Ground-Water Quality and Geohydrology of the Blue Ridge Physiographic Province, New River Basin, Virginia and North Carolina

By Mark D. Kozar, Charlynn J. Sheets, and Curt A. Hughes

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Foreword

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings.

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.00006309	cubic meter per second
mile (mi)	1.609	kilometer
million gallons per day per square mile (MGD/mi^2)	1,461	cubic meter per day per square kilometer
milliliter (mL)	0.0610	cubic inches
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (^oC) can be converted to degrees Fahrenheit (^oF), and conversely, by use of the following equations:

$$^oF = (1.8 \times {}^oC) + 32 \qquad\qquad {}^oC = ({}^oF - 32) \times 0.5555$$

Vertical datum: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929-- a geodetic datum derived from a general adjustment of the first order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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

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Abstract

Water samples collected from 30 wells throughout the Blue Ridge Physiographic Province in the New River Basin of North Carolina and Virginia were analyzed for a wide range of constituents including bacteria, common ions, nutrients, trace metals, radon, pesticides, and volatile organic compounds (VOCs). Most constituents detected were present at concentrations less than the United States Environmental Protection Agency (USEPA) maximum contaminant level (MCL) or secondary maximum contaminant level (SMCL) drinking-water standards.

Of 30 wells sampled, none tested positive for the presence of fecal coliform or *Escherichia Coli* (*E. coli*) bacteria. Water from 11 of 29 wells (38 percent) sampled tested positive for the presence of total coliform bacteria. Coliform and *E. coli* bacteria are used as indicators of the potential presence of pathogenic bacteria, viruses, and protozoans.

Only one sample contained nitrate+nitrite (14.1 mg/L) in excess of the 10.0 mg/L USEPA MCL. Likewise, only one sample contained fluoride exceeding the 2.0 mg/L SMCL. None of the samples contained trace metals in concentrations exceeding USEPA standards. Only 4 of 30 (13 percent) samples contained iron in concentrations exceeding the 300 µg/ L USEPA SMCL, and only 5 of 30 (17 percent) samples contained manganese in concentrations exceeding the 50 µg/L SMCL. Lead was detected in 3 of 30 (10 percent) samples, but no samples exceeded the 15 µg/ L USEPA action level for lead.

Radon, a radioactive gas and known carcinogen, was detected in concentrations exceeding the proposed USEPA 300 pCi/L MCL for radon in 26 of 30 (87 percent) wells sampled. In 10 of 30 (33 percent) samples, radon exceeded the 4,000 pCi/L proposed alternative MCL. The median radon concentration detected was 2,080 pCi/L (almost seven times the proposed MCL), and the maximum concentration detected was 30,900 pCi/L. Of 10 wells having radon concentrations greater than 4,000 pCi/L, eight were on or adjacent to faults; this finding suggests fault zones may be areas of uranium enrichment and allow radon migration upward along the fault.

No pesticides or VOCs were detected at concentrations exceeding USEPA MCLs or health-based guidelines. Concentrations of pesticides and VOCs detected were low. The maximum pesticide concentration was only 0.152 µg/L, and the maximum VOC concentration was only 1.20 µg/L. Only 10 of 86 pesticides and 14 of 86 VOCs analyzed for were detected. At least one pesticide was detected in 17 of 30 (57 percent) samples, and 21 of 30 (70 percent) samples contained detectable concentrations of at least one VOC. Atrazine, deethylatrazine (a degradation product of atrazine), simazine, DDE, and molinate were the most commonly detected pesticides. They were detected in 11 (37 percent), 9 (30 percent), 6 (20 percent), 4 (13 percent), and 2 (7 percent) of the 30 wells sampled, respectively. The most commonly detected VOCs were chloroform, 1,1,1-trichloroethane, benzene, toluene, methyl-ethyl-ketone, carbon-disulfide, tetrachloroethylene, methyl-*tert*-butyl-ether (MTBE), and 1,4 dichlorobenzene. These VOCs were detected in 40, 30, 23, 17, 17, 17, 13, 10, and 10 percent of the 30

wells sampled, respectively. The high detection frequency of pesticides and VOCs suggests that aquifers in the region may be susceptible to contamination.

Average annual ground-water recharge in the New River Basin, based on analysis of streamflow data, ranged from 11.4 to 22.3 in. with a median of 15.1 in. On average, 69 percent of ground-water recharge occurs during the colder months of November through May, when evapotranspiration is at a minimum. Only 31 percent of recharge typically occurs in June through October, a period of peak vegetation growth and correspondingly high rates of evapotranspiration. Median apparent ground-water age estimated from analysis of samples for chlorofluorocarbons (CFCs) is 16 years.

INTRODUCTION

The U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program conducted an investigation to establish base-line data for and to assess the quality of ground water within the New River Basin portion of the Blue Ridge Physiographic Province in Virginia and North Carolina. The region is located in a rural portion of these states. Tourism, silviculture, and to a lesser extent tobacco production and other agriculture, are the main economic interests in the region. Most of the people who do not live in one of the smaller towns in the region obtain their water from ground-water sources. Unfortunately, there has been little research to determine the quality of water derived from the igneous and metamorphic fractured bedrock aquifers of the region. Because of the lack of data and the fact that radon, a carcinogenic and radioactive gas, was believed to be prevalent within the study area, the NAWQA Program initiated a study to characterize the quality of ground water in the region.

Purpose and Scope

This report describes:
- the apparent age of ground water derived from fractured bedrock aquifers,
- the occurrence and distribution of trace metals in ground water derived from the igneous and metamorphic bedrock in the region,
- the occurrence and distribution of radon in ground water,
- the natural geochemical and land use factors that influence water quality,
- the impact of septic systems constructed in the permeable soils of the region on the bacteriological and chemical quality of ground water in the region,
- the occurrence and distribution of pesticides in ground water derived from agriculture and silviculture,
- the occurrence and distribution of VOCs within aquifers of the study area, and
- the impact of acid precipitation on the quality of ground water within the study area.

Description of Study Area

The study area is part of an elongate mountain system that stretches from Pennsylvania to Georgia (Fenneman and Johnson, 1946). It includes all or parts of seven counties in Virginia and three counties in North Carolina (fig. 1) and comprises a 2,106 square mile area of the Blue Ridge Physiographic Province drained by the New River. Population densities are typically less than 60 persons per square mile (U.S. Department of Commerce, 1992 and 1993). Steep mountainous terrane with deeply incised bedrock forms a dendritic drainage pattern in the study area. Precipitation in the region averages 48.3 inches annually (NOAA, 1992a and 1992b). Traditionally, the economy of the region was based on agriculture, especially the production of burly tobacco. Recently, there has been a shift away from tobacco production. Tourism and silviculture, especially the growing of Christmas trees, have become important to the region's economy. The northern portion of the study area is located near Floyd, Virginia and the southern portion is near Boone, North Carolina (fig. 1).
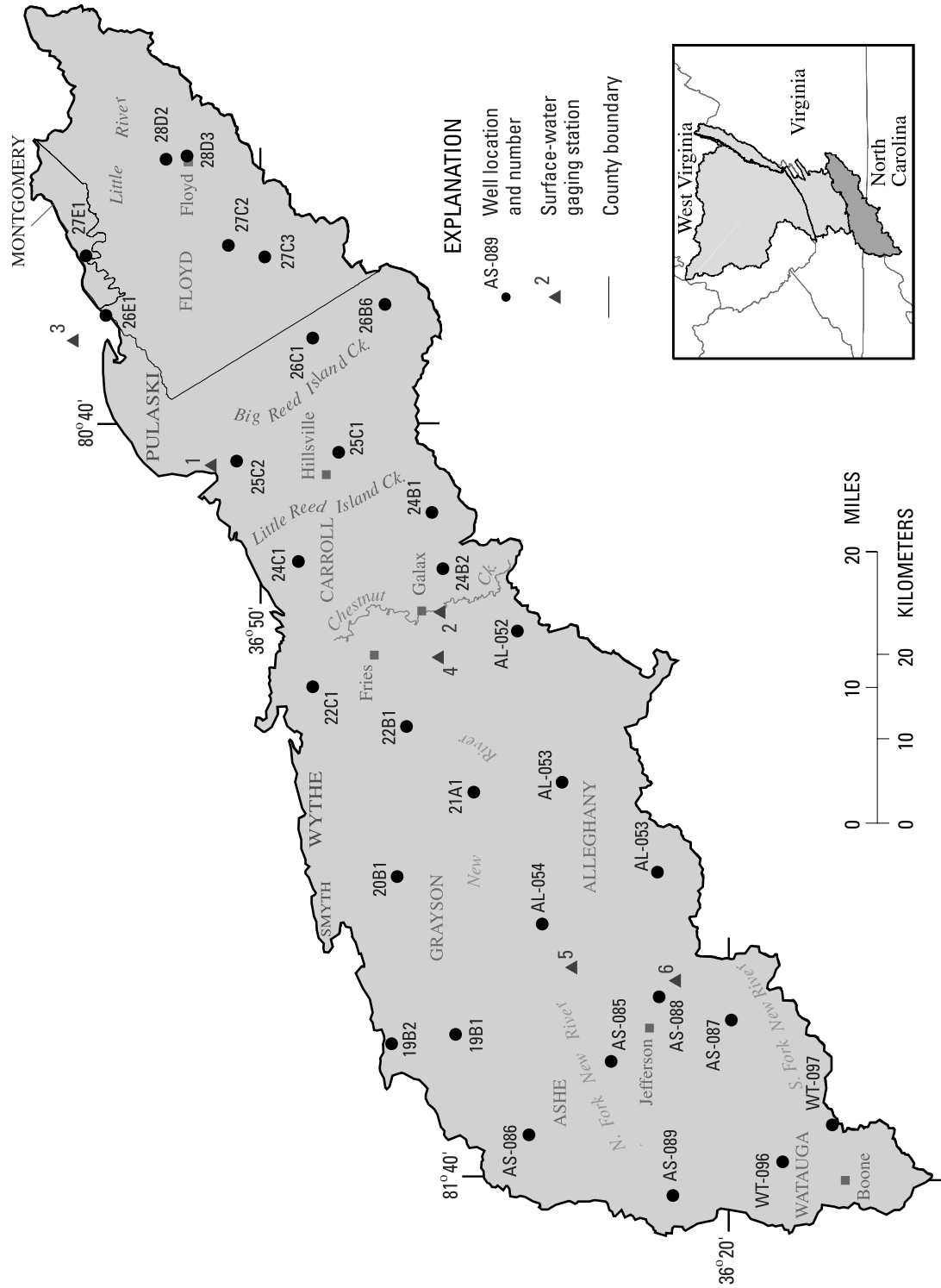
Acknowledgments

Figure 1. Location of the Blue Ridge Physiographic Province within the New River Basin, Virginia and North Carolina, location of wells sampled, and location of gaging stations where recharge was estimated.

STUDY METHODS

Water samples were collected from 30 bedrock wells (fig. 1) from July 1 to August 15, 1997, as part of routine NAWQA data-collection programs in the New River Basin. The wells were sampled for analysis of a broad range of constituents including bacteria, major ions, nutrients, trace elements, radon, pesticides, and volatile organic compounds (VOCs). For 19 of the 30 wells, samples were also collected for analysis of chlorofluorocarbons (CFCs) and submitted to the USGS CFC laboratory for dating analysis. Samples were collected at 12 of the 19 wells sampled for analysis of CFCs and analyzed for dissolved gases to estimate ground-water-recharge temperature.

Selection of Sampling Sites

Wells were selected for sampling on the basis of:
- age of well--typically less than 25 years old,
- acceptable surface casing condition--not rusted or allowing surface contaminants to enter well bore,
- adequate yield for sampling--minimum of five gallons per minute,
- adequate plumbing systems--pipes were not rusted and no water-treatment systems such as chlorinators or softeners were in line to affect samples, and
- submersible pumps in place--no jet pumps were used.

Initial sampling sites were selected randomly by use of a computer program. Suitable wells were then selected amongst potential random locations that met the criteria stated above. Well and site characteristics were determined in the field by visiting the site, obtaining drillers' records (where available), interviewing the owner of the well, and by measuring well depth, water level, and casing length. Minimum parameters that were collected for each selected well were well depth, length of casing, water level, well yield, location (latitude/longitude), topographic setting, contributing geologic unit, and elevation of the well.

The wells sampled were primarily domestic wells, although a few small public supply wells were also sampled. Specific-capacity tests were conducted at those sites where well yield was not known or where the well yield was believed to be low. These tests insured that enough water would be available for purging and sampling the well. Additional data collected for each well, if available, included land use in the well's recharge area, location of pump in the borehole, and location of water-bearing zones in the borehole.

Wells were sampled in the summer (July and August of 1997) for two reasons. First, base flow conditions typically occur in late summer and early fall and represent periods with minimal ground-water recharge. Water-quality constituents typically are found in higher concentrations in ground water during base-flow conditions. Dilution effects typically occur during periods of increased recharge in the winter and spring. Second, air temperature is much warmer in the summer, and bacteria in ground water are typically found in higher concentrations during warmer periods. During cold periods, the growth of bacteria and viruses is greatly reduced and they can even be killed by extreme cold temperatures. Water samples, therefore, were collected in the summer to document the quality of ground water under worst conditions.

Collection of Samples

Prior to sampling, all wells were purged to remove stagnant water from the casings and ensure that representative water samples were collected from the target aquifers. In most instances, a minimum of at least three casing volumes of water was purged from the wells. Dissolved oxygen, pH, specific conductance, water temperature, and reduction-oxidation potential (redox) were monitored continuously during purging using a multi-parameter water-quality monitor. Water samples were taken from spigots located as close to the well as possible, usually from taps on the pressure tanks. The shortest possible length of sampling tubing (usually 5 ft) was used to connect the well to the water-quality monitor and to sampling equipment. Samples were collected after measured field parameters had stabilized, according to USGS NAWQA sampling protocols (Koterba and others, 1995), to minimize the effects of storage tank, casing, and well plumbing on the water samples. The water samples were then filtered (if necessary), preserved (samples for trace element analysis were acidified with nitric acid and samples for nutrient analysis were acidified with sulfuric acid), packed on ice, and shipped daily to the USGS National Water-Quality Laboratory via overnight courier.

Quality-assurance samples consisting of field blanks, replicates, and spiked samples were also collected to determine sampling and analytical variability and bias. Recovery percentages for three field-spiked VOC and pesticide samples did not indicate problems

with recovery of spiked constituents. Likewise, replicate samples for two radon samples were acceptable, within 2 and 8 percent, respectively. Field blanks, however, which help to determine whether samples have been contaminated during collection or shipment to analytical laboratories, revealed potential sampling bias for a few constituents (table 1). Concentrations of aluminum in field blanks indicated potentially significant contamination problems with dissolved aluminum, especially for those samples with concentrations less than 3.6 µg/L (table 1). Minor contamination may also be evident for the DDT insecticide residue p,p'-DDE and the VOCs toluene, trichloroethylene, methyl-*tert*-butyl-ether (MTBE), chloroform, and benzene. Other than aluminum, significant contamination of environmental data is not indicated by the quality-assurance data.

Samples for analysis of dissolved-gases (oxygen, nitrogen, methane, carbon dioxide and argon) were collected by placing a silicone rubber discharge tube from the well-discharge line into the bottom of a 160 mL glass bottle. The 160-mL bottle was then placed in the bottom of a 1-L glass beaker and allowed to overflow until it was completely submerged. A rubber stopper with a hypodermic needle inserted was then used to seal the 160-mL glass bottle below the water level of the 1-L glass beaker. The hypodermic needle was then quickly removed after the rubber stopper was inserted into the 160-ml bottle (Busenburg and Plummer, 1992).

Five samples each were collected at wells sampled and analyzed for CFCs. The samples were collected by placing a 62-mL borosilicate glass ampule into an apparatus that completely isolated the ampule from atmospheric contamination. Ultra-pure nitrogen was used to flush the apparatus and ampule before ground water was allowed to flow into the ampule. Once the ampule was filled with water, it was sealed by fusing the stem of the ampule with a gas torch. After sealing, the samples were carefully packed in a

Table 1. Quality-assurance data for wells sampled in the Blue Ridge Physiographic Province, New River Basin, Virginia and North Carolina

[µg/L, micrograms per Liter; mg/L milligrams per Liter; <, less than]

Constituent	Unit of concentration	Method detection limit	Blank samples			Routine samples	
			Number of samples	Number of detections	Range of concentrations	Number of samples	Range of concentrations
Aluminum	µg/L	1.0	3	3	2.7-3.6	30	2.3-7.3
Calcium	mg/L	0.020	6	4	0.003-0.026	30	1.4-50.0
Iron	µg/L	3.0	3	1	9.3	30	<3.0-2,400
Nitrate + Nitrite, as N	mg/L	0.050	3	1	0.082	30	<0.050-14.1
Silica	mg/L	0.090	3	2	0.015-0.021	30	8.5-31.0
Benzene	µg/L	0.032	3	1	0.020	30	0.010-0.020
Chloroform	µg/L	0.052	3	1	0.050	30	0.007-0.251
Methyl-*tert*-butyl-ether	µg/L	0.112	3	1	0.030	30	0.030-1.20
p,p'-DDE	µg/L	0.006	3	1	0.0015	30	0.001-0.002
Toluene	µg/L	0.038	3	1	0.040	30	0.010-0.060
Trichloro-ethylene	µg/L	0.038	3	1	0.010	30	0.006

foam-lined shipping container and sent to the USGS CFC laboratory for analysis. Upon receipt by the laboratory, concentrations of CFCs in the samples were determined by use of purge and trap gas chromatography with an electron capture detector (Busenburg and Plummer, 1992). Three of the five ampules collected per site were analyzed. An average of the age dates computed from the three samples was used to estimate the apparent ground-water ages referenced in this report. The remaining two samples were used only if an ampule was broken or if the laboratory wanted to confirm an analysis.

GEOHYDROLOGY

To understand ground-water-flow processes in the study area, a brief description of the geohydrologic framework is presented. Ground-water-age data collected during this study was used to better define conceptual models of ground-water flow within the region.

Bedrock in the Blue Ridge Physiographic Province is comprised of primarily steeply dipping, extensively faulted and folded metamorphic and igneous rocks, although a few carbonate rocks are interspersed with granite and gneiss in the North Carolina portion of the province (Brown and others, 1985; Virginia Department of Mines, Minerals and Energy, 1993). The major rock types in the study area are gneiss, phyllite, amphibolite, dunite, gabbro, granite, greenstone, schist, and conglomerate (fig. 2), as well as metamorphosed siltstone, sandstone, graywacke, and felsite. Regolith and fractures in the bedrock are the primary avenues of storage and flow of ground water in the region. Regolith overlies most bedrock aquifers in the region and consists of saprolite, colluvium, and alluvium (Coble and Others, 1985).

Table 2. Dissolved-gas and recharge-temperature data for 12 wells sampled in the Blue Ridge Physiographic Province, New River Basin

[^{o}C, degrees Celsius; mg/L, milligrams per Liter; ft, feet; cm^3/L, cubic centimeters per Liter]

Field Sample Name	Field Temp. ^{o}C	N_2 (mg/L)	Ar (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	Recharge elevation (ft)	Recharge Temp. ^{o}C	Excess Air (cm^3/L)
20B1	12.4	20.150	0.6880	3.94	28.17	0.0000	3,320	8.8	3.62
22C1	13.5	18.840	0.6661	4.41	36.60	0.0000	2,520	9.9	2.22
27C3	12.9	17.902	0.6341	3.49	2.33	0.0000	2,920	11.2	1.99
26C1	13.0	17.954	0.6555	3.38	13.16	0.0000	2,660	9.2	1.16
22B1	12.8	18.745	0.6600	2.74	8.63	0.0000	2,680	10.2	2.33
28D3	13.4	17.576	0.6235	2.56	46.09	0.0009	2,520	12.5	1.84
26E1	13.8	24.956	0.7758	6.61	15.23	0.0000	2,085	9.9	8.08
25C1	14.8	17.510	0.6360	5.35	12.21	0.0000	2,800	10.4	1.23
AL053	14.8	18.727	0.6457	0.03	14.52	0.0005	3,583	10.5	2.97
AS087	12.4	18.506	0.6549	0.66	5.00	0.0000	3,480	9.1	2.20
19B2	11.0	18.886	0.6742	5.89	6.77	0.0004	3,650	7.4	2.05
24B2	12.3	16.545	0.6246	0.40	32.70	0.0003	2,790	9.8	0.05
Median	13.0	18.616	0.6552	3.44	13.84	0.0000	2,795	9.9	2.12
Maximum	14.8	16.545	0.7758	6.61	46.09	0.0009	3,650	12.5	8.08
Minimum	11.0	24.956	0.6235	0.03	2.33	0.0000	2,085	7.4	0.05

EXPLANATION

——— COUNTY BOUNDARY

ROCK TYPE

- Amphibolite-Gneiss
- Arenite
- Biotite-Gneiss-Monzonite
- Biotite-Gneiss-Phyllite
- Conglomerate
- Dolomite
- Dunite
- Amphibolite-Schist
- Gneiss
- Granite
- Greenstone
- Metafelsite
- Metagraywacke
- Metasiltstone
- Phyllite-Schist
- Quartzite
- Sandstone-Dolomite-Shale
- Schist-Metagraywacke
- Ryolite-Felsite
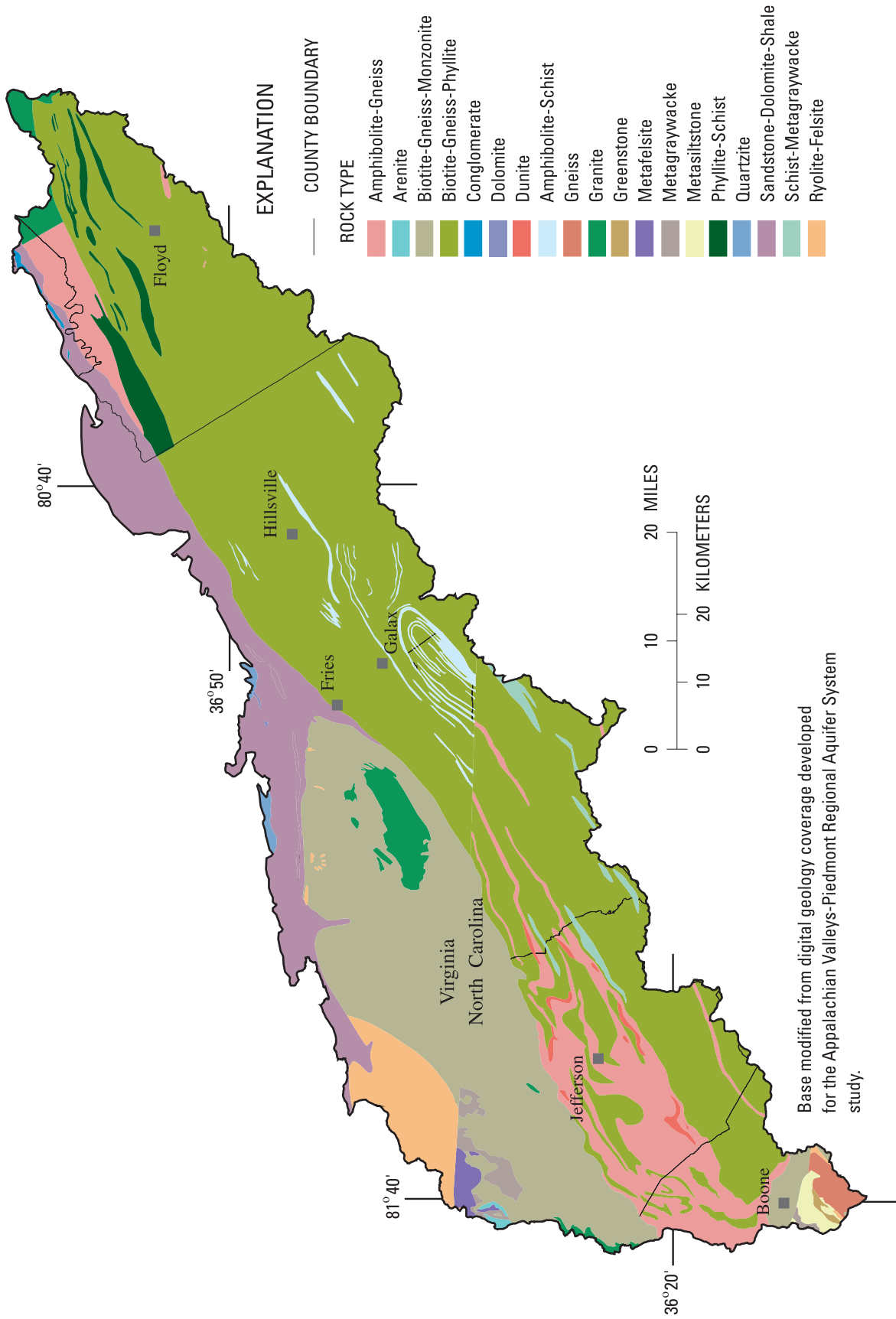
Figure 2. Rock types in the Blue Ridge Physiographic Province, New River Basin.

Base modified from digital geology coverage developed
for the Appalachian Valleys-Piedmont Regional Aquifer System
study.

Ground water usually flows along short flow paths from inter-stream recharge areas to the nearest stream. Bedrock fractures and regolith are directly connected and form a ground-water flow system in which the regolith serves as a reservoir, storing ground water and releasing the stored water through interconnecting fractures in the bedrock (Coble and Others, 1985).

The chance of constructing a high yield well in such a terrane is dependent on the number, size, and interconnectedness of fractures intercepted by the bore hole. The chance of intercepting fractures is greatest in valley settings and upland draws, and least on ridges and hilltops (Heath and Giese, 1980). Well yields can exceed 200 gal/min, but average well yields in the crystalline rocks are low, about 1 to 15 gal/min, although higher yielding wells of greater than 40 gal/min are not uncommon (Meng and others, 1985). Well depths in the study area range from about 50 to 400 feet but exceed 500 feet in rare instances.

Recharge

Concentrations of CFCs and estimates of recharge temperature, the average temperature of water at the time it is isolated from the atmosphere and recharges ground water, were needed to calculate the apparent age of ground water. Dissolved-gas samples (table 2) were collected for most CFC sample sites and used to calculate the recharge temperature needed for computation of ground-water age. Recharge temperature is calculated on the basis of the temperature dependent solubilities of nitrogen and argon dissolved in the water sample (Heaton, 1981). This data was used to help verify the time of year when most recharge to aquifers within the study area occurs. For wells for which dissolved-gas data were not collected, recharge temperature was estimated from nearby sites where dissolved-gas samples were collected.

Temperature data for National Weather Service climatological stations (NOAA, 1992a and b) in the New River Basin (table 3) were used to estimate annual average air temperature for the study area. The median recharge temperature of 9.9 $^{\circ}$C estimated from N_2 and Ar concentrations (table 2) was colder than the average annual air temperature of 10.5 $^{\circ}$C (table 3). Recharge temperatures ranged from 7.4 to 12.5 $^{\circ}$C (table 2). The dissolved-gas data yielded estimates of recharge temperature that were similar to those estimated from data collected in Virginia, Maryland, and Delaware (Busenburg and Plummer, 1991). Because average annual recharge temperatures (computed from N_2 and Ar

Table 3. Average annual air temperature and precipitation data for National Weather Service climatological stations in the Blue Ridge Physiographic Province, New River Basin

[N/D, no data available]

Climatological Station	Average Annual Air Temperature (Celsius)	Annual Precipitation (inches)
Blowing Rock, N.C.	9.5	65.3
Floyd, Va.	10.7	41.4
Galax, Va.	11.4	42.9
Glendale Springs, N.C.	N/D	55.9
Hillsville, Va.	N/D	43.2
Idlewild, N.C.	N/D	55.8
Independence, Va.	N/D	41.1
Jefferson, N.C.	10.8	48.3
Sparta, N.C.	N/D	51.3
Transou, Va.	10.3	N/D
Troutdale, Va.	N/D	47.2
Median (all sites)	10.7	47.8
Mean (all sites)	10.5	49.2

concentrations) are less than the average annual air temperature, recharge is primarily occurring in colder periods when evapotranspiration is minimal.

Hydrograph-analysis techniques (Sloto and Crouse, 1996; Rutledge, 1993) were used to analyze flow data from six unregulated streams in the study area, to separate streamflow into its ground-water discharge and surface-runoff components, and to estimate ground-water recharge (table 4). Base flow, which is that component of streamflow derived from discharge of ground water to a stream, can be considered to be roughly equivalent to total effective recharge. The high proportion of streamflow (67 to 78 percent) derived from base-flow discharge (table 4) suggests that shallow aquifers in the Blue Ridge Province are extremely permeable and allow for rapid infiltration of recharge. Average annual effective recharge was estimated using hydrograph analysis techniques (Sloto and Crouse, 1996) and ranged from 11.4 to 22.3 inches with a median of 15.1 inches. Total recharge was estimated using the software package RORA

Table 4. Hydrograph analyses and average annual water budgets for six streams in the Blue Ridge Physiographic Province, New River Basin

[in., inches; mi², square miles; ft, feet; *, data presented were computed using the software package HYSEP (Sloto and Crouse, 1996) except for total ground-water recharge, which was computed using the software package RORA (Rutledge, 1993); superscript numbers correspond with surface-water gaging stations identified in Figure 1]

	Station number	Total base flow [effective recharge] (in.)	Total streamflow (in.)	Total direct runoff (in.)	Total ground-water recharge (in.)*	Base flow as percent of streamflow	Average precipitation (in.)	Total evapotranspiration (in.)	Riparian evapotranspiration (in.)	Gage datum elevation (ft.)	Drainage area (mi²)	Period of record
Big Reed Island Creek near Allisonia, Va.[1]	03167500	13.9	20.0	6.1	16.7	69	37.6	17.6	2.8	1,902.74	278.0	1940-1994
Chestnut Creek at Galax, Va.[2]	03165000	17.7	23.8	6.2	20.7	74	51.3	27.5	3.0	2,344.17	39.4	1945-1996
Little River at Graysontown, Va.[3]	03170000	11.4	16.7	5.3	13.7	68	43.2	26.5	2.3	1,816.04	300.0	1929-1996
New River at Galax, Va.[4]	03164000	15.7	23.6	7.8	19.3	67	51.3	27.7	3.6	2,208.04	1131.0	1930-1996
North Fork New River at Crumpler, N.C.[5]	03162500	14.5	21.7	7.2	18.9	67	48.3	26.6	4.4	2,518.81	277.0	1929-1957
South Fork New River at Jefferson, N.C.[6]	03161000	22.3	28.7	6.5	26.0	78	48.3	19.6	3.7	2,657.04	205.0	1929-1996
Median		15.1	22.6	6.4	19.1	69	48.3	26.6	3.3	2,090.02	278.0	
Maximum		22.3	28.7	7.8	26.0	78	51.3	27.7	4.4	2,657.04	1131.0	
Minimum		11.4	16.7	5.3	13.7	67	37.6	17.6	2.8	1,816.04	39.4	

Table 5. Median monthly ground-water-recharge rates for six streams in the Blue Ridge Physiographic Province, New River Basin

[in., inches, values in bold indicate periods of the year when most ground-water recharge occurs; Periods of record same as those presented in table 4]

Station	January (in.)	February (in.)	March (in.)	April (in.)	May (in.)	June (in.)	July (in.)	August (in.)	September (in.)	October (in.)	November (in.)	December (in.)	Annual Total (in.)
Big Reed Island Creek near Allisonia, Va.	**1.37**	**1.66**	**2.07**	**1.86**	**1.73**	1.23	1.09	1.04	1.01	1.01	1.25	**1.40**	16.7
Chestnut Creek at Galax, Va.	**1.86**	**2.02**	**2.63**	**2.17**	**1.82**	1.52	1.33	1.17	1.33	1.44	1.74	**1.66**	20.7
Little River at Graysontown, Va.	**1.20**	**1.50**	**1.84**	**1.52**	**1.38**	0.91	0.80	0.76	0.77	0.88	1.00	**1.11**	13.7
New River at Galax, Va.	**1.93**	**2.08**	**2.66**	**2.08**	**1.87**	1.35	1.12	1.04	1.05	1.24	1.41	**1.53**	19.3
North Fork New River at Crumpler, N.C.	**2.38**	**2.03**	**2.71**	**2.10**	**1.72**	1.14	1.10	1.07	0.91	1.00	**1.32**	**1.49**	18.9
South Fork New River at Jefferson, N.C.	**2.29**	**2.56**	**3.42**	**2.64**	**2.31**	1.77	1.67	1.63	1.70	1.76	**2.03**	**2.23**	26.0
Median	1.90	2.02	2.64	2.09	1.78	1.29	1.11	1.06	1.03	1.12	1.36	1.51	19.1
Maximum	2.38	2.56	3.42	2.64	2.31	1.77	1.67	1.63	1.70	1.76	2.03	2.23	26.0
Minimum	1.20	1.50	1.84	1.52	1.38	0.91	0.80	0.76	0.77	0.88	1.00	1.11	13.7

(Rutledge, 1993), which is based on the Rorabaugh method (Rorabaugh, 1964) of analyses of streamflow recessions. Total recharge is greater than effective recharge because it includes all components of water that actually recharge the aquifer. Effective recharge does not include that portion of water lost to evaporation or transpiration within the aquifer near the riparian margin of streams (riparian ET). Average annual total recharge ranged from a minimum of 13.7 to a maximum of 26.0 inches, with a median of 19.1 inches. The difference between total recharge and effective recharge, which is primarily riparian ET, ranged from 2.8 to 4.4 inches, with a median of 3.3 inches

Median monthly rates of ground-water recharge in each basin were computed and provided significant insight into the times of year when recharge primarily occurs (table 5). For the six stream basins analyzed, 69 percent of ground water recharges during the months of October through May, when evapotranspiration is at a minimum. Only 31 percent of recharge occurs typically in the months of June through October, a period of vegetation growth and correspondingly high rates of evapotranspiration. This data concurs with recharge-temperature estimates, which also indicate that ground-water recharge primarily occurs during colder months.

Water Budgets

If the average annual precipitation, recharge, and streamflow for an area are known, it is possible to estimate average annual water budgets for individual streams. Average values of recharge and streamflow for the gaging stations shown on figure 1, and the precipitation data listed in table 3 (NOAA, 1992a and b) were used in preparation of the budgets. A water budget has three components: (1) water inputs (2) water outputs, and (3) changes in water held in storage. The only source of water input to the study area is precipitation because there are no large interbasin transfers of water within the study area. Water outputs from the basin are primarily through streamflow and evapotranspiration. The water budget may be expressed mathematically as:

$$(1)\ P = SW_{Total} + ET_{Total} \pm \Delta S,$$

where,

P = precipitation,

SW_{Total} = Total surface-water streamflow, and

ΔS = change in ground water held in storage.

Changes in storage are negligible given a sufficient period of data and total streamflow can be separated into its ground-water base-flow ($GW_{base\ flow}$) discharge and surface-runoff (SW_{runoff}) components. Rearranging equation 1 we obtain:

$$(2)\ P = GW_{base\ flow} + SW_{runoff} + ET_{total}.$$

Although base-flow discharge ($GW_{base\ flow}$) is commonly assumed to be equivalent to effective recharge ($RCH_{effective}$), it is not reflective of total recharge (RCH_{total}). Total recharge is always larger than effective recharge and includes riparian evapotranspiration ($ET_{riparian}$). Riparian ET is that quantity of water evaporated or transpired by plants in the riparian zone adjacent to streams. Riparian ET is a component of total ET but is also a component of total recharge and should be accounted for only once. With these concepts taken into consideration, the final water-budget equation may be written as:

$$(3)\ P = RCH_{effective} + SW_{runoff} + ET_{total}, \text{ or}$$
$$(4)\ P = RCH_{total} + SW_{runoff} + (ET_{total} - ET_{riparian}).$$

Knowing average annual precipitation, effective recharge, and total direct surface-water runoff, evapotranspiration was estimated by difference and average annual water budgets for the six streams in the study area were prepared (table 4). Roughly 54 percent of all precipitation that falls on the land surface within the study area is lost to evaporation and transpiration by vegetation. Evapotranspiration rates for the six streams analyzed ranged from a minimum of 17.6 inches to a maximum of 27.7 inches with a median of 26.6 inches.

The water budgets presented in table 4 may be used as input data for future modeling studies in the area.

Although streamflow may be measured accurately and hydrograph-analysis techniques provide reasonable methods for determining base flow, direct surface runoff, ground-water recharge, and estimates of evapotranspiration (ET) are much more variable. The budgets and estimates of ET presented in this report are based on average annual precipitation from the nearest National Weather Service climatological station and total streamflow for a river gaging station in the basin of interest. Thus, a great deal of variability in the estimates of ET are possible. Although they may be characteristic of a particular watershed, they should not be applied directly to other watersheds within the study area due to the variability of precipitation, recharge, and streamflow from station to station.

Ground-Water Age

Chlorofluorocarbons, also known as Freons, are stable synthetic organic compounds commonly used as refrigerants and solvents. The concentration of CFCs in the atmosphere has steadily increased since their development in the late 1930's. Measurable concentrations were prevalent in the atmosphere by 1940. Chlorofluorocarbons are detectable at low concentrations (one part in 10^{15} by weight or 1 pg/L in water) and are commonly used as ground-water tracers (Busenburg and Plummer, 1992). Curves of atmospheric concentrations of CFC-11 and CFC-12 were reconstructed on the basis of production records (Chemical Manufacturer's Association, 1983) and rates of release to the atmosphere (McCarthy and others, 1977; Gamlen and others, 1986). Similar techniques were used to reconstruct atmospheric concentration curves for CFC-113 (Szabo and others, 1996). Assuming that CFC concentrations in recharge water are proportional to atmospheric concentrations at a particular time and location, apparent ground-water age can be estimated to within two years from these curves by knowing the concentration of CFCs in ground-water samples and the temperature of water at the time it was recharged (recharge temperature).

Dissolved-gas concentrations in water recharging an aquifer depend on atmospheric partial pressures and temperature dependent solubilities. Ground water maintains a record of the concentrations of certain gases, such as CFCs, which are relatively stable in an aquifer. Therefore, concentrations of CFCs in ground water can be compared to concentrations of CFCs in the atmosphere from about 1940, to estimate the apparent age of ground water recharged during that period (Busenburg and Plummer, 1992). Apparent ground-water age is based on the date when recharge water becomes isolated from the atmosphere in the unsaturated zone (Busenburg and Plummer, 1992). Apparent ground-water ages estimated on the basis of CFC-dating were used to refine the conceptual model of ground-water flow in the Blue Ridge Physiographic Province.

Chlorofluorocarbon data were collected from 19 randomly selected wells within the Blue Ridge Physiographic Province in the New River Basin (table 6). None of the samples collected were CFC free; therefore, ground water sampled within the Blue Ridge Physiographic Province is young. The median age of ground water in wells sampled within the study area was 16 years. There was little if any difference in the age of ground waters sampled from various topographic settings. Median apparent ground-water age for 4 hilltop, 10 hillside, and 5 valley wells were 15.0, 15.5, and 16 years, respectively. Apparent ground-water ages ranged from a minimum of 6 to a maximum of 33 years.

For a 2 ^{o}C error in estimated recharge temperature, apparent CFC age estimates for ground waters that are more than 30, 20 to 30, 10 to 20, and less than 10 years old will vary by plus or minus 0, 1, 2, and 2 to 3 years, respectively (Busenburg and Plummer, 1992). Another factor that may affect apparent CFC age determinations is "excess air." In many aquifers, air bubbles can be entrained in recharge water or can percolate along casings. The bubbles eventually dissolve in water, resulting in atmospheric gases being added to ground water. Excess air can increase the dissolved-gas and CFC concentrations in a water sample, causing the age estimates to be younger than the actual age (Heaton, 1981). Extensive sampling of ground water throughout the United States, however, indicates that excess air rarely exceeds 5 cm^3/L and thus does not normally affect CFC age determinations (Busenburg and Plummer, 1992). Only one sample had an excess air value in excess of 5 cm^3/L (table 2). Corrections for excess air in the estimation of recharge temperature or CFC ground-water age were, therefore, not deemed necessary.

Variations in apparent age may also result from (1) degradation of CFCs under anoxic (reducing) conditions (2) contamination of water samples by high concentrations of a particular

Table 6. Chlorofluorocarbon data and apparent ground-water-recharge dates for 19 wells sampled in the Blue Ridge Physiographic Province, New River Basin

[pg/kg, picograms per kilogram; Contam., Contaminated; pptv, parts per trillion per volume; N/D, no data available; D, sample degraded by methane, anoxic conditions or other factors]

Station Identifier	Recharge Temperature	Chlorofluorocarbon Concentration in Water (pg/kg)			Chlorofluorocarbon Partial Pressure (pptv)			Chlorofluorocarbon Apparent CFC Recharge Date			Estimated Recharge Date/Age in years
		CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	
25C1	10.4	355.84	163.62	29.59	138.87	278.80	27.82	1976.5	1978.0	1981.0	1980/17
25C1	10.4	354.52	159.34	30.64	138.35	271.52	28.81	1976.5	1977.5	1981.5	
25C1	10.4	451.88	200.72	71.03	176.35	342.03	66.79	1980.5	1982.0	1988.5	
20B1	8.8	388.67	176.46	41.99	141.53	283.23	36.48	1976.5	1978.0	1983.5	1978/19
20B1	8.8	390.34	179.29	40.55	142.13	287.78	35.23	1976.5	1978.0	1983.0	
20B1	8.8	6928.02	804.44	N/D	2522.71	1291.20	N/D	Contam.	Contam.	N/D	
22B1	10.2	198.79	303.84	16.06	76.40	510.48	14.86	D1971.5	1991.5	D1976.5	1990/7
22B1	10.2	188.06	290.37	17.87	72.27	487.85	16.53	D1971.0	1990.0	D1977.5	
22B1	10.2	187.25	281.88	16.16	71.96	473.59	14.95	D1971.0	1989.0	D1976.5	
AS087	9.1	84.87	62.65	9.48	31.61	102.68	8.44	1966.0	1968.0	1972.5	1968/29
AS087	9.1	87.71	62.88	4.66	32.67	103.06	4.15	1966.0	1968.0	1967.5	
AS087	9.1	104.31	58.89	9.16	38.85	96.52	8.15	1967.0	1967.5	1972.0	
WT097	8.2	12.23	184.00	3.98	4.34	288.65	3.35	D1955.5	1978.5	D1966.0	1979/18
WT097	8.2	55.20	187.03	11.70	19.57	293.40	9.86	D1963.0	1979.0	D1973.5	
WT097	8.2	86.67	180.41	12.10	30.73	283.01	10.20	D1965.5	1978.0	D1974.0	
26E1	9.9	367.73	310.98	37.13	136.02	503.75	32.99	D1976.5	1991.5	D1982.5	1991/6
26E1	9.9	363.94	312.17	36.94	134.62	505.67	32.82	D1976.0	1991.5	D1982.5	

Table 6. Chlorofluorocarbon data and apparent ground-water-recharge dates for 19 wells sampled in the Blue Ridge Physiographic Province, New River Basin —Continued

[pg/kg, picograms per kilogram; Contam., Contaminated; pptv, parts per trillion per volume; N/D, no data available; D, sample degraded by methane, anoxic conditions or other factors]

Station Identifier	Recharge Temperature	Chlorofluorocarbon Concentration in Water (pg/kg)			Chlorofluorocarbon Partial Pressure (pptv)			Chlorofluorocarbon Apparent CFC Recharge Date			Estimated Recharge Date/Age in years
		CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	
19B2	7.4	452.95	203.49	69.17	154.16	307.90	55.70	1978.0	1980.0	1987.0	1980/17
19B2	7.4	466.13	209.87	74.48	158.64	317.55	59.97	1978.5	1981.0	1987.5	
19B2	7.4	354.95	165.73	28.98	120.80	250.77	23.33	1975.0	1976.5	1980.0	
28D3	12.5	2200.47	334.14	39.87	950.43	622.66	42.03	Contam.	Contam.	1984.5	1984/13
28D3	12.5	2188.79	325.78	38.54	945.38	607.08	40.63	Contam.	Contam.	1984.5	
28D3	12.5	2332.38	335.85	40.00	1007.40	625.84	42.17	Contam.	Contam.	1984.5	
19B1	8.0	549.73	262.19	71.45	203.64	430.21	62.84	1984.0	1987.0	1988.0	1987/10
19B1	8.0	560.49	271.38	82.28	207.63	445.29	72.37	1984.5	1987.5	1989.0	
19B1	8.0	4168.51	366.67	167.74	1544.18	601.65	147.54	Contam.	Contam.	Contam.	
27C3	11.2	898.42	226.33	53.55	367.68	402.58	53.07	Contam.	1985.5	1986.5	1986/11
27C3	11.2	927.11	229.12	54.86	379.42	407.55	54.36	Contam.	1985.5	1986.5	
27C3	11.2	887.72	220.06	53.08	363.30	391.43	52.60	Contam.	1985.0	1986.5	
26C1	9.2	3748.42	1264.11	39.33	1362.35	2020.36	34.19	Contam.	Contam.	1983.0	1983/14
26C1	9.2	3510.15	1196.55	45.99	1275.75	1912.38	39.98	Contam.	Contam.	1984.0	
26C1	9.2	2963.31	1017.74	40.27	1077.01	1626.60	35.01	Contam.	Contam.	1983.0	
AS088	8.7	381.14	530.95	39.91	135.60	833.15	33.86	D1976.0	Contam.	1983.0	1983/14

Table 6. Chlorofluorocarbon data and apparent ground-water-recharge dates for 19 wells sampled in the Blue Ridge Physiographic Province, New River Basin —Continued

[pg/kg, picograms per kilogram; Contam., Contaminated; pptv, parts per trillion per volume; N/D, no data available; D, sample degraded by methane, anoxic conditions or other factors]

Station Identifier	Recharge Temperature	Chlorofluorocarbon Concentration in Water (pg/kg)			Chlorofluorocarbon Partial Pressure (pptv)			Chlorofluorocarbon Apparent CFC Recharge Date			Estimated Recharge Date/Age in years
		CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	
AS088	8.7	390.47	562.37	42.02	138.91	882.45	35.65	D1976.5	Contam.	1983.5	
AS088	8.7	374.44	543.53	38.39	133.21	852.88	32.57	D1976.0	Contam.	1982.5	
24C1	8.9	374.18	773.39	41.94	133.88	1219.06	35.83	D1976.5	Contam.	1983.5	1984/13
24C1	8.9	346.42	805.91	45.61	123.95	1270.32	38.96	D1975.5	Contam.	1984.0	
24C1	8.9	346.30	803.49	45.55	123.91	1266.51	38.91	D1975.5	Contam.	1984.0	
AS086	8.3	523.31	234.34	48.23	187.44	371.12	41.10	1982.0	1983.5	1984.5	1983/14
AS086	8.3	518.16	231.78	48.62	185.60	367.06	41.43	1982.0	1983.5	1984.5	
AS086	8.3	522.60	225.83	46.10	187.19	357.64	39.28	1982.0	1983.0	1984.0	
AS085	9.2	286.07	194.06	36.25	105.43	314.52	31.96	D1974.0	1980.5	1982.5	1981/16
AS085	9.2	304.21	196.95	37.34	112.12	319.20	32.92	D1974.5	1981.0	1982.5	
AS085	9.2	301.82	206.21	39.73	111.24	334.21	35.02	D1974.5	1981.5	1983.0	
22C1	9.9	192.06	191.66	28.35	72.19	315.46	25.59	D1971.0	1980.5	1980.5	1980/17
22C1	9.9	227.23	197.66	31.87	85.41	325.34	28.77	D1972.5	1981.0	1981.5	
22C1	9.9	207.56	189.32	28.69	78.01	311.61	25.90	D1971.5	1980.0	1980.5	
AL053	10.5	99.29	113.88	24.42	40.10	200.69	23.78	D1967.5	1974.0	1980.0	1977/20
AL053	10.5	100.71	117.58	25.49	40.67	207.20	24.82	D1967.5	1974.0	1980.5	
AL053	10.5	101.58	121.02	23.81	41.02	213.26	23.18	D1967.5	1974.5	1980.0	
AS089	9.4	3.59	33.15	0.00	1.35	54.66	0.00	D1952.0	1963.5	D1954.5	1964/33

Table 6. Chlorofluorocarbon data and apparent ground-water-recharge dates for 19 wells sampled in the Blue Ridge Physiographic Province, New River Basin —Continued

[pg/kg, picograms per kilogram; Contam., Contaminated; pptv, parts per trillion per volume; N/D, no data available; D, sample degraded by methane, anoxic conditions or other factors]

Station Identifier	Recharge Temperature	Chlorofluorocarbon Concentration in Water (pg/kg)			Chlorofluorocarbon Partial Pressure (pptv)			Chlorofluorocarbon Apparent CFC Recharge Date			Estimated Recharge Date/Age in years
		CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113	
AS089	9.4	3609.98	382.96	162.27	1355.26	631.47	145.89	Contam.	Contam.	Contam.	
AS089	9.4	4.15	36.94	0.00	1.56	60.92	0.00	D1952.5	1964.0	D1954.5	
24B2	9.8	2264.07	175.96	47.55	854.72	291.07	43.10	Contam.	1978.5	1984.5	1980/17
24B2	9.8	2197.32	173.24	45.06	829.52	286.57	40.84	Contam.	1978.0	1984.5	
24B2	9.8	2164.72	173.98	41.70	817.22	287.80	37.79	Contam.	1978.0	1984.0	

CFC, or (3) variability in the water contributed to a well from multiple water-bearing zones. Biodegradation under anoxic, methanogenic, reducing conditions may result in the degradation of certain organic compounds, including CFCs (Lovely and Woodward, 1992). Degradation of CFCs are suspected when dissolved-oxygen concentrations are low and (or) methane concentrations are high. On the basis of dissolved-gas (table 2) and CFC data (table 6) collected for this investigation, CFC-11 is particularly susceptible to degradation under reducing conditions. CFC-113 is somewhat prone to degradation under reducing conditions, but CFC-12 was found to be stable under both oxic and anoxic conditions. Degradation of CFC-11 in water samples was evident at nine of the 19 wells sampled for CFCs (table 6). No degradation of CFC-12 in water samples was evident for any of the 19 wells sampled, but water samples from four wells (tables 2 and 6) showed signs of CFC-113 degradation. CFC degradation was confirmed by careful laboratory examination of individual gas chromatograph and mass spectrometer chromatograms to see if CFC degradation by-products are present.

Conceptual Models of Ground-Water Flow

Ground-water flow in aquifers of the Blue Ridge Province is controlled primarily by geologic factors. Regolith and saprolite overlie fractured igneous and metamorphic bedrock in most areas of the Blue Ridge. These saprolite and regolith deposits can be permeable and can store large amounts of water. On ridge tops, saprolite is usually thin, and there is little capacity for ground-water storage. Wells drilled on hilltops, therefore, typically have lower yields than wells drilled on hillsides or in valleys. On hillsides, regolith can vary in thickness depending on the slope of the hillside, with thicker deposits accumulating on gentler slopes. At the base of steep hillsides colluvial deposits are common. Regolith and colluvium that accumulate on hillsides can provide a significant reservoir for ground-water storage and an avenue for ground-water flow.

Finally, thick deposits of regolith are common in valleys and may provide a significant reservoir for ground-water storage. Deposits of regolith, saprolite, alluvium, and colluvium are connected to an intricate system of fractures within the underlying igneous and metamorphic bedrock. The fracture system comprises faults, joints, bedding-plane separations, and foliations and provides a direct connection with the overlying permeable unconsolidated deposits. The depth to

which the fracture system extends is not clearly defined. Several wells within this study were more than 500 feet deep. One well was completed to a depth of 700 feet. Additional research is needed to more clearly determine the depth of circulation of ground water within the study area (Coble and Others, 1985).

Ground-water flow in and through the unconsolidated deposits and within the fractured bedrock can be rapid. The median ground-water age of 16 years indicates that ground-water recharge and flow occur rapidly. Chemical signatures within the ground water can also indicate the ease with which recharge occurs. Volatile organic compounds (VOCs) and pesticides are commonly detected at low levels in the Blue Ridge aquifer system. The presence of these compounds (to be discussed later in this report) suggests that ground-water recharge and flow occur rapidly, because these chemicals were not prevalent in the environment until after World War II. None of the sites sampled were free of CFCs, indicating young ground water and recent recharge.

GROUND-WATER QUALITY

Data collected for 30 wells sampled in the Blue Ridge portion of the New River Basin were used to assess the quality of ground water in the region. Human and natural factors affecting water quality were also considered. Analytical results of the samples from all wells are presented in the USGS Water-Resources Data for West Virginia, Water Year 1997 publication (Ward and others, 1998). Although no standards regulate contaminants in private wells, USEPA standards that apply to public water systems were used to assess the quality of ground water in the region.

Bacteria

Water samples from 30 wells were analyzed for total coliform, fecal coliform, and *E. coli* bacteria (table 7). All three types of bacteria are used as indicator organisms for the potential presence of pathogenic bacteria and viruses (American Public Health Association and others, 1992). Total coliforms are the most prevalent of the strains within the environment and may be derived from several sources, including the digestive tract of warm blooded animals and from soils. Fecal coliform and *E. coli*, however, are much more specific and are derived solely from the intestinal tract (fecal origin) of warm blooded animals, including humans (American

Public Health Association and others, 1992). The presence of any of the three indicator organisms should be considered a potential indicator of contamination of an aquifer by potentially harmful pathogenic bacteria and (or) viruses.

Samples from 11 of 29 wells (38 percent) tested positive for the presence of total coliform bacteria (one sample was improperly incubated and not used for analysis). Of these same 29 sites, none tested positive for *E. coli* bacteria. None of the 30 samples tested positive for the presence of fecal coliform bacteria. The fact that no fecal coliform or *E. coli* bacteria were detected in any of the wells sampled is encouraging. The presence of total coliforms, although possibly derived from non-fecal sources, may indicate the potential for bacterial contamination of ground water in the study area. The U.S. Environmental Protection Agency (USEPA) maximum contaminant level goal (MCLG) for bacteria in ground water is zero (U.S. Environmental Protection Agency, 1999a). The maximum total coliform concentration detected was 14 colonies per 100 mL of sample, and only six of the 11 sites that tested positive for total coliform bacteria contained more than one colony per 100 mL of sample (table 7). Thus, some local minor contamination of ground water from nearby septic systems, pasture areas, or other sources is indicated by the data presented here. Although the data do not indicate a widespread problem with microbiological contamination, highly permeable soils typical in the region can allow rapid infiltration of contaminants into ground water.

Several measures may be taken to reduce existing contamination and possibly prevent further microbiological contamination of aquifers in the region. First, grouting of wells will typically reduce the chance of a well being contaminated by bacteria or other contaminants leaking around the annular space of well casings. Second, control of land-use activities near a well can help reduce the risk of bacterial contamination of ground water by eliminating sources of microbiological contamination. Quartering of livestock and domestic pets near a well can result in microbiological contamination of ground water.

Table 7. Summary of bacteria data for samples collected from 30 wells in the Blue Ridge Physiographic Province, New River Basin

Indicator Bacteria	Sites Testing Positive/Sites sampled (percent)	Maximum Bacteria Concentration (Colonies/100 mL)
Total Coliform	11/29 (38 %)	14
Fecal Coliform	0/30 (0 %)	None Detected
Escherichia Coli	0/29 (0 %)	None Detected

Inorganic Constituents

Inorganic constituents consist of those ions or elements that do not contain carbon and primarily include three groups of constituents-- major ions, trace elements, and nutrients. Radon-222, a radioactive and carcinogenic gas, also is an inorganic constituent that is prevalent in the study area. Each of these groups will be discussed in detail. Water-quality parameters measured directly in the field during the time of sampling include pH, dissolved oxygen, water temperature, specific conductance, turbidity, and reduction-oxidation potential (redox). As these "field parameters" are closely related to the common ions, they will be discussed in the section of this report along with the common ions.

Major Ions. In this is report the term "major ions" will be used to refer to those constituents that are commonly found in ground water -- including calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, fluoride, and silica. Most of these common ions are derived by natural geochemical evolution of ground water as it dissolves minerals within the bedrock through which it flows. They are therefore primarily responsible for the total dissolved solids concentration of water. Analyses of common ion data indicate that the majority of wells sampled have a calcium bicarbonate water type (fig. 3). Within the study area, water in 17 of 30 (57 percent) wells sampled was a calcium bicarbonate type; water in 4 of 30 (13 percent) was a calcium-magnesium bicarbonate type; water in 4 of 30 (13 percent) was a calcium-sodium bicarbonate type; and water from 2 of 30 (7 percent) was a magnesium bicarbonate type. Of the 30 sites sampled 27 of 30 (90 percent) exhibited a bicarbonate signature. Only 3 of the 30 sites sampled (10 percent) did not exhibit a bicarbonate signature, with one site each exhibiting a sodium/magnesium chloride type, a

calcium sulfate type, and a magnesium bicarbonate/sulfate type. No chemical signature could be identified as being respective of a particular topographic setting or well depth.

None of the common ions have a maximum contaminant level (MCL), a health based drinking water standard established by the USEPA. Sulfate, chloride, and fluoride (fig. 4), however, do have secondary maximum contaminant levels (SMCLs). MCLs are established based on health criteria, but SMCLs are based on other factors, such as taste, odor, color, staining of plumbing fixtures, or laxative effect. The USEPA SMCLs for chloride, sulfate, and fluoride are 250, 250, and 2.0 mg/L, respectively. None of the 30 wells sampled exceeded the USEPA SMCL for sulfate and chloride, and only one sample exceeded the SMCL for fluoride. Median fluoride, sulfate, and chlo-

ride concentrations of the wells sampled were <0.10, 3.4, and 2.1 mg/L, respectively (table 8). These concentrations are low and characteristic of dilute ground waters with little alkalinity or buffering capacity. Median concentrations of the other major ions such as calcium, magnesium, sodium, potassium, and silica were also characteristically present in low concentrations (table 8).

The total dissolved solids concentration of the 30 samples collected were typically low, ranging from 23 to 259 mg/L with a median of 80 mg/L (fig. 4). None of the 30 wells sampled exceeded the USEPA SMCL of 500 mg/L. Hardness, which is related primarily to concentrations of calcium and magnesium, also was typically low-ranging from 6 to 230 mg/L with a median of 34 mg/L. Water with hardness values from 0 to 60 mg/L is considered soft, values of 61 to 120

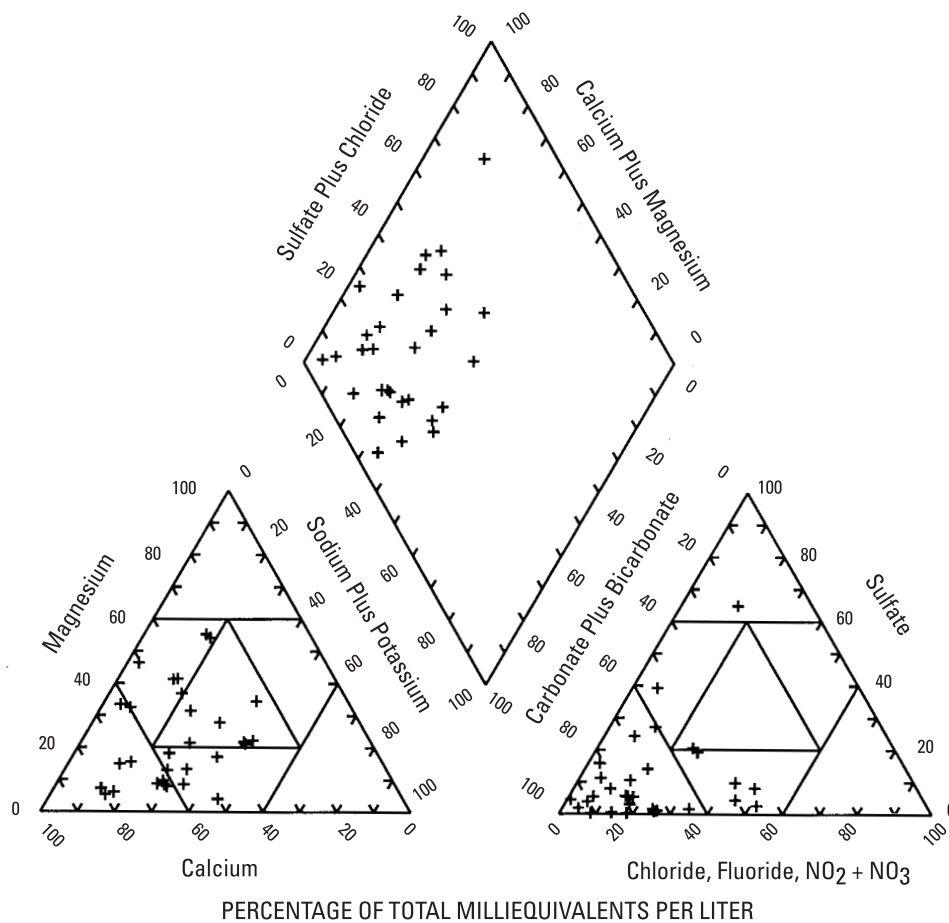PERCENTAGE OF TOTAL MILLIEQUIVALENTS PER LITER

Figure 3. Piper (trilinear) diagram showing water type for each of the 30 wells sampled in the Blue Ridge Physiographic Province, New River Basin.
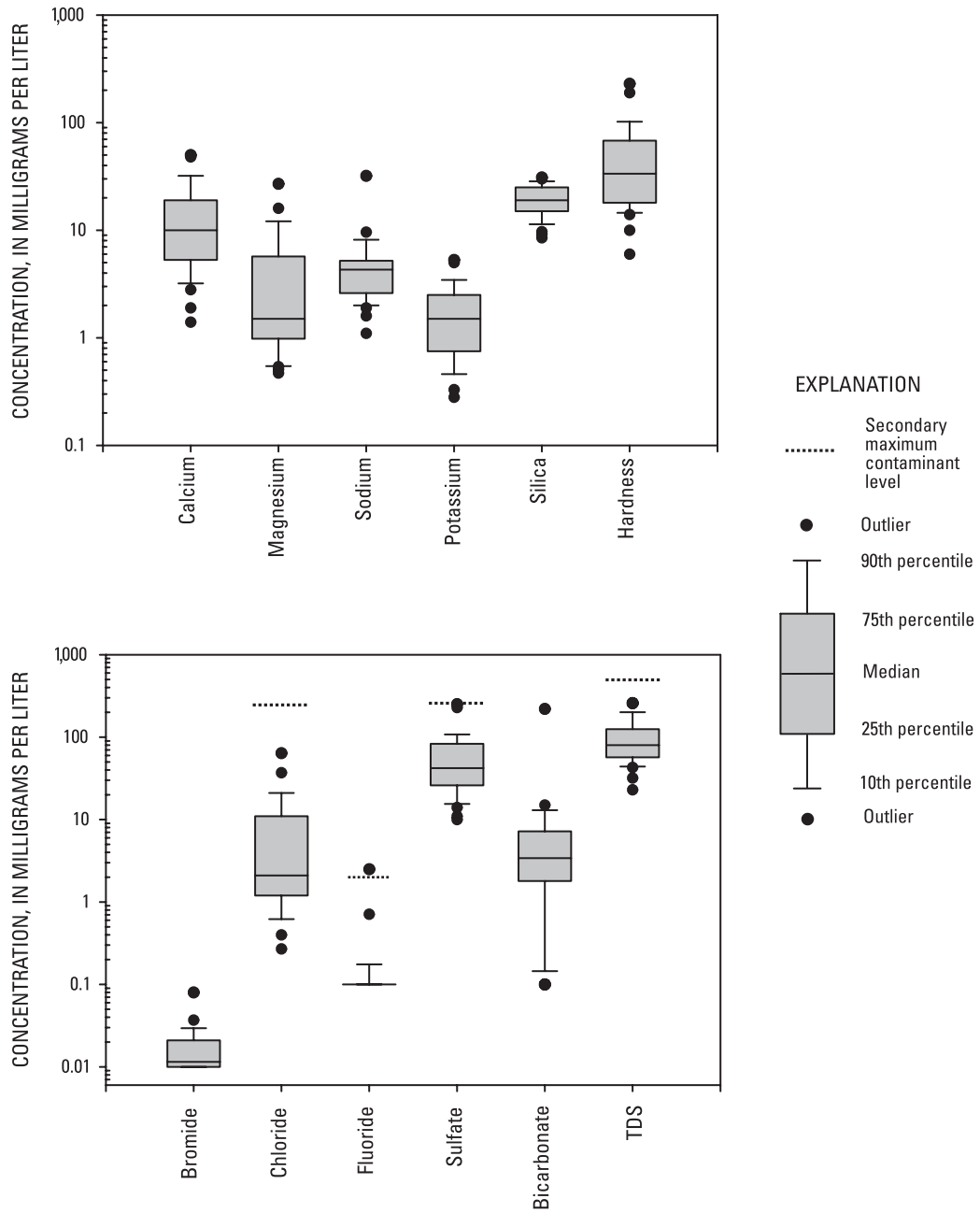
Figure 4. Distribution of concentrations of common anions and cations data, total dissolved solids (TDS), and hardness in samples collected from 30 wells in the Blue Ridge Physiographic Province, New River Basin.

mg/L are considered moderately hard, values of 121 to 180 are considered hard, and values greater than 180 are considered very hard (Hem, 1992). Based on these values, 21 of the 30 (70 percent) wells sampled had soft water; 7 (23 percent) had moderately hard water; none would be classified as hard, and only 2 (7 percent) had very hard water.

Specific conductance of the 30 wells sampled ranged from 9 to 453 µS/cm, with a median conductivity of 110 µS/cm. These low conductivity values indicate that water in the Blue Ridge is typically dilute, with a low total dissolved solids concentration. The pH of water from the 30 wells sampled ranged from 5.1 to 8.0 with a median of 6.2. This finding also indicates that the waters are typically dilute and slightly acidic, probably a function of the low conductivity and buffering capacity of the water (to be discussed) and most likely derived from shallow recharge, likely from acid precipitation. Twenty two of the 30 (73 percent) wells sampled had pH values less than or equal to the 6.5 lower limit (United States Environmental Protection Agency, 1999a) USEPA SMCL. Acidic waters may promote corrosion of plumbing fixtures and pipes and also are prone to leach contaminants such as zinc, copper, and lead from plumbing lines. Alkalinity is a measure of the ability of a water to reduce or buffer acid. The alkalinity of the 30 wells sampled ranged from 8 to 207 mg/L with a median of 34.5 mg/L. These low alkalinity values typically are not high enough to offer significant buffering capacity to the ground water typical of the aquifer.

Nutrients. Nutrients are constituents such as nitrate, ammonia, nitrite, phosphorous, and orthophosphorous that are essential to plants for normal growth. In high concentrations, however, nutrients (nitrate greater than 10 mg/L as N and nitrite greater than the 1.0 mg/L as N USEPA MCLs) can have adverse effects on human health. Ingestion of water with greater than 10 mg/L of nitrate can cause methemoglobinemia in infants (Hem, 1992). Water from 1 of the 30 sites sampled had a nitrate concentration greater than 10 mg/L (fig. 5) and none had a nitrite concentration greater than 1 mg/L. Likewise, phosphorous, ammonia, and orthophosphorous were all present in low concentrations (table 8). The primary sources of nutrients in ground water within the region are from agricultural land-use practices (fertilizers and manure), septic systems, and from trace amounts in precipitation. Discharge of effluent from septic systems is also a possible source of nutrient contamina-

tion. The low concentrations of nutrients and the lack of bacteria detected in the water samples collected, however, indicate that neither septic systems nor agricultural land use are major sources of ground-water contamination in the region.

Trace Elements. Concentrations of trace elements were generally low or were not detected within the study area (table 8) except for aluminum, barium, copper, iron, manganese, and zinc (fig. 5). Iron and manganese, which are regulated as secondary contaminants on the basis of aesthetics rather than health based criteria, exceeded the 300 and 50 µg/L USEPA SMCLs at 13 percent (4 of 30) and 17 percent (5 of 30) of sites sampled, respectively. Lead was detected in 10 percent of the sites sampled. The maximum contaminant level goal (MCLG) for lead is 0 µg/L and the USEPA action level for lead at the tap is 15 µg/L. None of the sites sampled exceeded the USEPA action level for lead. Samples from the three wells where lead was detected had pH values less than 5.8 and specific conductance less than 70 µS/cm, suggesting dilute acidic waters may have the ability to mobilize lead present in bedrock aquifers or in lead plumbing systems. Concentrations of the remaining trace metals did not exceed USEPA drinking-water standards.

The source of trace elements is not apparent and any attempt to identify potential sources would be speculative. Some trace metals, however, are found in bedrock, especially in igneous and metamorphic rocks, which are common in the study area. Anthropogenic sources are a second possible source of trace metals. Some agricultural pesticides, such as lead arsenate and other compounds used in the past, have been shown to be potential sources of contamination. Zinc is another trace metal used in certain pesticides. Finally, improper disposal of metallic refuse such as old automobiles, drums, pipes, refrigerators, and barbed wire, as is common in many rural areas, could be another potential source of trace metals in the environment. Regardless of the source, the low detection frequency of trace metals within the study area does not indicate widespread or serious contamination issues with respect to trace metals.

Table 8. Results of chemical analyses of samples from 30 wells in the Blue Ridge Physiographic Province, New River Basin

[μS/cm, microsiemens per centimeter; NTU, nephelometric turbidity units; mg/L, milligrams per liter; col/100mL, colonies per 100 milliliters; μg/L micrograms per liter; pCi/L, picocuries per liter; USEPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; MCLG, maximum contaminant level goal; PMCL, proposed maximum contaminant level; AMCL, alternate maximum contaminant level; N/A, not applicable]

Constituent	Non-detect value	Units of measurement	Percent of sites with detections	Median concentration	Maximum concentration	USEPA drinking-water standsards: MCL[a], SMCL[b], MCLG[c], PMCL[d], AMCL[e]	Percent of sites exceeding drinking-water standard
Field Measurements							
Specific conductance	1	μS/cm	100	110.0	453	N/A	N/A
pH	0.1	pH units	100	6.2	8.0	6.5-8.5[b]	73
Turbidity	0.10	NTU	93	0.36	15	N/A	N/A
Dissolved oxygen	0.1	mg/L	100	5.0	9.6	N/A	N/A
Bacteria							
Total coliform	1	col/100mL	38	<1	14	0[a]	38
Escherichia coli	1	col/100mL	0	<1	<1	0[a]	0
Fecal coliform	1	col/100mL	0	<1	<1	0[a]	0
Major ions							
Hardness (CaCO$_3$)	1	mg/L	100	34	230	N/A	N/A
Calcium (Ca)	0.02	mg/L	100	10.0	50	N/A	N/A
Magnesium (Mg)	0.01	mg/L	100	1.5	27	N/A	N/A
Sodium (Na)	0.20	mg/L	100	4.3	32	N/A	N/A
Potassium (K)	0.10	mg/L	100	1.5	5.3	N/A	N/A
Bicarbonate (HCO$_3$)	1	mg/L	100	42	252	N/A	N/A
Carbonate (CO$_3$)	1	mg/L	0	<1	<1	N/A	N/A

Table 8. Results of chemical analyses of samples from 30 wells in the Blue Ridge Physiographic Province, New River Basin —Continued

[µS/cm, microsiemens per centimeter; NTU, nephelometric turbidity units; mg/L, milligrams per liter; col/100mL, colonies per 100 milliliters; µg/L micrograms per liter; pCi/L, picocuries per liter; USEPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; MCLG, maximum contaminant level goal; PMCL, proposed maximum contaminant level; AMCL, alternate maximum contaminant level; N/A, not applicable]

Constituent	Non-detect value	Units of measurement	Percent of sites with detections	Median concentration	Maximum concentration	USEPA drinking-water standsards: MCL[a], SMCL[b], MCLG[c], PMCL[d], AMCL[e]	Percent of sites exceeding drinking-water standard
Major ions, continued							
Alkalinity (CaCO$_3$)	1	mg/L	100	34.5	207	N/A	N/A
Sulfate (SO$_4$)	0.10	mg/L	97	3.4	220	250[b]	0
Chloride (Cl)	0.10	mg/L	100	2.1	64	250[b]	0
Bromide (Br)	0.01	mg/L	60	0.01	0.08	N/A	N/A
Fluoride (F)	0.10	mg/L	17	<0.10	2.5	4[b]	0
Silica (SiO$_4$)	0.10	mg/L	100	19	31	N/A	N/A
Dissolved solids	1.00	mg/L	100	80	259	500[b]	7
Nutrients							
Nitrite (N)	0.010	mg/L	0	<0.010	<0.010	1[a]	0
Nitrate + nitrite (N)	0.050	mg/L	87	0.419	14.1	10[a]	3
Ammonia (N)	0.015	mg/L	17	<0.015	0.046	N/A	N/A
Ammonia + organic (N)	0.20	mg/L	0	<0.20	<0.20	N/A	N/A
Phosphorus (P)	0.010	mg/L	33	<0.010	0.085	N/A	N/A
Ortho-Phophate (P)	0.010	mg/L	60	0.013	0.091	N/A	N/A
Dissolved organic carbon	0.10	mg/L	77	0.20	0.50	N/A	N/A
Trace elements							
Aluminum (Al)	1.0	µg/L	100	3.6	7.3	50-200[b]	0
Antimony (Sb)	1.0	µg/L	0	<1.0	<1.0	6[a]	0
Arsenic (As)	1.0	µg/L	0	<1.0	<1.0	50[a] or 5[d]	0
Barium (Ba)	1.0	µg/L	97	13	162	2,000[a]	0
Beryllium (Be)	1.0	µg/L	0	<1.0	<1.0	4[a]	0

Table 8. Results of chemical analyses of samples from 30 wells in the Blue Ridge Physiographic Province, New River Basin —Continued

[μS/cm, microsiemens per centimeter; NTU, nephelometric turbidity units; mg/L, milligrams per liter; col/100mL, colonies per 100 milliliters; μg/L, micrograms per liter; pCi/L, picocuries per liter; USEPA, U.S. Environmental Protection Agency; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level; MCLG, maximum contaminant level goal; PMCL, proposed maximum contaminant level; AMCL, alternate maximum contaminant level, N/A, not applicable]

Constituent	Non-detect value	Units of measurement	Percent of sites with detections	Median concentration	Maximum concentration	USEPA drinking-water standards: MCL[a], SMCL[b], MCLG[c], PMCL[d], AMCL[e]	Percent of sites exceeding drinking-water standard
Trace elements, continued							
Cadmium (Cd)	1.0	μg/L	0	<1.0	<1.0	5[a]	0
Chromium (Cr)	1.0	μg/L	70	1.3	6.9	100[a]	0
Cobalt (Co)	1.0	μg/L	10	<1.0	6.9	N/A	N/A
Copper (Cu)	1.0	μg/L	60	1.8	21	1,300[a]	0
Iron (Fe)	3.00	μg/L	57	4.6	2,400	300[b]	13
Lead (Pb)	1.0	μg/L	10	<1.0	2.8	0[c] or 15[a]	10
Manganese (Mn)	1.0	μg/L	57	1.6	252	50[b]	17
Molybdenum (Mo)	1.0	μg/L	13	<1.0	4.7	N/A	N/A
Nickel (Ni)	1.0	μg/L	23	<1.0	5.4	100	0
Selenium (Se)	1.0	μg/L	0	<1.0	<2.0	50[a]	0
Silver (Ag)	1.0	μg/L	0	<1.0	<1.0	100[b]	0
Zinc (Zn)	1.0	μg/L	97	17.5	1,030	5,000[b]	0
Radioactive elements							
Radon (Rn)	80	pCi/L	93	2,080	30,900	300[d] or 4,000[e]	87[d] or 33[e]
Uranium (U)	1.0	μg/L	10	<1.0	2.8	N/A	N/A

Radon. Radon 222 is a naturally occurring radioactive gas and a known carcinogen. It is one of the natural decay products of uranium and eventually decays to form lead. The half life of radon is only 3.8 days (Otton and Gunderson, 1993). Because radon is a gas, it can easily pass through cracks or crevices in the foundation of a house and accumulate in living quarters. Radon in water can also escape into air when the water is used for bathing, washing, or laundry.

High concentrations of radon are typically found in light colored volcanic rocks, granites, dark shales, sedimentary rocks that contain phosphorous, and metamorphic rocks derived from these rocks (Otton and Gunderson, 1993). Such rocks may contain as much as 100 parts per million of uranium. Soils derived from bedrock with high uranium content can also contain significant concentrations of radon. Because the Blue Ridge is comprised of igneous and metamorphic rocks and the region is suspected to have a high potential for radon occurrence, the USGS initiated a sampling plan to assess the occurrence and distribution of radon in the area as part of routine NAWQA sampling.

The current MCL for radon in indoor air is four picocuries per Liter (pCi/L). The USEPA has also proposed an MCL of 300 pCi/L and a 4,000 pCi/L alternative maximum contaminant level (AMCL) for radon in ground water. The two standards have been established primarily because people may be exposed to radon by either breathing indoor air, which is the second leading cause of lung cancer, or by ingesting water that contains radon (Otton and Gunderson, 1993). The inhalation risk, however, is much greater than the ingestion risk. If appropriate measures are taken to eliminate indoor air sources of radon, the 4,000 pCi/L standard is applicable; if not, the more stringent 300 pCi/L standard applies (U.S. Environmental Protection Agency, 1999b).

Radon 222 was detected in water samples from 28 of 30 wells. Twenty six of the 30 samples (87 percent) contained radon in concentrations exceeding the proposed USEPA MCL of 300 pCi/L (fig. 5), and 10 of 30 (33 percent) exceeded the 4,000 pCi/L proposed AMCL. The median radon concentration detected was 2,080 pCi/L, almost seven times the proposed MCL (fig. 5). The radon concentrations detected here are among the highest detected in the region including Virginia, Maryland, and Pennsylvania (Lindsey and Ator, 1996) and present a risk of exposure for the people who live in the region.

Radon concentrations in the study area are also high in comparison to national averages. A comparison of radon concentrations in the study area was made with similar data for 3,094 wells sampled nationwide as part of the USGS NAWQA Program. The maximum concentration of radon detected nationally was 40,000 pCi/L, and the maximum concentration detected in the study area was 30,900 pCi/L. The median radon concentration of 2,080 pCi/L for the wells sampled within the study area was five times higher than the median concentration of 410 pCi/L for all wells sampled nationally (Sarah Ryker, U.S. Geological Survey, written commun., 1999). High concentrations of radon in ground water (> 300 pCi/L) should be viewed as a possible indicator of high levels of radon in indoor air. Homeowners in the region may wish to consider having their indoor air and water from their wells analyzed for the presence of radon.

Factors related to radon occurrence and distribution were analyzed. No statistically significant relation was found between radon and well depth, well construction, topographic setting, or other water-quality parameters. Wells sampled and associated radon concentrations detected in each well were plotted on geologic maps of Virginia and North Carolina. No correlation could be determined between lithology and radon concentrations in ground water. Of 10 wells with radon concentrations greater than the 4,000 pCi/L AMCL, eight were on or adjacent to faults. Increased fracturing of bedrock along fault zones may provide a route for radon to migrate upward from basement rock or other rock with high uranium content. Also, mylonization occurs in shear zones along faults. Mylonization is a process in which the uranium content is increased by the introduction of uranium bearing minerals into the shear zone and by volume loss, which leaves the rocks within the shear zone relatively enriched with uranium (Gundersen and others, 1987).
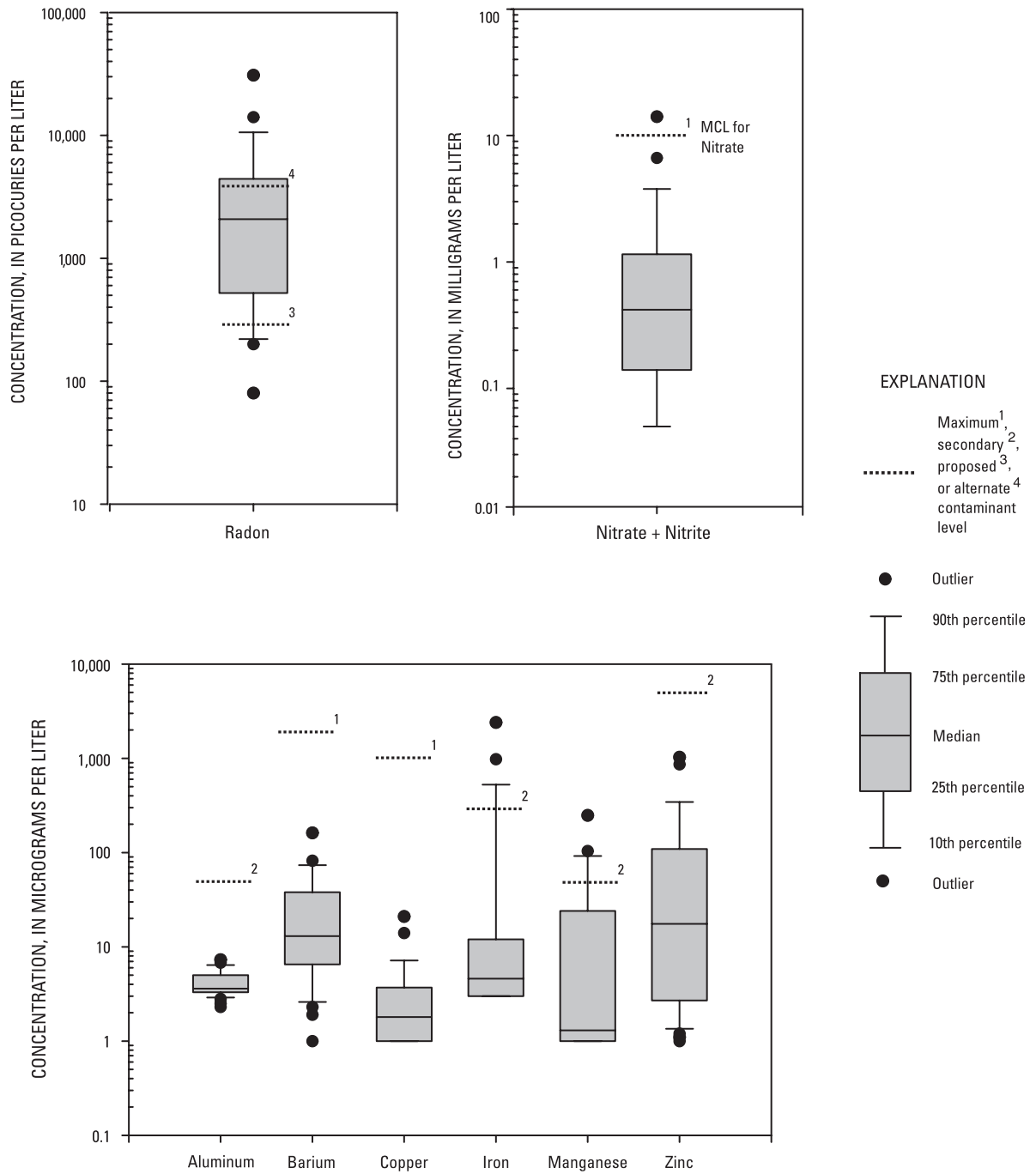
Figure 5. Distribution of concentrations of radon, nitrate + nitrite, and trace elements collected from 30 wells sampled in the Blue Ridge Physiographic Province, New River Basin.

Organic Constituents

The samples from the 30 wells were analyzed for two classes of organic chemicals, pesticides and volatile organic compounds (VOCs). Pesticides include insecticides, herbicides, fungicides, and other chemical compounds used in agricultural and domestic applications for controlling insect populations, weeds, fungi, and other pests. The VOCs include common industrial solvents, gasoline derivatives, and disinfection by-products. Because agriculture and silviculture are common in the study area, pesticide use and occurrence in ground water were suspected. Also, VOCs have been detected in precipitation, and gasoline is widely used throughout the study area. Because of the widespread use of these compounds and the relative lack of data on their occurrence and distribution within the study area, the USGS analyzed a wide range of pesticides and VOCs in the 30 wells sampled. A complete list of the pesticides and VOCs analyzed for and concentrations detected in samples can be found in the USGS Water Resources Data for West Virginia, Water Year 1997 publication (Ward and others, 1998).

Pesticides. Of 86 pesticides analyzed, only 10 were detected in at least one of the 30 samples (table 9), all at relatively low concentrations, near the detection limit. At least one pesticide was detected in 17 of the 30 (57 percent) wells sampled. Atrazine, deethylatrazine, simazine, DDE, and molinate were the most commonly detected pesticides, and these were detected in 11 (37 percent), 9 (30 percent), 6 (20 percent), 4 (13 percent), and 2 (7 percent) of wells sampled, respectively. Dinoseb, lindane, chlorpyrifos, carbaryl, and alpha-BHC were each detected once (3 percent of sites sampled). Of the pesticides detected, lindane, chlorpyrifos, and carbaryl are insecticides, and atrazine, simazine, molinate, and dinoseb are herbicides. DDE is a metabolite of the insecticide DDT; alpha-BHC is an isomer of the insecticide lindane, and deethylatrazine is a metabolite of the herbicide atrazine. The maximum concentration of a pesticide detected was only 0.152 µg/L.

Detections of pesticides in the study area were comparable to detections in more than 1,000 wells sampled in agricultural land-use settings nationwide (table 9). Atrazine, deethylatrazine, and simazine were detected in 45, 43, and 22 percent of agricultural sites sampled nationally and were detected in 37, 30, and 20 percent of sites sampled, respectively, within the study area. Pesticide occurrence within the study area was therefore found to be slightly below the national average for agricultural areas.

Table 9. Pesticides detected in water samples collected from 30 wells in the Blue Ridge Physiographic Province, New River Basin

[E, estimated value; HBGL, Health Based Guidance Level; N/D, No data; MCL, maximum contaminant level; µg/L, micrograms per Liter; #, national pesticide data for comparison obtained from USGS NAWQA Program 1991-1994]

Constituent	Number (%) of sites with detections	Detection limit (µg/L)	Maximum concentration detected (µg/L)	Drinking-water criteria (µg/L)	Percent detections Nationally[#]
Alpha, BHC	1 (3 %)	0.002	0.033	N/D	0.1
Atrazine	11 (37 %)	0.001	0.115	3 MCL	45
Carbaryl	1 (3 %)	0.003	E0.003	N/D	0.8
Chlorpyrifos	1 (3 %)	0.004	E0.004	N/D	0.5
Deethylatrazine	9 (30 %)	0.002	E0.136	3 MCL	43
Lindane	1 (3 %)	0.004	0.152	0.2 MCL	0.1
Molinate	2 (7 %)	0.004	E0.003	N/D	0.4
P, P', DDE	4 (13 %)	0.006	E0.002	0.1 HBGL	3.9
Simazine	6 (20 %)	0.005	0.025	4 MCL	22
Dinoseb	1 (3 %)	0.035	E0.030	7 MCL	0.3

Unlike many agricultural areas of the country where row crops dominate, agriculture within the study area is dominated by pasture, christmas tree silviculture, and burly tobacco production. The high occurrence of pesticide detections within the study area suggests that the fractured bedrock aquifers of the region are susceptible to contamination by pesticide usage. An interagency study of the effect of pesticide use on ground water in North Carolina was sponsored by the North Carolina Department of Agriculture and North Carolina Department of Environment, Health, and Natural Resources (Wade and others, 1997). Approximately 198 wells were sampled statewide including 55 ambient monitoring wells, 97 shallow monitoring wells, and 46 domestic wells. Of these 198 wells, nine were sampled in the NAWQA study area (Ashe and Alleghany Counties). Of these nine, simazine and deethylatrazine were detected in three monitoring wells, and lindane was detected in one domestic well. The maximum concentrations of simazine, deethylatrazine and lindane detected in the interagency study were 1.2, 1.0, and 0.15 µg/L, respectively. Atrazine is commonly used on corn; chlorpyrifos is commonly used on tobacco, and simazine is commonly used on Christmas trees. None of the other compounds detected are listed as commonly used in the study area (Wade and others, 1997).

Volatile Organic Compounds. Gasoline by-products such as benzene, toluene, ethylbenzene, xylene (BTEX compounds) and the fuel oxygenate methyl-*tert*-butyl-ether (MTBE) are common ground-water contaminants. Many VOCs are commonly used in industrial manufacturing processes (1,1,1-trichloroethane, 1,2,4-trichlorobenzene, benzene, carbon disulfide, ethylbenzene, and toluene) or as solvents, paint thinners or degreasers (cis-1,2-dichloroethene, isopropylbenzene, and methyl-ethyl-ketone). Several are commonly used as dry cleaning fluids (trichloroethylene and tetrachloroethylene), and 1,4-dichlorobenzene is a common constituent in moth balls, some insecticides, and in various disinfectants. Trihalomethanes (THMs) are compounds such as trichloromethane (chloroform), dibromochloromethane, bromodichloromethane, and tribromomethane (bromoform), which can form as a result of disinfection of water supplies by chlorination.

Numerous VOCs were detected during this study. At least one VOC was detected in 21 of the 30 (70 percent) wells sampled. Fourteen separate compounds were detected in ground water within the study area (table 10). The most commonly detected VOC was chloroform, which was detected in 40 percent of wells sampled. One use for chloroform is as a mildewcide for tobacco seedlings. Because of the history of tobacco production in the region, this may be a potential source of chloroform in the study area. Chloroform also may form as a by-product of chlorination of water and is one of the THMs previously discussed. One common practice for eliminating bacteria in well water is to add sodium hypochlorite (bleach) directly to a well. This process has also been successful in treating wells with high concentrations of iron bacteria. The chlorination of wells using bleach may, therefore, be a potential indirect source of chloroform. Chloroform is also used as an insecticidal fumigant on stored corn, barley, oats, rice, rye, sorghum, and wheat, and is used as a solvent in the manufacture of a wide variety of chemicals and industrial compounds.

The second most commonly detected VOC was 1,1,1-trichloroethane, found in 30 percent of the sites sampled. It is a common industrial solvent. Benzene and toluene were detected in 23 percent and 17 percent respectively of the 30 sites sampled. Benzene and toluene are components of gasoline, are commonly used in many industrial processes, and are commonly found in ground water. Methyl-ethyl-ketone and carbon-disulfide were detected in 17 percent of the sites sampled. Methyl-ethyl-ketone is a commonly used industrial solvent and cleaning agent. Carbon disulfide is used in the manufacture of rayon, cellophane, carbon tetrachloride, xanthogenates, electronic vacuum tubes, and soil disinfectants, and is a common solvent and as an inhibitor in a wide variety of chemical manufacturing processes. Tetrachloroethylene was detected in 13 percent of the 30 samples collected. Tetrachloroethylene is commonly used in the textile industry for dry-cleaning, in both cold cleaning and vapor degreasing of metals, as a chemical intermediate in the synthesis of fluorocarbons, as a heat-exchange fluid, and in typewriter correction fluids. MTBE and 1,4-dichlorobenzene were both detected in 10 percent of the wells sampled. MTBE is a fuel oxygenate and is commonly found in ground water. The compound 1,4-dichlorobenzene is used as an active ingredient in moth balls, insecticides, and disinfectants. The compound 1,2,4-trichlorobenzene, cis-1,2-dichloroethene, ethylbenzene, isopropylbenzene, and trichloroethylene were detected only once, all at estimated (less than 0.020 mg/L) concentrations.

Table 10. Volatile organic compounds detected in water samples collected from 30 wells in the Blue Ridge Physiographic Province, New River Basin

[E, estimated value; MCL, maximum contaminant level; N/D, no data; µg/L, micrograms per liter; LHA, lifetime health advisory level; τ, MCL for total trihalomethanes (which includes chloroform)]

Constituent	Number (%) of sites with detections	Detection limit (µg/L)	Maximum concentration detected (µg/L)	Drinking-water criteria (µg/L)
1,1,1-Trichloroethane	9 (30%)	0.032	0.223	200 MCL
1,2,4-Trichlorobenzene	1 (3%)	0.188	E0.020	70 MCL
1,4-Dichlorobenzene	3 (10%)	0.050	E0.010	75 MCL
Benzene	7 (23%)	0.050	E0.050	5 MCL
Carbon-disulfide	5 (17%)	0.080	E0.020	N/D
Chloroform	12 (40%)	0.052	0.251	100 MCLτ
Cis-1,2-dichloroethene	1 (3%)	0.038	E0.006	70 MCL
Ethylbenzene	1 (3%)	0.030	E0.010	700 MCL
Isopropylbenzene	1 (3%)	0.032	E0.010	N/D
Methyl-ethyl-ketone	5 (17%)	1.65	E0.400	N/D
Methyl-*tert*-butyl-ether	3 (10%)	0.112	1.20	20 LHA
Tetrachloroethylene	4 (13%)	0.038	0.328	5 MCL
Toluene	5 (17%)	0.038	E0.060	1,000 MCL
Trichloroethylene	1 (3%)	0.038	E0.006	5 MCL

Concentrations of VOCs in the study area were not compared with national data sets of VOCs in rural (Squillace and others, 1999) and agricultural (USGS, 1998) areas, because the method reporting limit (mrl) at the time the samples were collected for the national data sets was 0.200 µg/L, except for 1,2-dibromo-3-chloropropane, which had an mrl of 1.00 µg/L. With the development of more advanced analytical techniques, the mrl was lowered significantly for most of the compounds. For certain compounds detected as part of this study, estimated concentrations were determined to be as low as 0.005 µg/L. For a complete list of the compounds analyzed and the associated mrls for each compound refer to the USGS Water Resources Data for West Virginia, Water Year 1997 publication (Ward and others, 1998). Only five of the 14 VOCs were detected at a concentration greater than 0.200 µg/L. Chloroform, 1,1,1-trichloroethane, MTBE, and tetrachloroethylene were detected at concentrations greater than 0.200 µg/L only once, while methyl-ethyl-ketone was detected in four of 30 samples analyzed.

The high detection frequency of VOCs (70 percent of sites had detectable concentrations of at least one VOC) in ground water suggests that the fractured igneous and metamorphic bedrock aquifers in the study area may be susceptible to contamination. The low concentrations of VOCs (maximum concentration only 1.20 µg/L for MTBE) detected, however, indicate that VOC contamination of ground water in the study area is not a serious problem at present. Both atmospheric and anthropogenic sources of VOCs may contribute to the low levels of VOCs detected in ground water within the study area.

FACTORS AFFECTING WATER QUALITY

Three factors commonly affect ground-water quality--geochemical sources, anthropogenic sources, and atmospheric deposition. Anthropogenic sources are human activities such as agriculture, industry, septic fields, sewage-treatment plants, landfills, the timber industry, coal mining, and chemical manufacturing, to name just a few. Each of the three factors will be discussed on the basis of available water-quality, geologic, and precipitation-chemistry data.

Geochemical Factors

Igneous and metamorphic rocks constitute most of the bedrock in the study area, although there are a few outcrops of limestone. Geologic maps for North Carolina and Virginia show that the principal rock types in the region are granite, gneiss, phyllite, schist, amphibolite, rhyolite, sandstone, quartz, and various grades of metamorphosed sandstones, shales, and siltstone. Geochemical data describing the mineralogic composition of rocks in the study area are sparse. It is therefore difficult to link the occurrence of certain constituents in ground water to a specific type of rock. A complete synopsis of geochemistry in the study area is beyond the scope of this report. Bedrock and the associated minerals it contains are a source of many dissolved minerals in ground water within the study area.

Several of the most common bedrock derived constituents in ground water are calcium, magnesium, sodium, potassium, silica, sulfate, chloride, fluoride, silica, carbonate, and bicarbonate. These constituents affect the dissolved-solids concentration of ground water and contribute to the hardness of water in the region. Water from 70 percent (21 of 30) of the wells sampled is characterized as soft, which suggests that the ground water is relatively young and has not had a significant amount of time to dissolve minerals in bedrock. The median depth to water below land surface is 34.5 feet, indicating a shallow ground-water flow system.

In many aquifer systems, especially fractured bedrock aquifers, cation exchange processes between calcium and sodium are common. Deep connate brines or sodium present within bedrock minerals are probable sources of sodium for cation exchange within bedrock aquifers. Cation exchange occurs as calcium, which tends to be present in shallow ground water, is exchanged for sodium as ground water flows to greater depths within an aquifer. This process is evident as analysis of calcium to sodium ratios with respect to topographic setting (fig. 6) revealed lower calcium to sodium ratios in valley settings than in hilltop settings. Calcium to sodium ratios for hillside settings were intermediate between hilltop and valley settings, as would be expected.
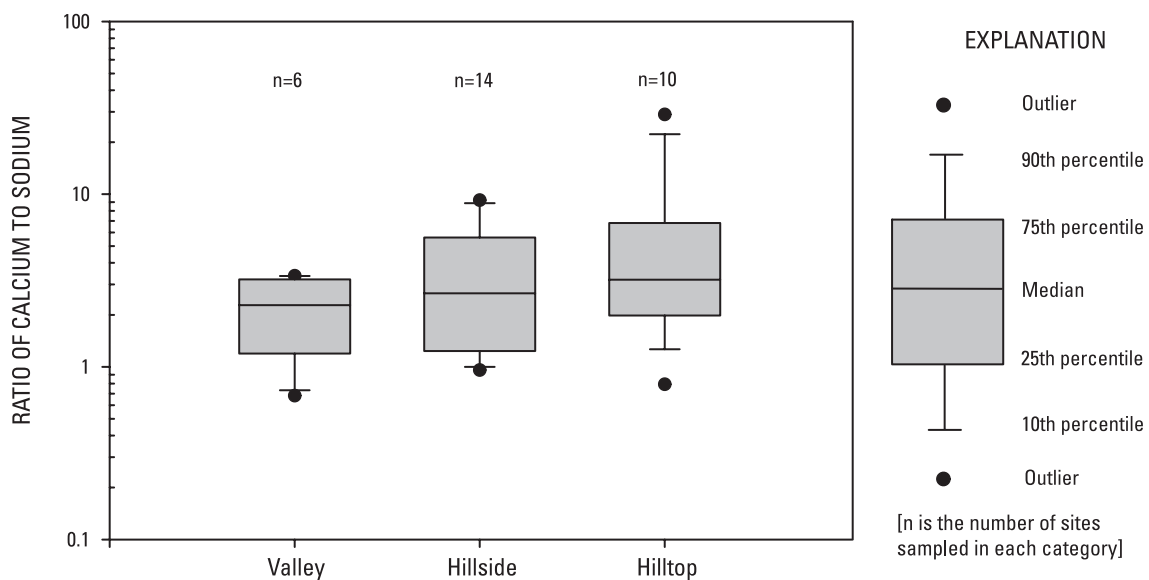

Figure 6. Distribution of calcium to sodium ratio for valley, hillside, and hilltop wells sampled in the Blue Ridge Physiographic Province, New River Basin.

Anthropogenic Factors

The effects of human activity on water quality in the study area has already been discussed; therefore, only a brief synopsis of these anthropogenic effects will be presented here. Within the study area, only VOCs, pesticides, and to a lesser extent, total coliform bacteria, are likely derived from human activity. Although pesticides and total coliform bacteria were commonly detected in the 30 samples collected, concentrations of pesticides and bacteria were typically low and generally are not major problems within the study area. The maximum concentration of a pesticide detected as part of this study was only 0.152 µg/L for lindane. Also, fecal coliform and *E. coli* bacteria, which are more indicative of potential human health hazards than is total coliform bacteria, were not detected; therefore, the primary constituents detected in ground water derived from human activity are VOCs.

Because of the variety of potential uses for the VOCs detected, it would be nearly impossible to determine which specific activity is responsible for the occurrence of VOCs in ground water within the study area. To further complicate matters, atmospheric deposition of VOCs can be a significant source of groundwater contamination for certain compounds in various areas of the country (Baehr and others, 1999).

At least one VOC was detected in 21 of the 30 (70 percent) wells sampled and 14 separate VOCs were detected in ground water within the study area (table 10). As VOCs are primarily synthetic compounds, or in the case of THMs, are derived as chlorination by-products, their presence in ground water verifies an anthropogenic source. The VOCs detected, however, were all at extremely low concentrations, well below USEPA MCLs. The maximum concentration of a VOC detected in the 30 samples collected was for MTBE at a concentration of only 1.20 µg/L. Although it is not possible at present to determine the source of VOCs in ground water within the area, research suggests that many of the BTEX compounds and MTBE may be derived principally from precipitation (Baehr and others, 1999).

Relations among Precipitation, Topography, and Ground Water

In a recent study of VOC concentrations in southern New Jersey, it was determined that atmospheric deposition could account for concentrations of BTEX compounds in ground water less than 0.1 µg/L (Baehr and others, 1999). A similar study conducted in Germany (Schleyer and others, 1993) found similar concentrations of toluene in precipitation (0.047 - 0.048 µg/L), soil water (0.039 - 0.085 µg/L), and ground water (0.043 µg/L). The maximum concentration of BTEX compounds detected in the study area was only 0.060 µg/L; atmospheric deposition could possibly account for much of the concentrations of BTEX compounds detected in the study area. For other VOCs such as tetrachloroethylene, 1,1,1-trichloroethylene, carbon disulfide, and chloroform, the study estimated, based on Henry's Law, that the maximum possible concentrations of these constituents in ground water would be less than or equal to approximately 0.003 µg/L. Concentrations greater than 0.003 µg/L would therefore indicate a source other than or in addition to atmospheric deposition. Atmospheric deposition, therefore, is probably not a primary source of VOCs other than for BTEX compounds within the study area. Additional data, however, is needed to confirm the sources of BTEX compounds and other VOCs in ground water.

Precipitation may also be a source of nutrients and dissolved ions in ground water. To investigate this, chemical data for ground water from different topographic settings were compared to chemistry of precipitation. Concentrations of calcium, magnesium, potassium, sodium, ammonia, nitrate, chloride, and sulfate, as well as pH and specific conductance of ground water in hilltop, hillside, and valley wells were compared to those in precipitation (table 11). Although it is not possible to prove statistically, because of small sample sizes, precipitation could be a major source of nitrate in shallow ground water in hilltop and hillside settings. The average nitrate concentration in precipitation for the nearest precipitation-quality monitoring station at Mount Mitchell in North Carolina (72 miles southwest of study area) is 0.630 mg/L, but average nitrate concentrations in shallow ground water in hilltop and hillside settings within the study area are only 0.283 and 0.419 mg/L, respectively.

Table 11. Median, maximum, and minimum values of selected water-quality constituents for 30 wells sampled in the Blue Ridge Physiographic Province, New River Basin, and for precipitation data collected at the National Acid Deposition Monitoring station on Mount Mitchell, North Carolina

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per Liter]

	pH	Specific Conductance (µS/cm)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
				Hilltop Wells						
Median	6.2	78.0	7.8	1.85	1.20	3.00	<0.015	0.283	1.7	2.55
Maximum	7.3	453.	50.0	27.0	2.70	5.90	0.046	14.1	27.0	9.60
Minimum	5.1	37.0	1.9	0.790	0.280	1.10	<0.015	<0.050	0.60	0.19
				Hillside Wells						
Median	6.4	79.0	8.6	1.25	1.15	3.80	<0.015	0.419	1.9	2.60
Maximum	7.6	230.	29.0	6.60	3.50	7.70	0.033	6.65	37.0	220.
Minimum	5.5	9.0	1.4	0.470	0.460	1.60	<0.015	<0.050	0.30	<0.10
				Valley Wells						
Median	6.3	177.	14.5	4.35	2.55	8.00	<0.015	1.14	15.0	9.10
Maximum	8.0	435.	19.0	16.0	5.30	32.0	<0.015	4.89	64.0	15.0
Minimum	5.7	115.	10.0	0.510	1.60	5.00	<0.015	<0.050	1.2	3.70
				Precipitation						
Median	4.6	13.8	0.04	0.010	0.011	0.063	0.150	0.630	0.10	1.20
Maximum	4.7	16.5	0.04	0.012	0.025	0.082	0.170	0.680	0.14	1.49
Minimum	4.4	10.2	0.02	0.005	0.006	0.031	0.080	0.450	0.06	0.87

Concentrations of nitrate in shallow ground water in valley settings (1.14 mg/L) down gradient from recharge areas are higher than in ground water sampled in hilltop (0.283 mg/L) or hillside (0.419 mg/L) settings. This finding suggests that other sources of nitrogen are likely affecting the quality of ground water in valley settings. Concentrations of nitrate in wells in hilltop and hillside settings are rather dilute but increase substantially as ground-water flows down gradient to discharge areas in valleys. Possible sources of nitrogen in valley settings could be leaky or inadequate septic systems, agriculture, fertilizers, and pastures. Minerals derived from bedrock within the study area would not be expected to significantly contribute nitrate to the fractured bedrock aquifers as they typically contain only trace amounts of nitrogen. Sulfate, which has median concentrations of 2.55 and 2.60 mg/L in hilltop and hillside wells, is also likely derived, at least partly from atmospheric deposition. Precipitation at Mount Mitchell has a median sulfate concentration of 1.20 mg/L. For the water samples collected in valley settings, sulfate had a median concentration of 9.10 mg/L, suggesting that minerals, especially sulfide minerals, present within the bedrock are likely sources of increased sulfate in valley settings.

SUMMARY AND CONCLUSIONS

The USGS NAWQA Program investigated ground water within the Blue Ridge Physiographic Province in Virginia and North Carolina to establish base-line data and assess ground-water quality. A broad suite of water-quality constituents including common ions, nutrients, bacteria, trace metals, volatile organic compounds (VOCs), pesticides, radon, and chlorofluorocarbons (CFCs), was analyzed in samples collected from 30 wells throughout the region.

Hydrograph analysis techniques were used to analyze streamflow data from six unregulated streams within the study area and to separate streamflow into its ground-water base flow and surface runoff components. Ground-water base flow in streams ranged from 67 to 78 percent of the annual streamflow with a median base flow of 69 percent. Based on average monthly rates of ground-water recharge computed for six stream basins, 69 percent of ground-water recharge occurs during November through May, when evapotranspiration is at a minimum. Only 31 percent of recharge occurs typically in June through October, a period of vegetation growth and correspondingly high rates of evapotranspiration. Total annual recharge, estimated from streamflow recessions, ranged from 13.7 to 26.0 inches with a median of 19.1 inches. Effective recharge, the portion of recharge that eventually discharges to streams, was slightly less, because of riparian evapotranspiration, ranging from 11.4 to 22.3 inches with a median of 15.1 inches.

Chlorofluorocarbon (CFC) data were collected from 19 wells within the study area. The median age of ground water in wells sampled was 16 years. There was little if any difference in age of ground water sampled from various topographic settings. Apparent ground-water ages ranged from a minimum of six to a maximum of 33 years. None of the 19 samples collected for CFC analysis were CFC free, suggesting relatively recent recharge and young ground water.

Thirty samples were analyzed for total coliform, fecal coliform, and *E. coli* bacteria. Fecal coliform and *E. coli.* bacteria were not detected in any of the samples collected. Water from 11 of 29 wells (38 percent) sampled tested positive for total coliform bacteria (one sample experienced problems during the incubation process). The fact that no fecal coliform or *E. coli* bacteria were detected is encouraging and the relative lack of bacteria in the samples collected suggests that fractured bedrock aquifers in the study area have not been adversely affected by bacterial contamination.

Water samples from 30 wells were also analyzed for common ions and trace metals. Most constituents detected were present at concentrations less than U.S. Environmental Protection Agency maximum contaminant level (MCL) or secondary maximum contaminant level (SMCL) drinking-water standards. Only 1 of the 30 wells sampled had a concentration of nitrate (14.1 mg/L) in excess of the 10 mg/L USEPA MCL. Likewise only one well sampled had a concentration of fluoride (2.5 mg/L) exceeding the 2.0 mg/L USEPA SMCL for fluoride. Twenty one (70 percent) of the wells sampled were determined to have soft water and 9 (30 percent) were classified as moderately hard to very hard. None of the samples collected contained trace metals in excess of USEPA MCLs. Iron and manganese, which are regulated as secondary contaminants based on aesthetics rather than health based criteria, exceeded the 300 and 50 mg/L USEPA SMCLs in 4 (13 percent) and 5 (17 percent) of sites sampled respectively. Lead was detected in 3 (10 percent) of the sites sampled but none exceeded the USEPA action level of 15 µg/L.

Radon is a naturally occurring radioactive gas and a known carcinogen. Ground water from 26 of 30 wells (87 percent) sampled contained radon in concentrations greater than the proposed USEPA MCL of 300 pCi/L, and 10 samples (33 percent) had radon in concentrations exceeding the 4,000 pCi/L proposed alternate MCL (AMCL). The median radon concentration detected in the wells sampled was 2,080 pCi/L (almost seven times the proposed MCL), and the maximum concentration detected was 30,900 pCi/L. Of 10 wells having radon concentrations greater than 4,000 pCi/L, eight were located on or adjacent to faults. Increased fracturing of bedrock along fault zones may provide a route for radon migration, and mylonization along shear zones can result in uranium (and radon) enrichment within the fault zone.

Water samples were analyzed for 86 pesticides but only 10 were detected, all at low concentrations. At least one pesticide was detected in 17 of the 30 (57 percent) wells sampled. This finding suggests that the fractured bedrock aquifers of the region are susceptible to contamination by pesticides. Atrazine, deethylatrazine, simazine, DDE, and molinate were the most commonly detected pesticides and were detected in 11 (37 percent), 9 (30 percent), 6 (20 percent), 4 (13 percent), and 2 (7 percent) of the 30 wells sampled, respectively.

At least one VOC was detected in 21 of the 30 (70 percent) wells sampled but the maximum VOC concentration detected was only 1.20 µg/L. None of the VOCs detected exceeded USEPA MCLs or health based guidelines. Fourteen separate compounds were detected in ground water within the study area. The most commonly detected VOCs were chloroform, 1,1,1-trichloroethane, benzene, toluene, methyl-ethyl-ketone, carbon-disulfide, tetrachloroethylene, methyl-*tert*-butyl-ether (MTBE) and 1,4-dichlorobenzene which were detected in 40, 30, 23, 17, 17, 17, 13, 10, and 10 percent of the 30 wells sampled, respectively.

Analysis of calcium to sodium ratios with respect to topographic setting for the water samples collected revealed lower calcium to sodium ratios in water from wells in valley settings than in hilltop settings. Such ratios suggest cation exchange processes between calcium and sodium are common in valley settings within the study area. Deep connate brines or sodium present within bedrock minerals are probable sources of sodium for cation exchange within bedrock aquifers. Cation exchange occurs as calcium, which tends to be present in shallow ground water, is exchanged for sodium as ground water flows to greater depths within an aquifer. Calcium to sodium ratios for hillside settings were intermediate between hilltop and valley settings.

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