  $\delta^{13}\text{C}_{\text{CH}_4}$ ) in groundwater can be plotted to evaluate several possible sources of methane, including thermogenic, biogenic, or mixed sources (fig. 19A–C). Dominantly deep microbial stimulated methane with mixing is shown in Coleman (1994). Methane originating from biogenic and thermogenic sources and a mix of the two is shown in Whiticar (1999), and a dominantly thermogenic source is shown in Molofsky and others (2011). Methane in all groundwater samples falls within a cluster distinct from that of the Marcellus Shale gas collected from Greene County, Pa., and distinct from gases collected from Ordovician-, Silurian- and Devonian-age formations in West Virginia and Pennsylvania (Sharma and others, 2013a; 2014a; 2014b). The isotopic signatures of methane in the 11 samples from this study are generally similar to the isotopic signatures of coal-bed methane—a mixture of methane from both biogenic and thermogenic processes, or a mixture of methane from all three sources, biogenic, thermogenic and coal-bed methane.

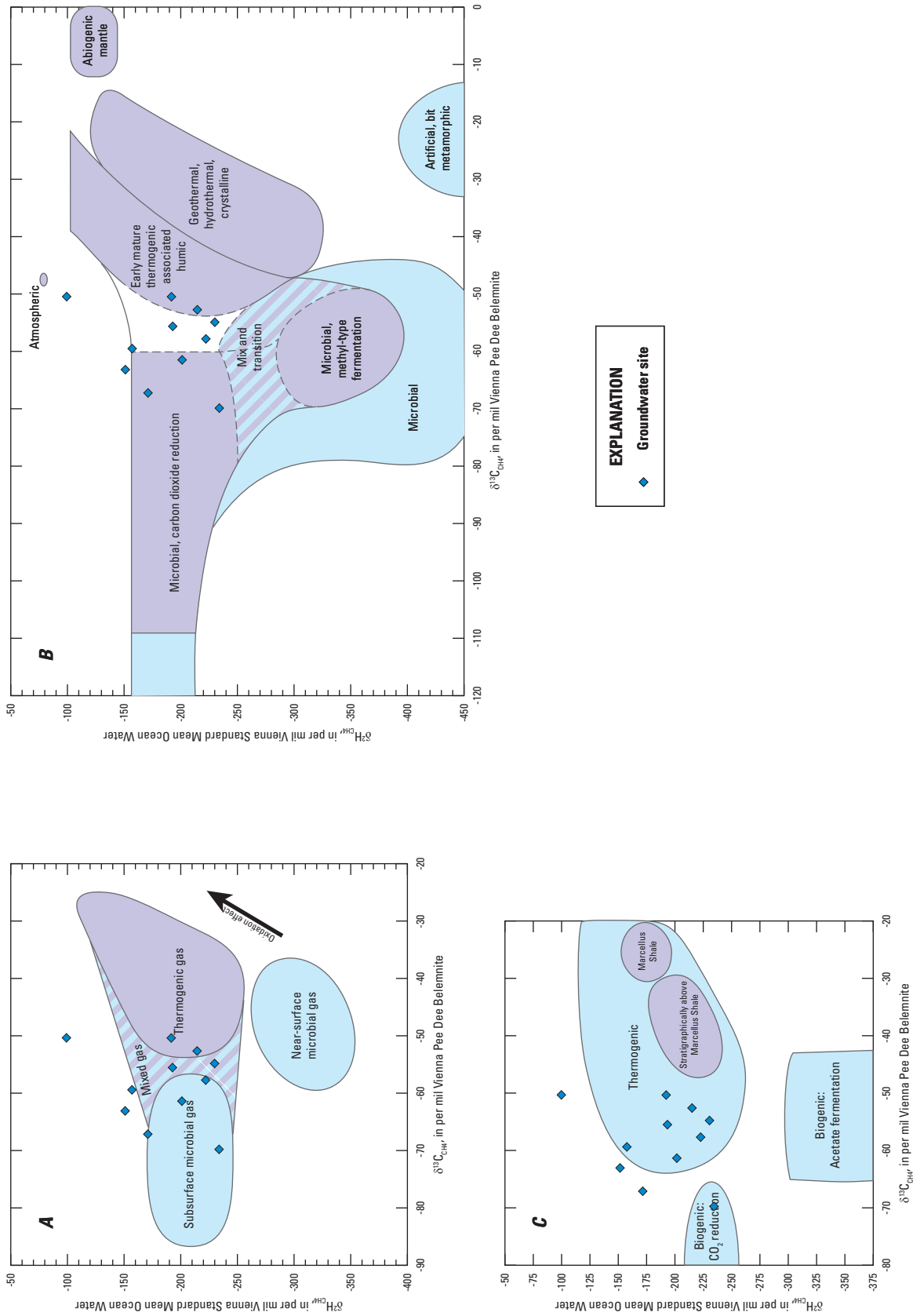
## Base-Flow Survey

No major deviations from the GMWL were observed for base-flow samples, indicating that meteoric water and shallow groundwater are major components in these streams. Water samples collected from streams at highest elevations, 1,335 to 2,854 feet above MSL, on the eastern and southern edges of the study area had the most depleted values of  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  and  $\delta^2\text{H}_{\text{H}_2\text{O}}$  owing to the elevation effect (Dansgaard, 1964, Pelak and Sharma, 2014). None of the base-flow samples had enriched  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  and  $\delta^2\text{H}_{\text{H}_2\text{O}}$  composition, which is seen in backflow waters associated with Marcellus Shale development (Dresel and Rose, 2010; Warner and others, 2012; Sharma and others, 2014a). In addition, none of the base-flow samples show preferential enrichment of  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  over  $\delta^2\text{H}_{\text{H}_2\text{O}}$ , leading to a more horizontal shift to the right of the GMWL, as seen in the brines of the area (Warner and others, 2012; Sharma and others, 2014a; Pelak and Sharma, 2014). Variations in  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  and  $\delta^2\text{H}_{\text{H}_2\text{O}}$  are likely due to local differences in soil water, groundwater recharge, and elevation effects.



**Figure 18.** Oxygen and hydrogen isotopic composition of water in A, groundwater samples and B, base-flow samples collected as part of the Marcellus Shale baseline study in the Monongahela River Basin, West Virginia, 2011–12, and the Global Meteoric Water Line (Global Meteoric Water Line from Craig, 1961).

The main sources of dissolved inorganic carbon (DIC) in surface waters are the decay of organic matter, carbonate dissolution, and diffusion of atmospheric  $\text{CO}_2$ . The relative contribution of carbon from different end members and carbon speciation ultimately controls the overall  $\delta^{13}\text{C}_{\text{DIC}}$  composition of the water. The range of  $\delta^{13}\text{C}_{\text{DIC}}$  in most natural waters receiving almost equal contributions from decaying organic matter and soil carbonate dissolution is from -16 to -11 per mil (‰) Vienna Pee Dee belemnite (VPDB; Clark and Fritz, 1997). The  $\delta^{13}\text{C}_{\text{DIC}}$  in most of the base-flow survey samples



**Figure 19.** Isotopic signatures of dissolved methane in 11 groundwater samples collected as part of the Marcellus Shale baseline study, Monongahela River Basin, West Virginia, 2011, in samples from the Marcellus Shale gas separation tank, and in various other sources: *A*, deep, microbially stimulated methane (Coleman, 1994); *B*, biogenic, thermogenic, and mixed source methane (Whiticar, 1999); and *C*, predominantly thermogenic methane signature (Molofsky and others, 2011).

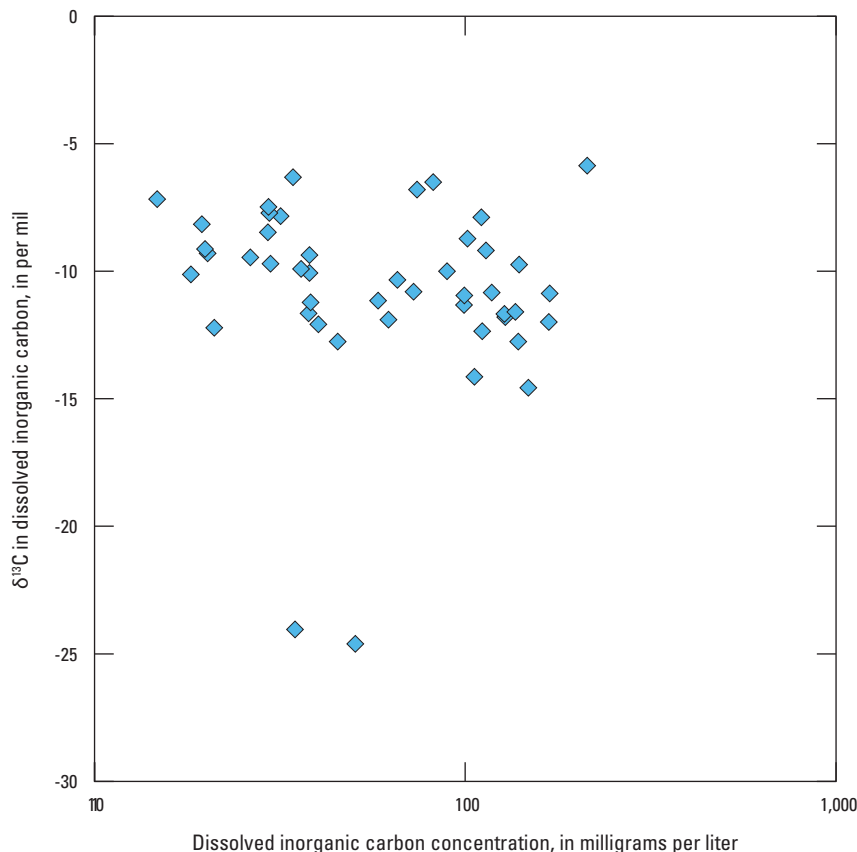
ranged from -14.57 to -5.87 ‰ VPDB, but two samples had  $\delta^{13}\text{C}_{\text{DIC}}$  values of -24.61 ‰ and -24.05 ‰ VPDB (fig. 19). These two samples were collected from the High Production and Near Low Production bins in study area. In a recent study, the  $\delta^{13}\text{C}_{\text{DIC}}$  values of backflow water collected from Marcellus Shale wells was found to be highly enriched with an average value +21 ‰ VPDB owing to late stage biogenic methanogenesis (Sharma and others, 2013b). However, no water samples had positive  $\delta^{13}\text{C}_{\text{DIC}}$  signatures similar to that of backflow water from Marcellus Shale operations. The two samples with low  $\delta^{13}\text{C}_{\text{DIC}}$  values ( $\sim -24$  ‰) are most likely receiving carbon from oxidation of isotopically depleted sources, such as soil organic matter decay or coals/shales in the region, which are known to have a range of -25.4 to -21.6 ‰ VPDB (Sharma and others, 2013b). Out of the remaining samples, 58 percent have  $\delta^{13}\text{C}_{\text{DIC}}$  values greater than -11 ‰, indicating a contribution from dissolution of isotopically enriched carbonate rocks (fig. 20).

Oxidation of pyritic sulfides in coal beds can result in the production of sulfuric acid ( $\text{H}_2\text{SO}_4$ ), which can result in enhanced dissolution of isotopically enriched carbonate (Sharma and others, 2013b). In addition, degassing of isotopically depleted  $\text{CO}_2$  species from total DIC in standing or slow

moving streams or invasion of isotopically enriched atmospheric  $\text{CO}_2$  in waters with low partial pressures of  $\text{CO}_2$  can also result in slight enrichment of  $\delta^{13}\text{C}_{\text{DIC}}$  in waters (Atekwana and Krishnamurthy, 1998; Doctor and others, 2008; Sharma and others, 2013b). This indicates that some of the enriched  $\delta^{13}\text{C}_{\text{DIC}}$  signatures seen in streams could be the result of a contribution from mine discharges or atmospheric exchange, especially in slow moving streams.

The stable isotopes of  $\delta^{34}\text{S}_{\text{SO}_4}$  and  $\delta^{18}\text{O}_{\text{SO}_4}$  have been used to distinguish sources of dissolved sulfate in streams and the processes controlling the overall sulfate concentration. The stable isotopes for the base-flow samples were  $\delta^{34}\text{S}_{\text{SO}_4}$ , ranging from -7.60 to +13.40 ‰ Vienna Canyon Diablo Troilite (VCDT) and  $\delta^{18}\text{O}_{\text{SO}_4}$ , ranging from -6.4 ‰ to +10.6 ‰.

No pattern was observed among concentrations of  $\delta^{18}\text{O}_{\text{SO}_4}$  and  $\delta^{34}\text{S}_{\text{SO}_4}$  and Marcellus Shale gas-production bins. It is assumed that the primary source of dissolved sulfate in the samples for this study is from the oxidation of pyritic minerals (Cravotta, 2008a). The large variation in values of  $\delta^{34}\text{S}_{\text{SO}_4}$  in this study could be due to the wide range in values for pyrite minerals found in many strata in the study area (Mulder, 2012). There is little to no fractionation of sulfur during



**Figure 20.** Isotopic composition of dissolved inorganic carbon in base-flow samples collected as part of the Marcellus Shale baseline study, Monongahela River Basin, West Virginia, 2012.

the oxidation of sulfide, meaning  $\delta^{34}\text{S}_{\text{SO}_4}$  values will remain virtually the same as that in the material they were derived from. The  $\delta^{34}\text{S}_{\text{SO}_4}$  value of pyrite in general has a wide range, from -25 to 0 ‰ VCDT (Clark and Fritz, 1997). A recent study (Sharma and others, 2013b) found that coals and shales of the Pittsburgh coal bed had  $\delta^{34}\text{S}_{\text{SO}_4}$  values ranging from +0.6 ‰ to +2.4 ‰ VCDT. Reducing conditions for the surface waters in this study would be limited to stagnant pools with an organic substrate, wetland areas, and similar situations; the bacterial sulfate reduction of pyrite in surface water is limited. However, bacterial sulfate reduction occurring in anaerobic waters, such as water from coal mines, causes  $\delta^{34}\text{S}_{\text{SO}_4}$  and  $\delta^{18}\text{O}_{\text{SO}_4}$  enrichment as a result of the preferential use of the lighter  $^{32}\text{S}$  isotope by sulfate-reducing bacteria. Contributions to streamflow from flooded underground mines or abandoned surface mines are common and widespread in the study area (McColloch and others, 2012). Reducing conditions are possible in mine pools, and bacterial reduction of sulfate in these pools confounds the interpretation of the isotopic composition of sulfate. Because the samples show  $\delta^{34}\text{S}_{\text{SO}_4}$  values ranging from -7.60 to +13.40 ‰ VCDT, it is not clear whether samples with enriched values of  $\delta^{34}\text{S}_{\text{SO}_4}$  are due to streams receiving input from dissolved sulfate that has been bacterially reduced or whether the pyrite from which the sulfate is derived has enriched values (>0 ‰) for  $\delta^{34}\text{S}_{\text{SO}_4}$ .

Stable isotope values of  $\delta^{18}\text{O}_{\text{SO}_4}$  also show a wide range of values for the base-flow samples. The source of oxygen in dissolved sulfate is derived from the oxygen in water and from atmospheric  $\text{O}_2$  (Gu and others, 2008; Toran and Harris, 1989). The value of  $\delta^{18}\text{O}_{\text{SO}_4}$  depends largely upon the environment in which the sulfide oxidation occurred. For base-flow samples, 85 percent had  $\delta^{18}\text{O}_{\text{SO}_4}$  values greater than 0‰, indicating that these samples are receiving  $^{18}\text{O}$  from atmospheric  $\text{O}_2$ , which has a more enriched value (+23.5 ‰; Kroopnick and Craig, 1972) relative to surface waters in the study area. Because of the large range in  $\delta^{34}\text{S}_{\text{SO}_4}$  and  $\delta^{18}\text{O}_{\text{SO}_4}$  values in the samples, multiple processes, such as sulfate reduction, atmospheric input, and a wide range of sulfur isotope values for pyrite, are likely to affect the isotopic composition of sulfate.

## Dissolved Gases

Gases, either atmospheric or derived from biogeochemical processes in aquifers, can provide information to better understand the source of recharge to the groundwater system. Nitrogen, oxygen, argon, and carbon dioxide, the primary gases in the atmosphere, are present at concentrations of approximately 78.1 percent ( $\text{N}_2$ ), 20.9 percent ( $\text{O}_2$ ), 0.93 percent (Ar), and 0.03 percent ( $\text{CO}_2$ ), respectively (Hem, 1985). Atmospheric gases are absorbed by precipitation; the partial pressures of the gases are in proportion to barometric pressure (Busenberg and others, 2001). When precipitation falls on the surface of the earth, some of the water seeps into soil and rock, recharging the groundwater system. As the water percolates through the soil and rock, soil gases become entrained and

eventually are dissolved in the recharge water. The addition of soil gases to recharge water can result in the presence of dissolved gases in proportions greater than that in the atmosphere, referred to as excess air (Busenberg and others, 2001).

Methane, another gas found in the groundwaters of the study area, is present in the atmosphere but at low concentrations (0.00015 ‰; Hem, 1985). Methane in groundwater is primarily due to methanogenesis, the breakdown of organic compounds, in either shallow biogenic environments, such as wetlands and landfills, or deeper thermogenic environments, such as oil and gas reservoirs. Methanogenesis in groundwater is indicative of reducing environments within the aquifer. Coal-bed methane (CBM) is another source of methane in groundwater, but it is not well understood whether CBM in the study area is derived from biogenic or thermogenic methanogenesis (Mulder, 2012).

In addition, because dissolved gas concentrations in the atmosphere are dependent on barometric pressure, the sum of all gases in the atmosphere is equal to the barometric pressure (Busenberg and others, 2001). The partial pressure of gases decreases as elevation increases and increases as elevation decreases. In addition, the temperature of water recharging an aquifer can be calculated from the concentrations of  $\text{N}_2$ , Ar, and other noble gases, based on the principles of Henry's Law, assuming that gases in the recharging water were in equilibrium with the atmosphere at the temperature at which recharge became isolated from the atmosphere (Busenberg and others, 2001). The analyses of dissolved gases in groundwater samples can provide significant insight into the origin of water recharging an aquifer.

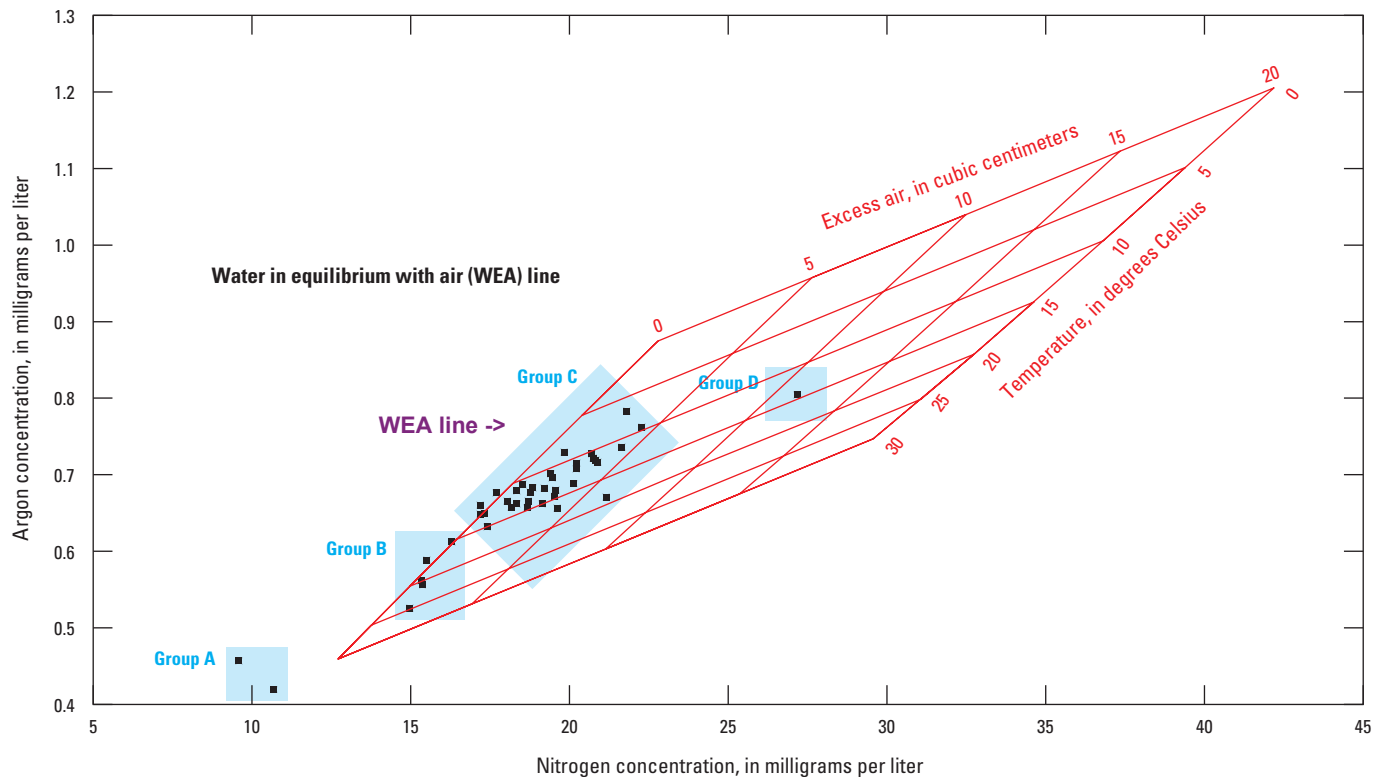
For this study, samples were collected from 39 wells and 2 springs in the study area and analyzed for dissolved gas concentrations of nitrogen ( $\text{N}_2$ ), argon (Ar), oxygen ( $\text{O}_2$ ), carbon dioxide ( $\text{CO}_2$ ), and methane ( $\text{CH}_4$ ), which are summarized in table 7. The concentration of Ar in relation to the concentration of  $\text{N}_2$  is shown in figure 21, which also shows estimates of excess air content and recharge temperature, based on normalized sea-level concentrations. Samples clustering along the water in equilibrium with air (WEA) line are indicative of shallow groundwater with dissolved gas concentrations similar to that of the atmosphere. In the dissolved gas plot, samples cluster in three distinct groups (A-B-C in fig. 21) with the exception of the sample from well UPS-0178 (D in fig. 21), which had no close affinity to any of the groups.

The dissolved-gas concentration signatures in most of the samples, 38 of 41, indicate a shallow groundwater source. These 38 samples cluster in two groups of 33 and 5 samples. The larger of the two clusters (group C in fig. 21) had excess air components between 0 mL and 5 mL and estimated recharge temperatures between 5 degrees Celsius ( $^{\circ}\text{C}$ ) and  $15^{\circ}\text{C}$ , dissolved gas profiles similar to those of typical shallow groundwater found in domestic wells within the study area (McCoy and Kozar, 2007). The estimated recharge temperatures point towards recharge occurring during colder months of the year. The cluster of five samples (group B, fig. 21) had

**Table 7.** Statistical summary of dissolved gases in groundwater samples collected as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, 2011.

[mg/L, milligrams per liter; <, less than]

Trace element in filtered samples	Method reporting level	Minimum concentration	Maximum concentration	Median concentration
Nitrogen, N <sub>2</sub> , dissolved, mg/L	0.001	9.6	27.2	18.8
Oxygen, O <sub>2</sub> , dissolved, mg/L	0.002	0.104	8.19	0.252
Argon, dissolved, mg/L	0.003	0.419	0.804	0.676
Carbon dioxide, dissolved, mg/L	0.04	0.33	68.8	18.5
Methane, dissolved, mg/L	0.001	<0.001	48.2	0.04



**Figure 21.** Concentrations of dissolved nitrogen in relation to concentrations of dissolved argon in samples from 39 wells and 2 springs collected as part of the baseline study, Monongahela River Basin, West Virginia, 2011, with associated estimates of recharge temperature and excess air, based on normalized sea-level concentrations. (WEA, water-in-equilibrium-with-air line; boxes labeled A through D indicate groups of similar samples)



little excess air and plot near the WEA line; only 1 of the 5 sites had a detectable concentration of methane. Two of the 5 sites are springs, and the remaining 3 sites are shallow wells with depths of 70, 80, and 145 feet. All five sites had warmer than average recharge-temperature estimates for groundwater in the study area, ranging from about 15 °C to 25 °C, likely representing a significant component of recharge that occurred just prior to the sampling in June through September 2011.

Of the three remaining samples, two were clustered (group A, fig. 21) and the third was not associated with any group (fig. 21). The two samples of group A are enriched in methane and have partial pressures of atmospheric gases that are below equilibrium with the atmosphere. These samples have the highest concentrations of methane gas of the 41 wells sampled, 21.9 mg/L and 48.2 mg/L. These samples likely reflect a mixture of shallow groundwater with a thermogenic gas component, possibly derived from deeper gas and hydrocarbon reservoirs. Low concentrations of atmospheric gases in these samples may also be partially a result of air stripping, whereby a portion of gases is carried along with the methane as it percolates upward from a hydrocarbon reservoir. The outlier sample (well Ups-0178) not associated with any group is distinguished from all other samples by a much higher than average N<sub>2</sub> concentration, 27.2 mg/L compared to an average concentration of 18.6 mg/L. None of the other atmospheric gases (O<sub>2</sub>, CO<sub>2</sub>, and Ar) were present in high concentrations. Methane was present at a concentration of 7.5 mg/L in water from well Ups-0178.

## Water-Quality Patterns

The primary goal of this study was to describe groundwater and base-flow water quality during the early stages of shale-gas development. Water-quality data from early shale-gas development then could be used for comparison with data collected later as development proceeds. The collection of the water-quality data has afforded an opportunity to examine patterns in water quality. Data from the groundwater survey and the base-flow survey were compared with historical data from sites in the study area to determine whether temporal changes had occurred. The base-flow survey was designed to facilitate a comparison of sites grouped by gas-production land use, and comparisons were made among these classifications. Additionally, groundwater survey data were examined using a multivariate analysis to discern relations among the water-quality data.

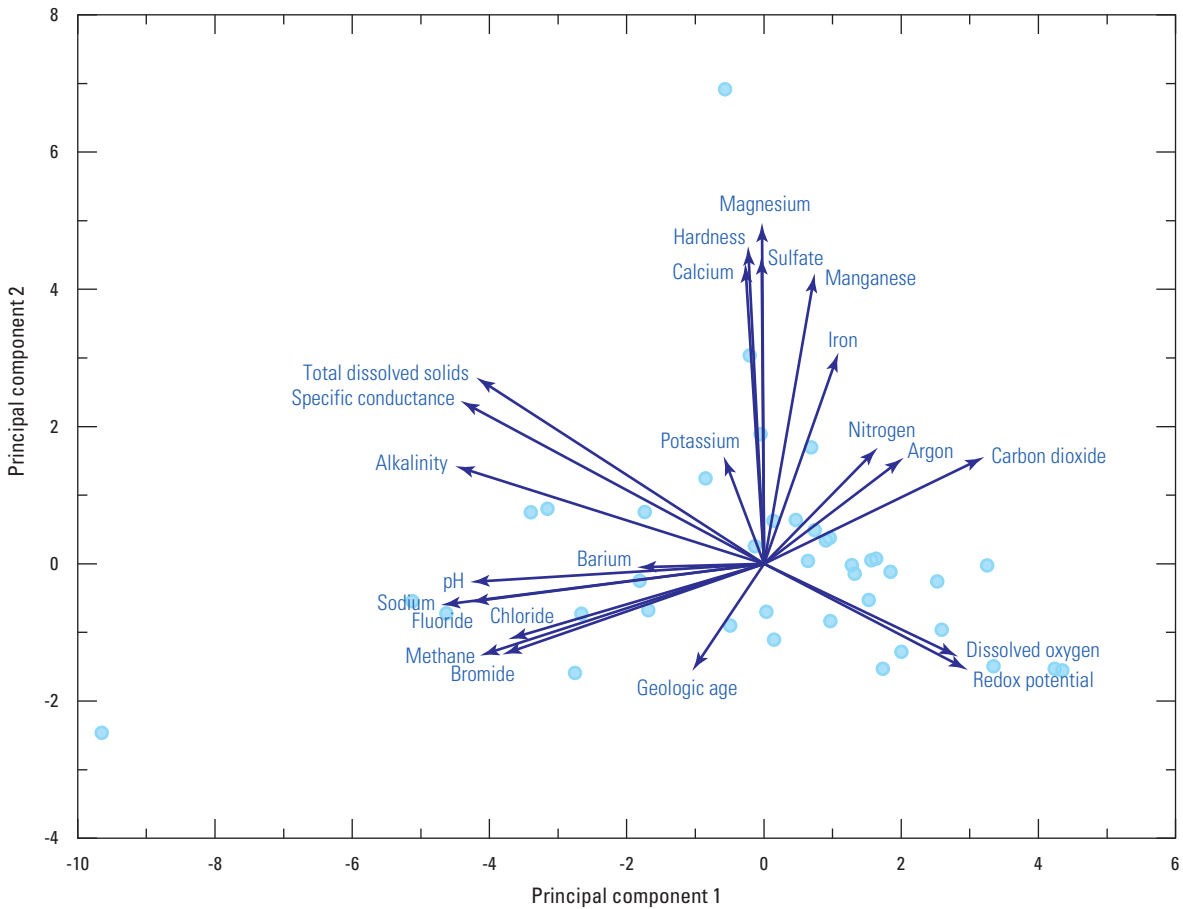
Patterns in groundwater quality were examined by comparing data collected in this study with data collected for other purposes, such as the West Virginia Ambient Groundwater Network database (Chambers and others, 2012), a principal components analysis, and a geospatial analysis of dissolved gas. The comparison of groundwater data from this study with historical data found no significant difference for any of the

constituents examined and therefore warrant no further discussion. The PCA and the geospatial analysis are discussed below.

A PCA was conducted to discern patterns in groundwater quality. An initial PCA was run on all available groundwater-quality constituents and properties, including major ions, trace metals, dissolved gases, radionuclides, isotopes, and well depth. Correlations among variables also were assessed by computing correlation matrices. Variables with a majority of missing values or values below the laboratory reporting level, variables that contributed insignificantly to component loadings, or variables that exhibited no correlation with other variables were excluded from subsequent PCAs. The first two principal components from the final PCA explained 54 percent of the variance—principal component 1, 31 percent and principal component 2, 23 percent—within the data matrix (fig. 22).

The first principal component indicates gradients of redox conditions and dissolved solids concentrations with strong negative loadings for sodium, bromide, chloride, fluoride, barium, total dissolved solids, specific conductance, pH, and methane, which were inversely proportional to dissolved oxygen, carbon dioxide, argon, nitrogen, and redox potential (table 8). This gradient may reflect a continuum from deeper waters with higher concentrations of sodium, barium, chloride, bromide, methane, and fluoride, constituents typically found in higher concentrations in deeper brines, and shallow, more dilute, more recent waters with higher concentrations of dissolved atmospheric gases. Whether this continuum reflects a typical gradient from recharge to shallow groundwaters to deeper groundwaters or indicates other pathways resulting in mixing of shallow groundwaters and deeper brines is unknown.

The second principal component had strong positive loadings for calcium, magnesium, potassium, iron, manganese, sulfate, total dissolved solids, specific conductance, argon, nitrogen, carbon dioxide, and hardness, and negative loadings for geologic age, methane, redox potential, bromide, and dissolved oxygen. In a pattern similar to the first principal component, the second component reflects a gradient from conditions typical of shallow groundwaters in the Appalachian region, which have high concentrations of total dissolved solids, iron, manganese, calcium, magnesium, and sulfate, to conditions more typical of deeper groundwaters. Carbonate dissolution and reduction of pyrite and siderite are dominant processes in the shallow aquifers of the region and can result in elevated concentrations of total dissolved solids, iron, calcium, and sulfate, whereas higher concentrations of chloride and bromide are more common in deeper waters. Because the primary cations and anions are inversely correlated with geologic age, this component may also reflect the effects of coal mining, which is prevalent in younger Pennsylvanian-age geologic formations, such as the Dunkard, Monongahela, Conemaugh, and Pottsville Groups, and the Allegheny, Kanawha, and New River Formations (fig. 2), all of which contain minable



**Figure 22.** Principal component axis scores for the two principal components for selected groundwater samples collected as part of the Marcellus Shale baseline study, Monongahela River Basin, West Virginia, 2011.

**Table 8.** Principal component loadings from analysis of 23 variables potentially affecting groundwater quality in the Monongahela River Basin in West Virginia, 2011.

[mg/L, milligrams per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius;  $\mu\text{g}/\text{L}$ , micrograms per liter; mV, millivolts;  $\text{CaCO}_3$ , calcium carbonate]

Component name	Component 1 loadings	Component 2 loadings	Component name	Component 1 loadings	Component 2 loadings
Specific conductance ( $\mu\text{S}/\text{cm}$ )	-0.311	0.194	Magnesium (mg/L)	<sup>1</sup>	0.405
pH (standard units)	-0.301	<sup>1</sup>	Potassium (mg/L)	<sup>1</sup>	0.128
Dissolved oxygen, field (mg/L)	0.199	-0.111	Sodium (mg/L)	-0.331	<sup>1</sup>
Argon (mg/L)	0.143	0.126	Alkalinity (mg/L as $\text{CaCO}_3$ )	-0.316	0.116
Nitrogen (mg/L)	0.117	0.138	Bromide (mg/L)	-0.268	-0.108
Carbon dioxide (mg/L)	0.226	0.127	Chloride (mg/L)	-0.262	<sup>1</sup>
Methane (mg/L)	-0.291	-0.109	Fluoride (mg/L)	-0.301	<sup>1</sup>
Geologic age <sup>2</sup>	<sup>1</sup>	-0.128	Sulfate (mg/L)	<sup>1</sup>	0.367
Redox Potential (mV)	0.209	-0.126	Barium ( $\mu\text{g}/\text{L}$ )	-0.130	<sup>1</sup>
Total dissolved solids (mg/L)	-0.295	0.221	Iron ( $\mu\text{g}/\text{L}$ )	<sup>1</sup>	0.251
Water hardness (mg/L)	<sup>1</sup>	0.378	Manganese ( $\mu\text{g}/\text{L}$ )	<sup>1</sup>	0.345
Calcium (mg/L)	<sup>1</sup>	0.357			

<sup>1</sup>Loadings less than 0.100 were not considered relevant and were not included.

<sup>2</sup>Geologic age used in this analysis is based on relative age of the geologic formation or group in millions of years.

coal seams. Mississippian- and Devonian-aged rocks within the study area do not contain minable coal seams.

The presence of constituents often associated with deeper brines, as indicated by the first principal component discussed above, and the frequent presence of methane in groundwater survey samples (56 percent of samples) may indicate mixing of a very small component of deeper groundwater with shallow groundwater. Bromide and methane frequently were present in the same groundwater samples.

To assess the potential for migration of brine waters and associated methane gas from deeper geologic strata or from shallow coal seams, the location of wells with elevated concentrations of methane were plotted on a map (fig. 23), along with the location of mined coal seams and shallow and deep structural geologic features (faults, synclines, and anticlines). None of the wells with samples containing methane concentrations greater than 1.0 mg/L are located within the footprint of current or abandoned underground or surface mines. The highest concentration of methane (48.2 mg/L) detected in this study was from a well (Ran-0276) at the southern end of the Elkins Valley Anticline. A nearby well (Ran-0278) also had an elevated concentration (8.39 mg/L) of methane. A thrust fault cuts through numerous formations, including the Marcellus Shale, and is expressed at the surface in the crest of the Elkins Valley Anticline (Ryder and others, 2008). However, no clear pattern linking methane concentrations to the presence of a geologic structure was noted because there were an approximately equal number of samples with detectable concentrations of methane from wells not located in or near geologic structures as there were samples from wells located in such structures.

No strong patterns were noted in the base-flow survey data. There were significant differences for some constituents in comparison to historical water-quality data or in comparisons among gas-production bins. Although there were no strong patterns obvious in the base-flow data, some more subtle patterns that may represent early changes in water quality as shale gas development proceeds were observed. These subtle patterns may warrant closer scrutiny as development intensifies and the effects of this development are realized over time.

Coal mining continues to exert a strong effect on water quality in the Monongahela River Basin (Anderson and others, 2000). A simple mining intensity index was developed for this report; mined areas in all the coal seams (West Virginia Geological and Economic Survey, 2011b) within a HUC-12 were summed, divided by the total surface area in the HUC-12, and expressed as a percentage. Values greater than 100 percent represent those areas where multiple seams that had been mined exceeded the overall surface area. No attempt was made to account for thickness, mining method or time, or mine discharge location. Had the primary focus of this study been on exploring the effects of coal mining on water

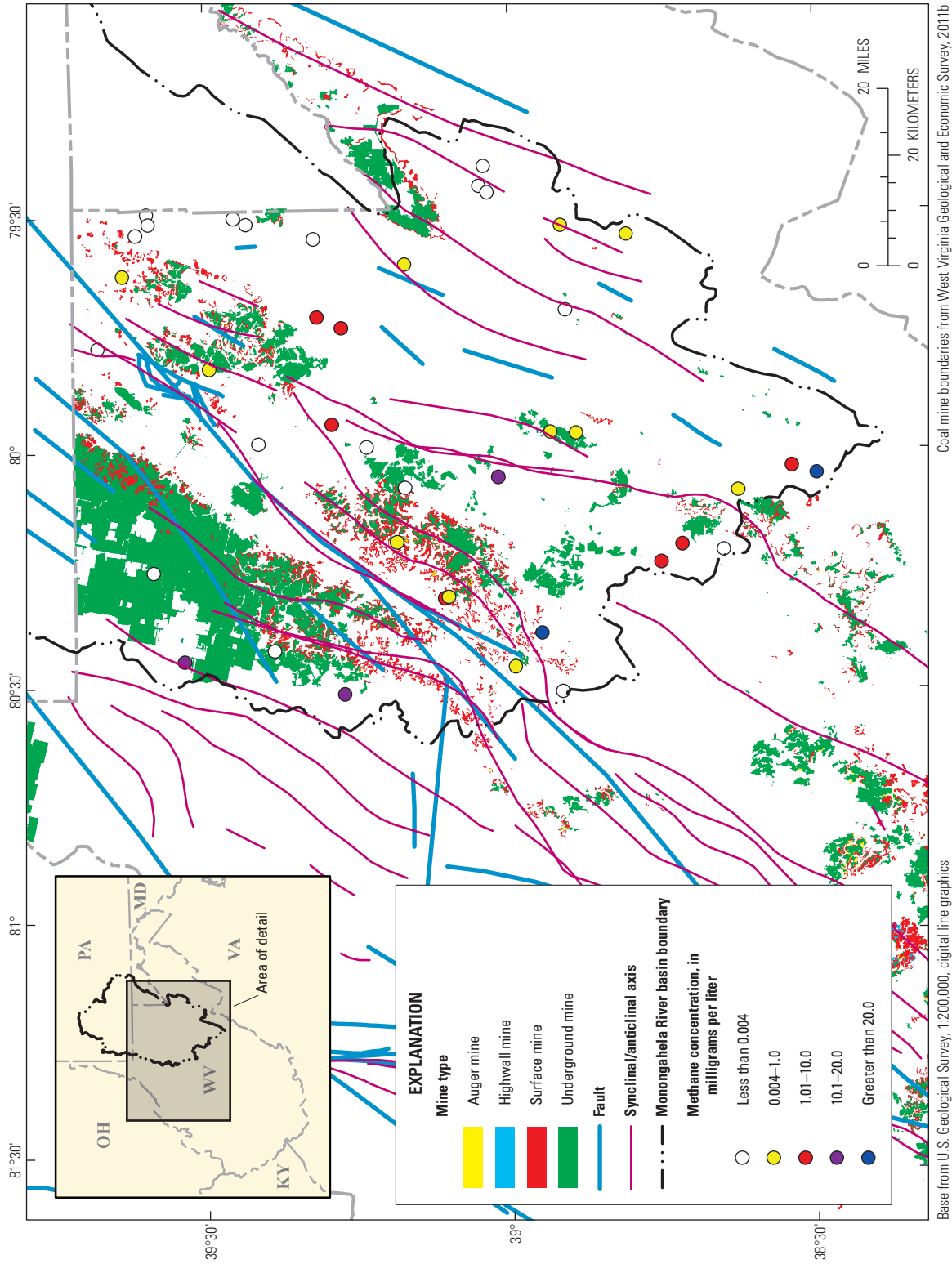
quality, accounting for these factors would have allowed the development of a more sophisticated index. Mining intensity was significantly related to sulfate concentration and specific conductance (fig. 24); both characteristics are related to mining in other studies (Anderson and others, 2000; McAuley and Kozar, 2006; Cravotta, 2008a).

Values for pH, chloride, and strontium from the base-flow survey were all significantly higher than historical data for the Monongahela River Basin. Higher pHs in base-flow survey samples are likely due to changes in coal-mining practices and treatment of mine drainage. The historical dataset spans a period of time before and through the implementation of mine regulation under the United States Surface Mine Control and Reclamation Act of 1977 (30 U.S.C. 1201-1328; 91 Stat.). Chloride and strontium are constituents associated with deep brines (Engle and Rowan, 2013). Increases in chloride concentrations may have many causes, including mine discharges. The increase in strontium is unlikely to be due to coal mining. Possible mechanisms for increases in deep-brine constituents in surface waters include upward migration of brines through faults and fractures, upward migration of brines along improperly constructed or sealed gas wells, and accidental discharge of well brines to surface waters. Further study would be necessary to determine the source of increased concentrations of chloride and strontium and mechanisms through which they enter surface water.

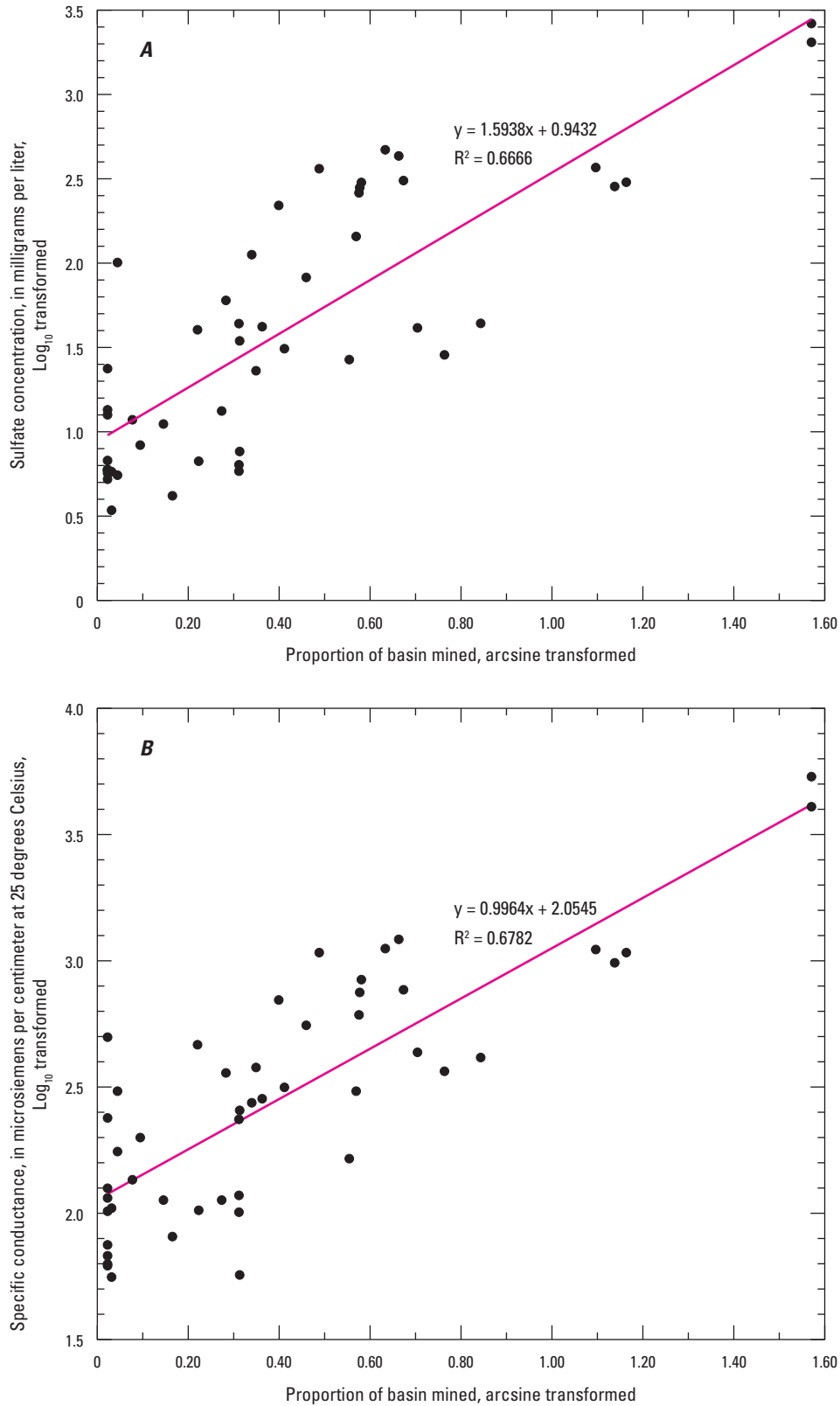
Concentrations of fluoride and barium, both constituents associated with deep brines (Engle and Rowan, 2013), varied significantly among base-flow survey samples grouped by gas-production bins. In the case of fluoride and barium, concentrations were significantly higher in the Near Production bin than in either the Production or Not Near Production bins. Further study would be needed to extrapolate this pattern.

Any similarity between the groundwaters and surface waters of a region are likely to be most evident in base flow. The stable isotope compositions of the groundwater- and surface-water base-flow survey samples were similar to one another as well as to precipitation in the area. Although the stable isotope composition indicates similar sources of the waters sampled in this study, the major ion compositions of the groundwater survey samples and the base-flow survey samples show distinct differences. Sulfate was the dominant anion in a greater proportion of base-flow survey samples than in groundwater survey samples and may reflect coal-mining land uses and the effects of mine drainage.

Further studies in this area could focus on deep brine constituents, examine the possibilities of flow-path alteration and inter-basin transfers of water, and more thoroughly investigate the influence of legacy gas wells in the region. The USGS is currently (2013–14) investigating the possibility of inter-basin transfer of water in the area, a study prompted by an examination of streamflow data collected as part of this study.



**Figure 23.** Concentrations of methane in groundwater samples collected as part of the Marcellus Shale baseline study, Monongahela River Basin, West Virginia, 2011, and the location of mined coal seams and geologic structural features.



**Figure 24.** Concentration of constituent or property in relation to the mining intensity, measured as the sum of mined areas in the 12-digit hydrologic unit code (HUC-12) areas, expressed as a proportion of the HUC-12 surface area for *A*, sulfate and *B*, specific conductance in base-flow samples collected as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, 2012.

## Summary

The Marcellus Shale gas field underlies parts of New York, Pennsylvania, Ohio, Virginia, Maryland, Tennessee, and West Virginia. Development of hydraulic fracturing and horizontal drilling technology led to extensive development of gas in the Marcellus Shale beginning about 2007. A recent assessment estimated that 84,198 billion cubic feet of natural gas were recoverable from the Marcellus Shale, enough natural gas to meet the needs of the entire Nation for about 15 years. The recovery of this gas is not without potential environmental consequences, including contamination of water resources by flowback water, hydraulic fracturing fluids, radioactivity in shale waste, and fluid waste disposal.

The primary goal of this study, conducted by the U.S. Geological Survey (USGS), in cooperation with the West Virginia Department of Environmental Protection, Division of Water and Waste Management, was to establish a baseline of water-quality conditions in West Virginia's Monongahela River Basin, an area of intensive development of the Marcellus Shale gas field. Groundwater (39 wells and 2 springs) and streamwater under base-flow conditions (50 stream sampling sites) were sampled, and the samples were analyzed for a broad suite of major ions, trace elements, naturally occurring radioactive materials (NORMs), and stable isotopes that can be used as markers for the potential effects of shale gas recovery. The baseline study, conducted during 2011–12, is intended to serve as a point of comparison for samples collected as the development of the Marcellus Shale gas field continues.

In addition to describing baseline conditions, results of water-quality analyses of samples collected during the groundwater and surface-water base-flow surveys were compared to historical water-quality data from USGS National Water Information System (NWIS) databases. The base-flow results were also examined for differences among gas-production classifications. Although no significant differences were observed in comparisons of groundwater survey data with historical data, there were a few significant differences for base-flow data, either with historical data or by Marcellus Shale gas-production classification (bins); the classification scheme did not account for conventional gas wells. The results for pH, chloride, and strontium were significantly higher in the base-flow survey samples than in the historical data. In a comparison of base-flow survey results classified by gas production, fluoride and barium were higher in bins with gas production than either bins adjacent to basins producing gas or bins neither producing gas nor adjacent to gas-producing bins. Four constituents that had a significant difference ( $p < 0.1$ )—chloride, strontium, fluoride, and barium—either compared to historical data or by gas-production category are often associated with deep saline groundwater. Saline water occurs naturally within 300 feet of the land surface in parts of the study area.

All samples were analyzed for total uranium. If uranium was detected in a sample, that sample was further analyzed for uranium and radium isotopes. One sample from well Pre-0163,

exceeded the 5.0 picocuries per liter (pCi/L) U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) with a combined value of Ra-226 and Ra-228 of 5.1 pCi/L. Other than 3 samples, 2 from the groundwater survey and 1 from the base-flow survey, that exceeded 1.0 pCi/L with either a single value of Ra-226 or Ra-228 or combined value, NORMs were not elevated above background levels in either groundwater or base-flow samples.

The composition of hydrogen and oxygen isotopes in groundwater samples shows signatures similar to those of the precipitation and river water in the area. The overall signatures in groundwater reflect both local effects and a Great Lakes signature affecting precipitation and, therefore, groundwater recharge. Additionally, no major deviations from the Global Meteoric Water Line were observed for base-flow samples, indicating that meteoric water and shallow groundwater represent a major component in these streams.

Isotope analysis showed no clear indication of mixing of shallow groundwater and deep groundwater brines, which are found in the Marcellus Shale. None of the water samples had preferential enrichment of  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  over  $\delta^2\text{H}_{\text{H}_2\text{O}}$ , which is seen in the deep brines of the area. Furthermore, no water samples had positive  $\delta^{13}\text{C}_{\text{DIC}}$  signatures similar to those of flowback water from Marcellus Shale operations. The isotopic signatures of the 11 methane samples from this study are generally similar to the isotopic signatures of coal-bed methane, typically a mixture of methane produced by both biogenic and thermogenic processes, or a mixture of coal-bed methane, biogenic, and thermogenic methane. Also, no pattern was observed in a comparison of concentrations of  $\delta^{18}\text{O}_{\text{SO}_4}$  and concentrations of  $\delta^{34}\text{S}_{\text{SO}_4}$  among Marcellus Shale gas-production bins. However, the interpretation of sulfate data was possibly confounded by reducing conditions and bacterial reduction of sulfate in mine pools, potentially altering sulfate signatures.

Dissolved-gas analyses indicate that most of the groundwater samples, 38 of 41, were from a shallow groundwater source. Of these 38 samples, 33 had dissolved gas profiles similar to those of typical shallow groundwater found in domestic wells within the study area. The remaining 5 samples, 2 of which were springs, were estimated to have had a significant component of recharge that occurred just prior to the sampling in June through September 2011. Of the three sites not having a typical shallow groundwater dissolved gas profile, two were enriched in methane and the third had a greater than average concentration of nitrogen.

This study represents a “snap shot in time,” an indication of regional water-quality conditions early in the development of the Marcellus Shale gas field. Changes in water quality may result from this development and without a set of baseline conditions these changes cannot be reliably discerned. Although not all encompassing, this dataset should provide a sufficient baseline to be used to identify changes in water quality as gas field development proceeds, regardless of whether the changes are due to the intensity of development or the changes are those that would occur over time.

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**Table 3.** Site information for streams sampled during base flow as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, July–October 2012.

[NWIS, National Water Information System; CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; @, at; HP, High Production, site in basin with gas production greater than 1,000 thousand cubic feet per year; LP, Low Producing, site in basin with gas production between zero and 1,000 thousand cubic feet per year; nearHP, site in basin adjacent to high-production basin; nearLP, site in basin adjacent to low-production basin; Marcellus >50, site in basin underlain by a greater than 50-foot Marcellus Shale thickness and neither a gas producing basin nor adjacent to a gas producing basin]

NWIS site name	Short name	NWIS station number	Latitude, in decimal degrees	Longitude, in decimal degrees	Drainage area, in square miles	Natural gas production bin	Simplified natural gas production bin
INDIAN CREEK AT CROWN, WV	Indian Ck	03062215	39.577	-80.097	11.8	NearLP	No Production
E07.0INDIAN CR @ HWY 45/2 BR @ OSGOOD WV	Indian Ck	393408080045039	39.569	-80.080	19.7	NearLP	No Production
D15.0SIMPSON CR @ HWY 13/13 BR @ ROSEMONT WV	Simpson Ck	391605080094739	39.268	-80.163	33.4	LP	Production
D12.0GNATTY CR @ HWY 20/20 BR @ ROMINES MILLS WV	Gnatty Ck	390947080154239	39.163	-80.261	32.7	HP	Production
D13.0ELK CR @ HWY 57/2 BR NR ROMINES MILLS WV	Elk Ck	391023080140539	39.173	-80.235	32.7	NearHP	No Production
D10.0HACKERS CR @ HWY 14 BR NR JANE LEW WV	Hackers Ck	390520080232239	39.089	-80.389	31.2	LP	Production
F03.0GLADY FK @ HWY 33 BR @ ALPENA WV	Glady Fk	385333079384039	38.893	-79.644	39.8	Marcellus >50	Marcellus >50
D21.0BINGAMON CR @ HWY 8 BR @ PINE BLUFF WV	Bingamon Ck	392457080192939	39.416	-80.325	32.3	HP	Production
E08.0WHITEDAY CR @ HWY 36 BR NR SMITHTOWN WV	Whiteday Ck	393250080023439	39.547	-80.043	31.1	LP	Production
E02.0PYLES FK @ HWY 250/5 BR NR METZ WV	Pyles Fk	393320080212239	39.556	-80.356	18.5	NearLP	No Production
C12.0R F BUCKHANNON R @ HWY 48 BR @ NEWLONTON WV	Right Fk Buckhammon	384440080140939	38.745	-80.236	25.4	HP	Production
F12.0CLOVER RUN @ HWY 21 BR @ ST. GEORGE WV	Clover Run	390853079424839	39.148	-79.713	28.6	Marcellus >50	Marcellus >50
C16.0FRENCH CR @ HWY 20 BR @ FRENCH CREEK WV	French Ck	385307080175339	38.885	-80.298	14.5	HP	Production

**Table 3.** Site information for streams sampled during base flow as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued

[NWIS, National Water Information System; CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; @, at; HP, High Production, site in basin with gas production greater than 1,000 thousand cubic feet per year; LP, Low Production, site in basin with gas production between zero and 1,000 thousand cubic feet per year; nearHP, site in basin adjacent to high-production basin; nearLP, site in basin adjacent to low-production basin; Marcellus >50, site in basin underlain by a greater than 50-foot Marcellus Shale thickness and neither a gas producing basin nor adjacent to a gas producing basin]

NWIS site name	Short name	NWIS station number	Latitude, in decimal degrees	Longitude, in decimal degrees	Drainage area, in square miles	Natural gas production bin	Simplified natural gas production bin
ROARING CREEK AT NORTON, WV	Roaring Ck	03050800	38.935	-79.950	29.2	NearLP	No Production
C13.0L F R F BUCKHANNON R @ HWY 46 BR @ CZAR WV	Left Fk Buckhannon at Czar	384352080084839	38.731	-80.146	15.4	nearHP	No Production
F11.0MINEAR RUN @ HWY 5 BR @ ST. GEORGE WV	Minear Run	391000079421039	39.167	-79.703	11.9	Marcellus >50	Marcellus >50
C15.0LAUREL FK @ HWY 20/10 BR NR ADRIAN, WV	Laurel Fk	385232080155239	38.876	-80.264	11.7	HP	Production
C05.0CHENOWETH CR @ HWY 23 BR @ ELKINS AIRPORT	Chenoweth Ck	385342079512439	38.895	-79.856	18.9	NearLP	No Production
D14.0BRUSHY FK @ HWY 42 BR NR STONEWOOD WV	Brushy Fk	391353080172039	39.231	-80.289	20.2	HP	Production
F21.0LAUREL RUN @ HWY 73/73 BR NR LAUREL RUN WV	Laurel Run	393903079432039	39.651	-79.722	20.2	NearLP	No Production
E06.0PRICKETTS CR @ HWY 73 BR @ MEADOWDALE WV	Pricketts Ck	392947080054139	39.496	-80.095	22.0	NearLP	No Production
C14.0L F BUCKHANNON R @ HWY 9 BR @ PALACE VLY WV	Left Fk Buckhannon at Palace Valley	384517080093039	38.755	-80.158	27.4	NearHP	No Production
D18.0SALEM CR @ HWY 5/9 BR NR MAKEN WV	Salem Ck	391817080291539	39.305	-80.487	16.4	HP	Production
C02.0BECKY CR @ HWY 56 BR NR HUTTONSVILLE WV	Becky Ck	385936079585339	38.660	-79.981	13.2	Marcellus >50	Marcellus >50
C01.0TYGART VLY R @ HWY 15 BR @ VALLEY HEAD WV	Tygart at Valley Head	383309080021539	38.553	-80.037	38.2	Marcellus >50	Marcellus >50
D19.0L TENMILE CR @ HWY 20 BR @ ROSEBUD WV	Tenmile Ck	392203080243739	39.368	-80.410	25.6	HP	Production

**Table 3.** Site information for streams sampled during base flow as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued

[NWIS, National Water Information System; CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; @, at; HP, High Production, site in basin with gas production greater than 1,000 thousand cubic feet per year; LP, Low Producing, site in basin with gas production between zero and 1,000 thousand cubic feet per year; nearHP, site in basin adjacent to high-production basin; nearLP, site in basin adjacent to low-production basin; Marcellus >50, site in basin underlain by a greater than 50-foot Marcellus Shale thickness and neither a gas producing basin nor adjacent to a gas producing basin]

NWIS site name	Short name	NWIS station number	Latitude, in decimal degrees	Longitude, in decimal degrees	Drainage area, in square miles	Natural gas production bin	Simplified natural gas production bin
C04.FILES CR @ HWY 219 BR @ BEVERLY WV	Files Ck	385015079523339	38.838	-79.876	20.8	NearLP	No Production
C03.0MILL CR @ HWY 46 BR @ MILL CREEK WV	Mill Ck	384401079584939	38.734	-79.980	16.1	Marcellus >50	Marcellus >50
E04.0PAW PAW CR @ HWY 17 BR @ GRANT TOWN WV	Paw Paw Ck	393308080100339	39.552	-80.167	28.6	LP	Production
G02.0MIRACLE RUN @ HWY 7 BR @ BULA WV	Miracle Run	394212080152739	39.703	-80.257	20.5	Marcellus >50	Marcellus >50
G01.0WEST VIRGINIA FK @ HWY 7 BR @ WANNA WV	WV Fk	394208080180239	39.702	-80.300	24.0	Marcellus >50	Marcellus >50
D24.0HUSTEAD FK @ HWY 3/16 BR @ BOOTHSVILLE WV	Hustead Fk	392335080114839	39.393	-80.196	16.8	HP	Production
G03.0DOLLS RUN @ HWY 7 BR NR CORE WV	Dolls Run	394227080065739	39.708	-80.116	11.0	Marcellus >50	Marcellus >50
D01.0WEST FK R @ HWY 44 BR @ WALKERSVILLE, WV	West Fk at Walkersville	385207080272939	38.869	-80.458	29.0	NearHP	No Production
C06.0LEADING CR @ HWY 3 BR NR KERNS WV	Leading Ck	390134079491139	39.026	-79.820	18.1	NearLP	No Production
D08.0FREEMANS CR @ BR @ VAL-LEY CHAPEL WV	Freemans Ck	390627080294039	39.108	-80.494	22.4	NearHP	No Production
D11.0LOST CR @ HWY 27/2 BR @ LOST CREEK WV	Lost Ck	391000080220739	39.167	-80.368	13.1	NearHP	No Production
C11.0RIGHT FK @ HWY 28/1 BR NR KEDRON WV	Right Fk	385346080065239	38.896	-80.114	30.0	LP	Production
D17.0TENMILE CR @ HWY 31 BR @ MAKEN WV	Tenmile Ck	391632080292039	39.276	-80.489	15.9	HP	Production

**Table 3.** Site information for streams sampled during base flow as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued

[NWIS, National Water Information System; CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; @, at; HP, High Production, site in basin with gas production greater than 1,000 thousand cubic feet per year; LP, Low Producing, site in basin with gas production between zero and 1,000 thousand cubic feet per year; nearHP, site in basin adjacent to high-production basin; nearLP, site in basin adjacent to low-production basin; Marcellus >50, site in basin underlain by a greater than 50-foot Marcellus Shale thickness and neither a gas producing basin nor adjacent to a gas producing basin]

NWIS site name	Short name	NWIS station number	Latitude, in decimal degrees	Longitude, in decimal degrees	Drainage area, in square miles	Natural gas production bin	Simplified natural gas production bin
D07.0POLK CR @ HWY 33 BR @ WESTON WV	Polk Ck	390253080283839	39.048	-80.477	11.0	NearHP	No Production
BUFFALO CREEK NEAR ROWLES-BURG, WV	Buffalo Ck	03069880	39.289	-79.704	12.2	Marcellus >50	Marcellus >50
E09.0DECKERS CR @ HWY 27 BR @ REEDSVILLE WV	Deckers Ck	393059079483739	39.516	-79.810	13.7	NearLP	No Production
C24.0TETER CR @ HWY 92 BR NR NESTORVILLE WV	Teter Ck	391212079545339	39.203	-79.915	40.7	NearLP	No Production
F10.0HORSESHOE RUN @ HWY 9 BR @ LEAD MINE WV	Horseshoe Run	391108079354239	39.186	-79.595	36.9	Marcellus >50	Marcellus >50
F09.0N FK BLACKWATER R @ HWY 27 BR @ COKETON WV	North Fk Blackwater	390820079304039	39.139	-79.511	13.6	Marcellus >50	Marcellus >50
C20.0PECKS RUN @ HWY 1/13 BR @ TETER WV	Pecks Run	390334080091839	39.060	-80.155	10.4	HP	Production
F14.0SALTICK CR @ RR BR @ ROWLESBURG WV	Saltlick Ck	392105079394839	39.351	-79.663	34.6	NearLP	No Production
C18.0SAND RUN NR BUCKHAN-NON WV	Sand Run near Buckhannon	385750080091039	38.964	-80.153	14.3	NearHP	No Production
C26.0L SANDY CR @ HWY 92/14 BR @ EVANSVILLE WV	Sandy Ck	391958079520739	39.333	-79.868	25.4	Marcellus >50	Marcellus >50
F19.0L SANDY CR @ HWY 3/4 BR NR BRANDONVILLE WV	Sandy Ck	393838079361239	39.644	-79.603	29.0	HP	Production

## Appendixes 1–2

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**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale baseline survey, Monongahela River Basin, West Virginia, June–September 2011.

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25°C;  $\mu\text{g}/\text{L}$ , micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable;  $\text{CaCO}_3$ , calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil;  $\text{pCi}/\text{L}$ , picocuries per liter;  $^{13}\text{C}$ , carbon-13,  $^{18}\text{O}$ , oxygen-18;  $^2\text{H}$ , deuterium;  $^{34}\text{S}$ , sulfur-34;  $\text{CH}_4$ , methane; DIC, dissolved inorganic carbon;  $\text{H}_2\text{O}$ , water;  $\text{SO}_4$ , sulfate]

Local well name	Sample date	Sample start time	Air pressure, in mmHg	Dissolved oxygen, in mg/L	Dissolved oxygen, in percent saturation	pH, in standard units	Specific conductance, in $\mu\text{S}/\text{cm}$	Water temperature, in °C	Turbidity, in formazin nephelometric units	Depth of well, in ft bls
Ran-0261 <sup>1</sup>	8/3/2011	920	698	2.5	25	7.1	110	11.9	0.5	NA
Ran-0276	7/5/2011	1330	695	0.3	3	9.4	794	13.4	0.5	320
Ran-0278	8/23/2011	930	698	0.2	2	8.7	396	13.7	0.1	100
Ran-0277	7/6/2011	1030	678	0.2	2	6.7	127	11.4	0.6	220
Ran-0280	7/6/2011	1410	694	6.2	68	6.5	158	14.8	1.8	80
Ran-0282	7/7/2011	1430	706	0.9	9	6.7	201	12.6	0.2	105
Ups-0178	7/7/2011	1100	712	6.6	66	7.8	403	12.5	1	158
Ran-0284	8/22/2011	1330	689	1.4	15	7	160	11.9	0.1	200
Ran-0259	8/2/2011	1020	703	1.7	18	6.7	147	13.1	0.1	155
Ran-0260	8/10/2011	940	694	0.1	1	8	407	11.7	1.6	222
Lew-0215	8/24/2011	1010	729	1.7	17	7.5	327	14	0.8	100
Ran-0275	8/2/2011	1410	714	1.2	13	6.7	235	15.5	0.2	500
Lew-0221	8/23/2011	1445	733	0.2	3	7.4	485	13.8	0.4	100
Lew-0218	8/1/2011	1140	733	1.7	17	6.7	741	14.1	1.3	60
Ups-0177	8/3/2011	1410	709	0.8	8	7.2	224	14.1	2	120
Tuc-0125	8/10/2011	1400	673	4.3	44	7.8	295	10.6	0.1	250
Tuc-0124	8/9/2011	920	668	7.4	76	7.2	314	10.9	0.8	100
Tuc-0129	8/9/2011	1155	670	5.5	56	7.2	393	10.5	0.2	45
Har-0175	8/24/2011	1405	729	1.9	20	7.9	548	14.8	0.4	45
Har-0170	8/1/2011	1700	735	0.2	2	7.3	410	15.5	0.3	75
Tuc-0127	8/8/2011	1420	712	1.2	12	8.2	192	13.6	0.1	60
Bar-0150	9/19/2011	1220	728	2.2	23	6.7	380	15.7	36	52
Bar-0149	8/25/2011	940	726	4.4	46	7.4	782	15.3	17	180
Bar-0151s	9/21/2011	1145	717	8.8	93	6	67	15.4	1.7	NA
Har-0173	7/28/2011	945	734	0.5	5	8.2	680	14.7	0.4	70
Pre-0124	8/11/2011	1020	710	0.3	3	7	349	15.5	0.5	205
Tay-0130	9/20/2011	1300	729	1.4	14	6.7	226	13.6	1.2	160
Pre-0173	8/12/2011	1000	717	1.3	13	7.9	174	13.3	0.2	57
Pre-0166	8/11/2011	1500	696	0.6	6	6.8	146	12.8	0.4	100
Har-0177	9/19/2011	1645	731	0.3	3	6.8	550	14.5	4.1	150
Tay-0129	7/27/2011	1005	734	4.9	49	6	103	13.7	360	113
Pre-0164	8/30/2011	1005	697	2.8	29	7	323	12.2	2.7	207
Pre-0177	8/29/2011	1500	696	2.6	27	7.6	225	12.1	0.5	145
Pre-0176	6/30/2011	1030	718	0.3	3	9.2	480	13.1	0.3	200
Mar-0300	7/26/2011	1100	731	0.7	7	8	613	16.4	0.5	70
Mar-0296	7/25/2011	1450	733	1.7	17	6.7	487	13.4	11	107
Pre-0162	6/29/2011	1355	691	8.1	80	4.5	46	10.6	2.1	145
Pre-0163	6/29/2011	1035	691	8.6	86	4.5	44	11	0.5	179
Pre-0172	8/30/2011	1325	704	7.2	76	4.5	233	14.4	0.1	65
Pre-0178	8/31/2011	1005	722	2.1	21	6.3	117	11.7	9.6	NA
Mng-0582	6/28/2011	1355	703	7.1	77	6.6	200	15.6	0.9	190



**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable; CaCO<sub>3</sub>, calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Local well name	Total dissolved solids, dried at 180°C, in mg/L	Hardness, water, in mg/L as CaCO <sub>3</sub>	Noncarbonate hardness, wf, in mg/L as CaCO <sub>3</sub>	Calcium, wf, in mg/L	Magnesium, wf, in mg/L	Potassium, wf, in mg/L	Sodium, wf, in mg/L	Alkalinity, wf, inflection point, laboratory titration, in mg/L as CaCO <sub>3</sub>	Alkalinity, wf, inflection point, field titration, in mg/L as CaCO <sub>3</sub>
Ran-0261 <sup>1</sup>	61	49.2	5	16.9	1.66	0.5	1.54	--	44.1
Ran-0276	467	2.24	--	0.672	0.105	1	186	--	316
Ran-0278	220	15.2	--	4.5	0.903	1.2	77.3	--	140
Ran-0277	75	48.2	0	12.5	4.05	1.53	3.58	--	48.1
Ran-0280	103	43.2	8	14.7	1.57	0.79	13	--	34.8
Ran-0282	98	35.5	--	10.1	2.42	1.19	20.3	--	54.6
Ups-0178	221	39.2	--	11.2	2.58	2.55	70.3	--	106
Ran-0284	90	52.6	--	13.7	4.35	1.31	9.25	--	69.8
Ran-0259	84	55.4	18	14.5	4.54	2.9	2.93	--	37
Ran-0260	226	85.2	--	26.2	4.56	2.26	48	--	130
Lew-0215	183	98.7	--	30.9	4.95	1.01	32.1	--	138
Ran-0275	134	69.7	8	19	5.14	2.45	12	--	61.9
Lew-0221	277	197	--	60.7	10.7	1.74	23.5	--	208
Lew-0218	522	307	148	91	19.1	1.59	32	--	159
Ups-0177	115	41.8	--	12.6	2.36	1.71	30.8	--	81.9
Tuc-0125	168	124	--	35.3	8.66	0.88	11.5	135	--
Tuc-0124	179	155	7	55.4	4.07	0.54	1.4	--	149
Tuc-0129	220	186	6	66	5.11	0.48	4.79	--	180
Har-0175	337	82.6	--	24.9	4.89	1.07	94.2	256	--
Har-0170	235	161	--	48	9.74	1.36	24.4	--	221
Tuc-0127	130	45.4	--	14.7	1.99	0.55	20.9	--	68.3
Bar-0150	213	178	--	55.3	9.49	1.17	9.41	158	--
Bar-0149	493	141	--	48.3	4.81	0.81	120	271	--
Bar-0151s	38	27	--	8.6	1.33	0.68	0.46	21.6	--
Har-0173	410	12.9	--	3.81	0.684	0.92	162	--	313
Pre-0124	200	123	--	39.6	5.68	0.88	19.2	132	--
Tay-0130	124	97.2	--	28.4	6.27	1.65	7.3	108	--
Pre-0173	101	47.4	--	11.3	4.28	1.25	17.2	76.9	--
Pre-0166	97	45.1	--	11.6	3.9	1.34	8.15	43.8	--
Har-0177	344	240	--	74.8	12.8	1.56	28.9	235	--
Tay-0129	54	30	2	7.04	3	0.99	0.91	--	28.3
Pre-0164	200	129	--	40.1	6.92	1.79	11	106	--
Pre-0177	131	109	--	39.7	2.29	0.64	1.71	105	--
Pre-0176	282	3.5	--	1.16	0.137	0.6	117	--	254
Mar-0300	359	70.6	--	22.7	2.99	1.09	118	--	298
Mar-0296	313	151	1	42.4	10.8	1.61	45.2	--	150
Pre-0162	27	6.49	2	1.96	0.376	0.49	0.81	--	4.8
Pre-0163	<12	8.06	6	2.12	0.662	0.43	0.47	--	1.9
Pre-0172	113	24	--	6.62	1.78	1.52	27.6	<4.0	--
Pre-0178	65	35.3	--	9.01	3.02	0.96	8.67	51.9	--
Mng-0582	116	95	27	24.6	8.15	1.48	1.9	--	67.7

**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable; CaCO<sub>3</sub>, calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13; <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Local well name	Bicarbonate, wf, inflection point, field titration, in mg/L	Bromide, wf, in mg/L	Carbon dioxide, water, in mg/L	Carbonate, wf, inflection point, field titration in mg/L	Chloride, wf, in mg/L	Fluoride, wf, in mg/L	Silica, wf, in mg/L	Sulfate, wf, in mg/L	Aluminum, wf, in µg/L
Ran-0261 <sup>1</sup>	53.7	0.015	6.9	--	2.08	<.04	3.17	5.13	4.2
Ran-0276	77.7	0.598	0.9	152	67.6	1.85	8.63	4.39	4.4
Ran-0278	170	0.384	0.6	--	45.5	0.22	11.9	<.09	1.7
Ran-0277	58.7	0.012	24.9	--	1.32	<.04	7.34	7.25	<1.7
Ran-0280	42.4	0.015	28.2	--	17	<.04	3.48	6.66	<1.7
Ran-0282	66.6	0.033	29.9	--	20.5	0.1	7.31	0.25	<1.7
Ups-0178	129	0.461	8.3	--	48.4	0.42	7.81	<.09	<1.7
Ran-0284	85	0.015	15	--	3.75	0.07	11.8	14.4	<1.7
Ran-0259	45.1	<.010	14	--	1.49	0.1	7.03	11.6	2.1
Ran-0260	159	0.163	2.7	--	40.8	0.18	9.83	9.63	<1.7
Lew-0215	168	0.034	7.8	--	8.44	0.24	13.4	12.7	<1.7
Ran-0275	75.4	0.018	24	--	20.9	0.09	6.93	22	<1.7
Lew-0221	254	0.078	18	--	27.1	0.16	14.2	<.09	<1.7
Lew-0218	194	0.035	58	--	6.48	0.42	18.4	231	<1.7
Ups-0177	99.8	0.119	10	--	14.5	0.33	7.42	<.09	<1.7
Tuc-0125	--	0.014	3.8	--	3.21	<.04	8.13	8.92	7.9
Tuc-0124	181	0.065	19	--	3.16	<.04	5.77	9.97	5.2
Tuc-0129	219	0.024	21	--	12	<.04	7.17	11.7	<1.7
Har-0175	--	0.027	7	--	2.19	0.29	10.4	39.2	<1.7
Har-0170	270	0.109	21	--	10.9	0.2	14	13.3	<1.7
Tuc-0127	83.3	0.081	0.9	--	11	0.07	9.82	10.7	7.1
Bar-0150	--	0.036	69	--	10.4	0.12	13.4	23.4	<1.7
Bar-0149	--	0.112	23	--	49.3	0.72	7.74	53.4	4
Bar-0151 <sub>s</sub>	--	<.010	42	--	0.57	<.04	8.48	7.6	10.4
Har-0173	382	0.107	4.1	--	39.1	0.59	12.1	0.21	<1.7
Pre-0124	--	0.071	26	--	21	0.05	18.1	6.1	<1.7
Tay-0130	--	0.033	38	--	3.78	0.16	8.47	1.63	<1.7
Pre-0173	--	0.029	1.8	--	5.83	0.07	12.1	0.46	<1.7
Pre-0166	--	<.010	14	--	7.03	0.05	14.7	13.2	<1.7
Har-0177	--	0.019	73	--	1.86	0.14	11.1	59.8	<1.7
Tay-0129	34.5	0.019	55	--	1.05	0.09	8.41	10.9	2.5
Pre-0164	--	0.019	18	--	21.2	0.08	11.4	20.1	<1.7
Pre-0177	--	<.010	5.5	--	2.75	<.04	3.31	6.21	1.8
Pre-0176	235	0.01	0.3	36.4	4.96	1.32	7.96	10.4	4.5
Mar-0300	364	0.156	5.8	--	42.9	0.7	13.6	<.09	<1.7
Mar-0296	182	0.066	59	--	12.2	0.12	8.99	83.6	5.7
Pre-0162	5.9	<.010	53.6	--	1.46	<.04	3.63	13.5	979
Pre-0163	2.3	<.010	58.9	--	0.94	<.04	5.03	13	563
Pre-0172	--	0.021	<225	--	53.6	0.07	5.09	14.1	696
Pre-0178	--	0.019	46	--	3.24	0.11	7.6	0.76	<1.7
Mng-0582	82.6	<.010	32	--	--	--	8.77	--	<1.7

**Appendix 1. Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued**

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable; CaCO<sub>3</sub>, calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Local well name	Barium, wf, in µg/L	Beryllium, wf, in µg/L	Cadmium, wf, in µg/L	Chromium, wf, in µg/L	Cobalt, wf, in µg/L	Copper, wf, in µg/L	Iron, wf, in µg/L	Lead, wf, in µg/L	Manganese, wf, in µg/L
Ran-0261 <sup>1</sup>	30.8	<.006	0.032	0.11	0.051	<.50	<.3.2	<.015	0.23
Ran-0276	125	0.008	<.016	<.06	<.020	<.50	<.3.2	<.015	3.52
Ran-0278	228	<.006	<.016	<.06	<.020	<.50	46.1	0.015	11.6
Ran-0277	172	0.031	<.016	<.06	2.04	<.50	3240	<.015	279
Ran-0280	37.5	<.006	0.026	<.06	0.302	1.3	10.2	0.389	0.77
Ran-0282	267	0.037	<.016	<.06	0.091	<.50	7910	<.015	348
Ups-0178	439	<.006	<.016	0.26	0.113	<.50	83	0.016	16.2
Ran-0284	292	0.022	<.016	<.06	0.027	<.50	1690	0.023	621
Ran-0259	400	0.039	<.016	<.06	0.359	<.50	3100	0.019	148
Ran-0260	563	<.006	<.016	<.06	0.154	<.50	31.6	<.015	28
Lew-0215	618	<.006	<.016	<.06	0.029	<.50	84.4	0.026	141
Ran-0275	660	0.041	<.016	<.06	0.175	<.50	5240	<.015	356
Lew-0221	1250	<.006	<.016	<.06	0.894	<.50	666	<.015	194
Lew-0218	62.4	0.027	<.016	<.06	1.36	<.50	11600	<.015	1670
Ups-0177	430	0.009	<.016	<.06	0.035	<.50	890	<.015	49.4
Tuc-0125	262	<.006	<.016	0.18	0.026	<.50	<.3.2	0.043	1.26
Tuc-0124	44.6	<.006	0.018	0.28	0.027	0.75	<.3.2	0.037	<.13
Tuc-0129	207	<.006	<.016	0.2	0.049	<.50	<.3.2	0.033	<.13
Har-0175	238	<.006	<.016	<.06	0.024	<.50	905	<.015	131
Har-0170	236	<.006	<.016	<.06	0.024	<.50	751	<.015	145
Tuc-0127	514	<.006	<.016	<.06	0.055	<.50	10.9	<.015	70.9
Bar-0150	346	<.006	<.016	<.06	0.084	<.50	1050	<.015	420
Bar-0149	93.9	<.006	<.016	0.75	0.077	<.50	8.4	0.099	12.2
Bar-0151s	22.1	0.063	0.027	0.15	0.073	<.50	<.3.2	<.015	2.99
Har-0173	528	0.007	<.016	<.06	0.251	<.50	27.7	<.015	8.96
Pre-0124	645	0.01	<.016	<.06	0.058	0.54	1560	0.017	416
Tay-0130	392	0.03	<.016	<.06	0.267	<.50	1940	0.036	185
Pre-0173	1400	<.006	<.016	<.06	<.020	<.50	64.4	<.015	61
Pre-0166	112	0.016	<.016	<.06	0.541	<.50	1440	<.015	149
Har-0177	192	<.006	<.016	<.06	0.149	<.50	775	<.015	353
Tay-0129	81.7	0.016	<.016	0.1	4.3	<.50	7830	<.015	290
Pre-0164	159	<.006	<.016	<.06	0.469	<.50	1360	0.04	256
Pre-0177	60.2	<.006	<.016	0.09	0.046	<.50	3.7	0.016	0.14
Pre-0176	31.7	<.006	<.016	<.06	0.153	<.50	<.3.2	<.015	2.57
Mar-0300	1350	<.006	<.016	<.06	0.046	<.50	84	0.016	32.6
Mar-0296	104	0.013	<.016	<.06	0.615	<.50	574	0.017	184
Pre-0162	35.8	0.134	0.347	0.12	2.5	2.8	3.6	0.619	61.4
Pre-0163	37.6	0.206	0.174	0.21	3.32	21.3	7.7	1.64	84.9
Pre-0172	186	0.495	0.658	0.07	9.48	155	14.5	3.74	291
Pre-0178	206	0.017	<.016	<.06	1.34	<.50	1920	<.015	263
Mng-0582	53.9	0.007	<.016	0.14	0.033	1.9	3.9	0.05	0.29

**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable; CaCO<sub>3</sub>, calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Local well name	Molybdenum, wf, in µg/L	Nickel, wf, in µg/L	Silver, wf, in µg/L	Strontium, wf, in µg/L	Zinc, wf, in µg/L	Antimony, wf, in µg/L	Arsenic, wf, in µg/L	Boron, wf, in µg/L	Selenium, wf, in µg/L
Ran-0261 <sup>1</sup>	0.07	0.15	<.005	36.4	1.5	<.027	0.09	6	0.07
Ran-0276	1.13	<.09	<.005	34.3	<1.4	0.09	5.3	370	<.03
Ran-0278	0.174	<.09	<.005	57.8	1.4	<.027	1	101	<.03
Ran-0277	0.069	0.89	<.005	178	13.5	<.027	2.1	5	<.03
Ran-0280	0.026	0.82	<.005	39	10.7	0.063	0.05	9	0.27
Ran-0282	0.023	<.09	<.005	91.3	4.9	<.027	0.19	16	<.03
Ups-0178	0.05	0.21	<.005	288	<1.4	<.027	0.11	41	<.03
Ran-0284	0.272	<.09	<.005	172	1.5	<.027	2.8	15	<.03
Ran-0259	<.014	0.49	<.005	197	2.2	<.027	0.08	11	<.03
Ran-0260	0.816	<.09	<.005	526	<1.4	0.03	0.31	52	0.04
Lew-0215	1.25	0.1	<.005	705	17.7	<.027	6.3	21	<.03
Ran-0275	0.146	0.33	<.005	508	2	<.027	0.18	14	<.03
Lew-0221	0.418	0.15	<.005	773	<1.4	0.039	0.73	22	<.03
Lew-0218	0.394	0.97	<.005	752	2.5	<.027	1.5	26	<.03
Ups-0177	0.014	<.09	<.005	234	1.6	<.027	<.02	33	<.03
Tuc-0125	0.817	<.09	<.005	495	10.6	0.036	1.2	14	0.27
Tuc-0124	0.154	0.19	<.005	105	4.4	<.027	0.13	5	0.1
Tuc-0129	0.054	0.14	<.005	115	<1.4	<.027	0.18	6	0.1
Har-0175	1.93	<.09	<.005	176	<1.4	<.027	2.7	40	<.03
Har-0170	0.327	<.09	<.005	555	<1.4	<.027	1.2	27	<.03
Tuc-0127	0.158	<.09	<.005	102	<1.4	<.027	1	31	<.03
Bar-0150	0.215	0.24	<.005	182	13	<.027	0.6	15	<.03
Bar-0149	2.4	0.59	<.005	244	3.2	0.048	0.29	77	0.06
Bar-0151s	<.014	1.7	<.005	16.8	2.9	<.027	0.03	7	0.05
Har-0173	0.686	<.09	<.005	197	<1.4	<.027	0.1	85	<.03
Pre-0124	0.127	0.18	<.005	212	7.5	<.027	5.7	91	<.03
Tay-0130	0.017	0.52	<.005	222	48.2	<.027	0.39	16	<.03
Pre-0173	0.088	<.09	<.005	558	3.1	<.027	0.97	108	<.03
Pre-0166	0.144	1.3	<.005	91	3.2	<.027	1.1	17	<.03
Har-0177	0.164	0.27	<.005	787	1.7	<.027	1.2	34	<.03
Tay-0129	0.07	4.4	<.005	21.8	6	<.027	4.1	7	<.03
Pre-0164	0.865	0.85	<.005	152	2.2	0.047	2.3	18	0.13
Pre-0177	0.328	0.17	<.005	63	7	0.035	0.28	6	0.15
Pre-0176	0.208	<.09	<.005	15.7	<1.4	<.027	0.05	128	<.03
Mar-0300	1.56	<.09	<.005	507	<1.4	<.027	0.45	94	<.03
Mar-0296	0.175	0.49	<.005	355	5.4	0.056	0.35	37	0.1
Pre-0162	<.014	2.3	<.005	9.6	24.5	<.027	<.02	7	0.11
Pre-0163	<.014	5.8	0.014	13.2	87.9	<.027	<.02	5	0.17
Pre-0172	<.014	8.1	0.015	37.4	78.8	<.027	0.07	11	0.09
Pre-0178	0.022	1.1	<.005	131	5.1	<.027	0.12	12	0.04
Mng-0582	0.041	0.2	<.005	91	26.1	0.042	0.09	19	0.3

**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable; CaCO<sub>3</sub>, calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Local well name	Alpha activity, wf, Thorium-230, in pCi/L	Gross beta, wf, Cesium-137, in pCi/L	Radium-224, wf, in pCi/L	Radium-226, wf, in pCi/L	Radium-228, wf, in pCi/L	Uranium, wf, in pCi/L	Uranium-234, wf, in pCi/L	Uranium235, wf pCi/L	Uranium-238, wf, in pCi/L
Ran-0261 <sup>1</sup>	R.6	R1.0	R.05	R.03	--	0.074	0.028	R-.007	0.015
Ran-0276	R1.2	R.8	R.1	R.1	--	0.043	0.13	R.009	0.025
Ran-0278	R-.6	1.1	R.00	1	--	<.004	--	--	--
Ran-0277	R.1	1.1	R-.1	R-.16	--	<.004	--	--	--
Ran-0280	R.2	2.3	R.2	0.15	--	0.005	0.03	R-.007	0.033
Ran-0282	0.9	1.3	R.2	0.29	--	<.004	--	--	--
Ups-0178	R.1	1.7	R-.10	0.15	--	<.004	--	--	--
Ran-0284	0.7	1.2	R.12	R.15	--	<.004	--	--	--
Ran-0259	1.9	3.3	R.16	0.15	--	<.004	--	--	--
Ran-0260	R-.1	2.1	0.4	0.31	0.3	0.122	0.13	R.009	0.043
Lew-0215	1	R.6	R.2	0.3	--	0.039	0.02	R.006	0.012
Ran-0275	1.5	3.3	0.34	0.3	0.44	<.004	--	--	--
Lew-0221	R1.0	2.7	0.33	0.65	0.49	<.004	--	--	--
Lew-0218	1.1	1.7	R.2	0.39	--	<.004	--	--	--
Ups-0177	1.1	2.6	R.03	0.2	--	<.004	--	--	--
Tuc-0125	R.6	1.4	R.03	0.08	--	0.518	0.34	R.004	0.16
Tuc-0124	R.3	R.6	R.00	0.26	--	0.487	0.22	0.021	0.12
Tuc-0129	1.9	R.3	0.14	R.05	R-.15	0.421	0.28	R.005	0.12
Har-0175	0.6	R.5	0.34	0.5	R.12	0.062	0.034	R-.003	0.012
Har-0170	R.9	R.1	R.29	0.28	--	<.004	--	--	--
Tuc-0127	0.7	0.9	R.03	0.2	--	<.004	--	--	--
Bar-0150	2	1.4	R-.09	0.8	--	0.017	0.024	R.009	R.007
Bar-0149	2	R-.5	0.25	0.14	R.06	0.682	0.43	0.025	0.24
Bar-0151s	0.9	R.2	--	R.07	--	0.029	R.010	R.003	R.005
Har-0173	2.7	1.1	R.20	0.27	--	<.004	--	--	--
Pre-0124	R-.2	1.5	0.42	0.48	0.5	0.007	0.03	R.005	R.004
Tay-0130	1.1	2.9	0.4	0.59	0.55	<.004	--	--	--
Pre-0173	3.6	1.8	R.25	0.85	--	<.004	--	--	--
Pre-0166	0.8	1.4	R.00	0.73	--	<.004	--	--	--
Har-0177	R.7	2	0.8	0.8	0.4	0.085	0.035	R.000	0.011
Tay-0129	1.5	1.1	R.00	0.14	--	<.004	--	--	--
Pre-0164	2	1.5	R-.16	R.10	--	0.205	0.084	0.009	0.079
Pre-0177	R.1	0.9	R-.11	0.33	--	0.237	0.109	R.008	0.067
Pre-0176	R.5	R.4	R.10	0.2	--	0.011	0.07	R.005	0.039
Mar-0300	1.2	0.8	R.4	0.5	--	0.005	R.011	R.003	0.011
Mar-0296	R-.4	1.7	R.3	0.22	--	0.166	--	--	--
Pre-0162	2.5	1	0.8	0.79	0.83	0.022	R.011	R-.004	0.011
Pre-0163	6.8	5.1	3.9	1.9	3.2	0.041	0.033	R.005	0.041
Pre-0172	6	4.8	2.2	1.5	2.48	0.025	0.024	R.000	R.007
Pre-0178	1	R.4	0.23	0.23	R.21	<.004	--	--	--
Mng-0582	R.3	R.6	0.5	0.21	R.20	0.164	0.04	R.000	R.016

**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius; μS/cm, microsiemens per centimeter at 25°C; μg/L, micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable; CaCO<sub>3</sub>, calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Local well name	Dissolved methane, in mg/L	Dissolved carbon dioxide, in mg/L	Dissolved nitrogen gas (N <sub>2</sub> ), in mg/L	Dissolved oxygen, in mg/L, laboratory analysis	Dissolved argon, in mg/L	<sup>18</sup> O <sub>SO4</sub> in ‰	<sup>34</sup> S <sub>SO4</sub> in ‰	<sup>13</sup> C <sub>DIC</sub> in ‰	<sup>2</sup> H <sub>H2O</sub> in ‰
Ran-0261 <sup>1</sup>	0.001	7.529	15.377	1.903	0.556	0.8	2.9	-12.2	-56.0
Ran-0276	48.204	0.742	9.585	0.104	0.457	1.8	5.6	-7.9	-60.1
Ran-0278	8.376	0.609	18.038	0.221	0.665	--	--	-13.2	-62.4
Ran-0277	0.04	23.735	19.453	0.246	0.696	1.6	4.0	-15.0	-67.8
Ran-0280	0.001	28.136	16.292	5.525	0.612	-2.4	3.1	-15.8	-57.0
Ran-0282	2.353	29.516	19.412	0.246	0.701	--	--	-16.1	-59.5
Ups-0178	7.31	8.401	27.179	0.259	0.805	--	--	-1.1	-59.9
Ran-0284	0.01	10.892	19.535	0.25	0.672	3.0	-17.1	-17.3	-65.1
Ran-0259	0.35	18.473	20.227	0.262	0.715	nd	nd	-14.1	-64.0
Ran-0260	0.963	3.469	19.141	0.236	0.662	1.3	-1.8	-13.6	-62.6
Lew-0215	0.001	7.584	20.899	0.266	0.717	2.3	-7.5	-18.5	-53.3
Ran-0275	0.143	19.434	18.668	0.248	0.657	3.1	1.5	-14.5	-60.3
Lew-0221	21.916	15.707	10.688	0.114	0.419	-3.3	8.9	-20.0	-51.1
Lew-0218	0.079	47.99	20.701	0.252	0.727	0.3	5.4	-17.5	-52.1
Ups-0177	12.839	8.911	17.689	0.202	0.676	--	--	-7.5	-61.0
Tuc-0125	0.001	5.836	18.768	1.349	0.677	0.7	3.5	-12.1	-63.2
Tuc-0124	0.001	22.685	20.825	2.172	0.719	0.1	-3.4	-12.8	-61.6
Tuc-0129	0.001	21.023	18.845	1.482	0.683	0.4	1.3	-13.2	-62.3
Har-0175	0.009	6.821	20.748	0.273	0.722	3.8	-4.9	-19.2	-53.0
Har-0170	2.112	13.589	20.214	0.249	0.708	10.9	14.6	-20.9	-52.0
Tuc-0127	0.325	0.787	18.712	0.249	0.665	1.3	-4.6	-18.4	-60.6
Bar-0150	0.001	49.47	21.16	0.223	0.671	3.2	-6.2	-16.8	-55.1
Bar-0149	0.406	17.225	17.411	0.228	0.632	5.4	4.5	-18.7	-51.1
Bar-0151s	0.001	48.887	15.511	6.095	0.588	-0.4	-0.4	-19.8	-59.9
Har-0173	12.264	3.595	18.173	0.212	0.657	--	--	-12.7	-51.7
Pre-0124	1.629	28.386	21.642	0.257	0.736	3.5	-3.9	-16.8	-60.7
Tay-0130	3.069	32.457	19.205	0.242	0.682	3.6	17.1	-9.8	-59.5
Pre-0173	3.159	2.137	18.348	0.237	0.662	--	--	-15.0	-60.5
Pre-0166	0.003	15.067	20.132	0.252	0.688	1.2	-7.4	-16.8	-66.6
Har-0177	0.001	60.142	19.833	0.554	0.729	-3.2	-1.1	-12.2	-50.0
Tay-0129	0.001	68.831	18.331	1.196	0.679	3.8	0.7	-17.3	-57.0
Pre-0164	0.001	20.281	19.623	0.233	0.656	-0.4	-7.0	-13.2	-62.5
Pre-0177	0.001	5.825	15.327	0.214	0.561	2.4	-2.5	-12.6	-59.8
Pre-0176	0.381	0.327	22.274	0.28	0.762	-0.3	3.8	-13.0	-58.5
Mar-0300	17.839	4.715	14.968	0.15	0.526	--	--	-19.5	-52.5
Mar-0296	0.001	47.655	19.568	0.245	0.679	7.8	8.1	-15.9	-51.1
Pre-0162	0.001	53.295	18.524	8.204	0.687	-0.8	1.5	-23.4	-63.5
Pre-0163	0.001	58.565	17.185	8.071	0.66	--	--	-22.9	-66.3
Pre-0172	0.001	64.834	17.199	5.76	0.648	1.4	1.8	-23.4	-61.9
Pre-0178	0.387	43.301	21.802	0.273	0.783	--	--	-18.1	-57.8
Mng-0582	0.001	31.883	17.32	3.047	0.65	0.8	2.8	-16.2	-63.5

**Appendix 1.** Data for groundwater samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, June–September 2011.—Continued

[<, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; °C, degrees Celsius;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25°C;  $\mu\text{g}/\text{L}$ , micrograms per liter; wf, filtered water; ft bls, feet below land surface; NA, not applicable;  $\text{CaCO}_3$ , calcium carbonate; --, no data; NA, not applicable; R, non-detect, result below sample-specific critical level; nd, not detected; ‰, per mil; pCi/L, picocuries per liter;  $^{13}\text{C}$ , carbon-13,  $^{18}\text{O}$ , oxygen-18;  $^2\text{H}$ , deuterium;  $^{34}\text{S}$ , sulfur-34;  $\text{CH}_4$ , methane; DIC, dissolved inorganic carbon;  $\text{H}_2\text{O}$ , water;  $\text{SO}_4$ , sulfate]

Local well name	$^{18}\text{O}_{\text{H}_2\text{O}}$ in ‰	$^{13}\text{C}_{\text{CH}_4}$ dissolved, in ‰	$^2\text{H}_{\text{CH}_4}$ dissolved, in ‰
Ran-0261 <sup>1</sup>	-9.0	nd	nd
Ran-0276	-9.0	-57.8	-222.1
Ran-0278	-9.1	-69.9	-233.9
Ran-0277	-10.0	--	--
Ran-0280	-8.6	nd	nd
Ran-0282	-9.1	-61.4	-201.1
Ups-0178	-9.4	nd	nd
Ran-0284	-10.1	nd	nd
Ran-0259	-9.9	nd	nd
Ran-0260	-9.8	-59.5	-157.0
Lew-0215	-8.3	nd	nd
Ran-0275	-9.4	nd	nd
Lew-0221	-8.2	-52.7	-214.5
Lew-0218	-8.2	-42.0	--
Ups-0177	-9.6	-54.9	-229.9
Tuc-0125	-9.7	--	--
Tuc-0124	-9.6	nd	nd
Tuc-0129	-9.4	nd	nd
Har-0175	-8.7	--	--
Har-0170	-8.5	nd	nd
Tuc-0127	-9.2	-63.1	-151.0
Bar-0150	-8.3	--	--
Bar-0149	-7.5	-50.4	-99.2
Bar-0151s	-9.0	--	--
Har-0173	-8.5	nd	nd
Pre-0124	-9.4	nd	nd
Tay-0130	-8.7	-50.4	-191.7
Pre-0173	-9.7	nd	nd
Pre-0166	-10.3	nd	nd
Har-0177	-8.0	--	--
Tay-0129	-9.1	nd	nd
Pre-0164	-10.1	nd	nd
Pre-0177	-9.5	--	--
Pre-0176	-9.1	nd	nd
Mar-0300	-8.4	-55.6	-192.8
Mar-0296	-8.5	nd	nd
Pre-0162	-9.5	--	--
Pre-0163	-9.8	nd	nd
Pre-0172	-9.8	--	--
Pre-0178	-9.1	-67.2	-171.0
Mng-0582	-9.5	nd	nd

<sup>1</sup>North Spring at Bowden, West Virginia.





**Appendix 2. Data for base-flow samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued**

[CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; <, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; ft<sup>3</sup>/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; cm, centimeter; CaCO<sub>3</sub>, calcium carbonate; --, no data; R, non-detect, result below sample-specific critical level; %, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Station number	Dissolved oxygen, in percent saturation	pH, in standard units	Specific conductance, in µS/cm	Water temperature, in °C	Turbidity, in formazin nephelometric units	Total dissolved solids, dried at 180°C, in mg/L	Hardness, water, in mg/L as CaCO <sub>3</sub>	Noncarbonate hardness, wf, in mg/L as CaCO <sub>3</sub>	Calcium, wf, in mg/L
03050800	101	5.4	274	19.2	0	168	112	112	28.3
03062215	133	8.3	5,380	21.3	2	4,380	1,090	750	291
03069880	100	7.3	75	10.5	0	44	29.1	2	8.94
383309080021539	101	8	176	17.2	0.7	102	76	3	25.7
383936079585339	104	7.7	105	22.1	0.2	73	47	5	15.2
384352080084839	104	8.2	256	22.6	0.5	165	30.8	--	9.63
384401079584939	98	7.5	81	22.4	2	55	38.5	7	12.6
384440080140939	103	8.6	113	20.6	0.8	66	25.2	--	7.68
384517080093039	98	7.2	57	16.6	0.3	37	20.2	5	5.51
385015079523339	87	7.2	102	20.5	0.6	77	42.2	2	13.3
385207080272939	55	7	200	22.8	3.4	113	68	10	21
385232080155239	98	7.4	101	17.2	0.8	69	40.6	10	13.2
385307080175339	62	7	118	18.1	5.9	72	47.3	4	14.6
385333079384039	100	7.2	56	20.1	2.1	45	23.5	3	7.3
385342079512439	97	7.7	239	23.9	0	144	88.4	9	28.4
385346080065239	89	7.4	103	20.7	0.2	60	46	7	15.6
385750080091039	103	7.6	305	20.4	2.5	195	137	105	28.9
390134079491139	102	7.2	115	28.1	6.2	63	42.5	4	12.9
390253080283839	90	7.8	466	19.6	0.6	278	189	48	53.1
390334080091839	108	7.6	751	14.4	8.4	495	386	277	105
390520080232239	171	8.7	701	25.7	4.6	486	280	154	74.9
390627080294039	105	7.9	360	23.7	6	225	174	65	48.1
390820079304039	106	8.1	165	12.5	6.8	98	72.1	34	21.4
390853079424839	97	7.2	62	16.4	0	44	24	6	6.63
390947080154239	101	8.2	1,220	20.9	10	908	500	256	126
391000079421039	94	7.2	63	16.6	2.6	44	24.1	4	6.5
391000080220739	68	7.6	557	19.6	12	334	230	110	65
391023080140539	97	8	769	19.3	3.6	622	378	252	97.1
391108079354239	100	7.5	68	12.1	1.8	49	25.8	5	7.33
391212079545339	103	7.6	96	10.3	--	64	39.7	8	12.3
391353080172039	104	8.1	843	21.8	2.9	615	453	320	120
391605080094739	98	8	1,120	19.8	1.5	872	534	442	145
391632080292039	53	7.4	378	18.4	16	216	150	5	44.4
391817080291539	102	7.9	499	20.8	3.8	280	151	40	46.7
391958079520739	93	4.8	305	9.6	0.9	190	106	99	31.2
392105079394839	100	7.6	126	11.2	0.2	71	52.7	14	15.6
392203080243739	113	8.1	1,080	23.1	--	744	418	228	125
392335080114839	120	8.2	285	23.2	2.7	174	122	56	37.7
392457080192939	127	8.4	1,110	25.2	--	762	259	101	69.7
392947080054139	117	8.5	316	25.3	0.9	192	127	26	40
393059079483739	100	7.4	611	11.5	2.4	441	314	261	104
393250080023439	113	8.6	136	25.3	1.8	80	53.8	11	16.9
393308080100339	67	7.7	1,080	19.6	18	725	276	92	75.2
393320080212239	71	7.8	366	21.9	12	211	95	--	28.8
393408080045039	111	8.3	4,080	21.2	1.5	3,300	889	649	227
393838079361239	101	7.7	236	9.3	1.1	139	85.6	48	23.6
393903079432039	113	7.9	125	21.9	--	74	37.6	14	11.8
394208080180239	53	7.6	435	18.9	20	263	121	--	35.1
394212080152739	92	8	985	20.4	5.3	626	193	40	50.3
394227080065739	110	8.3	415	21.3	2	242	147	3	43.2

**72 Water quality in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12**
**Appendix 2. Data for base-flow samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued**

[CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; <, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; ft<sup>3</sup>/s, cubic feet per second; °C, degrees Celsius; μS/cm, microsiemens per centimeter at 25°C; μg/L, micrograms per liter; wf, filtered water; cm, centimeter; CaCO<sub>3</sub>, calcium carbonate; --, no data; R, non-detect, result below sample-specific critical level; %, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Station number	Magnesium, wf, in mg/L	Potassium, wf, in mg/L	Sodium, wf, in mg/L	Alkalinity, wf, inflection point field titration, in mg/L as CaCO <sub>3</sub>	Bicarbonate, wf, inflection point field titration, in mg/L	Bromide, wf, in mg/L	Carbon dioxide, water, in mg/L	Carbonate, wf, inflection point field titration, in mg/L	Chloride, wf, in mg/L
03050800	10	1.33	3.99	0.1	0.4	0.027	2.6	--	5.68
03062215	86.3	8.85	949	337	401	0.692	3.2	4.5	100
03069880	1.63	1.36	2.91	26.9	32.8	0.016	2.7	--	3.25
383309080021539	2.85	1.14	6.26	73.4	88.4	0.018	1.5	0.5	6.24
383936079585339	2.17	1.08	1.93	41.7	50.8	0.021	1.6	0.1	1.61
384352080084839	1.61	1.13	45	83.5	101	0.024	0.9	0.6	3.73
384401079584939	1.72	0.92	0.89	31.6	38.5	0.018	1.9	--	0.87
384440080140939	1.45	0.78	14	36	43.7	0.02	0.2	0.1	2.44
384517080093039	1.55	0.66	2.65	14.8	18	0.025	1.8	--	2.21
385015079523339	2.16	1.29	3.26	40	48.7	0.018	5.1	--	3.11
385207080272939	3.74	2.76	11.9	58.1	70.9	0.083	11	--	15.9
385232080155239	1.8	1.34	3.75	30.9	37.6	0.048	2.7	0.1	6.59
385307080175339	2.63	1.76	4.37	42.9	52.2	0.031	7.7	--	5.69
385333079384039	1.26	0.88	1.27	20	24.4	0.015	2.3	--	1.1
385342079512439	4.2	1.93	12.7	79.2	95.7	0.04	3.3	0.4	15.4
385346080065239	1.72	1.04	2.02	39.4	48	0.026	3.4	--	2.14
385750080091039	15.6	2.18	4.24	31.8	38.6	0.03	1.5	0.1	6.13
390134079491139	2.47	1.98	4.61	38.2	46.5	0.027	4.2	0.1	6.16
390253080283839	13.7	4.9	25.7	141	170	0.069	4.8	1.4	42.8
390334080091839	29.8	3.59	22.8	109	133	0.035	5.5	0.1	8.86
390520080232239	22.4	3.31	50	125	152	0.045	0.5	0.6	5.96
390627080294039	13.1	3.85	6.25	110	134	0.031	2.7	0.1	3.82
390820079304039	4.49	1.6	5.04	38.4	46.7	0.026	0.6	0.1	6.79
390853079424839	1.81	1.06	2.06	18.5	22.5	0.017	2	--	1.73
390947080154239	44.9	3.93	102	244	286	0.039	3.3	5.1	6.94
391000079421039	1.89	1.26	1.72	20	24.4	0.018	2.6	--	1.88
391000080220739	16.3	3.55	26.7	119	145	0.052	6.5	0.3	40.3
391023080140539	32.8	3.1	50	126	154	0.038	2.7	--	7.29
391108079354239	1.8	1.23	2.45	20.8	25.4	0.014	1.2	--	3.81
391212079545339	2.15	1.4	3.35	31.8	38.8	0.014	1.5	--	4.09
391353080172039	37.2	4.33	17.6	133	160	0.041	2	0.9	6.39
391605080094739	41.2	3.53	56.1	92	111	0.038	1.7	0.4	5.39
391632080292039	9.36	3.92	24.6	145	174	0.035	13	0.9	9.02
391817080291539	8.28	5.07	41.2	111	134	0.069	2.5	0.6	63.1
391958079520739	6.78	2	7.5	5.8	8.3	0.018	208	--	8.15
392105079394839	3.3	1.33	4.02	39	47.6	0.019	1.8	--	6.06
392203080243739	25	4.72	93.8	190	228	0.049	3.1	1.9	10.8
392335080114839	6.71	2.81	8.96	65.7	79.5	0.036	0.7	0.3	11
392457080192939	20.2	3.45	151	158	192	0.164	1.2	0.4	26.6
392947080054139	6.56	2.59	16.7	103	123	0.029	0.6	--	13.9
393059079483739	13.5	5.12	8.31	53.1	64.6	0.036	4	--	10.7
393250080023439	2.76	1.76	5.15	43.3	52.3	0.018	0.2	0.2	6.38
393308080100339	21.3	3.38	134	184	223	0.259	7.1	0.4	41.5
393320080212239	5.55	1.88	40.5	116	141	0.156	4.1	0.3	21.8
393408080045039	77.4	7.05	697	241	290	0.459	2.2	1.8	71.2
393838079361239	6.48	2.36	12.9	38	46.3	0.037	1.4	--	17.4
393903079432039	1.93	0.9	8.29	23.4	28.4	0.022	0.6	--	14.2
394208080180239	7.91	2.86	49.8	160	194	0.051	7.7	0.6	14.4
394212080152739	16.4	3.09	151	154	184	0.21	2.8	1.5	42
394227080065739	9.46	2.82	32.2	145	174	0.067	1.5	0.8	14.6

**Appendix 2 .** Data for base-flow samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued

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Station number	Fluoride, wf, in mg/L	Silica, wf, in mg/L	Sulfate, wf, in mg/L	Aluminum, wf, in μg/L	Barium, wf, in μg/L	Beryllium, wf, in μg/L	Cadmium, wf, in μg/L	Chromium, wf, in μg/L	Cobalt, wf, in μg/L
03050800	<.04	7.01	112	99.8	51.3	0.245	0.188	<.07	2.9
03062215	0.26	10.1	2,640	<6.6	18.1	<.018	<.048	<.21	0.52
03069880	<.04	4.65	6.76	4.8	50.8	<.006	<.016	<.07	0.224
383309080021539	<.04	5.5	5.52	<2.2	49.8	<.006	<.016	<.07	0.323
383936079585339	<.04	6.28	5.79	2.9	36.5	<.006	<.016	<.07	0.043
384352080084839	0.1	3.27	34.5	19.8	43	<.006	<.016	0.07	0.346
384401079584939	<.04	2.83	4.17	22.7	41.9	<.006	<.016	<.07	0.107
384440080140939	<.04	2.22	13.3	8.7	43.4	0.006	<.016	<.07	0.194
384517080093039	<.04	2.67	7.64	5.6	35.5	0.008	0.034	<.07	0.09
385015079523339	<.04	3.94	5.86	3.2	48	<.006	<.016	<.07	0.324
385207080272939	<.04	3.72	8.32	3.6	84.6	<.006	<.016	<.07	0.727
385232080155239	0.05	3.66	5.84	38.8	74.5	0.025	0.017	<.07	0.524
385307080175339	0.05	4.87	6.36	10.8	49.5	0.009	<.016	0.08	0.788
385333079384039	<.04	3	3.42	9.1	37	0.006	0.017	<.07	0.347
385342079512439	<.04	4.45	13.5	3.9	58.7	<.006	<.016	<.07	0.507
385346080065239	<.04	2.56	6.7	8.1	67.3	0.014	<.016	<.07	0.416
385750080091039	0.05	4.04	101	10.5	51.7	0.007	<.016	<.07	0.348
390134079491139	<.04	2.2	5.24	19.1	57.7	0.011	0.019	0.07	1.11
390253080283839	0.13	3.16	40.2	2.7	71.6	<.006	<.016	0.07	0.64
390334080091839	0.16	1.69	280	61.9	58.5	0.012	0.067	<.07	3.99
390520080232239	0.18	3.86	220	12.2	64.9	<.006	<.016	<.07	0.224
390627080294039	0.1	3.75	60.1	6.9	70.8	<.006	<.016	<.07	0.862
390820079304039	0.06	2.95	26.8	35.7	35.1	0.01	0.018	0.11	1.5
390853079424839	<.04	4.91	5.69	3.6	27.6	<.006	<.016	<.07	0.078
390947080154239	0.23	4.45	433	10.2	54.8	<.006	<.016	<.07	0.337
391000079421039	<.04	4.28	5.98	5.1	30	<.006	<.016	<.07	0.08
391000080220739	0.12	4.12	82.2	4.9	95	<.006	<.016	<.07	0.894
391023080140539	0.14	4.58	309	14.2	49	<.006	<.016	<.07	0.272
391108079354239	<.04	3.87	5.95	5	32.3	<.006	<.016	<.07	0.461
391212079545339	<.04	3.36	7.45	4.6	42.3	<.006	<.016	<.07	0.157
391353080172039	0.15	4.06	301	5.6	65.9	<.006	<.016	<.07	0.578
391605080094739	0.25	9.93	470	41	36.7	<.006	<.016	<.07	0.753
391632080292039	0.1	4.23	23	11.5	98.4	<.006	<.016	<.07	0.423
391817080291539	0.14	3.06	23.7	10.8	86.5	0.039	0.053	0.1	0.435
391958079520739	0.09	9.61	144	4,420	47.3	1.8	0.21	0.37	20.6
392105079394839	<.04	4.27	12.6	2.7	58.9	<.006	<.016	<.07	0.106
392203080243739	0.27	6.32	363	13.1	66.2	<.006	<.016	<.07	0.341
392335080114839	0.09	3.98	42	8	62.2	<.006	<.016	<.07	0.327
392457080192939	0.22	2.64	369	7.1	67.5	<.006	<.016	<.07	0.434
392947080054139	0.11	2.91	31.1	13.9	78.7	<.006	<.016	<.07	0.548
393059079483739	0.18	2.55	261	4.2	37.4	0.006	0.025	<.07	1.01
393250080023439	0.06	2.05	11.8	25	56.2	<.006	<.016	<.07	0.311
393308080100339	0.2	3.65	302	9.5	69.8	0.007	<.016	<.07	0.681
393320080212239	0.17	4.63	28.6	15.9	82.5	<.006	0.022	<.07	0.483
393408080045039	0.27	7.28	2,040	6.5	20.9	<.012	0.033	<.14	0.401
393838079361239	0.06	4.47	43.7	13	48.3	0.01	<.016	<.07	0.304
393903079432039	0.05	2.95	12.1	23	48.9	0.012	0.017	<.07	0.081
394208080180239	0.15	3.08	41.3	11.4	83.9	<.006	<.016	<.07	0.599
394212080152739	0.17	1.68	284	10.2	72.4	<.006	<.016	<.07	0.769
394227080065739	0.14	4.99	43.9	8	65.1	<.006	<.016	<.07	0.172

**74 Water quality in the Marcellus Shale Gas Field of the Monongahela River Basin, West Virginia, 2011–12**
**Appendix 2 . Data for base-flow samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued**

[CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; <, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; ft<sup>3</sup>/s, cubic feet per second; °C, degrees Celsius; μS/cm, microsiemens per centimeter at 25°C; μg/L, micrograms per liter; wf, filtered water; cm, centimeter; CaCO<sub>3</sub>, calcium carbonate; --, no data; R, non-detect, result below sample-specific critical level; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Station number	Copper, wf, in μg/L	Iron, wf, in μg/L	Lead, wf, in μg/L	Manganese, wf, in μg/L	Molybdenum, wf, in μg/L	Nickel, wf, in μg/L	Silver, wf, in μg/L	Strontium, wf, in μg/L	Zinc, wf, in μg/L
03050800	<.80	32.6	<.025	351	<.014	18.5	<.005	71.9	33.7
03062215	<.2.4	10	<.075	91.1	0.442	1.2	<.015	4,470	<.4.2
03069880	<.80	23.4	0.048	3.5	0.06	0.34	<.005	39.3	<.1.4
383309080021539	<.80	4.9	<.025	5.95	0.23	0.22	<.005	75.2	<.1.4
383936079585339	<.80	<.3.2	<.025	1.66	0.077	0.14	<.005	45.9	<.1.4
384352080084839	<.80	87.9	<.025	14.8	0.222	0.43	<.005	49.6	<.1.4
384401079584939	<.80	66.8	0.032	12.8	0.041	0.27	<.005	27.1	<.1.4
384440080140939	<.80	70.2	0.025	21.3	0.077	0.42	<.005	28.3	<.1.4
384517080093039	0.8	11.7	0.039	6.06	0.078	0.28	<.005	23.6	<.1.4
385015079523339	<.80	93.9	0.032	21.2	0.075	0.35	<.005	43.2	<.1.4
385207080272939	<.80	596	0.071	441	0.194	0.62	<.005	118	<.1.4
385232080155239	<.80	158	0.048	26.8	0.098	1.1	<.005	73.7	<.1.4
385307080175339	0.83	505	0.104	155	0.137	0.75	<.005	61.1	<.1.4
385333079384039	<.80	72.5	0.055	22.1	0.067	0.38	<.005	23.8	<.1.4
385342079512439	<.80	185	0.031	37.3	1.45	0.44	<.005	106	<.1.4
385346080065239	<.80	177	0.044	20.3	0.039	0.75	<.005	36.9	<.1.4
385750080091039	<.80	59.3	0.028	24.4	0.068	0.99	<.005	54.9	<.1.4
390134079491139	0.8	662	0.201	108	0.205	0.98	<.005	50.9	<.1.4
390253080283839	1.4	64.8	0.051	258	1.25	1.3	<.005	215	<.1.4
390334080091839	0.85	41.7	<.025	473	0.234	5.5	<.005	448	2.6
390520080232239	0.81	13.6	<.025	67	0.619	0.75	<.005	494	<.1.4
390627080294039	0.84	29.6	0.06	132	1.05	0.93	<.005	197	<.1.4
390820079304039	<.80	134	0.11	18.6	0.248	1.8	<.005	141	1.7
390853079424839	0.86	12.6	0.028	1.78	0.035	0.14	<.005	26.8	<.1.4
390947080154239	<.80	9.3	<.025	64	0.843	1.1	<.005	960	<.1.4
391000079421039	<.80	10.4	<.025	2	0.035	0.2	<.005	25.5	<.1.4
391000080220739	<.80	37.5	0.056	349	1.04	1	<.005	228	<.1.4
391023080140539	<.80	18.8	<.025	45.1	0.466	0.96	<.005	633	<.1.4
391108079354239	<.80	9.9	0.048	4.43	0.039	0.27	<.005	28.8	<.1.4
391212079545339	<.80	98.9	<.025	5.54	0.169	0.4	<.005	43.7	<.1.4
391353080172039	0.87	12.3	<.025	50.5	0.901	1.3	<.005	568	<.1.4
391605080094739	<.80	5.7	<.025	124	0.259	2.6	<.005	971	<.1.4
391632080292039	<.80	45.8	0.065	278	1.4	0.64	<.005	253	<.1.4
391817080291539	1.8	32.6	0.13	45.5	1.06	0.94	0.037	245	<.1.4
391958079520739	3.7	1,040	0.387	401	0.019	34	<.005	149	85.4
392105079394839	<.80	5	<.025	3.09	0.099	0.25	<.005	86.8	<.1.4
392203080243739	<.80	6.6	<.025	83.4	0.64	1.1	<.005	1,720	<.1.4
392335080114839	1	16	0.031	14	0.787	0.77	<.005	117	<.1.4
392457080192939	<.80	8.8	<.025	21.8	1.03	1.6	<.005	930	<.1.4
392947080054139	1.1	31.5	0.06	11.4	0.804	0.87	<.005	152	<.1.4
393059079483739	<.80	32.9	<.025	174	0.131	2.6	<.005	278	2.3
393250080023439	0.8	57.9	0.042	13.4	0.265	0.72	<.005	65	<.1.4
393308080100339	0.8	19.4	0.044	383	2	0.99	<.005	689	<.1.4
393320080212239	0.99	89.8	0.111	45.7	1.4	0.5	<.005	195	<.1.4
393408080045039	<.1.6	16.7	<.050	49.6	0.548	1.1	<.010	3,210	<.2.8
393838079361239	<.80	150	1.21	18.9	0.107	1.6	<.005	66.8	<.1.4
393903079432039	<.80	29.5	<.025	19.7	0.109	0.66	<.005	31.2	<.1.4
394208080180239	0.81	88.9	0.11	240	1.35	0.63	<.005	254	<.1.4
394212080152739	1.1	43.7	0.062	50.2	2.21	2.5	<.005	400	<.1.4
394227080065739	<.80	22.9	<.025	15.8	0.787	0.47	<.005	228	<.1.4

**Appendix 2 . Data for base-flow samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued**

[CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; <, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; ft<sup>3</sup>/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter; wf, filtered water; cm, centimeter; CaCO<sub>3</sub>, calcium carbonate; --, no data; R, non-detect, result below sample-specific critical level; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Station number	Antimony, wf, in µg/L	Arsenic, wf, in µg/L	Boron, wf, in µg/L	Selenium, wf, in µg/L	Alpha activity, wf, Thorium-230, in pCi/L	Gross beta, wf, Cesium-137, in pCi/L	Radium-224, wf in pCi/L	Radium-226, wf, in pCi/L	Radium-228, wf, in pCi/L
03050800	<.027	0.07	13	0.57	0.7	2	0.52	R.10	0.29
03062215	<.081	0.37	312	0.2	R1	7.4	R.00	R.00	--
03069880	0.051	0.2	13	<.03	R-2	1.4	R.14	R.08	--
383309080021539	0.075	0.33	10	0.04	R.2	1	R.07	R.037	--
383936079585339	<.027	0.22	10	0.04	R-.04	0.6	R.06	R-.05	--
384352080084839	0.04	0.2	27	0.08	0.9	1.5	0.18	R.09	R.16
384401079584939	0.035	0.16	8	0.03	R.03	1.4	R.00	0.09	--
384440080140939	0.053	0.13	14	0.07	0.4	1.4	R.07	R.04	--
384517080093039	0.031	0.06	--	0.06	R-.1	1.1	R.08	0.15	--
385015079523339	0.066	0.35	14	0.03	R.0	1.9	R.07	R.05	--
385207080272939	0.086	0.54	18	0.11	R-.29	2.7	R-.06	R-.10	--
385232080155239	0.07	0.18	11	0.08	0.5	1.2	R-.16	R.00	--
385307080175339	0.108	0.58	15	0.11	R.1	1.7	R.00	R.13	--
385333079384039	0.069	0.34	7	0.04	R.3	1.4	R.00	R.10	--
385342079512439	0.124	0.63	24	0.15	0.7	2.2	R-.18	R.05	--
385346080065239	0.043	0.16	9	0.07	0.4	1.4	R.09	0.26	--
385750080091039	0.067	0.18	13	0.12	R.3	2.5	R-.08	R.00	--
390134079491139	0.14	1.1	22	0.1	R.3	2.1	R-.14	R.06	--
390253080283839	0.144	0.97	42	0.18	R.6	3.7	R.12	R.10	--
390334080091839	0.112	0.24	34	0.23	R.3	3.1	R.18	R.00	--
390520080232239	0.103	0.71	35	0.22	2	3.4	R.00	R.12	--
390627080294039	0.198	0.83	23	0.19	R.0	3.8	R.11	R.00	--
390820079304039	0.139	0.21	19	0.26	0.8	1.8	R.11	R.00	--
390853079424839	<.027	0.19	9	<.03	R-.09	0.9	R-.06	R.14	--
390947080154239	0.086	0.57	54	0.31	R1.1	3.6	R.08	R-.08	--
391000079421039	0.047	0.23	11	<.03	R-.33	1.2	R-.05	R.00	--
391000080220739	0.218	0.83	32	0.16	R.1	3.7	R.00	R-.06	--
391023080140539	0.067	0.28	38	0.15	1.1	3.3	0.8	3	R.00
391108079354239	0.053	0.2	9	<.03	0.4	R.7	R.00	R.05	--
391212079545339	0.038	0.16	10	0.06	R-.1	R.3	R.05	R.038	--
391353080172039	0.151	0.63	35	0.2	2.6	3.9	R.00	R-.05	--
391605080094739	0.077	0.24	58	0.14	R.9	3.8	R.00	R.10	--
391632080292039	0.118	0.96	39	0.16	R.7	3.1	R.22	R.12	--
391817080291539	0.285	1.4	65	0.49	R-.4	3.4	R.06	R.02	--
391958079520739	<.027	0.25	14	0.08	0.8	1.6	0.66	0.25	R.08
392105079394839	0.079	0.14	18	<.03	0.5	1	R.00	R.02	--
392203080243739	0.071	0.26	79	0.1	1.9	4.3	R.3	R-.15	--
392335080114839	0.106	0.51	26	0.13	R.1	2.4	R-.09	0.13	--
392457080192939	0.11	0.29	57	0.16	R.2	3.7	0.13	0.11	R.07
392947080054139	0.134	0.51	39	0.12	0.6	2.8	R.00	0.11	--
393059079483739	0.072	0.22	25	0.09	R-.7	5.1	R-.06	R.05	--
393250080023439	0.083	0.29	19	0.11	R.4	2.1	R.11	0.07	--
393308080100339	0.343	0.65	106	0.22	2	3.6	R.00	R.02	--
393320080212239	0.136	0.92	44	0.13	R.5	2.2	R-.02	0.07	--
393408080045039	0.072	0.35	217	0.15	R-4	6.1	R.00	0.16	--
393838079361239	0.054	0.12	17	0.08	R-.1	2.2	R-.20	R.04	--
393903079432039	0.033	0.14	15	0.06	0.6	1.3	0.28	0.11	0.41
394208080180239	0.146	1.3	49	0.2	0.8	2.4	R.04	R.06	--
394212080152739	0.165	0.81	81	0.22	R1	2.6	R.13	R.02	--
394227080065739	0.093	0.51	38	0.14	1.2	3.1	0.12	0.08	R.05

**Appendix 2.** Data for base-flow samples collected as part of the Marcellus Shale base-line survey, Monongahela River Basin, West Virginia, July–October 2012.—Continued

[CR, Creek; Ck, creek; HWY, highway; WV, West Virginia; BR, bridge; NR, near; FK, Fork; Fk, fork; ST., Saint; RR, railroad; <, less than; mmHg, millimeters of mercury; mg/L, milligrams per liter; ft<sup>3</sup>/s, cubic feet per second; °C, degrees Celsius; μS/cm, microsiemens per centimeter at 25°C; μg/L, micrograms per liter; wf, filtered water; cm, centimeter; CaCO<sub>3</sub>, calcium carbonate; --, no data; R, non-detect, result below sample-specific critical level; ‰, per mil; pCi/L, picocuries per liter; <sup>13</sup>C, carbon-13, <sup>18</sup>O, oxygen-18; <sup>2</sup>H, deuterium; <sup>34</sup>S, sulfur-34; CH<sub>4</sub>, methane; DIC, dissolved inorganic carbon; H<sub>2</sub>O, water; SO<sub>4</sub>, sulfate]

Station number	Uranium, wf, in μg/L	Uranium-234, wf, in pCi/L	Uranium-235, wf, in pCi/L	Uranium-238, wf, in pCi/L	<sup>18</sup> O <sub>SO4</sub> in ‰	<sup>34</sup> S <sub>SO4</sub> in ‰	<sup>13</sup> C <sub>DIC</sub> in ‰	<sup>2</sup> H <sub>H2O</sub> in ‰	<sup>18</sup> O <sub>H2O</sub> in ‰
03050800	0.011	R.000	R.005	R.000	-6.4	-0.9	--	-51.50	-9.32
03062215	0.51	0.26	R-.008	0.18	5.7	12.1	-8.80	--	-8.15
03069880	0.006	--	--	--	4.5	1.4	-9.46	-46.30	-8.90
383309080021539	0.079	R.009	R.011	R.000	4.4	1.0	-10.34	-54.80	-8.56
383936079585339	0.014	R.002	R.000	R.000	--	--	-11.23	-50.40	-7.77
384352080084839	0.066	0.036	R-.005	0.023	0.2	2.4	-6.80	-55.10	-9.15
384401079584939	0.011	R.006	R.004	R.009	5.5	4.7	-7.72	-50.50	-8.46
384440080140939	0.006	--	--	--	3.5	3.5	-7.85	-52.60	-7.80
384517080093039	<.004	--	--	--	2.9	5.1	-7.18	-54.80	-8.29
385015079523339	0.01	R-.009	0.011	R-.009	4.6	0.9	-12.09	-53.80	-8.83
385207080272939	0.043	R.014	R.000	R.010	6.6	3.9	-11.90	-36.70	-6.56
385232080155239	0.013	R.010	R.000	0.02	3.3	1.9	-9.71	-45.80	-7.51
385307080175339	0.023	R.007	R-.009	R.004	--	3.6	-12.77	-42.30	-6.74
385333079384039	0.007	--	--	--	3.9	3.9	-9.13	-45.00	-9.46
385342079512439	0.182	0.11	R.012	0.058	2.2	-7.6	-10.81	-45.00	-8.72
385346080065239	0.012	R.006	R.004	0.03	4.1	2.9	-9.37	-51.30	-7.70
385750080091039	0.033	R-.009	R.000	0.028	-1.1	-6.0	-8.48	-50.40	-8.22
390134079491139	0.024	R-.017	0.01	R-.009	5.3	2.2	-11.66	-39.70	-7.17
390253080283839	0.651	0.27	R.01	0.2	10.6	6.5	-11.80	--	-4.25
390334080091839	0.369	0.17	0.013	0.16	1.6	1.5	-8.73	-48.00	-7.78
390520080232239	0.785	0.34	0.021	0.26	-1.1	1.8	-7.89	-36.53	-7.14
390627080294039	0.7	0.4	R-.005	0.24	3.8	-3.4	-11.33	-25.90	-4.45
390820079304039	0.043	0.063	R.000	0.054	-0.2	-0.8	-6.32	-47.50	-8.59
390853079424839	<.004	--	--	--	3.9	3.8	-10.13	-48.60	-8.61
390947080154239	1.39	0.55	0.03	0.39	-1.9	0.1	-5.87	-49.90	-7.67
391000079421039	<.004	--	--	--	4.1	3.6	-9.30	-48.40	-8.43
391000080220739	0.816	0.33	0.01	0.19	1.1	1.2	-12.36	-38.00	-5.71
391023080140539	0.83	0.31	R.000	0.27	-1.1	0.3	-9.19	-50.70	-7.13
391108079354239	<.004	--	--	--	3.2	2.0	-8.16	-52.80	-8.75
391212079545339	0.023	R.000	R-.003	R.003	4.5	--	-7.48	-50.10	-8.51
391353080172039	1.3	0.59	0.027	0.44	4.0	-1.3	-10.84	-33.60	-6.22
391605080094739	0.447	0.2	R-.006	0.15	-2.5	0.3	-6.51	-46.90	-8.43
391632080292039	0.676	0.28	R.000	0.17	2.4	-2.1	-12.77	-41.40	-6.42
391817080291539	0.582	0.2	R.000	0.18	6.2	2.0	-10.96	-36.60	-6.11
391958079520739	0.255	0.09	R-.006	0.1	-3.3	0.4	--	-48.90	-8.55
392105079394839	0.005	--	--	--	3.7	1.3	-9.92	-49.83	-8.62
392203080243739	0.521	0.21	0.017	0.18	2.1	3.2	-10.88	-47.00	-7.35
392335080114839	0.22	0.14	R-.004	0.077	6.4	-4.7	-11.16	-34.00	-5.52
392457080192939	0.512	0.17	R.020	0.14	1.9	-4.9	-9.74	-42.10	-7.28
392947080054139	0.432	0.17	R.000	0.13	3.6	-3.4	-10.00	-38.10	-6.01
393059079483739	0.058	0.042	R.008	0.04	1.8	4.0	-24.61	-40.16	-6.70
393250080023439	0.064	0.023	R.000	0.011	7.4	2.1	-10.07	-24.40	-5.78
393308080100339	0.773	0.35	R.000	0.32	6.6	13.4	-12.00	-46.80	-6.89
393320080212239	0.365	0.12	R-.010	0.1	6.4	2.6	-14.14	-43.10	-7.12
393408080045039	0.452	0.16	R-.005	0.12	4.9	11.5	-9.52	--	-7.73
393838079361239	0.046	R.000	R-.004	0.02	1.1	-3.6	-24.05	-59.80	-8.75
393903079432039	0.012	R-.020	R-.005	R.012	4.0	1.1	-12.22	-42.40	-7.50
394208080180239	0.602	0.27	R.000	0.18	4.8	5.3	-14.57	-48.70	-7.36
394212080152739	0.779	0.31	0.017	0.25	5.3	11.8	-11.60	-47.80	-7.20
394227080065739	0.547	0.3	R.000	0.17	4.4	4.0	-11.68	-48.90	-7.52

For additional information call or write to:

Director, U.S. Geological Survey  
West Virginia Water Science Center  
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