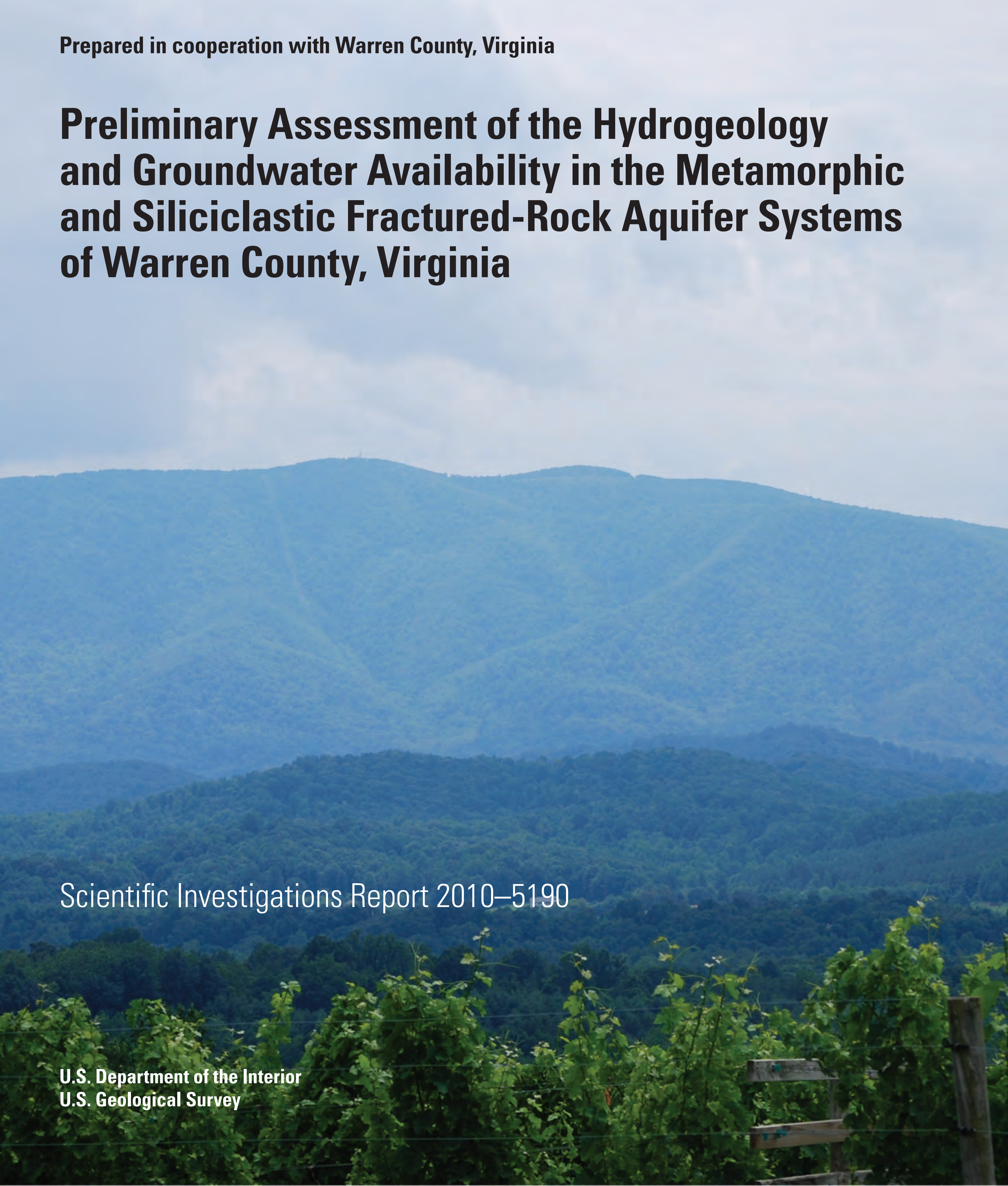

Prepared in cooperation with Warren County, Virginia

Preliminary Assessment of the Hydrogeology and Groundwater Availability in the Metamorphic and Siliciclastic Fractured-Rock Aquifer Systems of Warren County, Virginia

Scientific Investigations Report 2010–5190

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

Cover. **Hogback Mountain in Shenandoah National Park.** View looking near Boyds Mill to the southwest.
(Photograph by David L. Nelms, U.S. Geological Survey, July 2009.)

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Contents

Figures

Tables

Appendixes

Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
liter (L)	3.785	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)

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

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

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

Concentrations of chemical constituents are given in milligrams per liter (mg/L).

Acronyms and Abbreviations:

τ	Apparent tritium/helium-3 age
$^3H/^3He$	Tritium/helium-3
$^3He_{trit}$	Tritiogenic tritium
Ar	Argon
bls	Below land surface
BFI	Base-flow index
CFCs	Chlorofluorocarbons (Freon)
DEM	Digital elevation model
ER	Effective recharge (mean base flow or groundwater discharge)
ET	Evapotranspiration
FO DTS	Fiber-optic distributed temperature sensing system
GIS	Geographic information system
GPS	Global positioning system
GWSI	Ground-Water Site Inventory database
N_2	Nitrogen
Ne	Neon
NWS	National Weather Service
P	Precipitation
PRISM	Parameter-elevation regressions on independent slopes model
RET	Riparian evapotranspiration
RO	Mean surface-runoff
ΔS	Change in groundwater storage
SF_6	Sulfur hexafluoride
USGS	U.S. Geological Survey
VDEQ	Virginia Department of Environmental Quality
WU	Water usage (withdrawals)

Preliminary Assessment of the Hydrogeology and Groundwater Availability in the Metamorphic and Siliciclastic Fractured-Rock Aquifer Systems of Warren County, Virginia

By David L. Nelms and Roger M. Moberg, Jr.

Abstract

Expanding development and the prolonged drought from 1999 to 2002 drew attention to the quantity and sustainability of the groundwater resources in Warren County, Virginia. The groundwater flow systems of the county are complex and are controlled by the extremely folded and faulted geology that underlies the county. A study was conducted between May 2002 and October 2008 by the U.S. Geological Survey, in cooperation with Warren County, Virginia, to describe the hydrogeology of the metamorphic and siliciclastic fractured-rock aquifers and groundwater availability in the county and to establish a long-term water monitoring network. The study area encompasses approximately 170 square miles and includes the metamorphic rocks of the Blue Ridge Physiographic Province and siliciclastic rocks of the Great Valley section of the Valley and Ridge Physiographic Province.

Well depths tend to be shallowest in the siliciclastic rock unit (predominantly in the Martinsburg Formation) where 75 percent of the wells are less than 200 feet deep. Median depths to bedrock are generally less than 40 feet across the county and vary in response to the presence of surficial deposits, faults, siliciclastic rock type, and topographic setting. Water-bearing zones are generally within 200 feet of land surface; median depths, however, are slightly deeper for the hydrogeologic units of the Blue Ridge Province than for those of the Great Valley section of the county. Median well yields for the different rock units generally range from 10 to 20 gallons per minute. High-yielding wells tend to cluster along faults, along the eastern contact of the Martinsburg Formation, and within potential lineament zones. Specific capacity is relatively low and ranges from 0.003 to 1.43 gallons per minute per foot with median values from 0.12 to 0.24 gallon per minute per foot. Transmissivity values derived from specific capacity data range over four orders of magnitude from 0.6 to 380 feet squared per day.

Estimates of effective groundwater recharge from 2001 to 2007 ranged from 2.4 to 29.4 inches per year in the Gooney Run, Manassas Run, and Crooked Run Basins, with averages of 15.3, 14.2, and 5.3 inches per year, respectively. Base flow accounted for between 57 and 86 percent of mean streamflow in the Gooney Run and Manassas Run Basins and averaged about 70 percent in these Blue Ridge Province basins. In the siliciclastic rock-dominated Crooked Run Basin of the Great Valley, base flow accounted for between 33 and 65 percent of mean streamflow and averaged about 54 percent. The high base-flow index values (percentage of streamflow from base flow) in these basins indicate that groundwater is the dominant source of streamflow during wet and drought conditions. About 50 percent of the precipitation that fell on the Blue Ridge basins from 2001 to 2007 was removed by evapotranspiration, and between 33 and 36 percent of the precipitation reached the water table as effective recharge. Nearly 76 percent of the precipitation was removed by evapotranspiration in the Crooked Run Basin, and effective recharge averaged about 12 percent of precipitation between 2001 and 2007. Average values of runoff in all three basins were less than 15 percent of precipitation.

Groundwater flow systems in the county are extremely vulnerable to current climatic conditions. Successive years of below-average effective recharge cause declines in water levels, spring discharges, and streamflows. However, these systems can recover quickly because effective recharge increases with increasing precipitation. Lack of precipitation, especially snow, during the critical recharge period (January–April) can have an effect on the amount of recharge to the groundwater system and eventual stream base flow. Estimated values of annual mean base flow have approached and have been below the average regression-derived recharge rates during a period classified as having above-average precipitation. This relation is indicative of groundwater systems with limited storage that are highly responsive to current meteorological conditions. Slight changes in annual amounts of precipitation or timing of the precipitation can affect groundwater recharge. The report of well failures during this investigation may be related to the close relation between recharge and precipitation.

Introduction

The metamorphic and siliciclastic fractured-rock aquifer systems of the Blue Ridge Physiographic Province (Blue Ridge) and of the Great Valley section of the Valley and Ridge Physiographic Province (Valley and Ridge), respectively, are present over an extensive region of the Northern Shenandoah Valley and are increasingly being relied upon to supply water to local communities. This is an area with an expanding economy and a growing population, and, to meet future water needs, these aquifer systems are likely to be developed to supplement current withdrawals from the carbonate aquifer system and surface-water bodies in the region. A study was conducted between May 2002 and October 2008 by the U.S. Geological Survey (USGS), in cooperation with Warren County, VA, to describe the hydrogeology and groundwater availability of the metamorphic and siliciclastic fractured-rock aquifers in the county and to establish a long-term water monitoring network. An improved understanding of this complex aquifer system is required to effectively develop and manage it as a sustainable water supply. Hydrogeologic information provided by a detailed aquifer evaluation and description will provide useful information to better address questions about (1) the quantity of water available for use, (2) the effects of increased pumpage on groundwater levels and instream flows, and (3) the quality of the groundwater supply and its vulnerability to current and potential future sources of contamination.

Previous groundwater studies in Warren County generally have focused on proposed local development or hazardous waste sites. These studies were conducted without the benefit of knowledge gained from long-term data networks or from a systematic evaluation of the groundwater resources in the areas underlain by the metamorphic and siliciclastic rocks in the county. Future land-use and water-supply planning activities in the county should benefit from these data and knowledge gained during the course of this study.

Purpose and Scope

This report describes the hydrogeology and groundwater availability of the metamorphic and siliciclastic fractured-rock aquifer systems in Warren County, VA, and provides hydrogeologic information that can be used to guide the development and management of these important water resources. The area in this report encompasses the non-carbonate formations in Warren County, VA, consisting of the Blue Ridge rocks in the eastern half of the county and primarily of the Martinsburg Formation outcrop belt in the western half of the county. Water budgets that include effective groundwater recharge are presented for the Gooney Run, Crooked Run, and Manassas Run Basins for 2003–2007. In addition, water budgets are presented for ungaged basins for estimated water usage at buildout. This report also includes data on groundwater levels, spring discharges, and streamflows collected as part of a long-term water-resources monitoring network and data on apparent groundwater ages.

Description of the Study Area

Warren County is within the Blue Ridge and Valley and Ridge Physiographic Provinces of Virginia (Fenneman, 1938, p. 691), at the northern end of the Shenandoah Valley, about 75 miles (mi) west of Washington, D.C. (fig. 1). Clarke and Frederick Counties are to the north, Shenandoah County is to the west, and Fauquier and Rappahannock Counties are to the east. Warren County, including the independent town of Front Royal, encompasses about 217 square miles (mi^2). In 2000, Warren County had a population of 31,584 (U.S. Census Bureau, 2003). Altitudes range from 3,474 feet (ft) above National Geodetic Vertical Datum of 1929 (NGVD 29) on Hogback Mountain in the southeastern part of the county to about 410 ft above NGVD 29 where the Shenandoah River flows out of the county. The study area encompasses about 170 mi^2 and includes both the Blue Ridge and the Valley and Ridge Physiographic Provinces, the latter commonly referred to as the Great Valley section (fig. 1). The Great Valley section of the central Appalachian Valley and Ridge Province extends nearly 1,000 mi from southern New York to central Alabama (Yager and others, 2008). The area of investigation includes (1) the metamorphic rocks that underlie the Blue Ridge Physiographic Province in the eastern part of Warren County, which are the oldest bedrock units in the study area; and (2) the siliciclastic rocks (sandstone, siltstone, and shale) that underlie the western edge of the Great Valley section, which are the youngest bedrock units in the study area (fig. 1). The Blue Ridge is a mountainous terrain with steep slopes and well-developed drainage networks. In the siliciclastic areas, the terrain can be gently rolling or steep along the slopes and ridge of Massanutten Mountain. These areas are highly dissected with well-developed trellis drainage networks that align along the predominant fractures that are parallel and perpendicular to the strike of the bedding (Yager and others, 2008). In the central part of the county, the Great Valley section is predominantly underlain by soluble carbonate rocks that form karst features (such as sinkholes, caves, estavelles, swallet holes, and sinking streams) resulting from dissolution of these rocks.

Conceptual Model of Groundwater Flow

The groundwater flow systems in the Blue Ridge and in the Great Valley section of the Valley and Ridge Physiographic Province are complex and often are controlled by the underlying geology of the respective provinces. The hydrogeologic section shown in figure 2 represents a conceptual idea of groundwater movement through both of these flow systems and the karst flow systems of central Warren County. In both areas, the rocks are highly deformed by folding, faulting, and

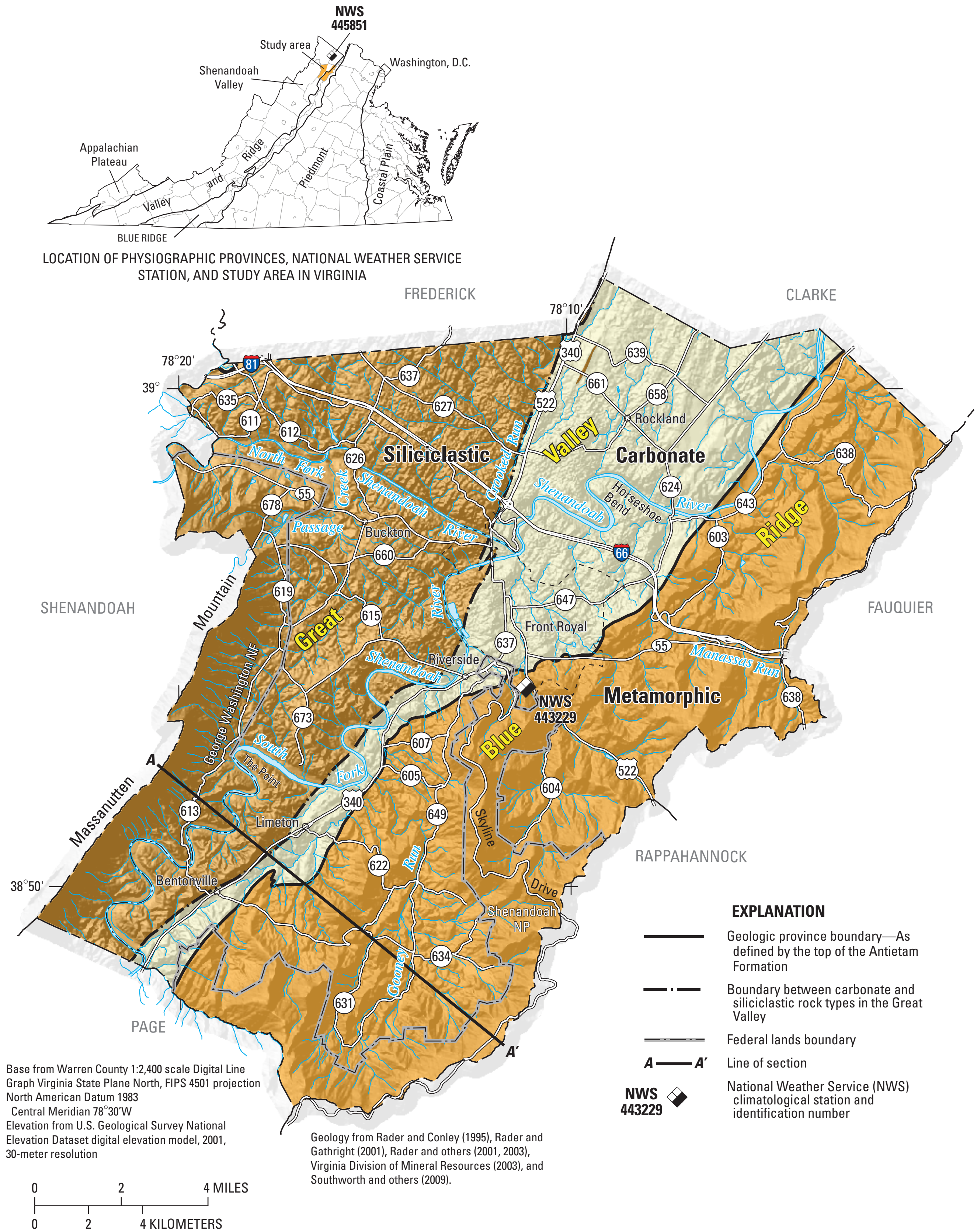

Figure 1. Generalized geologic province map of Warren County, Virginia, and location of study area.

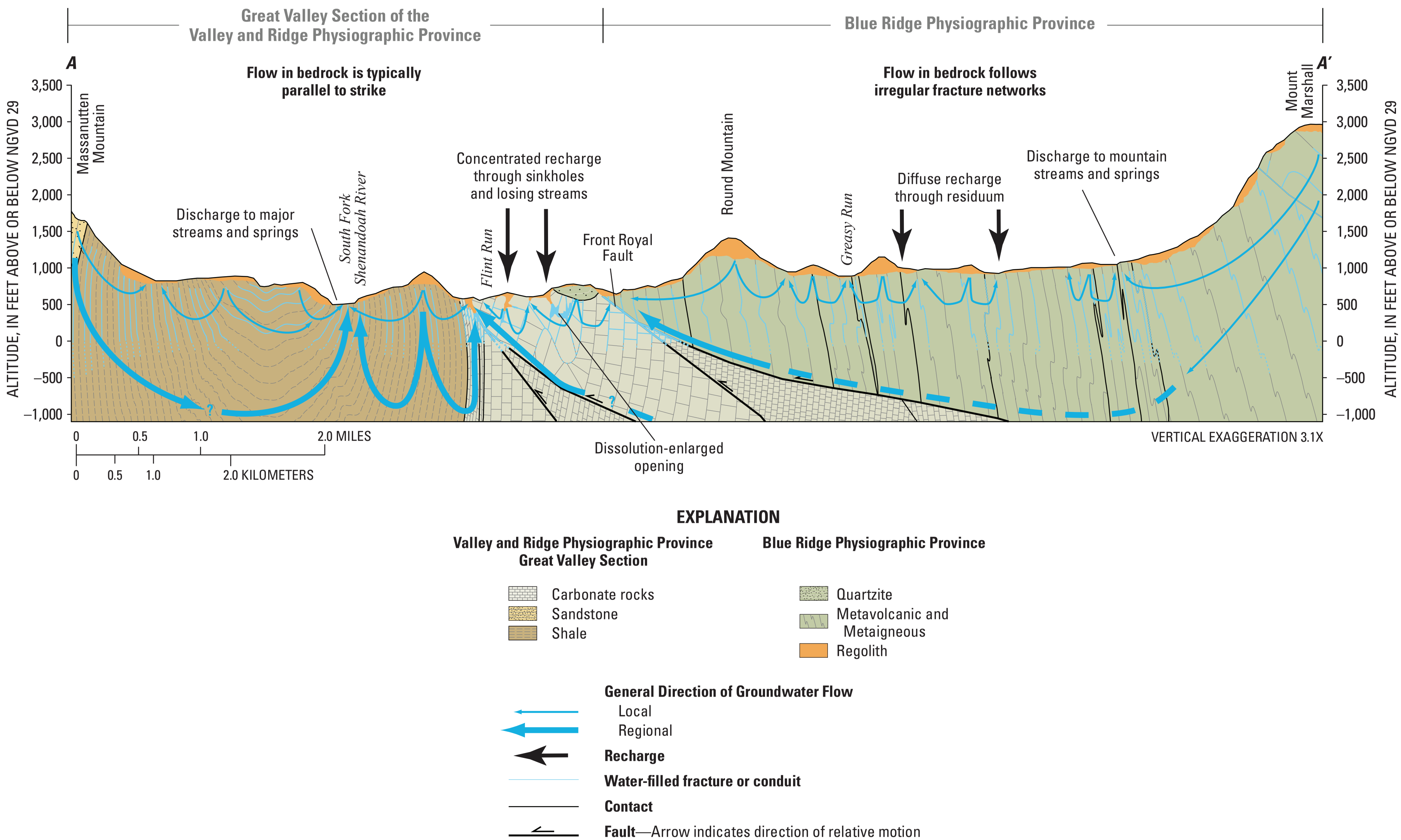

Figure 2. Generalized hydrogeologic section across Warren County, Virginia. Modified from Rader and Conley (1995). Line of section *A–A′* shown in figure 1.

weathering processes. In order to depict the depth range of most wells, the steepness of the geologic structures is over-exaggerated in figure 2. Groundwater flow generally follows the topography (for example, from higher elevation to lower elevation), but actual flow paths often are controlled by the underlying geologic structure.

Climate

Climatic data for the region were obtained from National Weather Service (NWS) climatological station 445851 Mt. Weather, which is located to the east in Loudoun County at an elevation of 1,720 ft above NGVD 29, and from NWS climatological station 443229 Front Royal, which is located in Warren County at an elevation of 930 ft above NGVD 29. The periods of record for these two stations are 103 and 12 years for temperature data and 104 and 12 years for precipitation data, respectively (National Oceanic and Atmospheric Administration, 2006). The normal values are based on the NWS's current normal climatological period from 1971 to 2000 for the Mt. Weather station, whereas the normal values for the Front Royal station are based on the period of record from 1996 to 2007. The mean annual air temperature at the Mt. Weather station is 10.6 degrees Celsius (°C) with the coldest month being January (–1.8 °C) and the warmest being July (22.3 °C). The colder periods of the year are between November and April, and the warmer periods are between May and October. The mean annual air temperature at the Front Royal station is 12.6 °C with the coldest month being January (1.6 °C) and the warmest being July (23.8 °C). The colder periods of the year are between November and April, and the warmer periods are between May and October.

Average annual precipitation at the Mt. Weather station is 43.3 inches (in.). During an average year, precipitation would be highest in May (4.5 in.) and lowest in February (2.5 in.). The average annual precipitation of 41.8 in. at the Front Royal station is about 2 in. lower than annual precipitation at the Mt. Weather station. In an average year, monthly totals are highest in September (6.3 in.) and lowest in December (2.0 in.) at the Front Royal station. Although precipitation is relatively evenly distributed throughout an average year, average monthly precipitation tends to be lower for December through February than for March through September (fig. 3).

A grid of average annual precipitation interpolated from parameter-elevation regressions on independent slopes model (PRISM) for Warren County, VA, is shown in figure 4 and was extracted from the National PRISM data (PRISM Climate Group, Oregon State University, *http://www.prismclimate.org*, created May 12, 2009). The normal values are based on the NWS's current normal climatological period from 1971 to 2000. PRISM is an analytical model that generates gridded estimates of annual precipitation from point data at NWS climatological stations and a digital elevation model (DEM) (Di Luzio and others, 2008). The PRISM grid estimates that average annual precipitation ranges from 38.5 to 59.6 in. across Warren County. The higher values illustrate the orographic effect on precipitation of the elevated areas of the Blue Ridge in the eastern part of the county. The lowest values also illustrate orographic effects caused by mountain ranges to the west in Shenandoah County and West Virginia

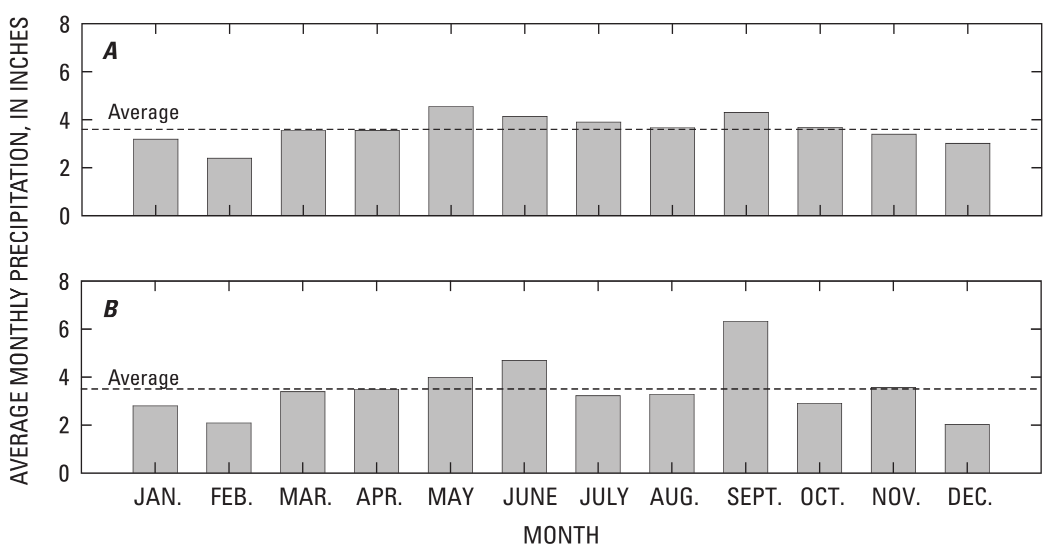

Figure 3. Average monthly precipitation for National Weather Service climatological stations *(A)* 445851 Mt. Weather in Loudoun County, Virginia, at an elevation of 1,720 feet above National Geodetic Vertical Datum of 1929 (NGVD 29) and *(B)* 443229 Front Royal in Warren County, Virginia, at an elevation of 930 ft above NGVD 29. The normal values for station 445851 are based on the National Weather Service's current normal climatological period from 1971 to 2000. The normal values for station 443229 are based on the period 1996 to 2007.

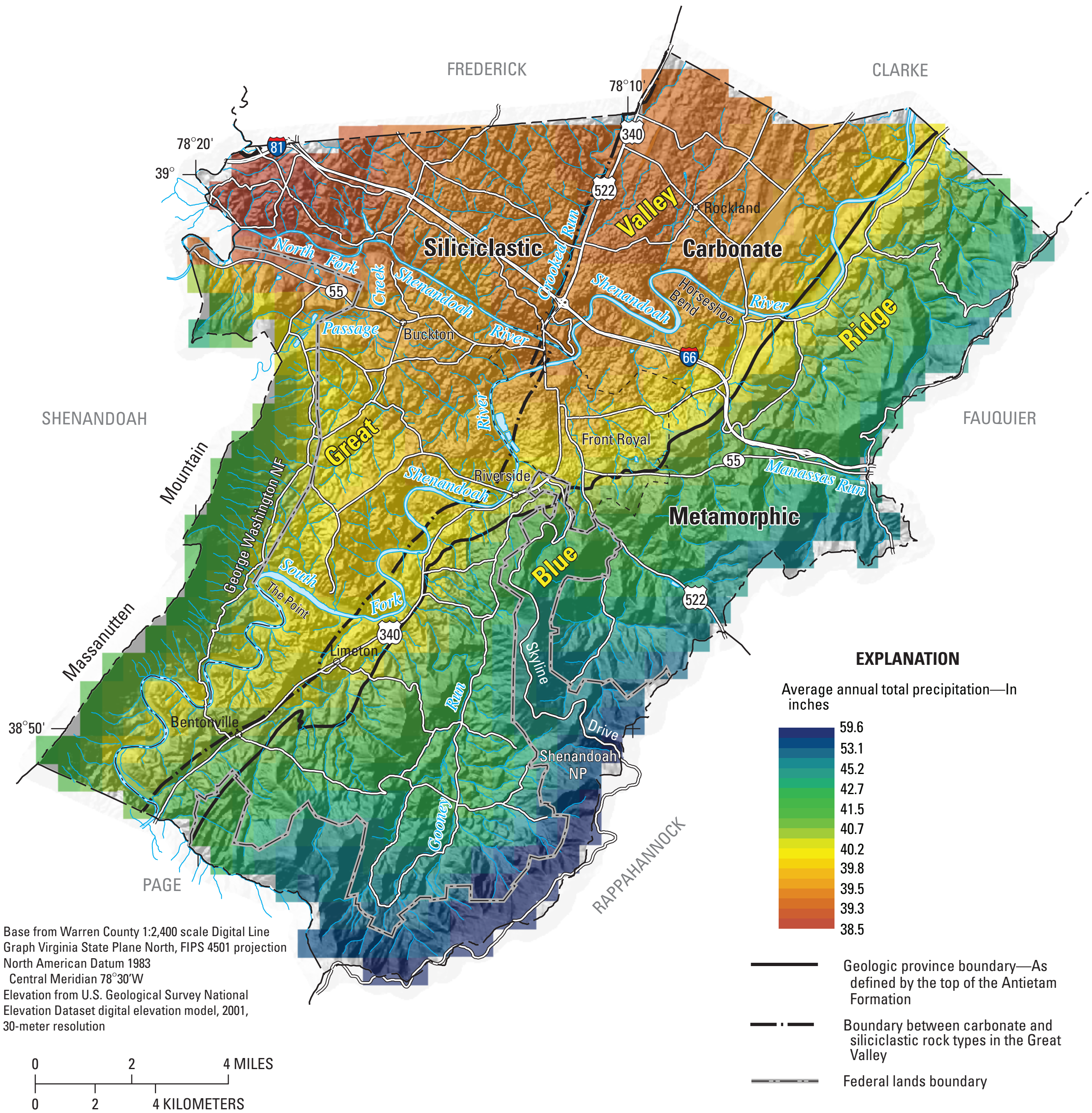

Figure 4. Average annual total precipitation for Warren County, Virginia, based on parameter-elevation regressions on independent slopes model (PRISM). The normal values are based on the National Weather Service's current normal climatological period from 1971 to 2000. Data from PRISM Climate Group, Oregon State University, http://www.prismclimate.org, created May 12, 2009.

to the west-northwest and Massanutten Mountain along the western boundary of the study area. The lowest average annual precipitation is present in the northern parts of the county in the Great Valley. This area is the northern extent of the rain shadow centered on Harrisonburg, VA, which is caused by the mountain ranges to the west (Nuckels and others, 1991).

Well- and Spring-Numbering System

A unique USGS identifier was assigned to each well and spring for this study, for the purpose of storing well-construction and site information in the Groundwater Site Inventory database, which is part of the National Water

Information System maintained by the USGS. These USGS identifiers are based on the Virginia coordinate grid number of the USGS standard series 7.5-minute topographic quadrangle in which the well is located, and the chronological order in which the well was entered. For example, the USGS number 45V 3 corresponds to the third well entered by the USGS in the area covered by the Front Royal quadrangle, which has a Virginia coordinate grid number of 45V. Springs are numbered in a similar manner with the addition of "S" after the Virginia coordinate grid number of the USGS standard series 7.5-minute topographic quadrangle.

Previous Investigations

Cady (1936) conducted the first comprehensive study of the groundwater resources of the Shenandoah Valley, which included Warren County. Cady noted that well depths were relatively shallow across the county and mostly ranged in depth between 50 and 150 ft, which is probably related to cable-tool drilling capabilities available at that time. He also noted the presence of an “8-foot cavity in the limestone having been encountered at 460 feet” in a well, 1.25 mi south of Front Royal that, according to the driller, had a yield that was “unlimited.” Of particular interest to the current study, Cady (1936) surprisingly noted that rocks in the Blue Ridge are a “fairly good source of ground water.” Hack (1965) provided a detailed explanation of the geomorphology of the Shenandoah Valley of Virginia and West Virginia. A regional investigation from Maine to Virginia by Cederstrom (1972) suggested that wells constructed for high capacity use are the best indicators of the potential of the rocks to yield water. Trainer and Watkins (1975) conducted a geohydrologic reconnaissance of the upper Potomac River Basin that focused on the hydrologic characteristics of the rocks, base flow and low flow of streams, water management, and chemical quality of groundwater. Rader and others (1996) compiled the geology of the Lord Fairfax Planning District at a scale of 1:100,000. Rader and Gathright (2001) and Rader and others (2001, 2003) compiled the geology of the northern Virginia area, including Warren County, at a 1:100,000 scale. Doctor and others (2008) provided details of the bedrock structural controls on the occurrence of sinkholes and springs in the northern Great Valley karst and also suggested that deep karst development may have been caused by rising fluids under hypogenic (confined) conditions in the geologic past. Yager and others (2008) developed a finite-element model for the Shenandoah Valley of Virginia and West Virginia that simulated groundwater flow in the folded, fractured sedimentary rocks by specifying variable directions of the hydraulic conductivity tensor in order to match changes in the strike and dip of bedrock across the valley.

Several investigations specifically dealt with the geology and hydrology of Warren County. DeKay (1972) described the development of groundwater supplies in Shenandoah National Park. The geology of the Front Royal, Strasburg, Linden, and Flint Hill quadrangles were mapped at a scale of 1:24,000 by Rader and Biggs (1975, 1976) and Lukert and Nuckols (1976) and included sections on hydrogeology by R.H. DeKay. Orndorff and others (1999) mapped the geology of the Middletown quadrangle at a scale of 1:24,000. Rader and Webb (1979) divided the county into 11 units in terms of factors affecting land modification, such as soils, drainage characteristics, erodibility, stability, ease of excavation, and potential use and limitations. Morgan and others (2003) mapped the Pleistocene and Holocene colluvial fans and terraces in parts of the Blue Ridge in the county. As part of the revision of the geology of Shenandoah National Park, Southworth and others (2009) mapped the geology of parts of Warren County. The U.S. Department of Agriculture conducted the soil survey of the county (Holmes and others, 1984). Allingham (1987) describes the results of a groundwater study conducted for Warren County. Several groundwater age-dating studies have sites in and adjacent to the county and indicate that apparent ages are less than 60 years (Plummer and others, 2001; Nelms and others, 2003). Orndorff (2006) studied the karst landscape in the Rockland area of the county in order to evaluate potential hazards and develop best-management practices to minimize effects of land-use activities on the karst system and biota.

Hydrogeology

The Blue Ridge and the western part of the Great Valley section of the Valley and Ridge in Warren County, VA, are characterized by metamorphic and siliciclastic fractured-rock aquifer systems, respectively. Mesoproterozoic to Lower Cambrian metamorphic rocks underlie the Blue Ridge in eastern Warren County. Siliciclastic rocks of the Upper Ordovician Martinsburg Formation and Silurian Massanutten Sandstone underlie the western part of the county. The bedrock in both of these areas is variably fractured, folded, and faulted (Yager and others, 2008), and the regolith material consists of a mantle of residuum (weathered bedrock), alluvium (stream deposits), and colluvium (gravity deposits). The underlying geology is a strong control on the occurrence and flow of groundwater, and water generally moves under fracture or diffuse-flow conditions. Lower Cambrian to Upper Ordovician limestone and dolostone underlie the central part of Warren County, in which karst aquifers that exhibit both conduit- and diffuse-flow conditions are developed.

Geology

The geology of Warren County is the major control on the occurrence and movement of groundwater. About 300 million years ago, the late Paleozoic Alleghanian orogeny folded and faulted all of the rocks that underlie the county. The terrain that has developed is a direct reflection of the underlying lithology and geologic structure. The mountainous terrain of the Blue Ridge formed in response to the resistant nature of the underlying metamorphic rocks (Hack, 1965). Generally, the Great Valley section is a gently to moderately rolling terrain with low relief, except on the slopes of Massanutten Mountain and areas underlain by the low permeability shale and siltstone of the Martinsburg Formation, which exhibit highly dissected drainage patterns.

Hydrogeologic Units

The Blue Ridge and the western part of the Great Valley section of Warren County can be subdivided into hydrogeologic units based on the mapped geologic formations (fig. 5). In general, these hydrogeologic units are grouped on the basis of gross lithology or rock type: Metamorphic—metavolcanic, metaigneous, and metasedimentary rocks; and Siliciclastic—sandstone, siltstone, and shale.

Figure 5. Generalized hydrogeologic units of Warren County, Virginia.

The hydrogeologic characteristics vary among these units and between the major rock type groupings. The carbonate rock unit in the Great Valley section of the central part of Warren County is an additional group, but it is not described in detail in this report. Descriptions of the individual hydrogeologic units are provided below. The map symbol indicated in the following text identifies the respective hydrogeologic unit in figure 5.

Metamorphic Rock Unit of the Blue Ridge Physiographic Province

The classification of hydrogeologic units as metamorphic is based on the grouping established in Yager and others (2008). These units represent the oldest rocks in Warren County and are on the eastern side of the Shenandoah Valley in the Blue Ridge. The metamorphic rock unit consists of Mesoproterozoic Old Rag Granite and the unnamed monzodiorite and gneissic units; Neoproterozoic metaclastic rocks of the Swift Run Formation; metadiabase dikes, metabasalt, and metavolcanic phyllite of the Neoproterozoic Catoctin Formation; and the metasedimentary rocks of the Lower Cambrian Weverton, Harpers, and Antietam Formations of the Chilhowee Group (fig. 5).

Orthopyroxene Granodiorite Gneiss

The Mesoproterozoic orthopyroxene granodiorite gneiss (Yod) consists of dark-gray, medium- to coarse-grained, amphibole-bearing orthopyroxene granodiorite gneiss that is compositionally layered and strongly foliated. Alternating centimeter-scale layers of quartz and feldspars with dark layers of pyroxene and amphibole define the compositional layers and strong foliation. This unit is composed of alkali feldspar (microcline or orthoclase), plagioclase, quartz, amphibole, and orthopyroxene (Southworth and others, 2009).

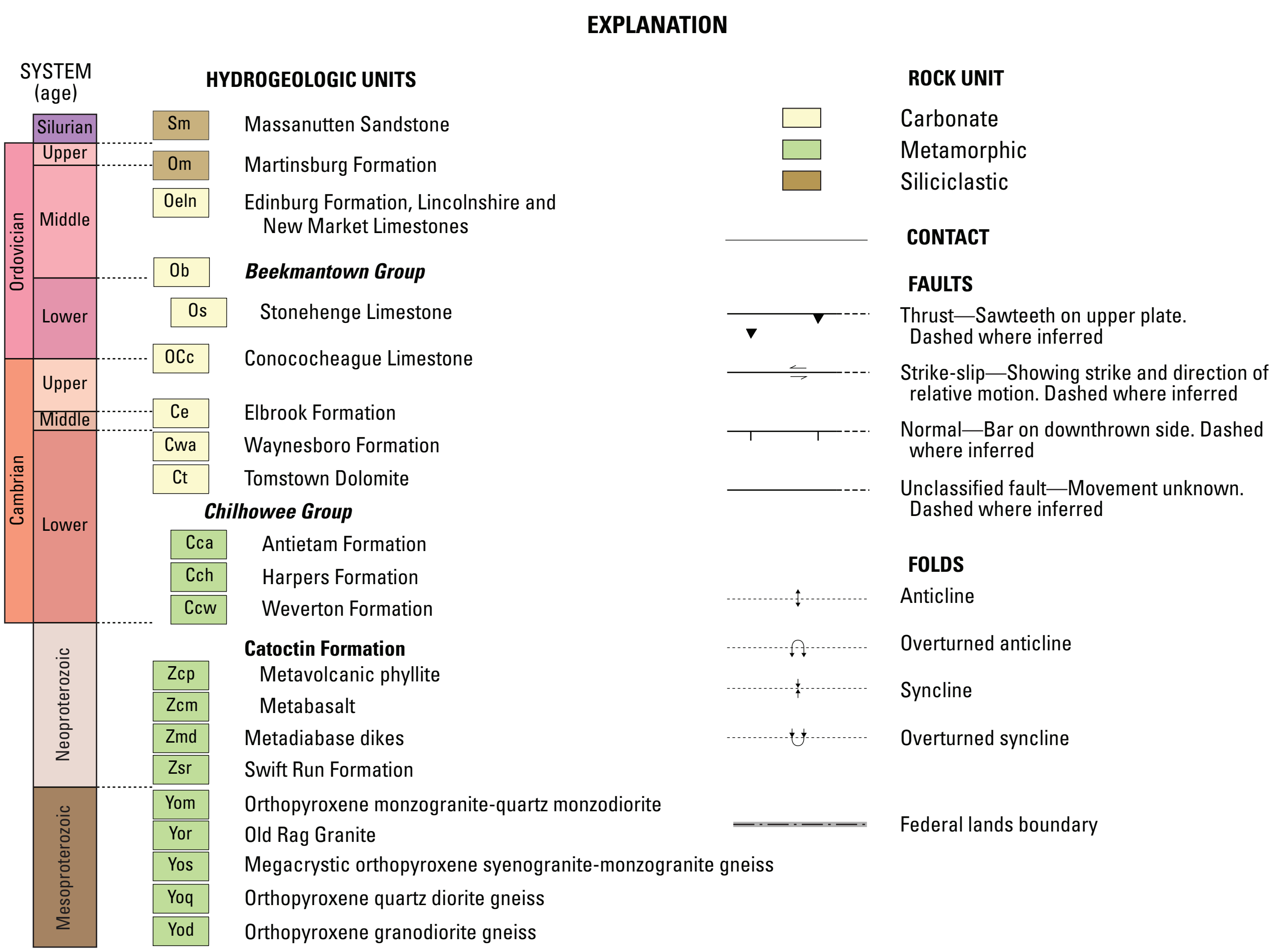

Figure 5. Generalized hydrogeologic units of Warren County, Virginia.—Continued

Orthopyroxene Quartz Diorite Gneiss

The Mesoproterozoic orthopyroxene quartz diorite gneiss (Yoq) consists of greenish-gray to black, medium-grained, compositionally layered, strongly foliated orthopyroxene quartz-diorite gneiss. This gneiss is orthopyroxene-, biotite-, and garnet-bearing and is present as a xenolith within the Old Rag Granite. Alternating domains of quartz and feldspar and of garnet, biotite, and orthopyroxene define the compositional layering. The gneiss is composed of orthoclase, plagioclase, quartz, orthopyroxene, and biotite (Southworth and others, 2009).

Megacrystic Orthopyroxene Syenogranite-Monzogranite Gneiss

The Mesoproterozoic megacrystic orthopyroxene syenogranite-monzogranite gneiss (Yos) consists of dark-gray to dark-greenish-gray, very coarse grained, megacrystic orthopyroxene syenogranite-monzogranite gneiss that is strongly foliated. This gneiss is orthopyroxene-, amphibole-, and clinopyroxene-bearing with subhedral to euhedral, monocrystalline alkali-feldspar megacrysts. Alternating quartzofeldspathic layers and domains of orthopyroxene and amphibole define the compositional layering, and the strong foliation parallels this layering. The gneiss is primarily composed of alkali-feldspar microperthite (microcline), plagioclase, and quartz, but also contains orthopyroxene, amphibole, and clinopyroxene. The gneiss weathers to form light-gray, spheroidal boulders (Southworth and others, 2009).

Old Rag Granite

The Mesoproterozoic Old Rag Granite (Yor) consists of white to light-gray, medium- to coarse-grained, inequigranular, garnetiferous leucogranite and garnetiferous syenogranite that is nonfoliated to weakly foliated and massive. The granite is biotite- and orthopyroxene-bearing and contains gray and blue quartz grains. The granite is primarily composed of orthoclase, plagioclase, quartz, garnet, and biotite. Dikes of medium-grained, equigranular alkali-feldspar granite, syenogranite, and pegmatite have intruded the Old Rag Granite (Southworth and others, 2009).

Orthopyroxene Monzogranite-Quartz Monzodiorite

The Mesoproterozoic orthopyroxene monzogranite-quartz monzodiorite (Yom) consists of dark-green to black, medium- to coarse-grained, inequigranular, orthopyroxene monzogranite and quartz monzodiorite that are massive and nonfoliated. The rocks are orthopyroxene-, amphibole-, and clinopyroxene-bearing. The unit is composed of alkali-feldspar microperthite (microcline), plagioclase, quartz, orthopyroxene, amphibole, and clinopyroxene. Planar alignment of ferromagnesian minerals defines the weak foliation (Southworth and others, 2009).

Swift Run Formation

The Neoproterozoic Swift Run Formation (Zsr) consists of three rock types: a pink to gray, sandy and pebbly meta-graywacke and meta-arkose that is dark greenish brown; a tuffaceous phyllite that is silver gray and purple; and thin beds of metabasalt. The thickness of the Swift Run is from 0 to 150 ft (Rader and Conley, 1995).

Metadiabase Dikes

The Neoproterozoic metadiabase dikes (Zmd) consist of dark-greenish-gray, fine- to medium-grained metadiabase that is massive to schistose in texture. The metadiabase is predominantly composed of chlorite, albite, epidote, and actinolite. This unit is similar in composition to the metabasalt of the Catoctin Formation and has been interpreted as feeder dikes for these volcanic flows (Southworth and others, 2009).

Catoctin Formation

In Warren County, the Neoproterozoic Catoctin Formation is divided into two units: metabasalt and metavolcanic phyllite (fig. 5). The metabasalt (Zcm) consists of dark-green, amygdaloidal metabasalt (greenstone) and chlorite schist interlayered with thin, discontinuous, finely laminated phyllitic metasiltstone and thin metasandstone and dark, variegated, vesicular tuffaceous phyllite and mud-lump (rip-up) breccias (Reed, 1955). The metabasalt is massive (very thick bedded) to schistose, aphanitic (fine grained) with well-developed cleavage and columnar jointing. Near the top and bottom of some metabasalt beds are albite, quartz, calcite, epidote, chlorite, and jasper amygdules (Rader and Conley, 1995). The metabasalt is interpreted as a series of basaltic flows, which tend to form prominent ledges. Epidosite locally is present as light green, blocky masses in the metabasalt breccia (Southworth and others, 2002, 2009). Badger and Sinha (1988) determined a rubidium-strontium (Rb/Sr) age of 570 ± 36 million years (Ma) for the metabasalt of the Catoctin Formation in Virginia.

The metavolcanic phyllite (Zcp) is dark grayish blue to dusky red phyllite and slate that is mottled to lustrous and contains white to green, elongated vesicles and smeared sericite and chlorite blebs. This unit has been interpreted as vesicular flows, volcanic tuffs, pumice, and volcanic ash deposits (Southworth and others, 2009). The overall thickness of the Catoctin is from 2,000 to 2,500 ft (Rader and Conley, 1995).

Weverton Formation of the Chilhowee Group

The Lower Cambrian Weverton Formation (Ccw) of the Chilhowee Group consists of a 150-ft basal quartz-cemented conglomerate. The basal conglomerate has subangular to rounded quartz and shale clasts within a matrix of sand-size quartz and lithic grains. The middle part of the Weverton consists of a light-gray, conglomeratic quartzite with greenish-gray sandy phyllite and micaceous sandstone interbeds. The upper 150 ft of the Weverton consists of quartz-pebble conglomerate and micaceous sandstone. Brezinski (1992) named and mapped these three units of the Weverton as the Buzzard Knob, Maryland Heights, and Owens Creek Members north of Warren County, but these units have not been delineated in the study area and are not shown in figure 5. The thickness of the Weverton is about 500 ft (Rader and Conley, 1995).

Harpers Formation of the Chilhowee Group

The Lower Cambrian Harpers Formation (Cch) of the Chilhowee Group consists of phyllite and sandy phyllite with interbedded gray to olive-gray lithic sandstone in the lower 900 ft. The upper 1,100 ft of the Harpers consist of sandstone and quartzite that are gray, fine to medium grained, and, in parts, ferruginous. The thickness of the Harpers is 2,000 ft (Rader and Conley, 1995).

Antietam Formation of the Chilhowee Group

The Lower Cambrian Antietam Formation (Cca) of the Chilhowee Group consists of very light gray quartzite interbedded with greenish-gray, sandy metasiltstone in the lower part. *Skolithos* tubes are numerous in the quartzite beds. The Antietam Formation becomes coarser grained higher in the formation from a bioturbated, very light gray, medium-bedded, well-sorted, fine- to medium-grained sandstone to a medium-gray, calcareous, crossbedded, coarse-grained sandstone (Southworth and others, 2002). The thickness of the Antietam is from 440 to 600 ft (Rader and Conley, 1995).

Siliciclastic Rock Unit of the Great Valley Section of the Valley and Ridge Physiographic Province

The siliciclastic rock unit is composed of clastic sedimentary rocks that primarily consist of silica-bearing minerals, such as quartz. In Warren County, the siliciclastic rocks are present in the western part of the Great Valley section and are the youngest rocks in the county. This unit consists of shale, sandstone, and siltstone of the Middle and Upper Ordovician Martinsburg Formation and sandstone, quartzite, conglomerate, and sandy shale of the Silurian Massanutten Sandstone (fig. 5).

Martinsburg Formation

The Middle and Upper Ordovician Martinsburg Formation (Om) consists of more than 3,000 ft of silty shale that is an olive-green to dark-gray siltstone and sandstone that is medium to coarse grained and locally contains pebbles. The Martinsburg in the Massanutten synclinorium along the western part of Warren County is the deepest water deposit for the Cambrian and Ordovician rocks of the Shenandoah Valley. The Stickley Run Member forms the basal unit of the Martinsburg Formation and may be as much as 900 ft thick (Epstein and others, 1995). The Stickley Run Member consists of gray to medium-dark-gray calcareous shale and medium-gray to grayish-black, olive-gray, grayish-orange limestone. The limestone is very thin bedded, platy, very fine grained, laminated, and argillaceous (clay rich). The upper 100 to 200 ft of the Martinsburg consists of sandstone that is brown, medium to coarse grained, and fossiliferous in the lower portion. The overall thickness of the Martinsburg ranges from 3,500 ft (Rader and Conley, 1995) to as much as 5,000 ft thick (Orndorff and others, 1999).

Massanutten Sandstone

The Silurian Massanutten Sandstone (Sm) consists of sandstone and quartzite that is white to medium gray and fine to coarse grained. Lenses of quartz-pebble conglomerate and thin, black sandy shale layers are present within the sandstone and quartzite and contain plant fossils (Pratt and others, 1978). The Massanutten Sandstone forms the ridgeline of Massanutten Mountain in the western part of Warren County. The thickness of the Massanutten is approximately 900 ft (Rader and Conley, 1995).

Carbonate Rock Unit of the Great Valley Section of the Valley and Ridge Physiographic Province

The carbonate rock unit consists of dolostone, shale, limestone, and sandstone of the Lower Cambrian Tomstown Dolomite and Waynesboro Formation; dolostone, dolomitic limestone, shale, and calcareous siltstone of the Middle and Upper Cambrian Elbrook Formation; laminated limestone, dolomitic limestone, dolostone, and calcareous sandstone of the Upper Cambrian and Lower Ordovician Conococheague Limestone including the Big Spring Station Member; dolostone, limestone, and chert of the Lower Ordovician Stonehenge Limestone (including Stoufferstown Member) and the Lower and Middle Ordovician Rockdale Run Formation of the Beekmantown Group; and limestone and shale of the Middle Ordovician Edinburg Formation, Lincolnshire and New Market Limestones (fig. 5). The combined thickness of the carbonate rock unit is approximately 10,000 ft (Rader and Conley, 1995).

Structural Geology

Warren County is located on the west limb of the Blue Ridge–South Mountain anticlinorium, which is also the eastern limb of the first-order Massanutten synclinorium. The Massanutten synclinorium is a complexly folded synclinorium with numerous tight, upright, second- and third-order disharmonic folds (anticlines and synclines) that verge up the limbs of the higher-order synclinorium. The Massanutten synclinorium contains about a 3-mi-thick section of siliciclastic and carbonate rocks. The eastern limb of the synclinorium is characterized by rocks with near vertical dips to the northwest or locally overturned beds dipping steeply to the southeast (Southworth and others, 2002; Yager and others, 2008). The rocks in Frederick County are on the western limb of the Massanutten synclinorium and dip gently southeast (Harlow and others, 2005; Yager and others, 2008).

The Mesoproterozoic to Lower Cambrian rocks of the Blue Ridge have been folded and thrust faulted over the younger rocks of the Great Valley and form the northwest flank of the Blue Ridge–South Mountain anticlinorium, which plunges gently northeastward (Gathright and Nystrom, 1974) and extends from southern Pennsylvania to central Virginia (Cloos, 1951). These rocks were folded and transported by faulting from the east a distance of more than 100 mi during the tectonic activity of the Alleghanian orogeny about 300 million years ago (Southworth and others, 2007). The Mesoproterozoic rocks of the Blue Ridge have undergone amphibolite- to granulite-facies metamorphism, and the younger rocks of the Blue Ridge have undergone lower greenschist-facies metamorphism. Most of the carbonate rocks of the Great Valley were not buried deep enough to become metamorphosed (Southworth and others, 2002, 2009).

The structural deformation in both the Valley and Ridge and Blue Ridge has created weaknesses in the competent bedrock that are of hydrologic significance because these features enhance weathering and create pathways for groundwater movement. Furthermore, bedding, joints, and foliations in the bedrock are preserved as relicts in the mantle of regolith material, which facilitates movement of water from the surface into the groundwater systems of the county (Harlow and others, 2005).

Bedding-Plane Partings, Joints, Cleavage, and Foliations

Groundwater moves through fractures in the bedrock that result from various processes. Groundwater movement and storage occurs in the secondary permeability of these partings. Bedding-plane partings (fig. 6) are separations between different beds in sedimentary rocks. Partings can develop along foliations in the metamorphic rocks of the Blue Ridge. The tectonic forces of the Alleghanian orogeny resulted in the formation of at least four types of joints (fractures) and their associated orientations in the rocks: dip, oblique, strike, and tension (fig. 6). Extension in the least principal stress direction causes dip joints to form perpendicular to fold axes. Conjugate sets of oblique joints form as the rocks are sheared. Strike joints form parallel to fold axes, whereas tension joints form along fold hinges (Harlow and others, 2005). Joint types vary with rock type. Brittle deformation is characteristic of the carbonate, sandstone, metavolcanic, and granitic rocks; ductile deformation is characteristic of the finer grained rocks such as the shale of the Martinsburg Formation and phyllite in the Blue Ridge. Joints also form along cleavage in rocks of the Great Valley and Blue Ridge. Axial planar cleavage is most evident in the shale of the Martinsburg Formation (Harlow and others, 2005), and flow along cleavage planes may be more prevalent than along bedding, especially in the Martinsburg Formation (C.S. Southworth, U.S. Geological Survey, written commun., 2009). Partings between the numerous metabasalt flows of the Catoctin Formation can be horizontal to moderately southeast dipping and form bedrock terraces and benches (Southworth and others, 2009). Columnar jointing also is present in the Catoctin Formation because of shrinkage during cooling of the basalt to form hexagonal joints, but it is relatively uncommon in the county (Lukert and Nuckols, 1976).

Dips of bedding-plane partings, cleavage, various joint types, and foliations (in the metamorphic rocks of the Blue Ridge) are highly variable, range from horizontal to vertical, and can be overturned. However, steeply dipping beds are prevalent in the county because of location on the highly deformed eastern limb of the Massanutten synclinorium. Dip directions generally are to the northwest or southeast (Southworth and others, 2002; Yager and others, 2008). Although the strike of the rocks in Warren County is variable, the general strike is N. 30° E. (Yager and others, 2008). Foliations in the metamorphic Mesoproterozoic rocks of the Blue Ridge follow the northwest strike of the belts (Southworth and others, 2009). Groundwater flows through partings developed along the dominant foliations, which are predominantly cleavage, rather than through primary bedding in the Blue Ridge (Yager and others, 2008).

Folds

Folds in Warren County are the result of at least two tectonic events from the east, which caused the limbs of the synclines and west limbs of anticlines to be oversteepened and locally overturned (Rader and Biggs, 1975). Deformation has the character of many subsidiary folds developed on the limbs of the major folds. Folds of various types formed in the Blue Ridge–South Mountain anticlinorium and the Massanutten synclinorium, which are broad, northeast-trending first-order

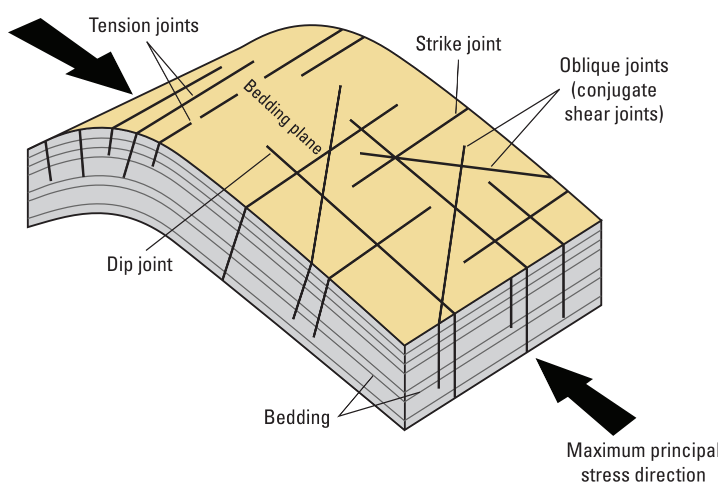

Figure 6. Joint types and bedding in folded rocks. Modified from Earth Science Australia (2004); Harlow and others (2005).

fold complexes (Southworth and others, 2009). These lower-order folds have axes that follow the strike of the rocks to the northeast and plunge to the north-northeast generally at low angles (Rader and Biggs, 1975). Orndorff and others (1999) noted an apparent disharmony in fold wavelength in response to rheological differences of the rock units. Folds in the Martinsburg Formation have shorter wavelengths than the folds in the Cambrian and Lower Ordovician carbonate rocks, with intermediate wavelengths in Middle Ordovician limestone. As an example, a small anticline in the Middle Ordovician Edinburg Formation near streamflow-gaging station 01631000 South Fork Shenandoah River near Front Royal, VA, is shown in figure 7. The sinuous appearance of some of the hydrogeologic units in figure 5 is the result of folding.

Faults

Faults mapped in Warren County are thrust, normal, transverse, or cross-strike faults. Thrust faults strike north-northeast parallel to the structural grain with variable dips generally to the southeast, whereas local back thrusts dip steeply to the northwest (Rader and Biggs, 1975; Yager and other, 2008). Gathright (1976) noted that bedrock exposures of these faults are rare and usually covered by unconsolidated deposits or a thick mantle of saprolite (weathered rock), but bedrock along the fault trace is intensely fractured as evidenced by brecciated and mylonitized rocks. The intense fracturing along these faults allows for preferential ground-water flow, but mylonitized zones may be sealed and inhibit flow and storage of groundwater. Some of the faults, especially along the boundary between the Great Valley section and Blue Ridge, have been folded and faulted as evidenced by the sinuous and offset fault traces in figure 5 (Southworth and others, 2007). The Front Royal fault (fig. 5) is a shallow-dipping thrust fault that is part of the frontal Blue Ridge thrust fault system (Southworth and others, 2009). The Front Royal fault in places trends obliquely across the structural grain (Southworth and others, 2009) and is an overthrust salient of the Blue Ridge–South Mountain anticlinorium (Rader and Biggs, 1975) in which rocks of the Blue Ridge overlie the younger rocks of the Great Valley section in the county.

The high-angle normal faults, which are transverse or cross-strike faults, generally strike north-northwest across the structural grain, but some of these faults parallel the structural grain in the Blue Ridge (fig. 5). These high-angle faults (60° to 75°) often truncate and offset folded rocks and thrust faults in the county and correspond with topographic lineaments (Bailey and others, 2006; Southworth and others, 2009). McCoy and others (2005a, b) and Kozar and others (2007) noted the effects that cross-strike faults have on hydraulic properties, well yields, and flow in the counties of West Virginia in the Shenandoah Valley.

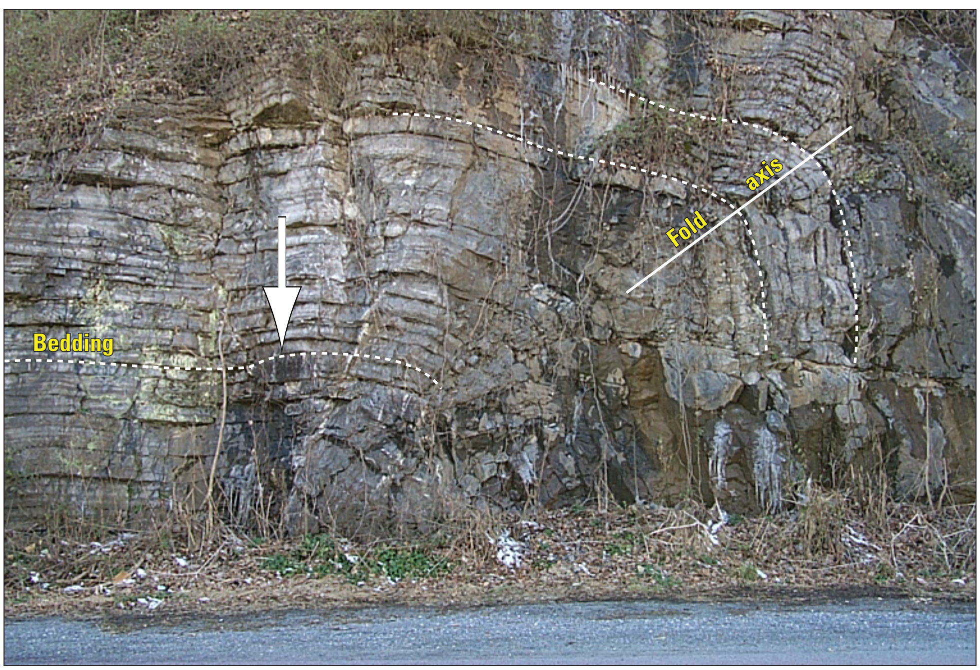

Figure 7. Fold in the Middle Ordovician Edinburg Formation in roadcut on State Route 679 at intersection with State Route 677 near streamflow-gaging station 01631000 South Fork Shenandoah River near Front Royal, Virginia. Note groundwater seepage along bedding-plane partings (arrow). Photograph by Michael Strader, U.S. Geological Survey, March 2005.

Surficial Geology

Deposits of unconsolidated surficial materials cover most of the area in Warren County and are noticeably absent where bedrock crops out. These deposits are the result of various processes, such as running water, chemical weathering, gravity, extreme rainfall events, and freeze-thaw cycles. Residuum and saprolite, which are the result of weathering of the parent bedrock, vary in thickness in response to factors, such as rock type, fracture density, and topographic setting. Hack (1965) states that residuum and saprolite in the Blue Ridge can range from stony clay loam of the relatively resistant rocks of the Catoctin Formation to a coarse-grained sandy saprolite with core stones in areas underlain by the granitic rocks. Areas underlain by the siliciclastic rocks of the Martinsburg Formation and the carbonate rocks of Middle Ordovician age and the upper parts of the Beekmantown Group tend to have a thin mantle of residual material, whereas the older carbonate units can have a thick mantle of residuum of siliceous residues with core stones of sandstone and chert (Hack, 1965). Southworth and others (2009) related the type of surficial deposit to topographic setting: (1) colluvium is present in the highlands, (2) debris-fan deposits are generally in coves and hollows of slopes, (3) alluvial fans are located on the lower slopes and valleys on the west side of the Blue Ridge, and (4) fluvial terrace deposits of sandstone cobbles are located along major rivers in the Shenandoah Valley. Groundwater movement in areas of the Blue Ridge where coarse material is present along the stream valleys can be rapid as interflow or subsurface stormflow (Wright, 1990). A thick apron of alluvial or colluvial deposits and areas with a thick mantle of coarse-grained residuum and saprolite could potentially allow for significant groundwater storage.

Hydrology

Warren County is characterized by metamorphic and siliciclastic fractured-rock aquifer systems as well as karst systems in the central part of the county that have developed in the folded and fractured rocks. Diffuse-flow conditions are characteristic of the fractured-rock aquifer systems in areas underlain by the metamorphic and siliciclastic rocks. Conduit- and diffuse-flow conditions are present in the karst aquifer systems (Wright, 1990). Porous media flow is present in the mantle of regolith material as well as preferential groundwater flow along relict structures in the regolith. The fractured-rock and karst aquifers generally are considered unconfined, and topography is the driving force behind groundwater movement; however, confined aquifers may be present locally (Harlow and others, 2005). The source of groundwater recharge is precipitation that falls in the county. Recharge occurs by percolation of water through the regolith mantle and along partings in the rock and by direct inflow into sinkholes and from sinking streams. Groundwater eventually discharges to streams often in the form of springs.

Hydrogeologic Characteristics

Each of the rock units has distinctive hydrogeologic characteristics that were evaluated by analyzing the records recorded by local well drillers. More than 350 well records from files maintained by the Virginia Departments of Environmental Quality (VDEQ) and Health, Virginia Division of Geology and Mineral Resources, Warren County, and USGS were analyzed. The results of this analysis are presented in tabular form (table 1) and in graphical form as boxplots (fig. 8), and they are described in detail below. The blue-shaded areas in figure 8 represent the 95-percent confidence intervals. In most cases, the respective confidence intervals for the rock units overlap, which indicates that wells drilled in the three rock units are not significantly different statistically. This is expected because nearly all of the wells in the analysis were drilled for domestic use (Cederstrom, 1972), where lower yields and shallower depths are acceptable for typical household use compared to municipal supply wells that generally need a much greater water supply. Maps shown in the following sections were derived from well-construction data by using an inverse distance-weighted method in ArcGIS® ArcMap® version 9.3 that used a power of 2, variable search radius of 12 points around each point to create a contour grid of the respective hydrogeologic characteristic.

During this investigation, a long-term water-monitoring network was initiated for the county. Water levels were measured continuously in well 45V 3; discharge and field water-quality properties were measured quarterly at springs 45VS 1 and 46VS 17 (appendix 1). Descriptions of seasonal and spatial changes in water levels and discharges are provided below. Streamflow and field water-quality properties were measured at gaging stations 01630700 Gooney Run at Route 622 near Glen Echo, VA, 01636242 Crooked Run below Route 340 at Riverton, VA, and 0163626650 Manassas Run at Route 645 near Front Royal, VA. Description of streamflow characteristics from these gages are discussed in the section on groundwater availability.

Well Depths

Reported well depths in Warren County (table 1; fig. 8) range from 46 to 1,345 feet below land surface (ft bls). The deepest well depth inventoried during this study was a 1,345-ft industrial well completed in the Martinsburg Formation that yielded 120 gallons per minute (gal/min) with 200 ft of drawdown. The shallowest ranges of well depths are generally from large-diameter, hand-dug or bored wells. Well depths tend to be shallowest in the siliciclastic rock unit (predominantly in the Martinsburg Formation) where 75 percent of the wells are less than 200 ft deep. In the metamorphic rocks of the Blue Ridge, more than 75 percent of the wells are less than 400 ft deep. More than 75 percent of the wells are less than 550 ft deep in the carbonate rocks. The distribution of well depths is slightly different than was determined for more than 1,800 wells in Clarke County (Nelms and Moberg, 2010),

Table 1. Well-construction characteristics for the rock types and hydrogeologic units in Warren County, Virginia.

[nd, not determined; n, number of sites. Hydrogeologic units: Yoq, Orthopyroxene quartz diorite gneiss; Yos, Megacrystic orthopyroxene syenogranite-monzogranite gneiss; Yor, Old Rag Granite; Yom, Orthopyroxene monzogranite-quartz monzodiorite; Zcm, Catoctin Formation metabasalts; Om, Martinsburg Formation; Ccw, Weverton Formation; Cch, Harpers Formation; Cca, Antietam Formation; Cwa, Waynesboro Formation; Ce, Elbrook Limestone; OCc, Concocheague Limestone; Os, Stonehenge Limestone; Ob, Beekmantown Group undivided; Oeln, Edinburg Formation, Lincolnshire, and New Market Limestones; Om, Martinsburg Formation]

Statistic	Rock type																
	Metamorphic									Silici-clastic	Carbonate						
	Hydrogeologic unit																
	Yoq	Yos	Yor	Yom	Zcm	Ccw	Cch	Cca	All	Om	Cwa	Ce	OCc	Os	Ob	Oeln	All
Well depth, in feet below land surface																	
Minimum	93	175	55	82	65	165	185	145	55	46	125	200	170	439	65	120	65
Mean	nd	nd	190	297	314	235	305	317	292	196	318	339	391	nd	316	268	335
Median	nd	nd	165	253	254	235	283	260	250	150	243	313	293	nd	310	230	300
Maximum	nd	nd	520	600	900	305	560	505	900	1345	705	680	720	nd	700	580	720
n	1	1	18	10	68	2	18	12	130	132	10	28	16	1	35	8	98
Well yield, in gallons per minute																	
Minimum	35	6	3	0.5	0.2	10	0.5	1	0.2	1	0	1	0.75	50	2	2	0
Mean	nd	nd	21.9	12.1	13.6	11	17.25	26.2	16.1	25	25.1	18	36.37	nd	27.2	57	27.6
Median	nd	nd	20	12	12	11	10	16	12	17.5	10	10	15	nd	17.5	13	12
Maximum	nd	nd	50	30	50	12	75	80	80	130	10	70	10	nd	10	200	20
n	1	1	18	10	68	2	18	12	130	132	10	28	16	1	35	8	98
Depth to bedrock, in feet below land surface																	
Minimum	3	nd	30	25	3	35	8	15	3	8	25	8	12	34	8	nd	8
Mean	nd	nd	59.5	53.3	36	35	56.3	48.1	43.9	36.7	62.5	29.8	28	nd	41.6	nd	39
Median	nd	nd	64	35	28	35	35	40	35	24	32.5	25	22	nd	35	nd	33
Maximum	nd	nd	80	88	108	35	370	140	370	100	134	90	50	nd	105	nd	134
n	1	1	18	10	68	2	18	12	130	132	10	28	16	1	35	8	98
Upper water-bearing zone reported, in feet below land surface																	
Minimum	nd	nd	52	160	61	280	95	70	52	40	85	93	202	426	55	140	55
Mean	nd	nd	91	284	213	280	219	240	220	151	251	267	446	nd	223	140	266
Median	nd	nd	91	258	181	280	200	232	200	130	158	270	491	nd	178	140	199
Maximum	nd	nd	130	460	600	280	420	420	600	455	560	585	600	nd	620	140	620
n	1	1	18	10	68	2	18	12	130	132	10	28	16	1	35	8	98
Lower water-bearing zone reported, in feet below land surface																	
Minimum	nd	nd	52	270	85	280	175	130	52	40	110	159	245	434	55	140	55
Mean	nd	nd	91	346	252	280	279	277	264	158	258	293	457	nd	252	140	288
Median	nd	nd	91	328	220	280	260	243	250	140	168	270	491	nd	225	140	248
Maximum	nd	nd	130	460	625	280	530	480	625	455	560	585	600	nd	620	140	620
n	1	1	18	10	68	2	18	12	130	132	10	28	16	1	35	8	98

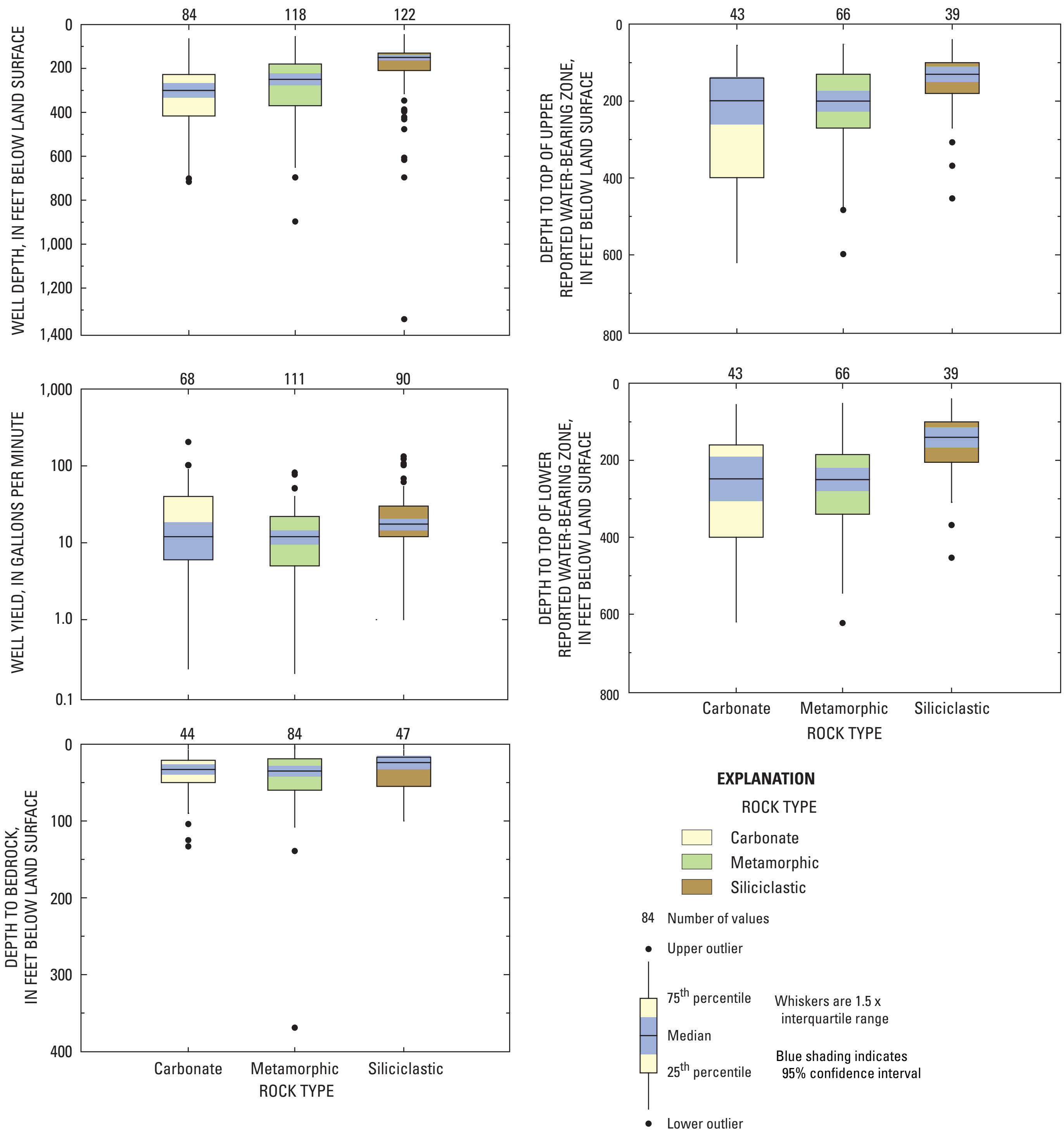

Figure 8. Summary statistics of well-construction and hydrologic characteristics of the rock types in Warren County, Virginia.

which borders Warren County on the north. In Clarke County, median well depths were (1) deeper in the metamorphic rocks of the Blue Ridge, which is a reflection of the elevated setting and relatively low hydraulic conductivity of these hydrogeologic units, and (2) shallower in the carbonate rocks in response to the occurrence of dissolution-enlarged openings and relatively low relief. The abundance of relatively shallow wells may contribute to the frequent occurrence of well failures reported in Warren County during drought and wet conditions.

Depth to Bedrock

Median reported depths to bedrock from driller's logs are generally less than 40 ft bls across the county (table 1; fig. 8). More than 75 percent of the wells reported depths to bedrock of less than 80 ft bls. The deepest depth to bedrock (370 ft) inventoried was for a well located 0.5 mi south of the Shenandoah River near Morgan Ford where Rader and Conley (1995) mapped terrace deposits overlying the Harpers Formation and the Happy Creek fault. Generally, depths to bedrock tend to be (1) relatively deep (greater than 50 ft bls) in the eastern part of the county, in areas where alluvial and colluvial deposits are extensive, and along faults; and (2) relatively shallow (less than 50 ft bls) in the interfluve areas, along the eastern slopes of Massanutten Mountain, and in areas underlain by the Martinsburg Formation (fig. 9). The rocks in the eastern part of the county are older and more highly deformed than those to the west; these factors, in conjunction with the presence of alluvial and colluvial deposits from the mountainous areas, could contribute to the formation of a thick residuum and consequently result in deeper depths to bedrock. The areas of deeper depths to bedrock in figure 9 coincide with the areas where alluvium and colluvium along the North Fork, South Fork, and Shenandoah Rivers are present along the base of

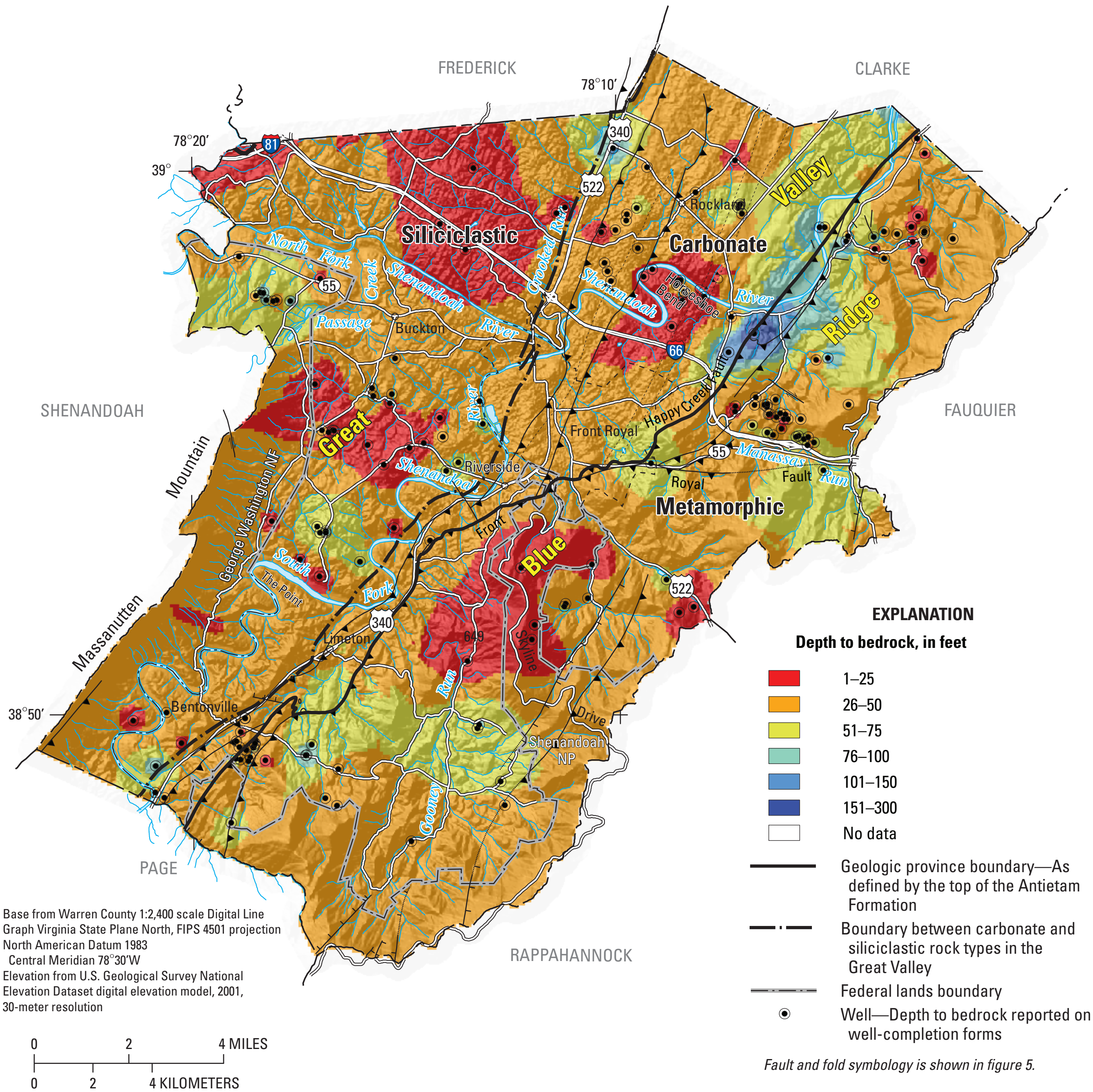

Figure 9. Depth to bedrock in Warren County, Virginia.

mountains and where smaller streams mantle the bedrock (Hack, 1965; Rader and Biggs, 1975, 1976; Lukert and Nuckols, 1976; Rader and Conley, 1995). Preferential movement of groundwater along faults, especially where the acidic rocks of the Blue Ridge are juxtaposed with carbonate rocks, could facilitate deep weathering profiles. The shallow bedrock depths in the interfluve areas may indicate that the rocks have low permeability, which can limit the development of deep weathering profiles. Hack (1965) states that the Martinsburg Formation generally lacks residuum. Much of the county has some mantle over the bedrock, but groundwater storage in this regolith is believed to be minimal (Harlow and others, 2005); however, the areas with a thick sequence of regolith overlying the bedrock, especially the carbonate areas, may have considerable groundwater storage potential.

Water-Bearing Zones

The depth to water-bearing zones on State well-completion reports, when recorded, provides insight into where groundwater is present at depth, which is an important characteristic in fractured-rock settings (table 1; fig. 8). A well can encounter single or multiple water-bearing zones. Often, only the major water-bearing zones are recorded, whereas the smaller quantities of water are usually missing from the reports. If a single water-bearing zone was recorded, then the depths of the upper and lower zones were considered to be equivalent. Median values for the depth of the upper water-bearing zones indicate that water generally is encountered between 130 and 400 ft bls throughout the county (fig. 8). Occasionally, the upper water-bearing zone is not encountered until depths greater than 400 ft bls (fig. 8). The reported water-bearing zones for wells completed in the siliciclastic rocks of the Martinsburg Formation are shallower than those in the carbonate and metamorphic rocks. Nelms and Moberg (2010) stated that, in general, median depths of the upper water-bearing zones in Clarke County are slightly deeper for the hydrogeologic units of the Blue Ridge, where relief is greater and hydraulic conductivity is generally lower, than those of the units in the Great Valley section of the county. To some degree, the same is true for Warren County, but sparse reporting of water-bearing zones did not allow for an equivalent evaluation. A similar, yet deeper, distribution of depth to the top of the lower water-bearing zones is evident in Warren County (table 1; fig. 8).

Spatial distribution of the depths to water-bearing zones across the county provides insight into the topographic and geologic controls on the occurrence of groundwater. The depth to the top of the upper water-bearing zone is mapped in figure 10. In general, the upper water-bearing zone is encountered in the first 200 ft bls. Depths generally are greater than 200 ft bls along faults and fold axes in Rockland and Bentonville and in elevated areas of the Blue Ridge in the northeastern and southeastern parts of the county (fig. 10). The deeper water zones along faults and fold axes could be the result of high permeability and ability to transmit water along these features. The deeper depths in the elevated areas may be because drilling had to continue past shallower depths in order to meet usage requirements.

A similar spatial pattern exists for the depth to the top of the lower water-bearing zone (fig. 11), but a larger area of the county encounters the lower bearing zones at depths greater than 200 ft bls. Cady (1936) and Hack (1965) suggest that water-bearing zones in carbonate rocks may be present to depths as great as 2,000 ft bls. Recent drilling in the carbonate rock unit in Frederick County encountered more than 100 gal/min from a single water zone at 1,339 ft bls, possibly associated with the Apple Pie Ridge fault (G.E. Harlow, Jr., U.S. Geological Survey, written commun., 2005). Wright (1990) reported that a well located on a ridgetop in the metamorphic rocks of the Blue Ridge in Clarke County encountered freshwater at about 5,000 ft bls. As stated earlier, the deepest well inventoried for this study in Warren County was 1,345 ft deep, was in the siliciclastic rocks (table 1), and yielded 120 gal/min. All of these examples indicate the possibility of encountering water-bearing zones at substantial depths.

The statistical and spatial distribution of water-bearing zones is consistent with the conceptual idea that the groundwater flow systems are topographically driven and controlled by geologic structure. The relatively shallow nature of the water-bearing zones and well depths may contribute to the frequent occurrence of well failures observed during this study. In addition, the aquifer systems in the county have been determined to be susceptible to contamination from near-surface sources (Nelms and others, 2003). The susceptibility to both droughts and contamination should be considered during future water-resources management activities in the county.

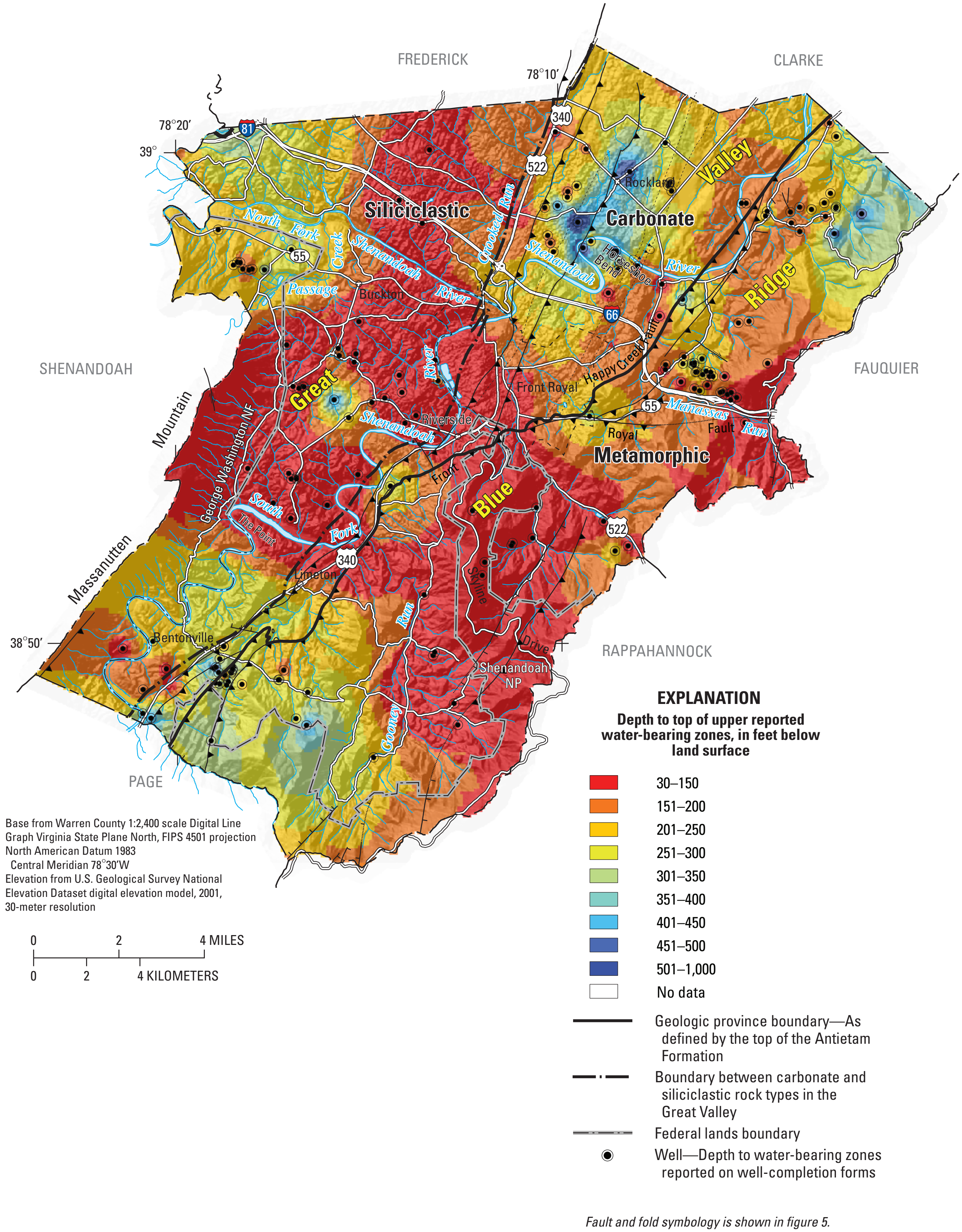

Figure 10. Depth to top of upper reported water-bearing zones in Warren County, Virginia.

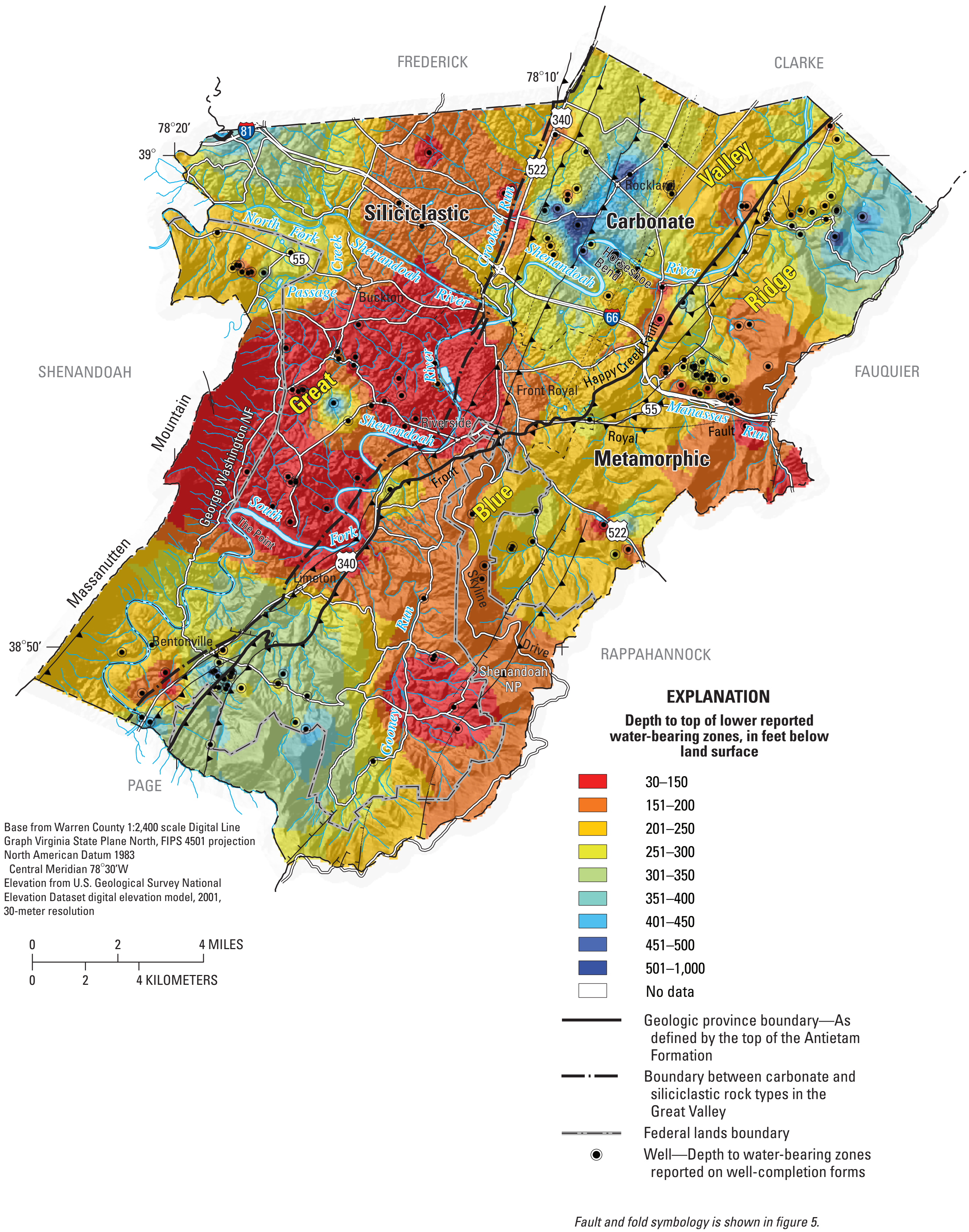

Figure 11. Depth to top of lower reported water-bearing zones in Warren County, Virginia.

Well Yields

Reported well yields in Warren County range from 0 to 200 gal/min (table 1; fig. 8). The median well yields for the different rock units generally range from 10 to 20 gal/min, which is typical for domestic wells in fractured-rock and karst aquifer systems. Dry holes are common, and filing of completion reports is not required. Most of the well-yield data are derived from short-duration, airlift tests conducted after total depth of the wells had been reached. Results from the Tukey's multiple comparison test, which is a nonparametric analysis of variance test performed on rank-transformed data to determine which group or groups are significantly different, indicate that the hydrogeologic units are not significantly different (p-values > 0.05). This lack of statistical difference is to be expected because a majority of the wells are for domestic use (Cederstrom, 1972), and maximum yields for the rock units may not have been obtained. Generally, the higher yields are in wells finished in the carbonate and siliciclastic (predominantly the Martinsburg Formation) rock units (fig. 12). Productivity of the carbonate aquifers is well known, but the high yields in the Martinsburg Formation

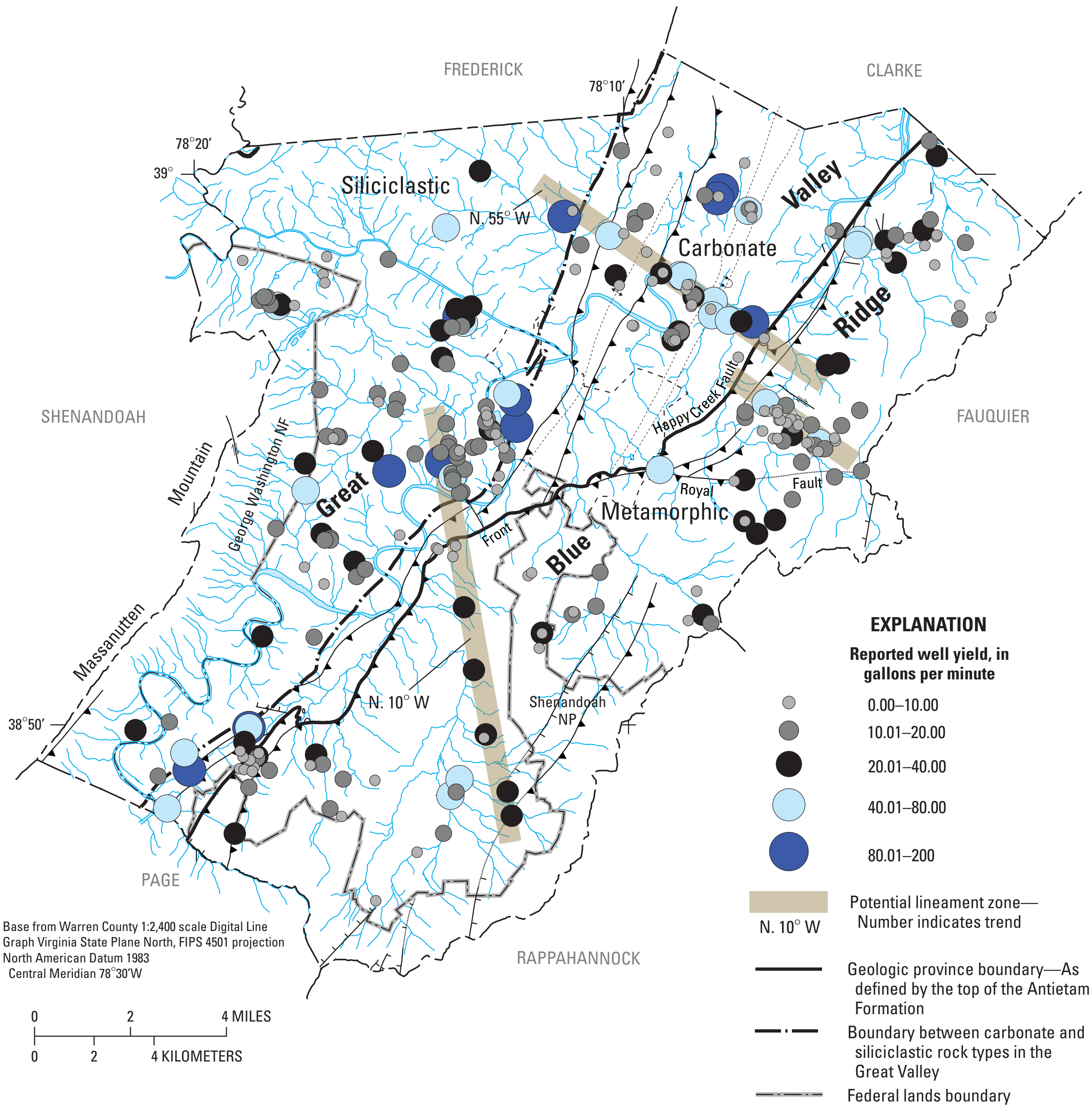

Figure 12. Reported well yields in Warren County, Virginia.

Fault and fold symbology is shown in figure 5.

contradict the normal premise that the Martinsburg is a low-yielding unit (Cady, 1936, 1938; Trainer and Watkins, 1975; Hinkle and Sterrett, 1976, 1977, 1978; Wright, 1990; Yager and others, 2008). A majority of the high-yielding wells in the Martinsburg is present along the eastern margin of this formation. The extent of the Martinsburg Formation depicted in figure 5 includes the Stickley Run Member, which is a carbonate rock. Therefore, the high-yielding wells may obtain water from carbonate rocks rather than from the siliciclastic rocks of the Martinsburg Formation. In Berkeley County, WV, Shultz and others (1995) determined that the Martinsburg had higher median well yields than those from the carbonate rocks. Nelms and Moberg (2010) identified a similar pattern in the Martinsburg and stated that a majority of these wells were located within Landsat lineament zones, near or along mapped faults, within isolated fault slices, or near the eastern contact of the Martinsburg with the older carbonate units where well depths could penetrate the basal Stickley Run Member. Another possible explanation is that the shale in the Martinsburg Formation is typically highly fractured, much more so than the carbonates; therefore, the secondary permeability may be greater (M.D. Kozar, U.S. Geological Survey, written commun., 2010). Furthermore, Shultz and others (1995) and Kozar and Weary (2009) showed that proximity to faults affects well yields for all rock types in the Great Valley of the northern Shenandoah Valley region.

In the Blue Ridge, well yields tend be slightly greater in the valleys and hillsides than on ridgetops. This pattern typically is seen in fractured-rock settings, and the prevailing theory is that fractures may be more concentrated in valley settings than along ridgetops (Powell and Abe, 1985).

Alignment of high-yielding wells can suggest control by an underlying geologic structure. Wells with reported yields greater than 40 gal/min align along the straight segment of the Shenandoah River just east of Horseshoe Bend. Extension of this alignment across the carbonate rock units connects two wells having similar high yields near the eastern contact of the Martinsburg Formation. The trend (N. 55° W., fig. 12) of the alignment nearly parallels the trend of Landsat lineament zones identified in Clarke County by Hubbard (1990) and of the small transverse fault southeast of Happy Creek fault (fig. 12). The alignment of high-yielding wells across many hydrogeologic units coincident with the straight stream segment at a trend similar to lineament zones to the north suggests the presence of structural weakness usually associated with lineaments, cross-strike faults, or both. Interestingly, a subtle alignment of high-yielding wells with a trend of N. 55° W. just south of the small transverse fault mentioned above may suggest structural offset or width of the lineament zone. McCoy and others (2005a, b) and Kozar and others (2007) noted the importance that cross-strike faults have on hydraulic properties, well yields, and flow in Berkeley and Jefferson Counties, WV. In the Gooney Run watershed, wells with yields between 20 and 40 gal/min align with a trend of N. 10° W. (fig. 12) that extends to a cluster of high-yielding wells located just north of the first major bend in the South Fork Shenandoah River downstream from Front Royal. This trend is similar to that of a lineament zone in Clarke County that nearly crosses the entire county (Hubbard, 1990). Future mapping could identify structural features that might be conducive for locating high-yield wells in the county.

A density analysis using ArcGIS® ArcMap® version 9.3 was conducted to further identify areas where well yields tend to cluster either as low (less than 5 gal/min) or high (greater than 50 gal/min) yields. Many of the areas with the highest density of low-yielding wells are present in the center of fault blocks, and wells depths are not deep enough to penetrate the bounding faults (fig. 13). High-yielding wells in the county generally tend to cluster along faults, along potential lineament zones, in areas underlain by carbonate rocks, along the major rivers, and along the eastern extent of the Martinsburg Formation (fig. 14). A comparison of density clusters (figs. 13, 14) indicates that some areas contain a dense concentration of both low- and high-yielding wells. This is one example of the degree of complexity inherent with fractured-rock and karst aquifer systems, which has been identified in other areas within the northern Shenandoah Valley region (McCoy and others, 2005a, b; Nelms and Moberg, 2010). The clusters of both low- and high-yielding wells near Horseshoe Bend on the Shenandoah River and near Bentonville in the south illustrate this complexity. Interpretations of the well-yield density analysis are affected by data distribution across the study area.

The statistical and spatial analyses described previously are not a rigorous evaluation of the yielding capacity of the hydrogeologic units in the county. As stated earlier, wells in the dataset were drilled for domestic purposes and have been sited in accordance with local ordinances and not to maximize well yield. In addition, most of the drilled wells are 6 in. in diameter, which can be a limiting factor in well production. Also, more than 75 percent of the wells have depths less than 400 ft. Cady (1936) observed that the average yield of wells drilled deeper than 300 ft in the carbonate rocks is three times as great as those drilled shallower than 300 ft. The relation between well yield and depth for the metamorphic rocks has not been thoroughly investigated. Cressler and others (1983), Daniel (1989), Swain (1993), Hansen and Simcox (1994), and Loiselle and Evans (1995) indicated that yields may increase with depth of exploration in crystalline rocks.

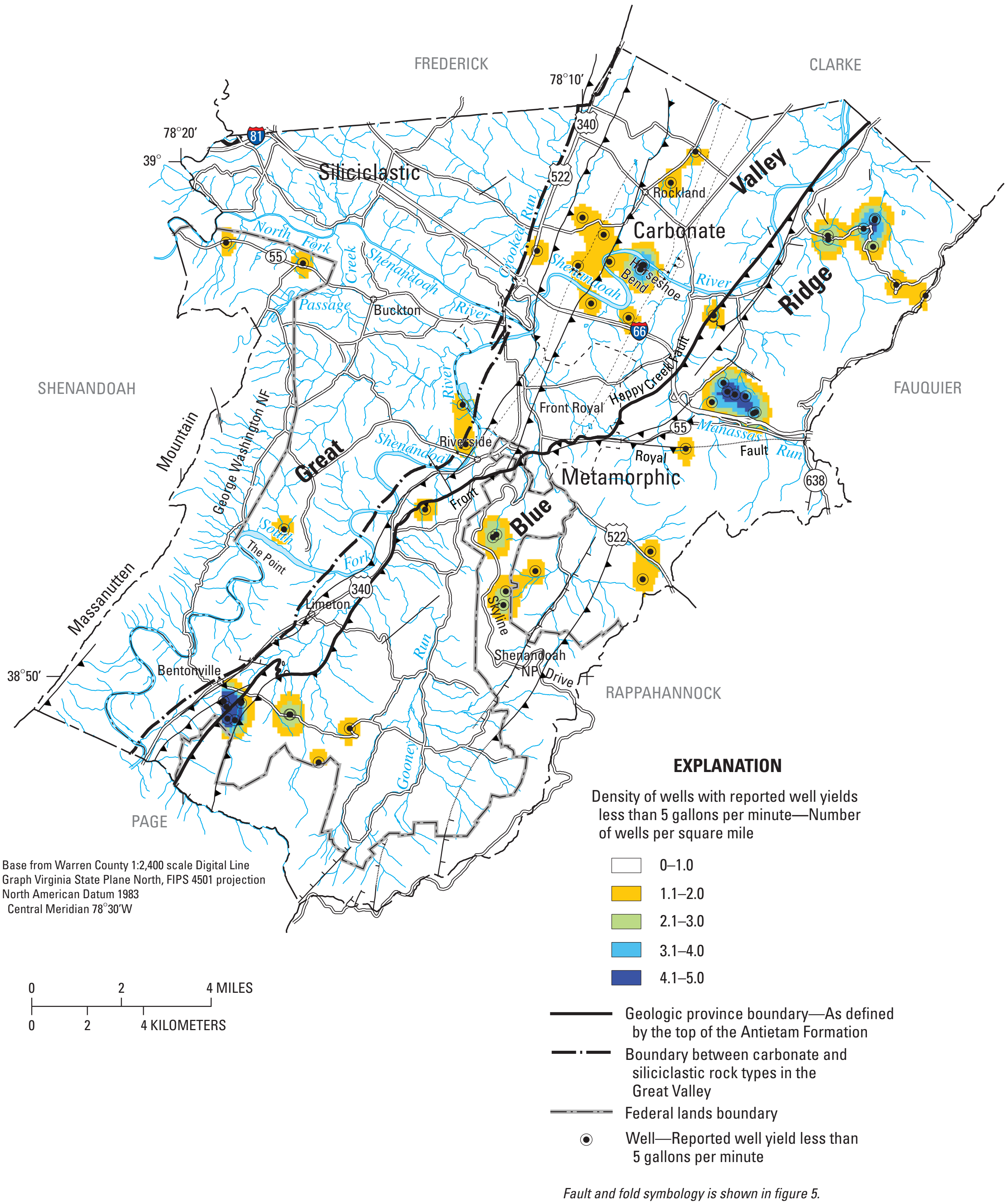

Figure 13. Density of wells with reported well yields less than 5 gallons per minute in Warren County, Virginia.

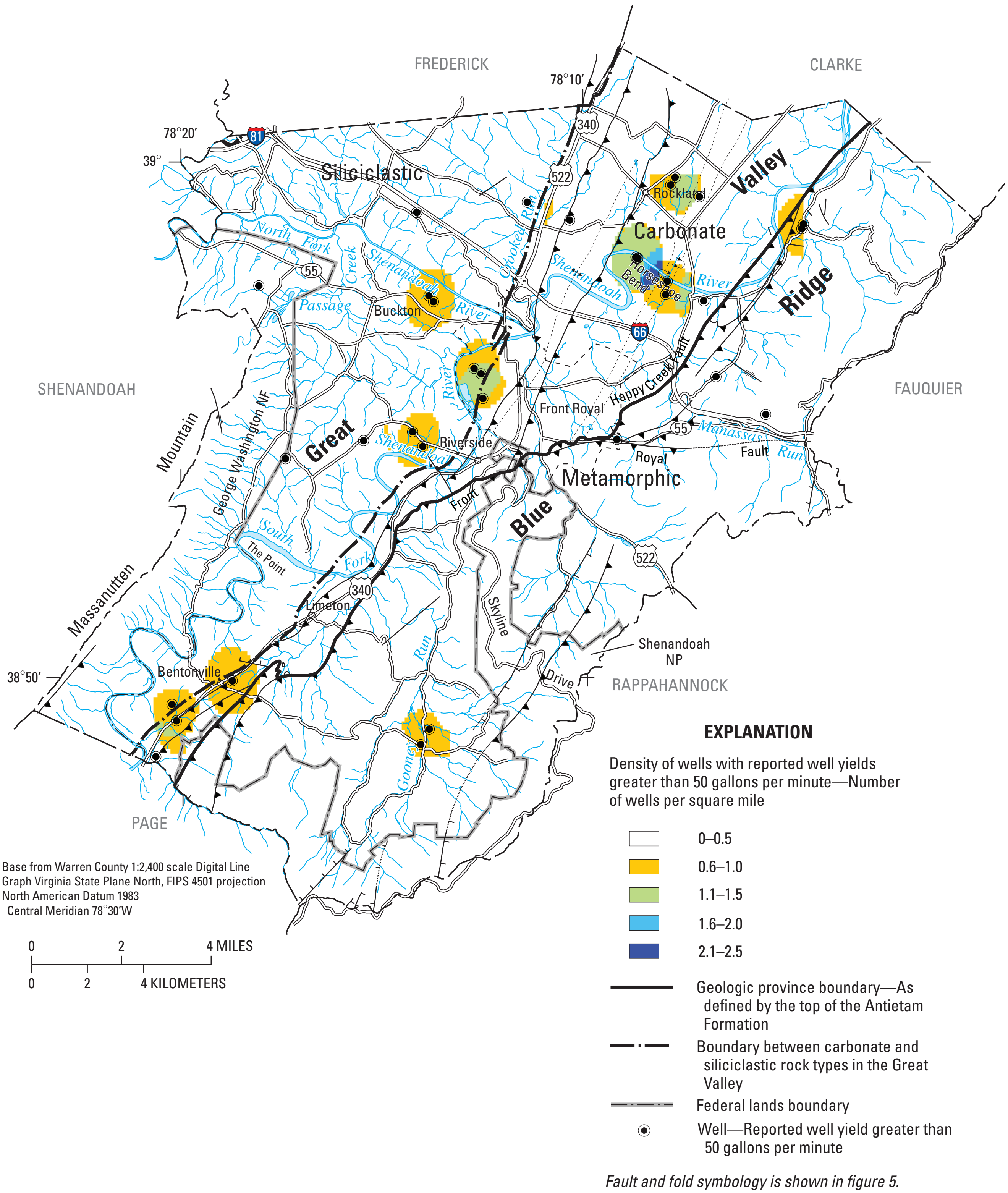

Figure 14. Density of wells with reported well yields greater than 50 gallons per minute in Warren County, Virginia.

Aquifer Properties

Sufficient data to calculate specific capacity (*Q/s*), which is the ratio of well yield to water-level drawdown in a pumped well, were available for 50 wells located in Warren County. Specific capacity from short duration pumping tests (less than 2 hours) in the three rock types is relatively low and ranges from 0.003 to 1.43 gallons per minute per foot [(gal/min)/ft] with median values from 0.12 to 0.24 (gal/min)/ft (table 2). Although median values for the rock units differ slightly, the distribution is similar to the findings from the analysis of well yields presented in the previous section where well yield was generally higher in the siliciclastic unit (Martinsburg Formation) and carbonate unit than in the metamorphic unit. Values of transmissivity (*T*) were estimated using the following equations (Driscoll, 1986) for these specific capacity data:

$$T = 1{,}500(Q/s), \text{ for unconfined aquifers, and} \quad (1)$$

$$T = 2{,}000(Q/s), \text{ for confined aquifers,} \quad (2)$$

where *T* is transmissivity in gallons per day per foot, *Q* is well yield in gallons per minute, and *s* is water-level drawdown in feet. Equations 1 and 2 were used to provide estimates for both unconfined and confined conditions present in the county. Transmissivity values derived from the specific capacity data range over four orders of magnitude from 0.6 to 380 feet squared per day (ft^2/d; table 2). The median values of transmissivity for the different rock units are of the same order of magnitude, but the overall range and median values of transmissivity for the metamorphic rock unit are lower than the overall ranges and median values for the other rock units. Median values of transmissivity for the metamorphic, siliciclastic, and carbonate rock units under unconfined conditions are 24, 49, and 40 ft^2/d, respectively, and under confined conditions are 32, 65, and 54 ft^2/d, respectively. Yager and others (2008) also estimated transmissivity values for the Shenandoah Valley from specific capacity data; median values of transmissivity for the metamorphic, siliciclastic, and carbonate rock units were 54, 108, and 269 ft^2/d, respectively. In the future, accurate and consistent reporting of well yield, test duration, and static and production water levels could facilitate more detailed evaluations of the yielding potentials and aquifer properties of the different rock units.

Water Levels

Fluctuations in water levels can result from natural and anthropogenic factors. The primary natural factors are precipitation, groundwater evapotranspiration, and discharge from the aquifer system to springs and streams (Harlow and others, 2005). Other natural factors are barometric, earth tide, and earthquake effects. Pumpage withdrawals for water-supply demands as well as surface and subsurface injection are the primary anthropogenic activities that cause groundwater-level fluctuations. In general, recharge of precipitation to the aquifer

Table 2. Transmissivity values estimated from specific capacity tests of supply wells by rock type in Warren County, Virginia.

[n, number of sites; (gal/min)/ft, gallon per minute per foot of drawdown; ft^2/d, foot squared per day]

Rock type	n	Minimum	Median	Maximum
Specific capacity, in (gal/min)/ft				
Metamorphic	14	0.007	0.12	0.41
Siliciclastic	29	0.003	0.24	1.00
Carbonate	7	0.03	0.20	1.43
Transmissivity[a] (unconfined conditions), in ft^2/d				
Metamorphic	14	1.4	24	83
Siliciclastic	29	0.6	49	200
Carbonate	7	5.7	40	290
Transmissivity[a] (confined conditions), in ft^2/d				
Metamorphic	14	1.8	32	110
Siliciclastic	29	0.8	65	270
Carbonate	7	7.6	54	380

[a] Estimates of transmissivity are based on equations from Driscoll (1986):

$T = 1{,}500(Q/s)$ for unconfined aquifers

$T = 2{,}000(Q/s)$ for confined aquifers

where *T* is transmissivity in gallons per day per foot, *Q* is discharge in gallons per minute, and *s* is drawdown in the pumped well in feet.

system causes water levels to rise. Over time, such as seasonally, these levels slowly decline as water discharges to springs and streams in the area and as evapotranspiration limits groundwater recharge. Harlow and others (2005) describe the amount of seasonal water-level fluctuation as being variable and controlled by (1) contributing area of recharge, (2) topographic relief, (3) position in the flow system, (4) amount of evapotranspiration (*ET*), (5) aquifer permeability, and (6) groundwater discharge to springs and streams. Seasonal water-level fluctuations tend to be greater in the elevated recharge areas and in areas underlain by low permeability rocks; however, water levels in discharge areas near streams and springs and in areas underlain by permeable rocks tend to fluctuate less.

The establishment of a long-term water-level network in Warren County began during this investigation to quantify seasonal groundwater-level fluctuations. A pressure transducer was temporarily installed in well 45V 4 to monitor continuous water levels at 15-minute intervals as the area around this well was modified from agricultural to a mixed land use (fig. 15). Well 45V 4 was a 610-ft-deep, 6-in.-diameter observation well with 55 ft of casing and a water-bearing zone at 140 ft bls. This well is located in an elevated area within the siliciclastic rock unit near the boundary with the carbonate rock unit, penetrates 230 ft of shale, and terminates in the Stickley Run Member of the Martinsburg Formation. Continuous water levels were recorded between May 2004 and November 2005 (fig. 16). During this period, water levels fluctuated approximately 6 ft and tended to respond to precipitation events, especially in the summer months when water levels would sharply rise. This sharp rise may be a loading response caused by water-saturated sediments exerting pressure on water in the unsaturated zone, causing the water table in the aquifer to be at pressures greater than atmospheric. Because the wellbore is vented to atmospheric pressure, the water in the well quickly rises, yet the volume of groundwater recharge may be small. In January 2005, the water levels declined about 4 ft in 6 days (fig. 16). This decrease in water levels coincided with construction activities (figs. 17, 18). The overall short-term effect of extensive local earth removal and modification activities and construction of several nearby ponds was minimal, however, and water levels quickly began to recover. A similar, yet smaller, decline in water levels occurred at the beginning of February 2005 and is likely related to construction activities similar to those that occurred in January 2005. Within 1 month, the water levels had recovered, and the remainder of the water-level record closely mirrored regional conditions observed in well 46W175 located in Clarke County, which has the longest period of record in the northern Shenandoah Valley of Virginia (Nelms and Moberg, 2010). Well 45V 4 was abandoned in November 2005.

Water levels were measured quarterly in well 45V 3 from May 2004 until November 2005 when a pressure transducer was installed to monitor continuous water levels at 15-minute intervals and to provide information on seasonal water-level fluctuations for areas underlain by the Martinsburg Formation (fig. 16). Well 45V 3 is a 435-ft-deep, 10-in.-diameter production well with 58 ft of casing and a water-bearing zone at 140 ft bls. This well is located approximately 1,100 ft southwest of well 45V 4 (fig. 15) in an elevated area within the siliciclastic rock unit near the boundary with the carbonate rock unit. The original intent of this well was to supply a mixed-use land development, which is now on a public surface-water supply where irrigation water is provided by the constructed ponds mentioned earlier. Water levels recorded in well 45V 3 (fig. 16) indicate that water levels are generally responsive to current meteorological conditions. Intense thunderstorms, tropical storms, or hurricanes cause sudden, but temporary, water-level rises during the summer and autumn, similar to observations for well 45V 4. A sharp decline in water levels occurred between January and April 2005, and the magnitude of this change was nearly five times the change observed in well 45V 4 for that same period. The overall trend in water levels in well 45V 3 has been increasing since November 2005, which is the opposite of water-level trends observed in long-term wells 46W175 (fig. 16) and 46W179 in Clarke County (Nelms and Moberg, 2010). Explanation of these opposing trends is perplexing and may be the result of differences in recharge mechanisms, storage potential, or land-use activity. Well 45V 3 is the only well in the northern Shenandoah Valley of Virginia in which water levels in the Martinsburg Formation are continuously monitored. Wells 46W175 and 46W179 monitor water levels in carbonate bedrock and residuum, respectively. Differences in recharge mechanisms and storage between carbonate and siliciclastic rock units seem reasonable considering the relatively low permeability and potentially large storage potential in the highly fractured shale of the Martinsburg Formation. In other words, infiltration into the siliciclastic units may occur more slowly than infiltration into carbonate rock units.

The degree of alteration of the landscape is evident from aerial photographs acquired in 2002 and 2007 as part of the Commonwealth of Virginia's Base Mapping Program (fig. 17). The significant tree removal (decreased transpiration), recontouring of the landscape (decreased or rerouted runoff), and irrigation water use could collectively contribute to enhance recharge to the aquifer system, which would result in higher local water levels. Another possibility is that water levels in well 45V 3 are still recovering from the substantial decrease observed in January 2005. Well 45V 3 is located in the higher elevations of the development area, and land surface is about 40 ft higher than at well 45V 4. A majority of the landscape modification occurred at the lower elevations, and figure 18 shows an example of the degree of downcutting. The topography slopes, and groundwater probably flows away from well 45V 3; this may have been enhanced by blasting and re-contouring in the lower areas. The water levels in well 45V 3 may have not had sufficient time to equilibrate to the modified landscape. Continued monitoring in this well, and additional water-level measurements in wells completed in the Martinsburg Formation, could assist in assessing local and regional water-level trends.

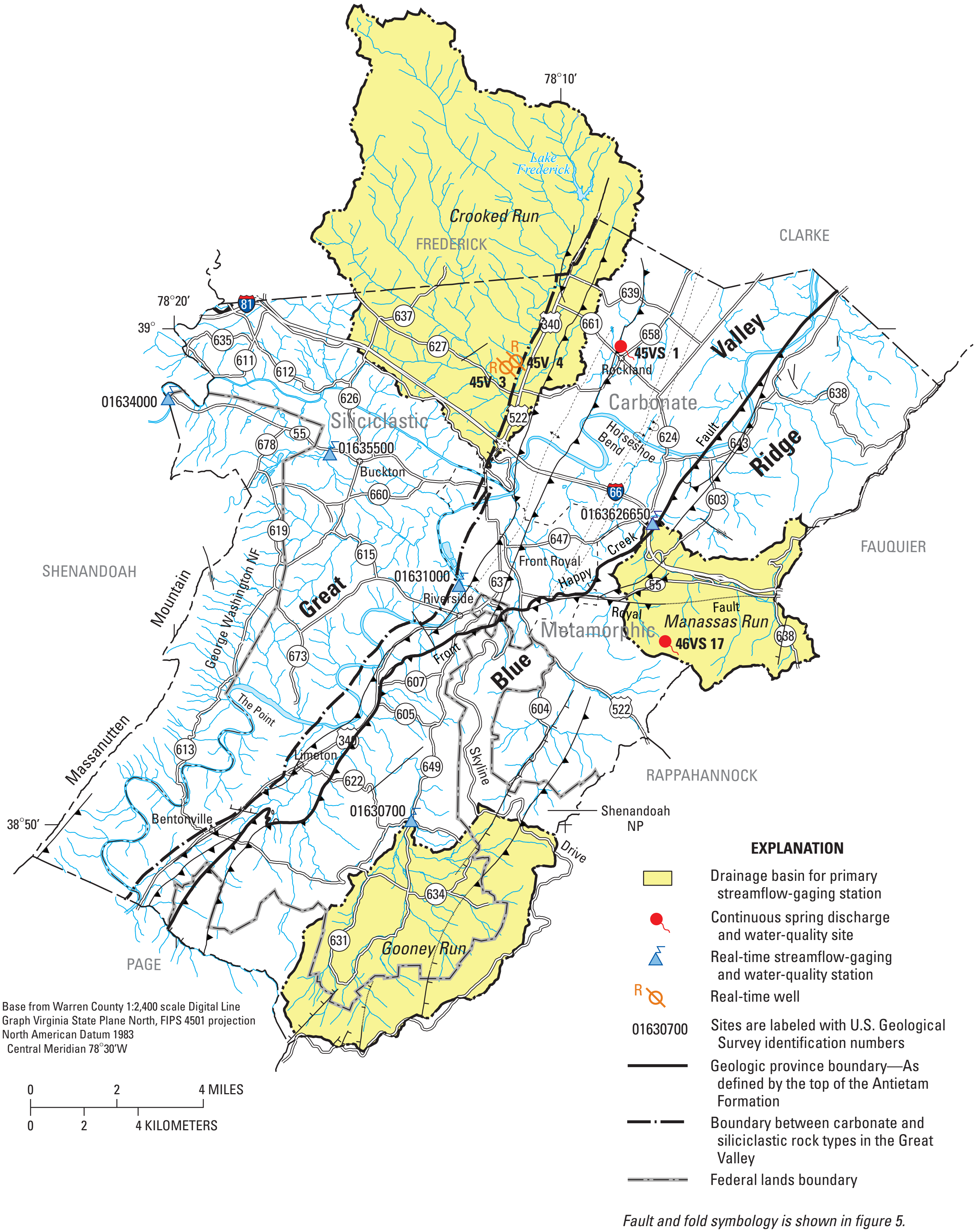

Figure 15. Streamflow-gaging stations, springs, and wells in the long-term water monitoring network for Warren County, Virginia.

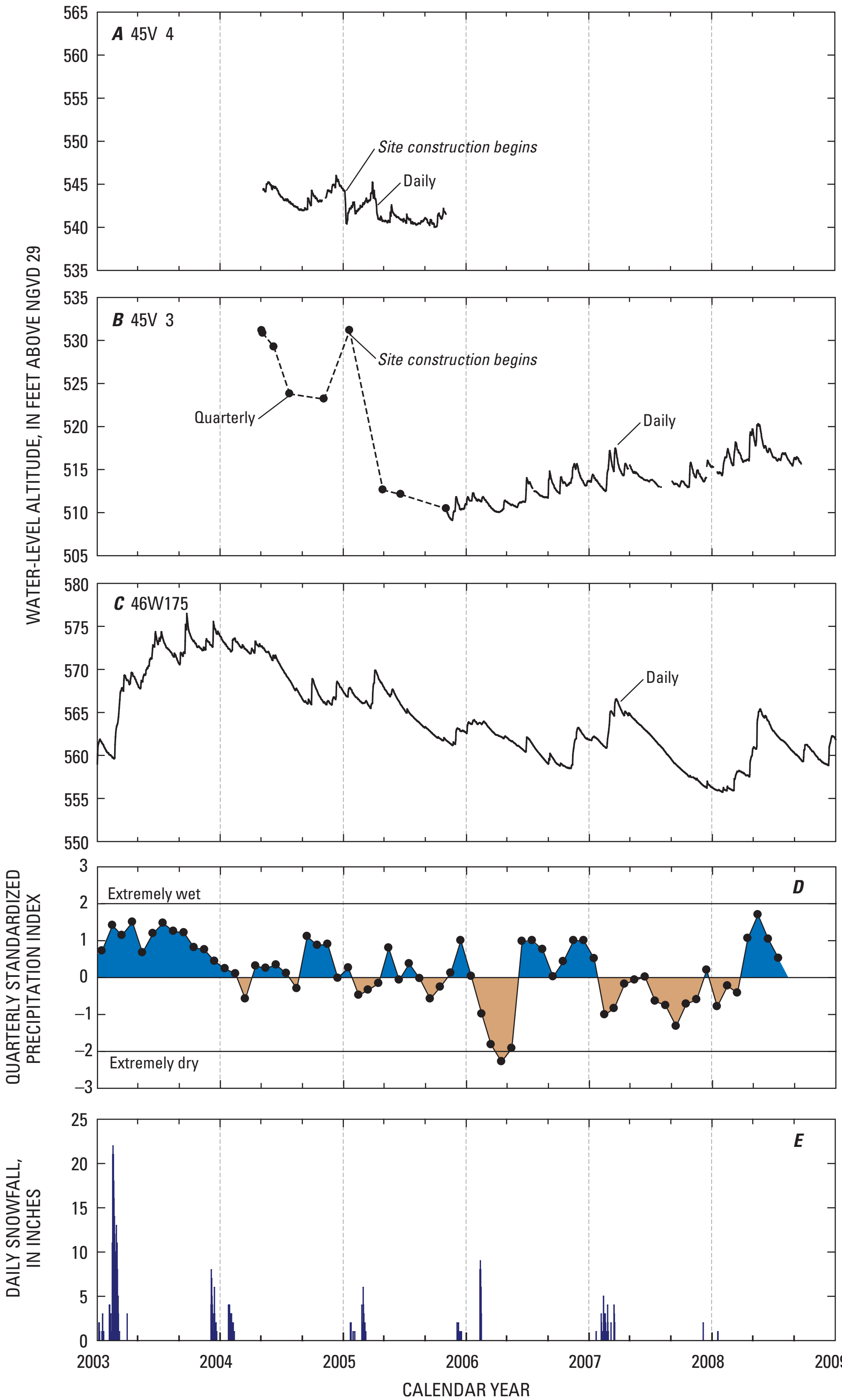

Figure 16. Relation between water levels in wells *(A)* 45V 4 and *(B)* 45V 3 in Warren County, Virginia, and in *(C)* well 46W175 in Clarke County, Virginia, and *(D)* quarterly standardized precipitation index and *(E)* daily snowfall at National Weather Service climatological station 443229 Front Royal, Virginia.

Figure 17. Land use in *(A)* 2002 and *(B)* 2007 for the area surrounding wells 45V 3 and 45V 4 in Warren County, Virginia.

Figure 18. Landscape modification around well 45V 4 in Warren County, Virginia. Photograph taken by Roger M. Moberg, Jr., U.S. Geological Survey, November 3, 2005.

Although well 45V 3 yielded 130 gal/min, storage is probably somewhat limited as evidenced by the demonstrated effects of barometric pressure and earth tides, as well as earthquake effects in the water-level data. The combined effects of barometric pressure and earth tides (diurnal cycles) are indicated by fluctuations of less than 0.1 ft change in water levels shown in figure 19. Because of cyclic heating of atmospheric water vapor and ozone, daily barometric lows generally occur in the early morning and early afternoon, and highs occur in the late morning and late afternoon (Chapman and Lindzen, 1970; Merritt, 2004). In addition, barometric pressure changes in response to passage of storms can affect groundwater levels (Merritt, 2004). The gravitational forces of the Sun and Moon acting upon the rotating Earth cause solid earth tides, like ocean tides. Earth tides cause the underlying rock matrix to expand and contract, which causes the pressure of the water to rise and fall in the aquifer (Merritt, 2004). The earth tide cycle (high and low tides) contributes to the diurnal water-level fluctuations shown in figure 19 with a maximum about every 12 hours. The maximum earth tide ranges occur when the Sun and Moon are aligned at new- and full-Moon phases, and a minimum occurs at first- and third-quarter phases of the Moon. Because groundwater-level fluctuations from both earth tides and barometric fluctuations normally are less than 0.1 ft in magnitude, the effects can be considered negligible in the water-level record, as most recharge events generally are of a greater magnitude.

Water-level oscillations in response to the sudden arrival of teleseismic wave trains also have been observed in well 45V 3. Similar to earth tides, yet more rapid, these seismic wave trains cause the rock matrix to expand and contract, which causes oscillatory pore pressure changes (Cooper and others, 1965; Liu and others, 1989). Water, which is incompressible, flows into and out of the well in response to the pore pressure changes. Water levels in well 45V 3 responded to the magnitude 8.4 earthquake that occurred on September 12, 2007, in Southern Sumatra, Indonesia, about 10,000 mi away (fig. 19). Water-level oscillations of 0.1 ft were recorded in well 45V 3 about 45 minutes after the earthquake occurred and lasted for nearly 90 minutes. Generally, magnitude 7.0 or greater earthquakes located thousands of miles away can cause a slight response in water levels monitored in well 45V 3; local and even regional earthquakes of lower magnitude, however, have no effect on water levels in this well.

Streamflow and Spring Discharge

The quantity of water discharging from the aquifer systems in the county can be characterized by streamflow and spring discharge. A large part of streamflow is groundwater discharge (base flow). Springs oftentimes are the origination of flows at the headwaters for many of the streams in the county. Dry stream segments during drought conditions usually are the result of cessation of flow at an upstream spring. A long-term network to monitor streamflow and spring discharge was established during this investigation. Three streamflow-gaging stations were established: 01630700 (Gooney Run at Route 622 near Glen Echo), 01636242 (Crooked Run below Route 340 at Riverton), and 0163626650 (Manassas Run at Route 645 near Front Royal) (fig. 15). In the mid-Atlantic region of the United States, 1 cubic foot per second (ft^3/s) of flow generally requires 1 mi^2 of drainage area

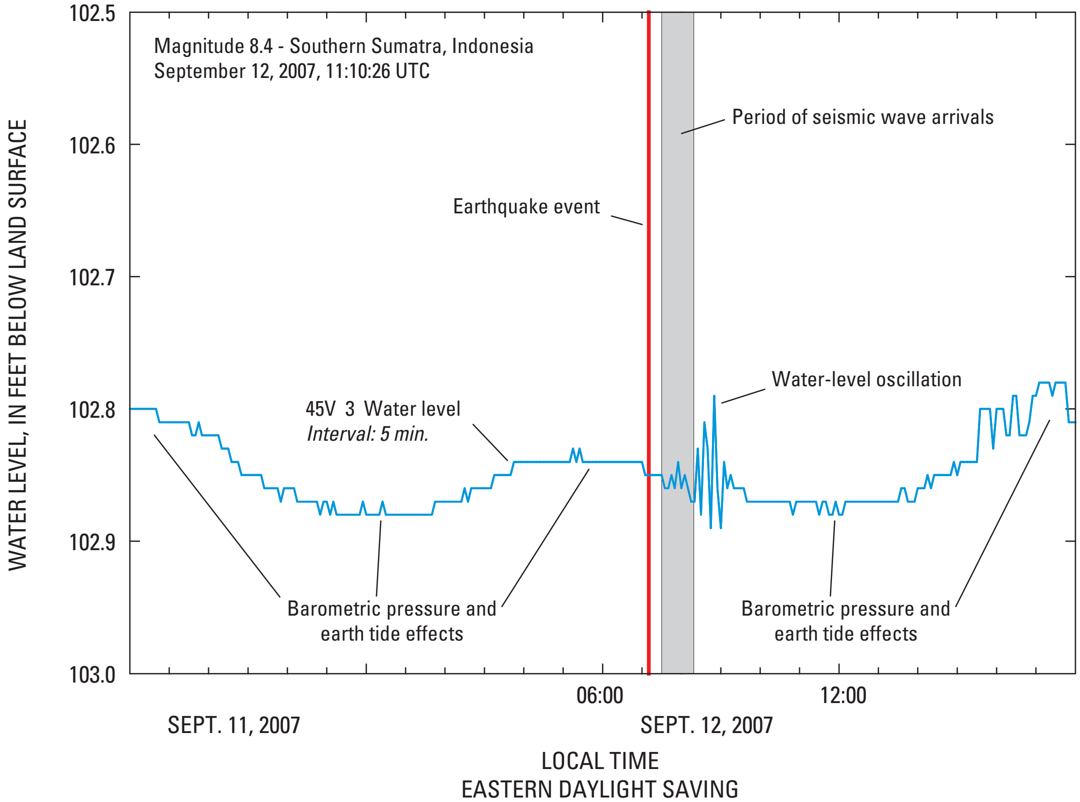

Figure 19. Relation between water levels in well 45V 3 in Warren County, Virginia, and combined effects of barometric pressure and Earth tides, and of teleseismic earthquakes.

(Poff, 1999). Mean streamflows for the period of record (2002 through 2008) at streamflow gages 01630700, 01636242, and 0163626650 were 34.8, 24.9, and 18.0 ft^3/s, respectively (fig. 20). Abundant deposits of alluvium and colluvium overlie the metamorphic rock unit in the Gooney Run and Manassas Run Basins. The ratios of mean streamflow to drainage area in these two basins are 1.6 and 1.7 ft^3/s of flow per square mile of drainage area, respectively; these ratios probably are the result of above-average rainfall during the period of record and are not representative of average hydrologic conditions. Streamflow at gage 01636242 is regulated by Lake Frederick and has a ratio of mean streamflow to drainage area of about half of what is normal for the mid-Atlantic region. This low ratio may be related to reduced releases from Lake Frederick after the drought between 1999 and 2002. Results of hydrograph separation for these gaging stations are discussed later in this report.

Pressure transducers were installed at two springs—45VS 1 (Weddle) and 46VS 17 (High Knob)—to measure stage, and estimates of continuous spring discharge were made by correlating periodic discharge measurements with the recorded stage (fig. 15). Physical limitations at these sites prevented the development of stage-discharge ratings; the quarterly discharge measurements (fig. 21), however, can provide insight into the range of flows and possible size of the drainage areas that contribute flow to these springs. Spring 45VS 1 is located in the Rockland area of the county, which is underlain by the carbonate rock unit. Quarterly discharge measurements between August 2003 and October 2008 (appendix 1) ranged from 0.001 to 1.76 ft^3/s with an average of 0.42 ft^3/s (fig. 21), which indicates that the drainage area on average is approximately less than 0.5 mi^2. Results of dye-tracing tests in the area by Orndorff (2006) indicated relatively short flow paths for springs larger than spring 45VS 1. For carbonate springs, Jones (1987) stated that flow to springs is not controlled by surface-water divides but probably follows the geologic structure. The seasonality of flow is evident in the hydrographs (fig. 21). Flow generally increases in the winter and early spring when evapotranspiration is at a minimum, and flow decreases from late spring to late autumn. The overall decreasing trend during the period of record is similar to the trend observed in carbonate springs and wells in neighboring Clarke County and is indicative of an aquifer system that over time drains to a base level controlled by springs and streams in the area (Nelms and Moberg, 2010).

Spring 46VS 17 is located in the Blue Ridge on the northwest slope of High Knob Mountain. The spring is developed where the slope breaks at the contact between bedrock of the Catoctin Formation and the overlying deposit of alluvium and colluvium. Quarterly discharge measurements between August 2003 and October 2008 (appendix 1) ranged from dry to 0.22 ft^3/s, with an average of 0.07 ft^3/s

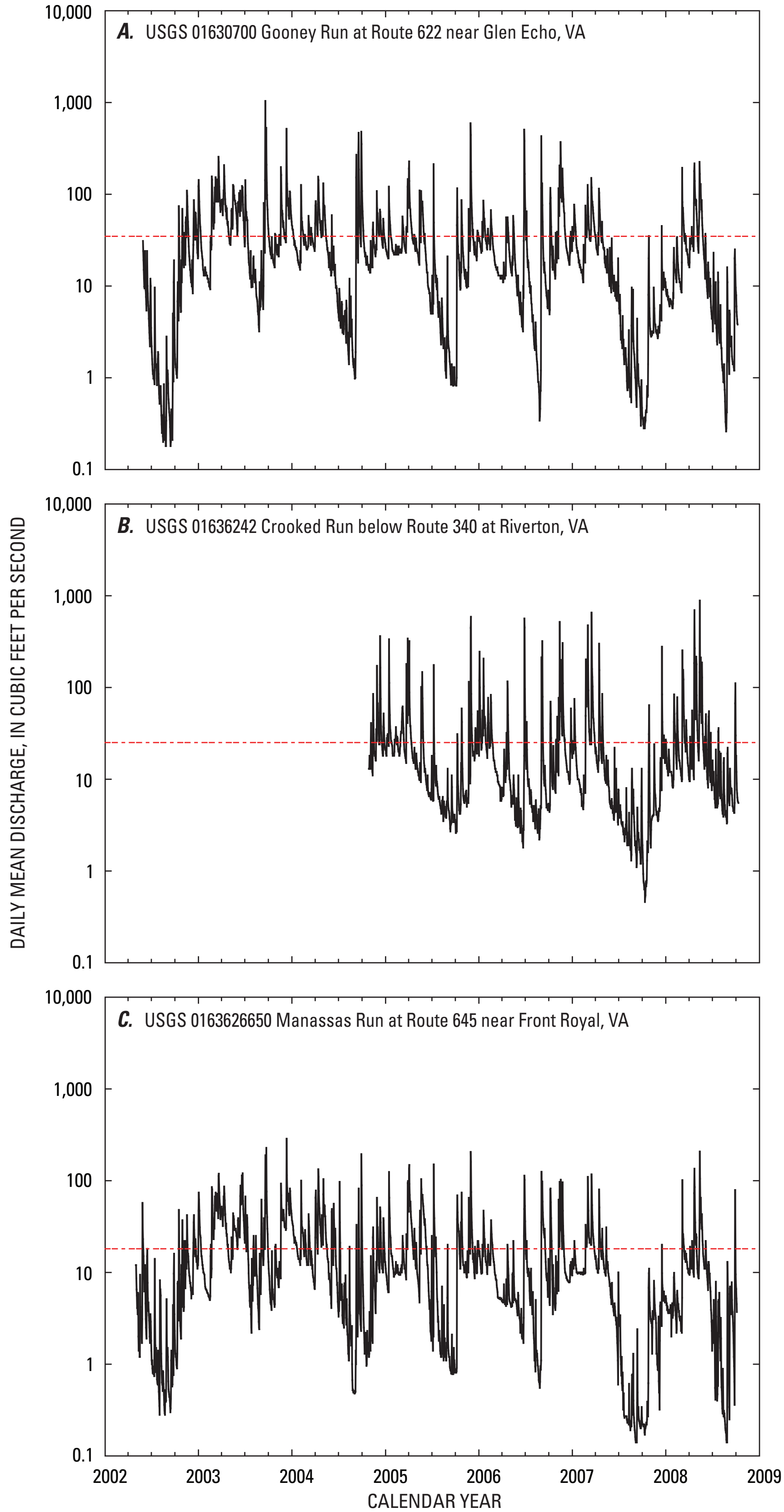

Figure 20. Daily mean discharge at streamflow-gaging stations *(A)* 01630700 Gooney Run at Route 622 near Glen Echo, Virginia, *(B)* 01636242 Crooked Run below Route 340 at Riverton, Virginia, and *(C)* 0163626650 Manassas Run at Route 645 near Front Royal, Virginia. Red dashed line indicates average of daily mean streamflows at each gaging station for the respective period of record.

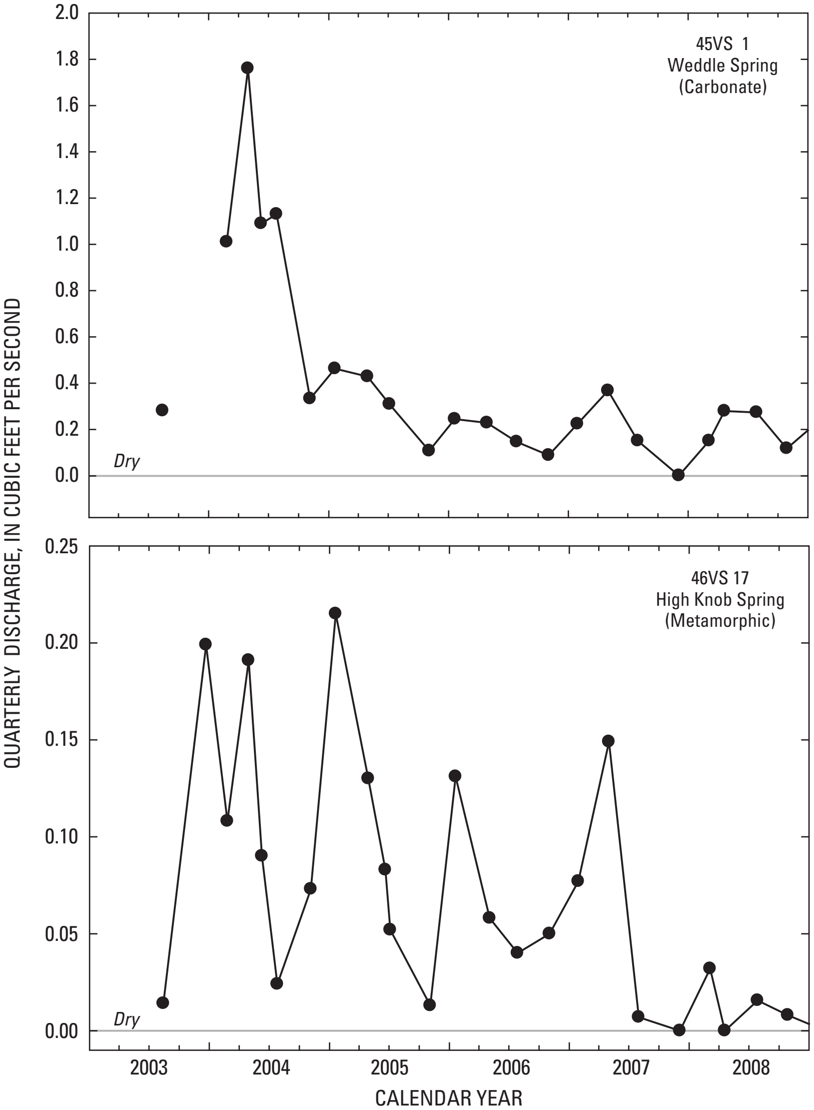

Figure 21. Quarterly discharges from springs 45VS 1 and 46VS 17 in Warren County, Virginia.

(fig. 21), which indicates that the drainage area on average is approximately less than 0.1 mi^2. This estimate of drainage area is similar to the drainage area above the spring delineated using the topographic divides (0.12 mi^2). Nelms and Moberg (2010) state that delineation of a spring's drainage area based on surface-water divides in the Blue Ridge generally provides sufficient area to supply the mean discharge and probably represents the major contributing area to the spring. The seasonality of discharge is not readily identifiable in spring 46VS 17 and is more responsive to current meteorological conditions (fig. 21). Nelms and Moberg (2010) identified a similar lack of seasonality in Blue Ridge springs and attributed it to relatively low discharge rates, probable small drainage areas, and the susceptibility of these aquifer systems to current meteorological conditions.

As discussed earlier, values of mean discharge can be used to estimate drainage area. In the Blue Ridge, delineation of the drainage area of a spring based on surface-water divides often provides sufficient area to supply the mean discharge and probably represents the contributing area to the spring. In the Great Valley, mean discharge often only provides a guide for the size of the area needed. Wright (1990) stated that these estimates of discharge per unit area may not represent an easily definable or discrete area surrounding a spring and may or may not be coincident with surface-water divides.

Relation of Geology to Groundwater Flow

In the Blue Ridge, relict structures in the regolith material can transmit water from elevated areas to nearby streams in the form of interflow and shallow groundwater flow where the water table is above the top of bedrock. The unconsolidated surficial materials in the riparian areas of the Blue Ridge can function as local flow systems above the fractured-rock aquifers. Groundwater flow in the bedrock of the Blue Ridge is likely controlled by the orientation of the foliations and joints, but the dominant flow direction is difficult to ascertain. Southworth (1990) suggested that water recharged on the western slopes of the mountains of the Blue Ridge flows down the dip of the rock units and eventually discharges to springs and in valleys on the eastern sides of the mountains. The well-developed dendritic drainage networks in the Blue Ridge are probably a reflection of the irregular and highly variable fracture network developed in the underlying metamorphic bedrock, faults, and the weathering characteristics of these rocks. The abundance of alluvial and colluvial deposits along these streams facilitates rapid transmission of interflow or subsurface stormflow (Wright, 1990).

In the Great Valley section, the preferred direction of groundwater flow is probably along strike of bedding planes and cleavage in the sedimentary rock units; therefore, the dominant direction of groundwater flow is generally from elevated areas to the northeast or southwest along the strike of the rocks. Groundwater flow along the other joint types is topographically driven along the strike of the respective feature. In the siliciclastic rocks of the Great Valley section of the county, regional flow may be limited by the highly dissected terrain, and local flow systems may dominate. Drainage networks in the Great Valley section of the county often follow cross joints in the rock (Hack and Young, 1959). Many of the streams and creeks flow normal to strike; however, many of the low-order tributaries parallel the strike of the rocks especially in the northwestern part of the county. Stream density (length of streams per drainage area) is generally low for areas underlain by the permeable carbonate rocks and higher for the less permeable rock types such as those in the Blue Ridge.

Orndorff and Harlow (2002) and Harlow and others (2005) noted that springs in the Shenandoah Valley are structurally controlled and usually are present where fault planes intersect the surface. Numerous springs in Warren County are present along faults and within lineament zones in both the Great Valley and Blue Ridge; however, many springs also are present along fold axes where joints verge. Travertine deposits commonly are present at and downstream from springs in the Great Valley and are formed by waters that are supersaturated with respect to calcium carbonate (Orndorff and Harlow, 2002).

Relation Between Groundwater and Surface Water

Groundwater is a major component of streamflow, usually in the form of direct discharge from springs at the headwaters of streams and directly through streambeds or streambanks. In the Blue Ridge, rapid transmission of interflow, subsurface stormflow, spring discharge, and, to some degree, direct groundwater discharge from the bedrock sustain streamflow. Generally, streamflow is limited by current meteorological conditions such that periods of flow cessation frequently occur in the elevated areas of the Blue Ridge and Massanutten Mountain during extended dry periods, especially in the late summer and early autumn. The overburden (regolith material) overlying the bedrock in the Blue Ridge plays a more important role than it does in the Great Valley section. Wright (1990) emphasized the importance of subsurface stormflow in the overburden that can rapidly transmit water to springs and streams in the Blue Ridge. The porous nature of the regolith material in the stream valleys is conducive for infiltration, movement, and temporary storage of subsurface water. Although this water is considered to be groundwater, in reality, the subsurface stormflow and, to some degree, interflow are probably more representative of water moving quickly through the overburden and not of the bedrock as evidenced by the seasonality of flow conditions and rapid response to extreme precipitation events.

Diurnal streamflow cycles frequently observed between April and October at gaging stations 01630700 (Gooney Run) and 0163626650 (Manassas Run) illustrate the connection between groundwater in the coarse surficial deposits of the riparian areas and streamflow. Infiltration in losing reaches and riparian evapotranspiration can cause diurnal flow cycles (Constantz and others, 1994; Lundquist and Cayan, 2002; Czikowsky and Fitzjarrald, 2004). Streamflow at gaging stations 01630700 (Gooney Run) and 0163626650 (Manassas Run) sharply decreases about 3 hours after sunrise and then gradually increases about 4 hours after sunset during the growing season (fig. 22). This asymmetrical diurnal streamflow signal is characteristic of evapotranspiration effects (Czikowsky and Fitzjarrald, 2004). In addition, Czikowsky and Fitzjarrald (2004) state that these diurnal signals are not in response to thermal expansion of the water or in response to losing reaches where large diurnal temperature ranges affect the viscosity of the water, which can alter the hydraulic conductivity of the streambed (Constantz and others, 1994). As the period of the streamflow recession increases, the amplitude of the diurnal signal tends to decrease. Changes in evapotranspiration rates as the growing season progresses contribute to variations in the amplitude effects (Czikowsky and Fitzjarrald, 2004). The steep slope of the stream profile and permeable nature of the coarse surficial deposits suggest rapid drainage of groundwater to the stream, which would increase the distance between the root zone and the water table. At extreme low-flow conditions (below 1 ft^3/s), the diurnal streamflow signal is not evident. Diurnal streamflow signals are seldom observed at gaging station 01636242 (Crooked Run) because most of the stream is incised into the bedrock and groundwater levels are likely deeper; potential evapotranspiration effects, therefore, are minimal.

In the Great Valley section of the county, groundwater is the dominant source of streamflow during wet and drought conditions, and most of the streams and creeks begin as springs (Nelms and Moberg, 2010). Point discharge from springs can occur as the start of flows of streams and creeks, along banks, and as discrete discharge through streambeds in the Great Valley. For the most part, streams, creeks, and rivers simply function as aqueducts. In the carbonate terrains, surface-water flow often is a source of recharge to the groundwater system by inflow through sinkholes, swallet or swallow holes, streambeds (sinking or losing streams), and estavelles (Nelms and Moberg, 2010). Field reconnaissance of spring locations throughout the county was conducted during this investigation. Identification of subaqueous spring discharge in streams and creeks, especially along the major rivers, however, is difficult. Lane and others (2008) identified subaqueous spring discharge to the Shenandoah River in Clarke County by a thermal anomaly detected by using a fiber-optic distributed temperature sensing system. In Warren County, zones of increased conductive water at and below the streambed were identified during a multifrequency electromagnetic survey along the 2-mi reach downstream from gaging station 01631000 (South Fork Shenandoah River at Front Royal) in the siliciclastic rock unit (fig. 23). These zones may represent discrete areas of concentrated fractures where groundwater is either discharging to the river or flowing beneath the river as underflow. Managers of the water resources and those working to detect potential contaminant sources within the county should note that a large part of streamflow at different flow regimes comes directly from groundwater discharge.

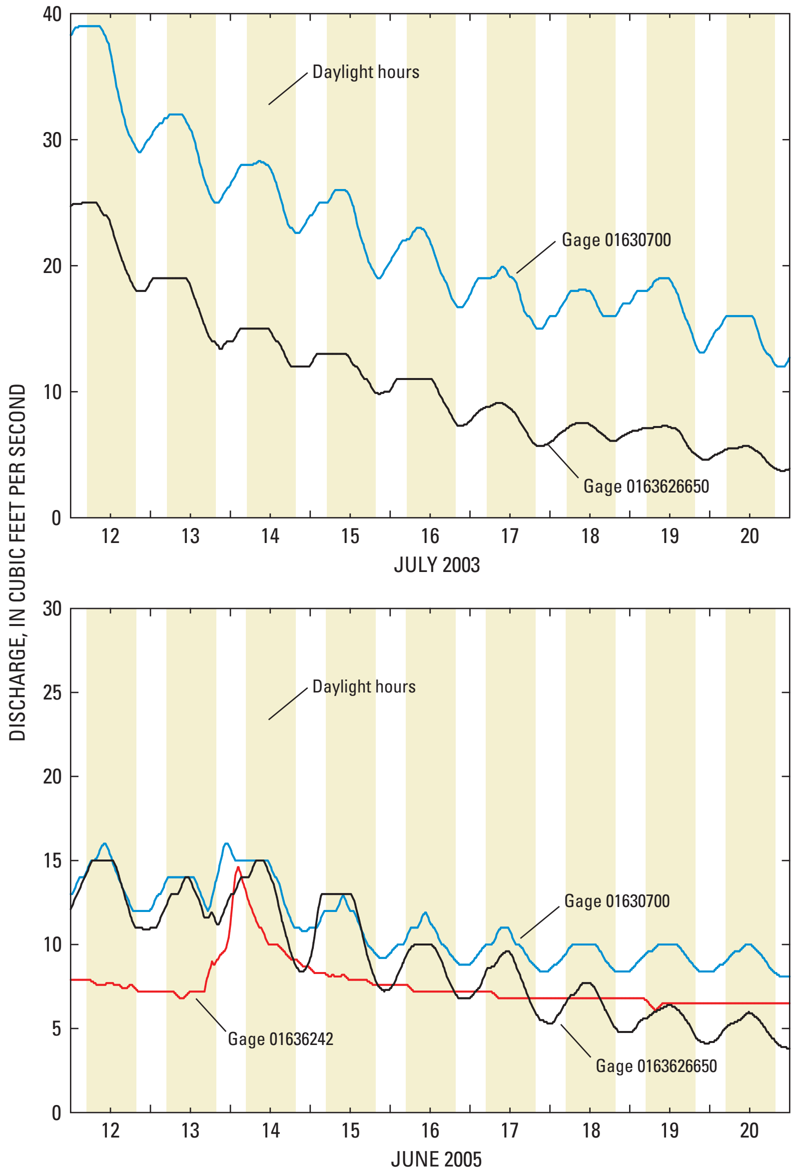

Figure 22. Relation between evapotranspiration and unit value discharge at streamflow-gaging stations 01630700 Gooney Run at Route 622 near Glen Echo, Virginia, 01636242 Crooked Run below Route 340 at Riverton, Virginia, and 0163626650 Manassas Run at Route 645 near Front Royal, Virginia. Unit value discharges have been smoothed with a ±1-hour average function.

Apparent Age of Groundwater

Groundwater apparent ages were estimated by a multiple tracer approach whereby the environmental tracers—chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and tritium/helium-3 ($^3H/^3He$)—are used to date young waters (less than 60 years). Two springs located in the Great Valley section and 12 springs and a public-supply well in the Blue Ridge of Warren County were sampled during the summer months of 2003–2005 (fig. 24). Timing of the sampling coincided with the period of the year when seasonal spring flows and groundwater levels are low; therefore, estimates of apparent groundwater ages should represent a higher percentage of the older groundwater ages in the flow systems. Analytical data are presented in appendixes 2–10. A detailed explanation of the sampling and analytical methods is provided in Nelms and Harlow (2003).

Groundwater dating with CFCs (Busenberg and Plummer, 1992) is based on Henry's law of solubility, which is a function of the temperature during recharge and salinity of the groundwater. Concentrations of dissolved nitrogen (N_2) and argon (Ar) were used to estimate recharge temperatures and

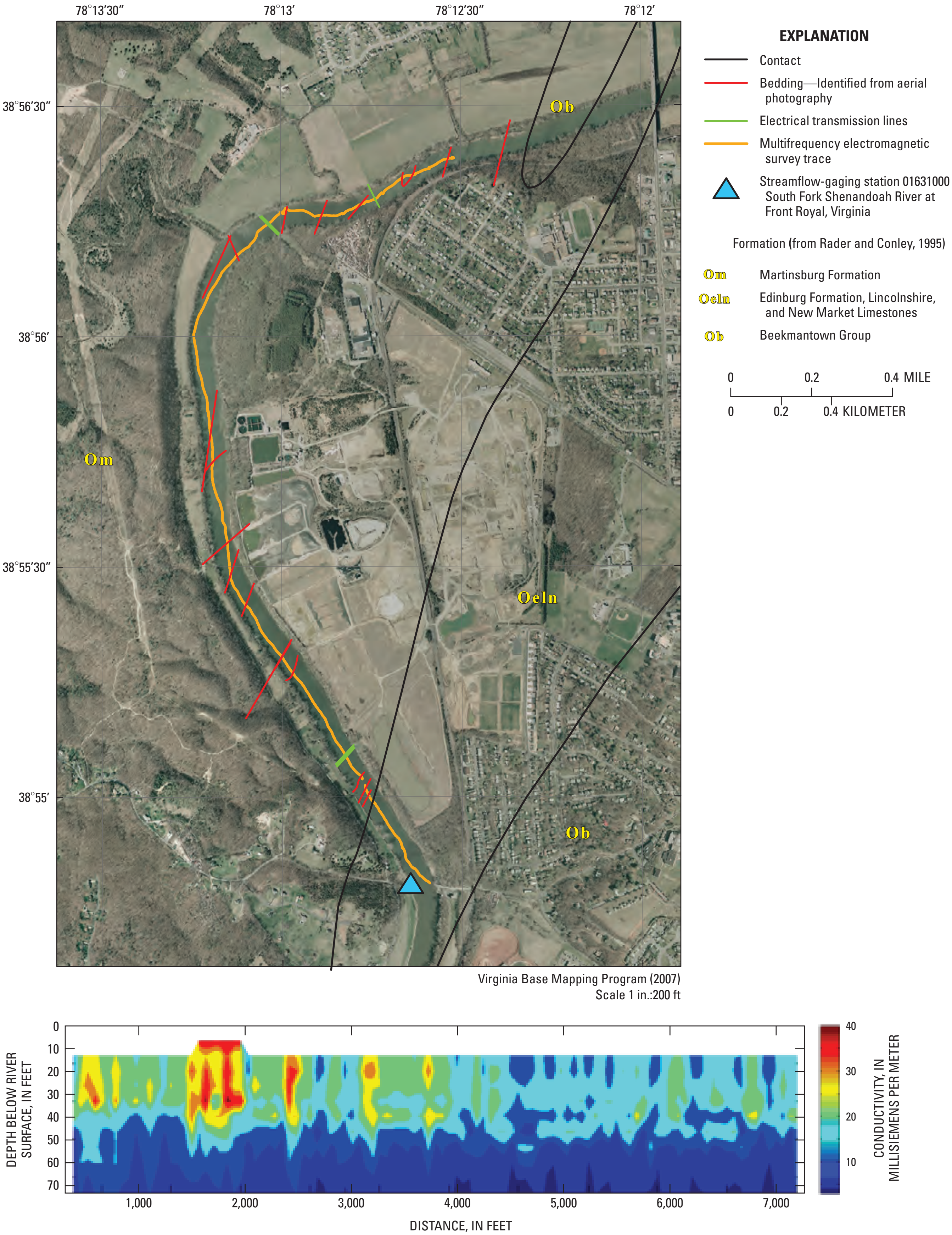

Figure 23. Multifrequency electromagnetic survey along the South Fork Shenandoah River near Front Royal, Virginia.

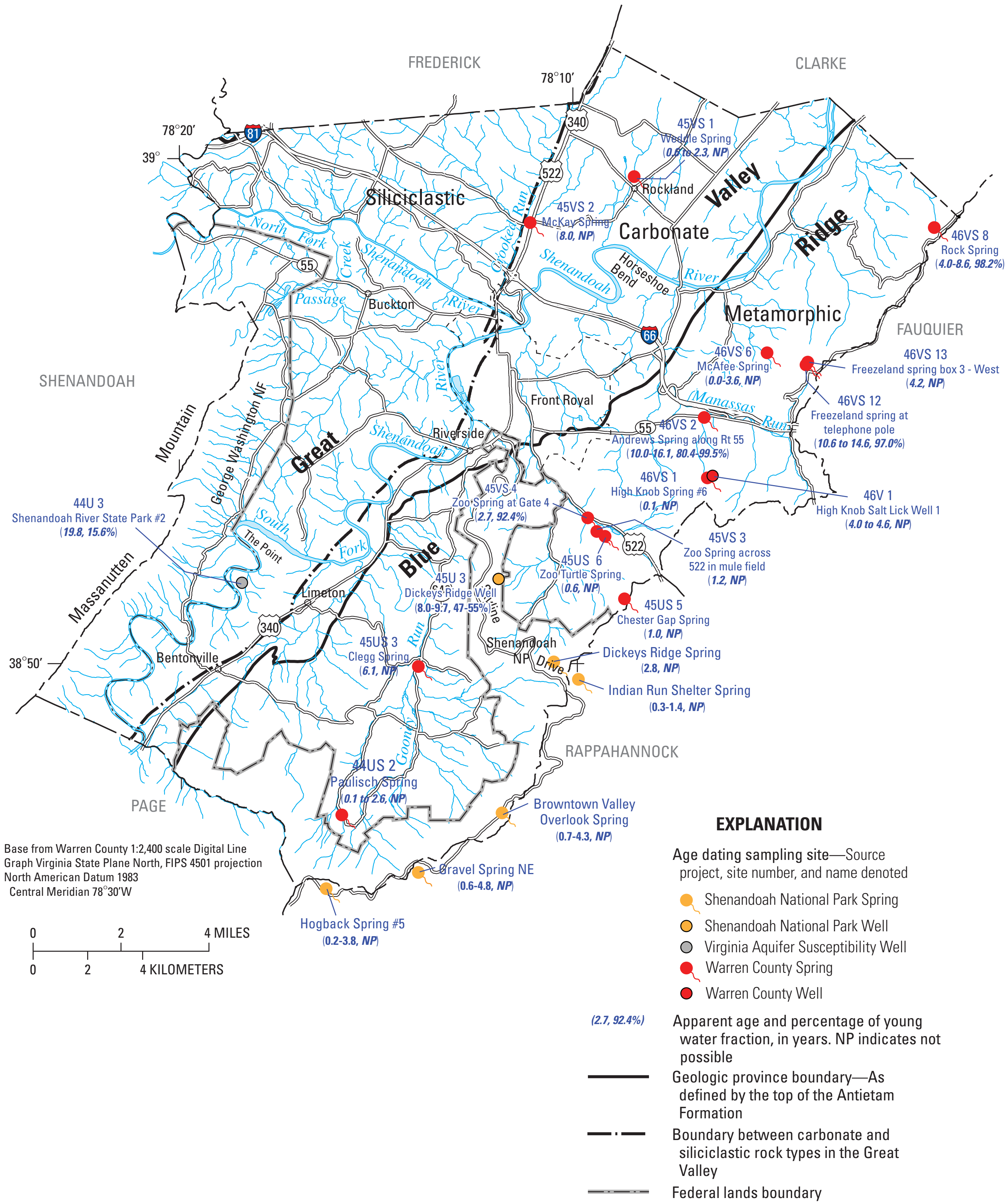

Figure 24. Apparent age and percentage of young water fraction for sampling sites in Warren County, Virginia. Apparent age data for Shenandoah National Park sites from Plummer and others (2000) and for Virginia Aquifer Susceptibility site from Nelms and others (2003).

excess air in groundwater (Heaton, 1981; Heaton and Vogel, 1981; Heaton and others, 1983; Busenberg and others, 1993), and salinity corrections are not necessary for waters as dilute as those from the springs sampled in Clarke County (Plummer and Busenberg, 2000). The apparent CFC age of the water sample was determined by comparing the calculated partial pressures of CFCs in solubility equilibrium with the sample to the historical atmospheric CFC concentrations in North American air (fig. 25).

The SF_6 dating method (Busenberg and Plummer, 2000) is similar to the CFC dating method (fig. 25). Unlike CFCs, SF_6 in groundwater can be derived from anthropogenic and terrigenic sources, and it is generally not affected by sorption and biodegradation processes. SF_6 can be affected by excess air in groundwater, which is attributed to air entrainment during recharge (Heaton and Vogel, 1981).

Tritium (^3H) is the radioactive isotope of hydrogen with a half-life of 12.43 years (International Atomic Energy Agency, 1981) and has been used as an indicator of groundwater recharge since 1952 (Clark and Fritz, 1997). Production of ^3H in the atmosphere naturally occurs by cosmic ray spallation, but the principal source since about 1952 has been the atmospheric testing of thermonuclear weapons (fig. 25). Because ^3H levels in water are not unique to a specific year, the ^3H method was used primarily to confirm the presence of young water. The $^3H/^3He$ method is based on the radioactive decay of ^3H to ^3He such that the helium isotope mass balance is used to determine the amount of tritiogenic ^3He ($^3He_{trit}$) derived from ^3H (Schlosser and others, 1988, 1989). If the $^3He_{trit}$ is confined in the aquifer, apparent $^3H/^3He$ ages of the water samples (τ) can be calculated from the following formula (Schlosser and others, 1988, 1989):

$$\tau = T_{1/2} / \ln 2 \times \left[1 + \frac{\left[^3He_{trit} \right]}{\left[^3H \right]} \right], \quad (3)$$

where $T_{1/2}$ is the half-life of tritium. Neon (Ne) concentrations are used to correct $^3He_{trit}$ for samples that contain terrigenic helium from crustal and mantle sources such as crystalline rocks.

Determination of final apparent age estimates was based on the comparison of the estimates from the different tracers and whether the sample indicates piston flow or binary mixtures (table 3). The final apparent age estimates range from less than 0.1 to 16.1 years. About 73 percent of the samples contained some fraction of waters with apparent ages that were less than 5 years. Because of contamination (in terms of age determinations) of the CFCs and year of recharge, the percentage of the young fraction in binary mixtures could not be determined for all samples. For the samples in which determination of the young fraction was possible, the young fraction ranged from approximately 80 to 99.5 percent. These high percentages indicate that a majority of the water discharging is close to being piston flow, which would have a young fraction of 100 percent.

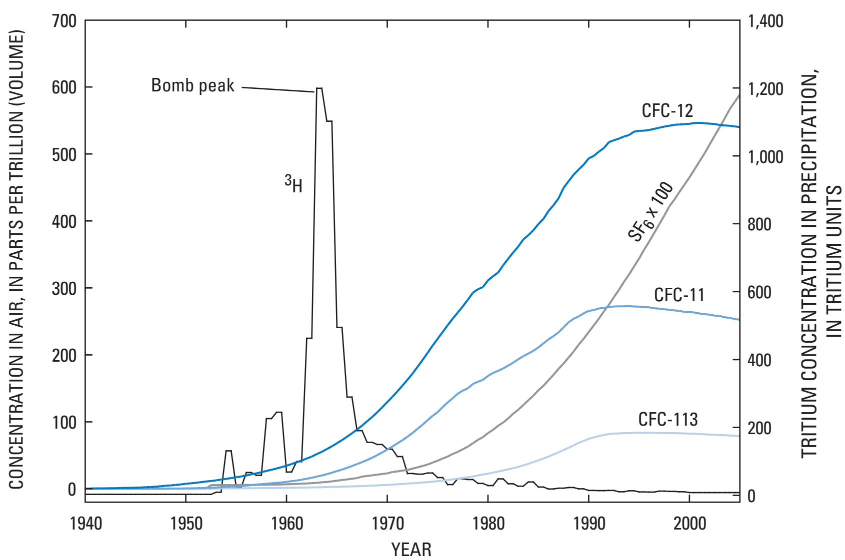

Figure 25. Atmospheric mixing ratios of chlorofluorocarbon-11 (CFC-11), chlorofluorocarbon-12 (CFC-12), chlorofluorocarbon-113 (CFC-113), and sulfur hexafluoride (SF_6) for North American air and estimated monthly concentration of tritium in precipitation for Virginia. Tritium data derived from estimation technique of Michel (1989) and are not corrected for radioactive decay. Modified from Plummer and Busenberg (2000).

Table 3. Apparent ages and uncertainties from chlorofluorocarbons, sulfur hexafluoride, and tritium/helium-3 dating methods and percentage of young fraction in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[CFC-11, (trichlorofluoromethane, $CFCl_3$); CFC-12, (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$); SF_6, sulfur hexafluoride; $^3H/^3He$, tritium/helium-3; NP, not possible; C, contaminated. Final apparent ages and percentages are shaded. Numbers in parentheses indicate possible recharge years before and after atmospheric peak concentration. See figure 24 for location of wells and springs]

USGS local no.	Date	Apparent age and uncertainty. in years											Percentage of young fraction		
		Piston flow													
		CFC-11 (1)	CFC-11 (2)	CFC-12 (1)	CFC-12 (2)	CFC-113 (1)	CFC-113 (2)	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	SF_6	$^3H/^3He$	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11
44US 2	08/18/2004	18.1 ± 0.7	NP	C	C	14.1 ± 0.4	NP	NP	NP	NP	2.6	0.1 ± 0.3	NP	NP	NP
45US 3	08/18/2004	22.1 ± 0.7	NP	C	C	15.1 ± 0.7	NP	NP	NP	NP	2.6	6.1 ± 0.4	NP	NP	NP
45US 5	08/18/2004	C	C	C	C	Mod.	C	NP	NP	NP	9.6	1.0 ± 0.2	NP	NP	NP
45US 6	08/08/2005	C	C	C	C	10.1 ± 2.8	10.1 ± 4.2	NP	NP	NP	20.1	0.6 ± 0.4	NP	NP	NP
45VS 1	08/14/2003	18.1	NP	12.6 ± 3.2	NP	13.6 ± 0.4	NP	NP	NP	NP	0.6	2.3 ± 0.2	NP	NP	NP
45VS 2	08/21/2003	13.1 ± 1.8	5.1 ± 4.6	12.1 ± 1.4	NP	C	C	NP	NP	NP	C	8.0 ± 0.6	NP	NP	NP
45VS 3	08/09/2005	11.1 ± 3.9	11.6 ± 5.7	Mod.	C	11.6 ± 3.2	8.1 ± 6.7	NP	NP	NP	19.1	1.2 ± 0.2	NP	NP	NP
45VS 4	08/09/2005	18.6 ± 0.4	NP	13.6 ± 1.4	NP	15.1 ± 0.7	NP	NP	NP	10.1	20.6	2.7 ± 0.3	NP	NP	92.4
46V 1	08/14/2003	C	C	18.1 ± 0.7	NP	15.1 ± 0.4	NP	NP	NP	NP	4.6	4.0 ± 0.2	NP	NP	NP
46VS 1	08/14/2003	16.6 ± 1.1	NP	13.1 ± 1.1	NP	8.1 ± 3.2	8.1 ± 6.7	NP	NP	NP	0.1	–0.1 ± 0.2	NP	NP	NP
46VS 2	08/18/2004	19.6 ± 0.7	NP	16.6 ± 0.7	NP	16.6 ± 0.4	NP	NP	16.1 ± 0.4	13.1	13.1	NP	NP	99.5	80.4
46VS 6	08/23/2004	C	C	C	C	C	C	NP	NP	NP	3.6	0.0 ± 0.3	NP	NP	NP
46VS 8	08/23/2004	14.1 ± 1.8	6.1 ± 4.6	3.6 ± 6.0	3.6	12.6 ± 1.1	3.6	NP	NP	9.6 ± 0.7	8.6	4.0 ± 0.4	NP	NP	98.2
46VS 12	08/10/2005	17.1 ± 0.7	2.1	Mod.	C	15.6 ± 0.4	NP	NP	NP	14.6	20.1	10.6 ± 0.6	NP	NP	97.0
46VS 13	08/10/2005	C	C	C	C	14.6 ± 1.1	0.6	NP	NP	NP	18.6	4.2 ± 0.4	NP	NP	NP

Generally, the youngest apparent ages and binary mixtures are present at springs and wells in the upper reaches of the watersheds, whereas the older ages are present in the lower reaches (fig. 24). Nelms and Moberg (2010) sampled springs in Clarke County between 2003 and 2005 and noted that apparent ages were older and the percentage of the young water fraction decreased during this period, which indicates a relation with hydrologic conditions. Extremely wet conditions existed in 2003 and became progressively drier between 2004 and 2005. This distribution and temporal changes of apparent ages and mixing fractions is consistent with an aquifer system that is topographically driven with local flow systems containing young waters that are superimposed on a subregional to regional flow system with older waters. Therefore, under different hydrologic conditions, temporal changes in water-quality trends and dye-tracer studies would be expected to occur.

Plummer and others (2001) determined that apparent $^{3}H/^{3}He$ ages for spring water in Shenandoah National Park located in the Blue Ridge predominantly ranged from 0 to 3 years (fig. 24). Large precipitation events caused specific conductance and temperature to increase in these springs within a few hours of the event and then to decrease to values less than pre-storm base-flow values. Plummer and others (2001) also determined that mobile atmospheric constituents have flushing rates through groundwater to streams that average less than 3 years at base-flow conditions. These findings illustrate the close relation between spring flow and precipitation in the Blue Ridge. Additionally, the movement of contaminants from the surface to outlets such as springs and streams can be very rapid in the Blue Ridge.

Water discharging from springs in Warren County is generally younger than water from wells. The apparent ages for the well samples, however, are still young enough to be considered susceptible to contamination (Nelms and others, 2003) and to droughts. Well 46V 1, which is located near the top of High Knob and about 1,000 ft from spring 46VS 1 (fig. 24), has water with apparent ages that range from 4.0 to 4.6 years; however, the apparent age of groundwater from spring 46VS 1 is 0.1 year. Well 45U 3 is located along Dickeys Ridge in Shenandoah National Park and has apparent ages that range from 8.0 to 9.7 years (Plummer and others, 2001). The CFC and $^{3}H/^{3}He$ data indicate that between 47 and 55 percent of young water mixes with old (pre-CFC) waters (Plummer and others, 2001). The water-bearing zones reported for well 45U 3 were 600 and 625 ft bls in the metabasalt of the Catoctin Formation (DeKay, 1972). Nelms and others (2003) estimated an apparent age of 19.8 years and a binary mixture of 15.6 percent young water with pre-CFC water for well 44U 3 located along the South Fork Shenandoah River west of Limeton.

Revised Conceptual Model of Groundwater Flow

In the Blue Ridge, elevated topography provides the driving force for groundwater flow, and the water table is generally a subdued reflection of the land surface (fig. 26). The high density of streams in the Blue Ridge is probably the result of the underlying low permeability rocks. The porous nature of the overlying regolith material (overburden) and the sharp contrast in permeability with the underlying bedrock coupled with numerous streams and steep terrain are probably more conducive for the development of local flow systems. Wright (1990) and Nelms and Moberg (2010) stated that subsurface stormflow through the porous overburden moves rapidly to streams and springs in the Blue Ridge because of the steep terrain. Although the terrain is steep, overland flow is probably a minor component of runoff compared to subsurface stormflow (Whipkey, 1965). When siting potential sources of contamination in the future, the importance of subsurface stormflow in the Blue Ridge should be taken into consideration, especially in areas near stream valleys filled with alluvial and colluvial deposits. Groundwater flow in the bedrock is controlled primarily by the irregular fracture network and steep terrain (Wright, 1990). Local flow systems may be controlled by stress relief or other brittle fracturing; however, bedding-plane partings in the metasedimentary rocks, partings between basalt flows in the Catoctin Formation, and foliations in the metamorphic rocks may facilitate more of a subregional- to regional-type flow. Southworth (1990) proposed that water recharged on the western slopes of the mountains of the Blue Ridge flows downdip along bedding planes and eventually discharges to springs and in valleys on the eastern sides of the mountains.

Conceptualization of the groundwater flow system in the siliciclastic rocks on the western edge of the county, predominantly underlain by the Martinsburg Formation, is more similar to the groundwater flow system of the Blue Ridge than to that in the carbonate rocks of the Great Valley. Although the Martinsburg terrain is less steep and lower in altitude than the terrain of the Blue Ridge, local flow systems probably are dominant in response to the high density of streams that have formed the trellis (structurally controlled) drainage network. However, subsurface stormflow is probably a minor factor because of the lack of regolith material overlying the Martinsburg Formation (Hack, 1965) and less steep terrain. Groundwater moves along cleavage, bedding-plane partings, and longitudinal and cross-strike joints in a stair-step pattern (fig. 27). The interfluve to stream areas may act as local flow cells, where groundwater flowing along paths parallel to the dip direction of the bedding is younger than groundwater flowing opposite the dip direction (Burton and others, 2002). Hack and Young (1959) stated that many of the streams and creeks flow along the cross-strike joints. Evapotranspiration and, to a lesser extent, surface runoff may be greater than in the other areas of the county because of the low permeability of the rock and the absence of regolith material. Springs seldom form in areas underlain by the Martinsburg, and seeps are much more common.

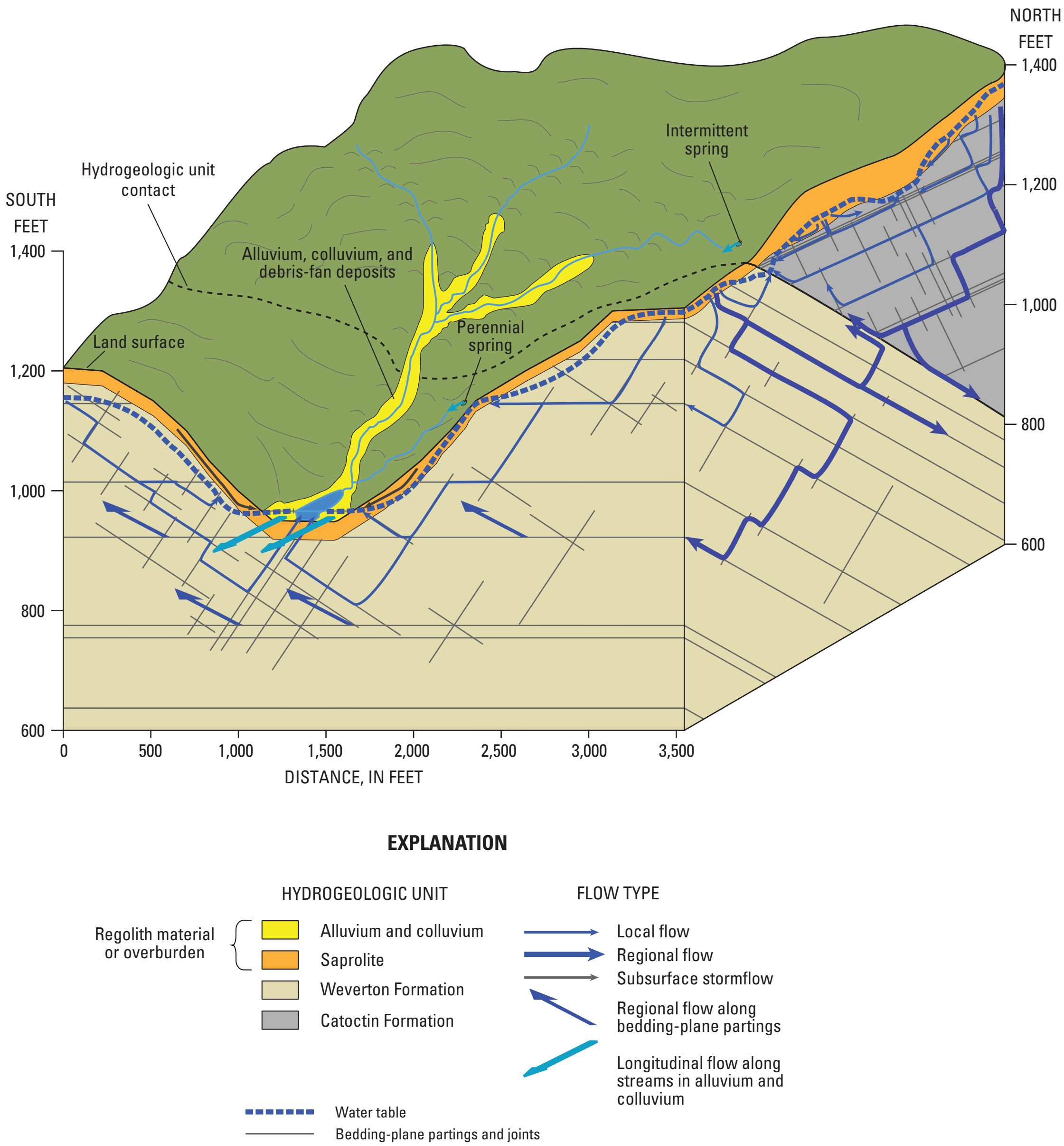

Figure 26. Generalized conceptual hydrogeologic longitudinal section of the flow system in the Blue Ridge Physiographic Province in Warren County, Virginia. Modified from Nelms and Moberg (2010).

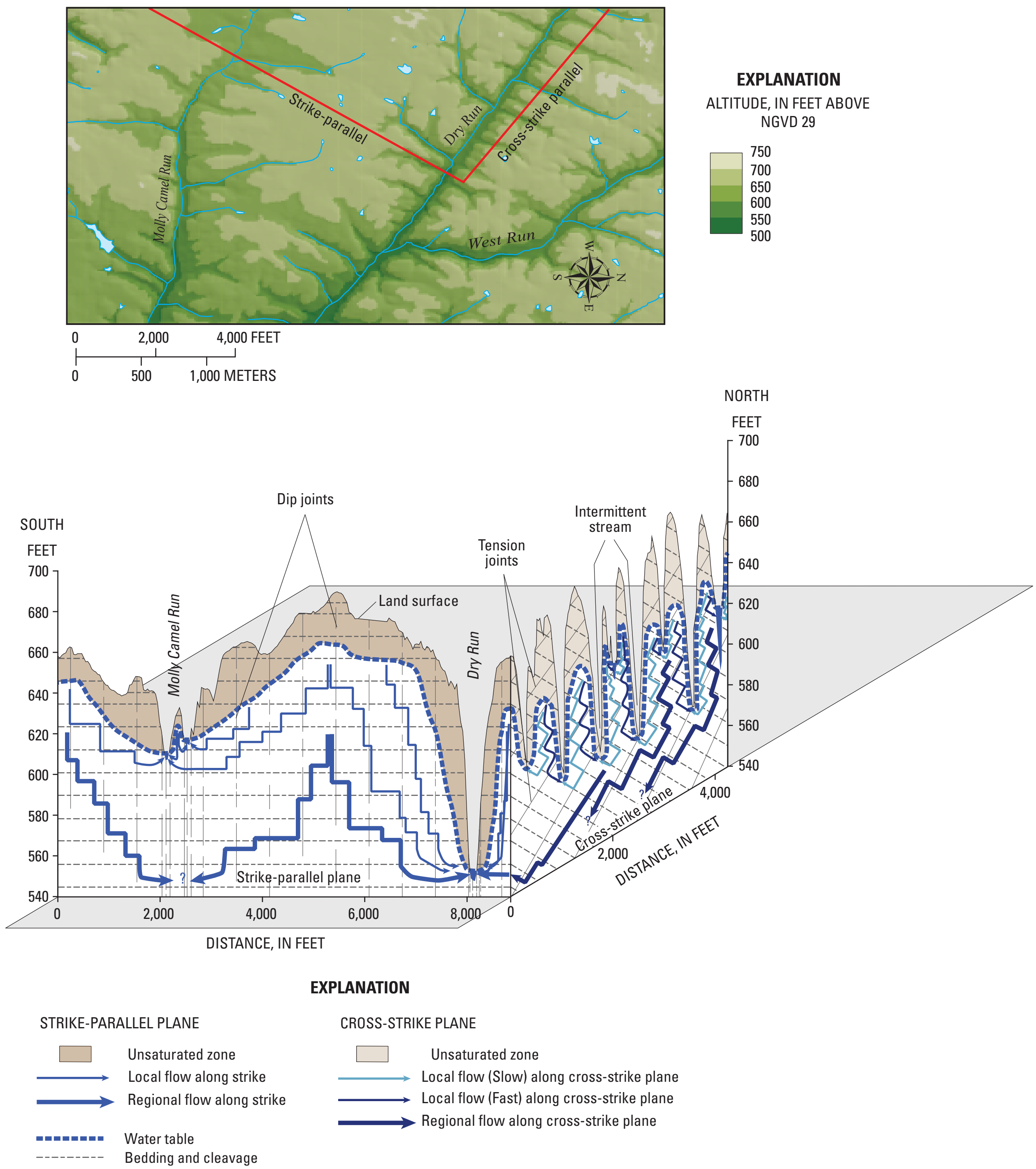

Figure 27. Generalized conceptual hydrogeologic sections along strike and cross-strike in the siliciclastic fractured-rock flow system (Martinsburg Formation) in Warren County, Virginia.

Groundwater Availability

The prolonged drought between 1999 and 2002 caused concern about current and future demands on the county's groundwater resources. In order to address these concerns, various components related to groundwater availability were determined during this investigation. Effective recharge rates to the groundwater system were estimated by a hydrograph separation technique that separates streamflow into base-flow (groundwater discharge) and surface-runoff components. Annual water budgets for the years 2001 through 2007 were developed for the basins gaged during this investigation. These water budgets include precipitation, mean annual streamflow and mean annual base-flow data, *ET,* changes in groundwater storage (from water-level data), estimates of specific yield, and water withdrawal data. For the 15 ungaged basins in the county, effective recharge was calculated using regression equations developed by Yager and others (2008) for the Shenandoah Valley area and was compared to projected water-supply demands.

Effective Recharge

Effective recharge (*ER*) is the part of precipitation that percolates to the water table and recharges the groundwater system but does not represent the total recharge to a basin. Total recharge has two components: (1) effective recharge and (2) riparian evapotranspiration (*RET*). *RET* is the quantity of water consumed by evaporation and transpiration by plants in riparian zones. Rutledge and Mesko (1996) reported that estimated values of *RET* ranged from 1 to 2 inches per year (in/yr) in the Appalachian Valley and Ridge from Alabama to New Jersey. Recharge occurs throughout a basin, but rates generally lessen toward discharge areas. Sinkholes in the Great Valley section and alluvium and colluvium in stream valleys of the Blue Ridge, however, can allow for substantial and rapid recharge. The amount of recharge depends on many factors, including antecedent soil-moisture conditions, the timing, duration, and intensity of precipitation, depth to the water table, and soil and bedrock characteristics (Harlow and others, 2005).

PART, a streamflow partitioning program (Rutledge, 1993), is a hydrograph separation technique that separates streamflow into its base-flow (groundwater discharge) and surface-runoff components. Effective recharge is equivalent to mean base flow (by means of unit conversion) because groundwater discharge over a long period approximately equals groundwater recharge (Richardson, 1982). Nelms and others (1997) estimated a median effective recharge of 11.1 in/yr in 46 basins and 8.4 in/yr in 73 basins in the northern Blue Ridge and Valley and Ridge Physiographic Provinces of Virginia, respectively. PART was applied to two unregulated streams [stations 01630700 (Gooney Run) and 0163626650 (Manassas Run)] and one regulated stream [station 01636242 (Crooked Run)] (table 4). A major assumption of PART is that the surface-water drainage basin and the recharge area coincide. Harlow and others (2005) noted that the validity of this assumption is uncertain. The unconsolidated deposits in the stream valleys of the Blue Ridge may have a larger effect on streamflow characteristics than the remaining areas of a basin do. Groundwater flow beneath surface-water divides in karst areas is well documented by dye-tracer studies (Jones, 1987; Orndorff, 2006). Regardless, the PART method provides a conservative estimate of effective recharge.

Streamflow-gaging station 01630700, Gooney Run at Route 622 near Glen Echo, VA, is in the southeastern corner of the county, has a drainage area of 20.5 mi^2, and has been in operation since May 2002 (fig. 15). The entire drainage area above this station is underlain by metamorphic bedrock, primarily the Mesoproterozoic granitic rocks, and debris-fan deposits and colluvium overlie the bedrock in about 33 percent of the basin. Very poorly sorted boulders and cobbles in a fine-grained matrix of sand, silt, and clay characterize the debris-fan deposits, and the colluvium consists of clast-supported cobbles and boulders (Southworth and others, 2009). The presence of these deposits over such a large area of the basin contributes to the strong diurnal streamflow signal (fig. 22) caused by *RET* frequently observed during base-flow conditions. To estimate annual effective recharge rates during the peak of the drought before the gage was installed, a linear regression equation was developed between effective recharge rates for gaging station 01630700 and those for streamflow-gaging station 01635500, Passage Creek above Route 55 near Buckton, VA (fig. 15), between 2003 and 2007. Estimates of effective groundwater recharge between 2001 and 2007 at the Gooney Run gage ranged from 10.0 to 28.1 in/yr with an average of 15.3 in/yr (table 4). Base flow accounted for between 64 and 86 percent of mean streamflow and averaged 71 percent between 2001 and 2007. These percentages are referred to as base-flow index (BFI). Nelms and others (1997) correlated partial-record streamflow data at gaging station 01630700 with continuous streamflow data and estimated an annual effective recharge rate of 16.5 in/yr.

Streamflow-gaging station 0163626650, Manassas Run at Route 645 near Front Royal, VA, is in the northeastern part of the county, has a drainage area of 11.2 mi^2, and has been in operation since May 2002 (fig. 15). The station is approximately 1,000 ft downstream from the Happy Creek fault. Metamorphic rocks of the Neoproterozoic Catoctin Formation and the Lower Cambrian Chilhowee Group underlie nearly the entire drainage area (99.3 percent) above this station. Carbonate rocks of the Lower Cambrian Waynesboro Formation underlie the small part of the basin downstream from the Happy Creek fault. Unconsolidated surficial deposits overlie the bedrock in about 11 percent of the basin and are concentrated along the stream valleys. The concentration of relatively coarse-grained surficial deposits along the stream valleys facilitates *RET* effects on streamflow, which are similar to the *RET* effects at gaging station 01630700 (Gooney Run) (fig. 22). To estimate annual effective recharge rates during the peak of the drought before the gage was installed, a linear

Table 4. Summary of annual water budget components for the Gooney Run, Crooked Run, and Manassas Run Basins in Warren County, Virginia, 2001–2007.

[DA, drainage area; mi², square miles; in/yr, inches per year; *P*, precipitation at National Weather Service station 443229 Front Royal SE located in Warren County, VA; *ET*, evapotranspiration; *SF*, mean streamflow; *RO*, runoff; *ER*, effective recharge estimated from streamflow partitioning program PART (Rutledge, 1993); Δ*S*, change in groundwater storage; *WU*, water usage; BFI, base-flow index. Percentages of annual precipitation are shown in parentheses. Blue-shaded rows indicate years with above-average precipitation, and unshaded rows indicate years with below-average precipitation]

Station no. (fig. 15)	Station	DA (mi²)	Calendar year[a]	Inflow[b] (in/yr)	Outflow[b] (in/yr)						Percent of normal *ER*	*WU* percent of *ER*	BFI
				P[c]	*ET*	*SF*[d]	*RO*[d]	*ER*[d]	Δ*S*[e]	*WU*[f]			
01630700	Gooney Run at Route 622 near Glen Echo, Virginia	20.5	2001	36.7	19.2	17.6	6.3	11.3	–0.2	0.1	67	0.7	64.1
			2002	43.4	25.8	17.9	6.5	11.4	–0.4	0.1	67	0.7	63.5
			2003	59.2	19.7	38.4	10.3	28.1	1.0	0.1	166	0.3	73.1
			2004	45.1	21.9	23.3	6.6	16.6	–0.1	0.1	99	0.5	71.5
			2005	39.6	19.4	19.9	5.4	14.6	0.2	0.1	86	0.6	73.1
			2006	43.2	21.1	22.0	6.9	15.0	0.0	0.1	89	0.6	68.4
			2007	31.6	19.8	11.7	1.7	10.0	0.0	0.1	59	0.8	85.6
			Average	42.7	21.0 (49.2)	21.5 (50.4)	6.3 (14.8)	15.3 (35.8)	0.1 (0.2)	0.1 (0.2)		0.5	70.9
01636242	Crooked Run below Route 340 at Riverton, Virginia	46.9	2001	36.7	29.7	7.0	4.7	2.4	–0.2	0.2	37	8.1	33.7
			2002	43.4	36.4	7.2	4.8	2.4	–0.4	0.2	37	7.9	33.4
			2003	59.2	34.2	22.7	7.9	14.8	2.1	0.2	230	1.3	65.3
			2004	45.1	34.2	11.0	4.8	6.2	–0.3	0.2	96	3.1	56.3
			2005	39.6	32.3	7.7	3.4	4.3	–0.5	0.2	66	4.5	55.6
			2006	43.2	34.8	7.8	4.1	3.7	0.5	0.2	58	5.1	47.8
			2007	31.6	25.1	6.1	2.9	3.3	0.2	0.2	51	5.9	53.3
			Average	42.7	32.4 (75.9)	9.9 (23.2)	4.6 (10.8)	5.3 (12.4)	0.2 (0.5)	0.2 (0.5)		3.6	53.5
0163626650	Manassas Run at Route 645 near Front Royal, Virginia	11.2	2001	36.7	20.2	16.4	6.9	9.5	–0.2	0.3	59	2.9	57.9
			2002	43.4	26.9	16.6	7.1	9.6	–0.4	0.3	60	2.8	57.4
			2003	59.2	20.6	37.4	8.0	29.4	1.0	0.3	183	0.9	78.7
			2004	45.1	23.2	21.7	6.9	14.8	–0.1	0.3	92	1.8	68.0
			2005	39.6	16.1	23.1	6.2	16.9	0.2	0.3	105	1.6	73.0
			2006	43.2	26.2	16.7	5.7	11.1	0.0	0.3	69	2.5	66.1
			2007	31.6	20.8	10.5	2.3	8.2	0.0	0.3	51	3.3	77.7
			Average	42.7	22.0 (51.5)	20.3 (47.5)	6.2 (14.5)	14.2 (33.3)	0.1 (0.2)	0.3 (0.7)		1.9	70.0

[a] For the years 2001–2002 at streamflow gages 01630700 and 0163626650 and for the years 2001–2004 at streamflow gage 01636242, estimates are based on linear regression with streamflow-gaging station 01635500 Passage Creek above Route 55 near Buckton, VA.

[b] Water-budget equation is $P = ET + RO + ER + \Delta S + WU$. Estimates of *SF* and *ER* were determined from PART, which is a streamflow partitioning program (Rutledge, 1993). *RO* is estimated as the difference between *SF* and *ER*. The terms *P*, *RO*, Δ*S*, *WU*, and *ER* are known, measured, or estimated; therefore, solution of the water-budget equation provides an estimation of *ET*.

[c] Normal annual precipitation of 39.7 inches at National Weather Service station 443229 Front Royal is based on the period of record from 1996 to 2007.

[d] To convert inches per year to cubic feet per second, divide value by 13.5837 and then multiply by drainage area (in square miles).

[e] Δ*S* is based on the highest water levels recorded for the respective calendar year subtracted from the highest value for the previous year. For the calendar years 2001–2004, Δ*S* was calculated using water-level data from well 46W175 in Clarke County, VA. For calendar years 2005–2007, Δ*S* was calculated using water levels measured at well 45V.

[f] Source is 2000 U.S. Census population data (U.S. Census Bureau, 2003). Individual water use is estimated to be 75 gallons per day.

regression equation was developed between effective recharge rates for gaging station 0163626650 and those for streamflow-gaging station 01635500 (Passage Creek). Estimates of effective groundwater recharge between 2001 and 2007 at the Manassas Run gage ranged from 8.2 to 29.4 in/yr with an average of 14.2 in/yr (table 4). Base flow accounted for between 57 and 79 percent of mean streamflow and averaged 70 percent between 2001 and 2007. The high BFI values at gaging stations 01630700 (Gooney Run) and 0163626650 (Manassas Run) indicate that groundwater is the dominant source of streamflow during wet and drought conditions.

The diurnal streamflow signals observed at gaging stations 01630700 (Gooney Run) and 0163626650 (Manassas Run) illustrate the combined effect that evapotranspiration processes and the presence of shallow unconsolidated surficial deposits in the stream valleys can have on streamflow in the Blue Ridge, particularly during the warmer months of the spring and summer seasons. A majority of the area in both basins is forested, especially along the riparian areas where these surficial deposits are present in and near the streams. Analysis of the diurnal streamflow signal, similar to the method developed by Czikowsky and Fitzjarrald (2004), provides estimates of *RET*. Periods of streamflow cyclicity between April and October were identified, and the differences between maximum daily streamflows for consecutive days were calculated to determine the amount of *RET*. Statistical analysis of these daily changes in streamflow provides estimates of *RET* for 2003–2008 (table 5). Average values for the annual means probably are biased high by inclusion of streamflows where diurnal signals may have included effects of recent precipitation events and not only responses to *RET*. However, the average values for annual medians (1.6 and 2.5 in.) are similar to values of *RET* estimated by Rutledge and Mesko (1996). A seasonal trend is evident where *RET* values tend to be high between April and June and progressively lessen as the growing season progresses (table 5). Because deforestation and construction of riparian buffer strips are likely to impact streamflow in these and in other Blue Ridge basins, monitoring might be advisable.

Streamflow-gaging station 01636242 Crooked Run below Route 340 at Riverton, VA, is in the northern part of the county, has a drainage area of 46.9 mi^2, and has been in operation since October 2004 (fig. 15). A majority of the drainage basin for this gage is located in neighboring counties to the north. The station is approximately 450 ft downstream from the contact between the siliciclastic rocks of the Middle and Upper Ordovician Martinsburg Formation and the Middle Ordovician carbonate rocks. The station is slightly less than 1 mi from the confluence with the Shenandoah River. Part of the flow in Crooked Run is regulated by Lake Frederick, which is located in Frederick County; however, only about 7 percent of the drainage area of Crooked Run is upstream

Table 5. Annual and seasonal estimates of riparian evapotranspiration based on periods of streamflow diurnal cycling at gages 01630700 Gooney Run at Route 622 near Glen Echo, Virginia, and 0163626650 Manassas Run at Route 645 near Front Royal, Virginia, from calendar years 2003 to 2008.

[Estimates of riparian evapotranspiration are in inches per year. DA, drainage area; mi^2, square miles]

Station no. (fig. 15)	Station	DA (mi^2)	Annual riparian evapotranspiration [a]			Seasonal riparian evapotranspiration [a]		
			Year	Mean	Median	Season [b]	Mean	Median
01630700	Gooney Run at Route 622 near Glen Echo, Virginia	20.5	2003	9.5	4.3	1	10.0	2.0
			2004	7.0	1.4	2	4.1	0.5
			2005	8.9	0.7	3	0.2	0.1
			2006	18.5	1.3			
			2007	3.4	1.0			
			2008	4.8	0.9			
			Average	8.7	1.6			
0163626650	Manassas Run at Route 645 near Front Royal, Virginia	11.2	2003	9.0	4.8	1	8.7	2.4
			2004	12.8	4.7	2	3.7	1.0
			2005	5.8	2.4	3	0.3	0.3
			2006	6.0	1.2			
			2007	3.3	0.7			
			2008	7.6	1.2			
			Average	7.4	2.5			

[a] Periods of streamflow cyclicity between April and October were identified, and the differences between maximum daily streamflows for consecutive days were calculated to determine the amount of riparian evapotranspiration.

[b] Seasons are grouped by the following months, and seasonal estimates of riparian evapotranspiration are from the period 2003–2008: 1–April, May, and June; 2–July, August, and September; and 3–October, November, and December.

from the spillway for Lake Frederick. Siliciclastic rocks of the Martinsburg Formation underlie about 74 percent of the drainage area above this station, and carbonate rocks underlie the remainder. Quaternary alluvium is present mainly along Crooked Run and is absent along the tributaries (Rader and Conley, 1995). For the most part, the streambeds for Crooked Run and its tributaries are in bedrock. The tributaries align with the cross-strike joints; however, Crooked Run generally follows the contact between the siliciclastic and carbonate rocks (fig. 15). In order to estimate annual effective recharge rates during the peak of the drought (2002) prior to gage installation, a linear regression equation was developed between effective recharge rates for gage 01636242 and those for streamflow-gaging station 01635500 between 2005 and 2007. Estimates of effective groundwater recharge between 2001 and 2007 range from 2.4 to 14.8 in/yr with an average at the Crooked Run gage of 5.3 in/yr (table 4). Base flow accounted for between 33 and 65 percent of mean streamflow and averaged 54 percent between 2001 and 2007. Although this stream is regulated, the average effective recharge is similar to the value of 4.9 in/yr estimated by Nelms and others (1997) for gaging station 01615000 Opequon Creek near Berryville, VA, which monitors a similar distribution of rock types. The average BFI (54 percent) is much lower than the averages for Gooney Run and Manassas Run and may be reflective of the low permeability of the Martinsburg Formation and (or) an artifact of regulation.

Analysis of data collected from Warren County's long-term water monitoring network and of effective recharge rates indicates a positive correlation with current climatic conditions. Comparison of annual recharge rates at streamflow gages 01630700, 0163626650, and 01636242 to annual precipitation illustrates the relation between these two hydrologic factors (fig. 28). Annual effective recharge ranges from 22 to 50 percent of annual precipitation for the gages in the Blue Ridge and averages from 33 to 36 percent (table 4). Annual effective recharge ranges from 6 to 25 percent of annual precipitation with an average of 12 percent for gage 01636242 in the siliciclastic rocks of the Valley and Ridge. The timing and type of precipitation are critical in determining the amount of water that will actually recharge the groundwater system. The prime period for groundwater recharge is between January and April of each year when plants are dormant, evapotranspiration is at a minimum, and average monthly precipitation is low. For example, in the years 2002 and 2006, precipitation and snowfall for the winter quarters were below average, and effective recharge rates deviate from the apparent correlation. Generally, water levels, spring discharges, and streamflows normally are at the yearly high by April of each year and progressively decline to their lowest in the early autumn. Intense rainfall associated with hurricanes, tropical storms, or thunderstorms can cause levels and flows to increase short term. However, it is uncertain whether actual recharge occurs during these storms or if the responses observed in observation wells are a function of saturated sediments in the unsaturated zone exerting pressure on the gases in the unsaturated zone, which, in turn, causes the water table to be at pressures greater than atmospheric pressures (Freeze and Cherry, 1979).

The relation between estimated effective recharge and annual precipitation was investigated by linear regression analysis. The equations developed for streamflow gages 01630700, 01636242, and 0163626650 are given in table 6. These equations should not be considered predictive because of the short period of record of these gages and the inclusion of estimated recharge rates by regression with another gage. The steep slopes of the regressions for gages 01630700 and 0163626650 (0.66*P* and 0.75*P*, respectively) indicate that effective recharge is closely related to precipitation. Variability, however, is less at gage 01630700 than at gage 0163626650 (fig. 28). The difference in variability between these gages may be in response to such factors as the amount and type of unconsolidated surficial material, amount and spatial distribution of precipitation, size of drainage basin, and shape and orientation of the drainage basin. The drainage area above gage 01630700 has (1) nearly 3 times the amount of unconsolidated surficial material, (2) higher mean annual precipitation and greater range of precipitation amounts, and (3) a drainage area that is about 2 times larger than the drainage area above gage 0163626650. The amphitheater-shaped, north-facing orientation of the drainage area for gage 01630700 (fig. 15) is uniquely different from the east-west aligned drainage area for gage 0163626650. All of these factors contribute to the variability between these basins; however, both of these basins are influenced by the abundance

Table 6. Linear regression equations relating effective recharge to annual precipitation at gages 01630700, Gooney Run at Route 622 near Glen Echo, Virginia, 01636242, Crooked Run below Route 340 at Riverton, Virginia, and 0163626650, Manassas Run at Route 645 near Front Royal, Virginia, 2001–2007.

[DA, drainage area; mi², square miles; in/yr, inches per year; R^2, coefficient of determination; *ER*, effective recharge; *P*, precipitation. Shading indicates dominant rock type: Green, metamorphic rocks in the Blue Ridge Physiographic Province; Brown, siliciclastic rocks of the Valley and Ridge Physiographic Province]

Station no. (fig. 15)	Gage	DA (mi²)	Equation (in/yr)	R^2
01630700	Gooney Run at Route 622 near Glen Echo, Virginia	20.5	$ER = 0.66P - 12.98$	0.87
01636242	Crooked Run below Route 340 at Riverton, Virginia	46.9	$ER = 0.45P - 13.78$	0.77
0163626650	Manassas Run at Route 645 near Front Royal, Virginia	11.2	$ER = 0.75P - 17.80$	0.76

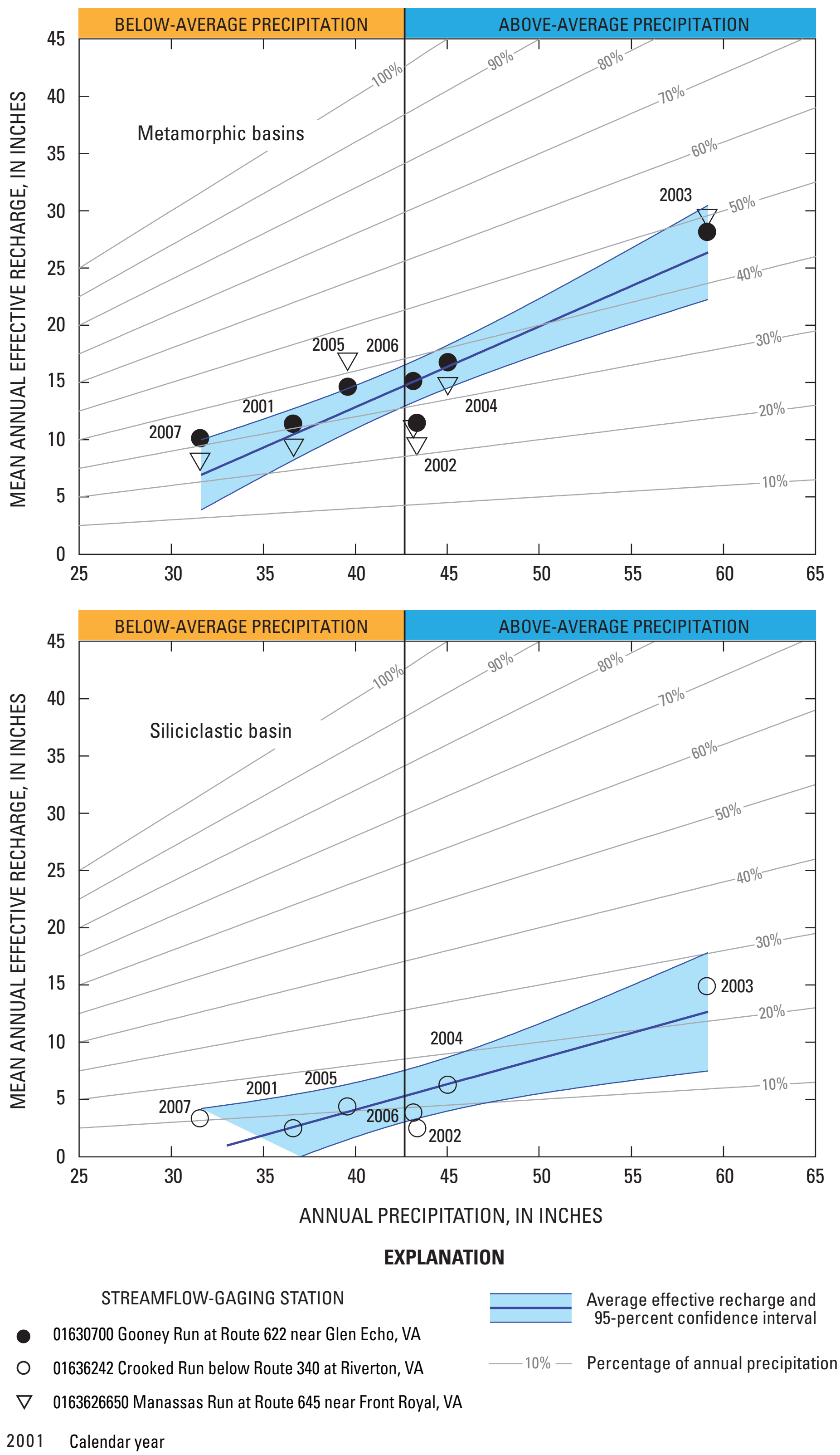

Figure 28. Relation between annual precipitation at National Weather Service climatological station 443229 Front Royal, Virginia, and effective recharge at streamflow-gaging stations 01630700 Gooney Run at Route 622 near Glen Echo, Virginia, 01636242 Crooked Run below Route 340 at Riverton, Virginia, and 0163626650 Manassas Run at Route 645 near Front Royal, Virginia. For the years 2001–2002 at streamflow-gaging stations 01630700 and 0163626650 and for the years 2001–2004 at streamflow-gaging station 01636242, estimates are based on linear regression with streamflow-gaging station 01635500 Passage Creek above Route 55 near Buckton, Virginia. Effective recharge rates for remaining years are estimated with the streamflow partitioning software package PART (Rutledge, 1993).

of unconsolidated surficial material overlying the bedrock (33 percent at gage 01630700 compared to 11 percent at gage 0163626650). The drastic difference in permeability between these deposits and the bedrock combined with correlation of recharge rates and precipitation, diurnal streamflow signals in response to *RET*, and factors listed above suggest that the unconsolidated surficial material in the riparian area functions as a local flow system above the fractured-rock aquifers. In the strict sense, the assumptions of PART are not violated, but estimated effective recharge rates may be more reflective of these local riparian flow systems and not of the fractured-rock aquifers. Development of these local flow systems for water supply is generally not feasible because the unconsolidated deposits are thin, of limited extent, and highly susceptible to current climatic conditions and surface contaminants. The fractured-rock aquifers are the principal source for current and future water supplies; the average recharge rates for gages 01630700 and 0163626650, therefore, should be used with caution and may not accurately represent recharge to the bedrock aquifers in the Blue Ridge.

The slope of the linear regression for gage 01636242 suggests that a positive relation exists between estimated effective recharge and annual precipitation (table 6). The low slope of the regression (0.45*P*) indicates that other factors, such as permeability, evapotranspiration, and runoff, may affect the relation between groundwater recharge and precipitation. The siliciclastic part of the Martinsburg Formation generally is considered to be relatively impermeable with a thin mantle of residuum (Cady, 1936, 1938; Hack, 1965; Trainer and Watkins, 1975; Hinkle and Sterrett, 1976, 1977, 1978; Wright, 1990; Yager and others, 2008). The dense stream network in this basin and average ratio of mean streamflow to drainage area (1.37 cubic feet per second per square mile [$(ft^3/s)/mi^2$]) is characteristic of low permeability terrains. The relatively high average value for *ET* (table 4) suggests that downward percolation of precipitation is slow, and evapotranspiration at or near land surface consumes the infiltrating water. The combination of the aforementioned factors and the lack of unconsolidated surficial deposits in the drainage area above gage 01636242 suggests that the estimated effective recharge rates reflect recharge to the fractured-rock aquifers in siliciclastic terrains.

Nelms and others (1997) estimated effective recharge rates for other gages in and around the county using hydrograph separation methods (PART). An effective recharge rate of 6.2 in/yr for 1933–1983 was estimated at gaging station 01635500 Passage Creek above Route 55 near Buckton, VA, which drains the siliciclastic rock unit. Gaging station 01636270 Borden Marsh Run at Route 624 near Boyce, VA, which is predominantly underlain by the carbonate rock unit, had an estimated effective recharge rate of 12.8 in/yr. Effective recharge rates for the North Fork and South Fork Shenandoah River (stations 01633000 and 01631000, respectively) were estimated to be 6.3 and 8.8 in/yr, respectively. Harlow and others (2005) estimated an effective recharge rate of 7.7 in/yr for 1938–2002 at gaging station 01634500 Cedar Creek near Winchester, VA, with the entire drainage area above this station underlain by siliciclastic bedrock. The period studied by Harlow and others (2005) was at the height of the 1999–2002 drought. Effective recharge estimated for 2001–2002 ranged from 3.2 to 6.2 in/yr for siliciclastic and carbonate basins. Nelms and Moberg (2010) estimated average effective recharge rates of approximately 12 in/yr for two carbonate basins in Clarke County for 2001–2007.

The knowledge that groundwater is a major component of streamflow in the county should be noted when evaluating water-resources issues. The values for BFI, which is base flow as a percentage of mean streamflow, indicate that groundwater composes about 70 and 54 percent of mean streamflow in the metamorphic and siliciclastic terrains, respectively (table 4). Harlow and others (2005) and Nelms and Moberg (2010) determined that groundwater is an even greater component of streamflow in carbonate terrains with values of BFI between 80 and 90 percent. Both of these investigations state that springs are commonly the start of flows for streams in the carbonate terrains, and spring discharges, especially during drought conditions, often are a large part of the streamflow.

Water Budgets for Gaged Basins

Water budgets represent an estimate of the amount of water entering and leaving a basin plus or minus changes in storage during a specified time period (Harlow and others, 2005). Precipitation is the dominant inflow to a basin; outflows are streamflow, *ET*, and groundwater and surface-water withdrawals. All of the water-budget components are in terms of mean annual values. The water-budget equation can take many forms (Healy and others, 2007), but a simplified version that is most relevant in water-supply planning can be written as:

$$P = ET + RO + \Delta S + WU + ER, \qquad (4)$$

where

- P is precipitation, in inches per year;
- ET is evapotranspiration, in inches per year;
- RO is mean runoff, in inches per year;
- ΔS is change in groundwater storage, in inches per year;
- WU is water usage (withdrawals), in inches per year; and
- ER is effective recharge (mean base flow or groundwater discharge), in inches per year.

This form of the water-budget equation assumes that groundwater and surface-water divides are coincident and does not take into account underflow that may enter or leave a basin. Underflow in a basin in Pennsylvania that is underlain by carbonate rock has been estimated to be 2.4 in/yr (Senior and others, 1997).

The terms *P, RO,* Δ*S, WU, and ER* are either known, measured, or estimated; solution of the water-budget equation, therefore, provides an estimation of *ET*. Harlow and others (2005) noted that the term *ET* also includes deviations from the assumptions of the equation, such as underflow between basins, other losses, and errors in the other terms. Average annual water budgets for calendar years 2001 and 2007 were prepared for Gooney Run, Manassas Run, and Crooked Run Basins (table 4) using methods discussed in this report.

Annual precipitation data (*P*, table 4), which include rainfall and snowfall, were obtained from the NWS climatological station 443229 Front Royal located in Warren County. Annual precipitation between 2001 and 2007 ranged from 31.6 to 59.2 in. with an average value of 42.7, which is 3 in. more than the average value for the station for the period of record from 1996 to 2007. Therefore, the dominant inflow component (*P*) of the calculated water budgets probably represents an average annual precipitation value for above-normal conditions (table 4). Calendar years 2001, 2005, and 2007 are the only years for which estimates are provided for below-average precipitation conditions.

The estimation of *ET* is one of the shortcomings of any water-budget calculation. For the water budgets determined for the Gooney Run, Manassas Run, and Crooked Run Basins, *ET* is estimated by solution of equation 4 and also includes underflow, other losses, and errors (Harlow and others, 2005). However, the declines in water levels, spring discharges, and streamflows during the spring and summer months indicate that *ET* is probably the dominant outflow component for any water budget in the area. About 50 percent of the precipitation that fell on the Gooney Run and Manassas Run Basins between 2001 and 2007 was removed by *ET*; a much larger percentage (76 percent) of precipitation was removed by *ET* in the Crooked Run Basin (table 4). Harlow and others (2005) determined that *ET* was between 74 to 90 percent of the precipitation between 2001 and 2002 at the height of the last major drought in the region. *ET* for a period of average precipitation in two carbonate drainage basins in Clarke County was about 65 percent of precipitation (Nelms and Moberg, 2010).

The *RO* (surface or mean runoff) term is estimated by subtracting effective recharge (*ER*, table 4) (base flow) from mean streamflow (*SF*). The steep terrain of the Blue Ridge province is conducive for runoff, yet in the Gooney Run and Manassas Run Basins, *RO* was only about 15 percent of the precipitation for a period of above-average precipitation. Whipkey (1965) stated that overland flow is a lesser component of runoff than subsurface stormflow. The relatively high permeability of the unconsolidated surficial material could allow runoff to be intercepted by these deposits prior to the stream. The gently sloping to flat terrain in the Crooked Run Basin is not conducive to runoff; only 11 percent of the precipitation is runoff. Harlow and others (2005) determined that *RO* for predominantly carbonate drainage basins was well below 10 percent of the precipitation in 2001–2002 at the height of the last major drought in the region. Even during a period of average precipitation, *RO* in carbonate basins in Clarke County was less than 4 percent of precipitation (Nelms and Moberg, 2010). The high permeability of the carbonate rocks and low relief are not conducive for runoff.

Changes in groundwater storage (Δ*S*) are normally negligible in water-budget calculations in fractured-rock and karst terrains. Values for Δ*S* were included in the water budgets in table 4. For the calendar years 2001–2004, changes in groundwater storage were calculated using water-level data from well 46W175 located in Clarke County, VA. Changes in storage for the remaining years were calculated by using water levels measured at well 45V 3. In order to calculate Δ*S*, the water-level changes were multiplied by 0.01, which is the estimated specific yield of the zone of water-level fluctuation (Harlow and others, 2005). Although water-level fluctuations can be large in the county, changes in groundwater storage on average are very small (table 4).

The amount of water withdrawn from a basin is the component of greatest interest in any water budget. In all three basins, domestic withdrawal of groundwater is the primary use of water and was considered to be consumptive. In order to calculate total water usage (*WU*), shapefiles of the basin boundaries were intersected with population data (U.S. Census Bureau, 2003); the respective basin population estimates were multiplied by 75 gallons per day (gal/d), which is the per person water-use estimate for Virginia (Hutson and others, 2004). The total daily domestic water usage for each basin was then converted to a yearly estimate and normalized across each respective basin (table 4). *WU* in Gooney Run, Manassas Run, and Crooked Run Basins is estimated to be 0.1, 0.3, and 0.2 in/yr, respectively, which is equal to 0.08, 0.14, and 0.43 million gallons per day (Mgal/d), respectively. The total daily domestic water usage appears to be substantial; but in terms of the overall water budget, *WU* on average is only a small percentage (table 4). The assumption, however, that *WU* is consumptive is not completely valid because the predominant method of sewage disposal in the county is by onsite septic wastewater-treatment systems. Landers and Ankcorn (2008) documented increases in base flow for watersheds with a high density of septic systems (greater than 200 systems per square mile) in metropolitan Atlanta, GA, in response to septic outflow of municipal surface-water supplies. Keyworth (2009) estimated that 85 percent of the wastewater discharged to septic systems is returned to the groundwater system.

For water-supply planning in fractured-rock and karst terrains, the most useful water-budget component is *ER* (effective recharge). Groundwater storage in the type of aquifer systems in Warren County is minimal; therefore, the amount of water that recharges the groundwater system each year is critical. For the period 2001–2007, about 34 percent of the precipitation that fell in the Gooney Run and Manassas Run Basins reached the water table as recharge (table 4). As stated earlier, a majority of this recharge is to the local riparian flow systems and not to the bedrock. During the same period, only 12 percent of the precipitation in the Crooked Run Basin was *ER*. Analysis of data collected by the long-term water monitoring network indicates that these systems are extremely vulnerable to current climatic conditions. Successive years of below-average *ER* cause declines in water levels, spring discharges, and streamflows; however, these systems can recover quickly as *ER* increases. As is shown in figure 28, *ER* tends to increase as precipitation increases, but lack of precipitation, especially snow, during the critical recharge periods (January–April) can have a substantial effect on the amount of *ER*. Evaluation of the effect that future development will have on the water resources often assumes an *ER* rate of 50 percent of normal. This assumption may be reasonable in the Crooked Run Basin, but may not adequately assess future effects in the Blue Ridge basins. An even lower percentage estimate could help plan for droughts in the future that may be more severe than the drought between 1999 and 2002. Future water-supply planning efforts should also include consideration of the percentage of water withdrawals in relation to *ER*. Future development could cause reductions in groundwater recharge (resulting from increases in impervious area), increased water consumption, or the transfer of water to other basins, and concomitant reductions in mean streamflow would be expected in these systems where groundwater is such a major component of streamflow.

Water Budgets for Ungaged Basins

Warren County was divided into 15 basins (fig. 29) based on the delineation of watershed boundaries digitized by the Virginia Department of Conservation and Recreation (Karl Huber, Virginia Department of Conservation and Recreation, written commun., 2006). In order to estimate *ER* rates for each of these ungaged basins (table 7), a linear regression model developed by Yager and others (2008), which is based on the percentage of the basin underlain by respective rock types, was used. The equation uses *ER* rates estimated by Nelms and others (1997) for 20 basins in the Shenandoah Valley and is

$$Rech = 5.5 + 4.3Carb + 3.6Meta + 10.1West, \quad (5)$$

where the percentage of basin underlain by the respective rock unit [carbonate (*Carb*), metamorphic (*Meta*), and western-toe carbonate (*West*) are the explanatory variables]. The percentage of siliciclastic rocks is included implicitly (5.5), and the resultant *ER* rates are in inches per year. The results from this method (table 7) indicate an *ER* rate of 9.7 in/yr for the basins predominantly underlain by carbonate rocks, *ER* rates of 8.2 to 9.3 in/yr in the Blue Ridge areas, and *ER* rates of 5.5 to 6.9 in/yr for basins predominantly underlain by the siliciclastic rock unit. The range in regression-derived recharge rates for the siliciclastic basins is very similar to the average value (5.3 in/yr) estimated from hydrograph separation for the drainage area above the Crooked Run streamflow gage 01636242 (table 4). Regression-derived *ER* rates for the basins predominantly underlain by the metamorphic rock unit of the Blue Ridge are about 40 percent less than those determined using hydrograph separation methods for the drainage areas for gages 01630700 and 0163626650 (15.3 in/yr and 14.2 in/yr, respectively). Yager and others (2008) primarily focused on the fractured-rock and karst aquifers of the Shenandoah Valley and used regression-derived recharge rates in model design, calibration, and sensitivity. Therefore, the regression-derived *ER* rates represent a more robust estimate of *ER* rates for the parts of the groundwater flow system used for water supply than the rates estimated from hydrograph separation, which may be influenced by local riparian flow systems in the unconsolidated surficial deposits.

Concerns about future demands on the groundwater resources can be addressed by evaluating certain components of water budgets in these ungaged basins. Warren County is densely parceled with more than 20,000 individual parcels with an average size of 5.4 acres, but about 10,300 of these parcels are less than 1 acre (fig. 29). An analysis was conducted to estimate total domestic water use at future buildout of these parcels. Single-family dwellings at buildout were assumed for each parcel in a basin with 2.48 people per household using 75 gal/d per person. The water-use totals shown in table 7 range from 0.04 to 1.38 in/yr, which is equivalent to 0.001 to 1.03 Mgal/d. Total domestic withdrawals in the county are estimated to be 3.8 Mgal/d at future buildout. Current evaluations of proposed developments by the county are based on the relation between demand and 50 percent of average *ER* rates. The regression-derived *ER* rates in table 7 are considered to be average values, and various percentages of these rates are shown in figure 30 in relation to expected water use at buildout.

Water use at buildout is a small percentage of the average *ER* rates estimated for each ungaged basin and does not exceed the management threshold of 50 percent of average *ER* rate for the respective basins (fig. 30). Consideration of lower percentages of average rates of *ER*, which would be characteristic of drought conditions, indicate that water use at buildout could be a substantial portion of recharge, and, in some basins, this use could exceed groundwater recharge. Successive years of below-average rainfall and snowfall, especially during the prime groundwater recharge months between January and April, would have a cumulative effect on recharge. The county has documented well failures during drought and wet conditions. These failures could have resulted from several factors including precipitation amounts and timing, shallow well depths, recharge rates less than the basinwide average value used for water-resources management, and well interference issues, among others. As stated earlier, groundwater is a dominant part of mean streamflow, and its effects on surface water should be considered in any water-resources management evaluation. Long-term monitoring data are necessary in the evaluation process to document changes in streamflows and groundwater levels as development progresses. In addition, Bredehoeft (2002) suggests that use of groundwater models are a better means of assessing sustainable development than those based solely on recharge, and accurate groundwater simulations rely upon long-term hydrologic data.

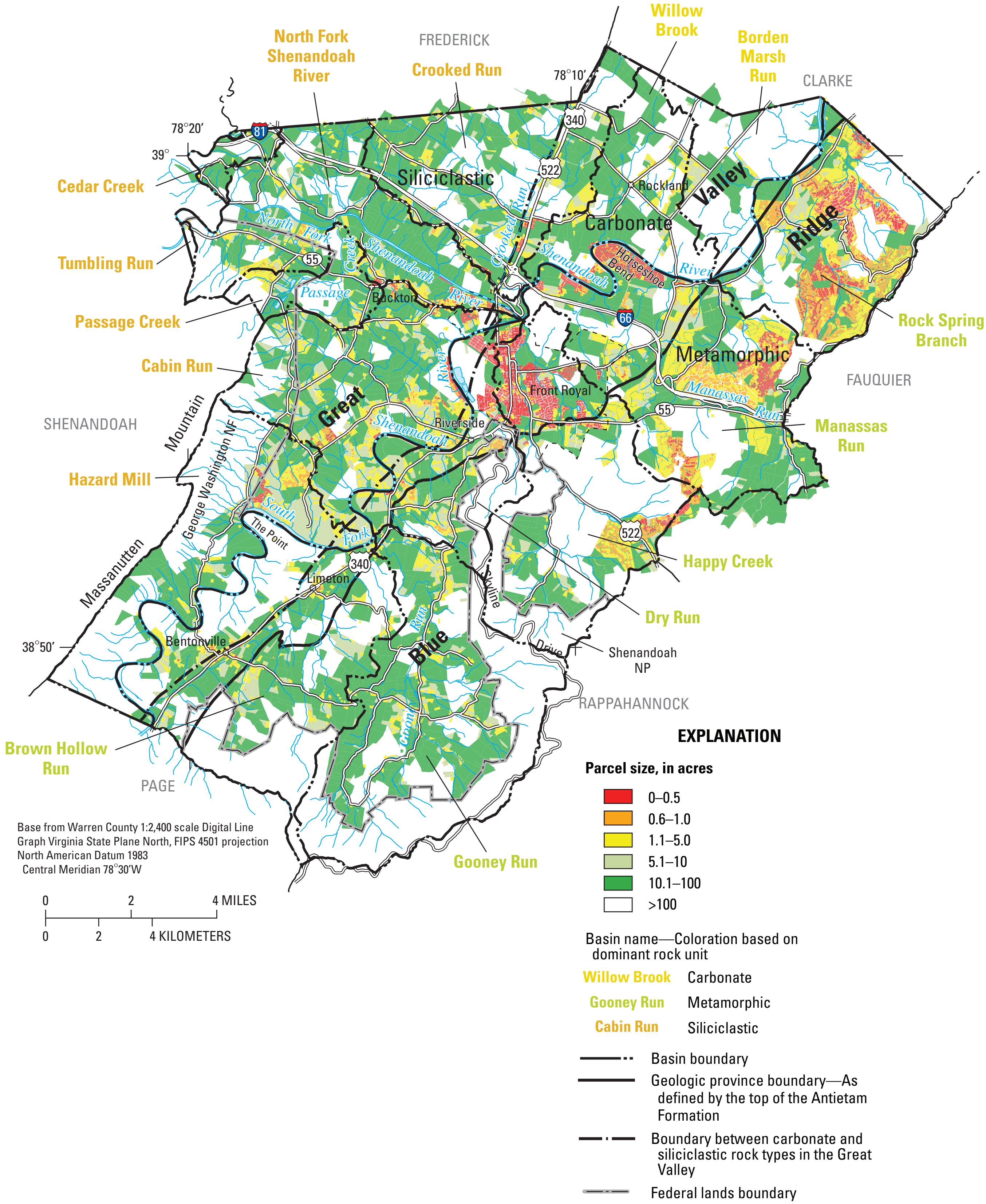

Figure 29. Drainage basins and parcel acreage in Warren County, Virginia.

Table 7. Physical and geologic characteristics, estimated effective recharge rates, and estimated water use at buildout of ungaged basins in Warren County, Virginia.

[NGVD 29, National Geodetic Vertical Datum of 1929; Min, minimum; Max, maximum; np, not present. Shading indicates dominant rock type: Green, metamorphic rocks in the Blue Ridge Physiographic Province; Brown, siliciclastic rocks of the Valley and Ridge Physiographic Province; Yellow, carbonate rocks of the Valley and Ridge Physiographic Province]

Basin		Area (square miles)	Altitude (feet above NGVD 29)				Slope (degrees)			Area (square miles)	Stream density (miles per square mile)		
											Rock type		
Number	Name		Min	Mean	Max	Relief	Min	Mean	Max		Carbonate	Metamorphic	Siliciclastic
PS45-BR	Brown Hollow Run	25.6	487	915	3,443	2,956	0	10.7	53.5	2.36	0.75	0.9	0.71
PS45-VR	Hazard Mill	16.3	490	875	2,263	1,773	0	12.6	56.8	3.53	0.09	np	3.44
PS46-BR	Gooney Run	27.3	488	1,503	3,470	2,982	0	13.9	59.6	2.24	0.02	2.22	np
PS47-BR	Dry Run	10.4	454	829	2,418	1,964	0	10	45.6	2.08	0.79	1.05	0.24
PS47-VR	Cabin Run	18.3	454	691	2,007	1,553	0	8.5	58.3	3.33	0.13	np	3.2
PS48-BR	Happy Creek	22.1	458	1,160	2,564	2,106	0	11	46.0	2	0.48	1.51	np
PS70-VR	Tumbling Run	0.2	486	788	2,063	1,577	0	15.8	49.2	1.34	np	np	1.34
PS75-VR	Cedar Creek	1.7	486	607	714	228	0	6.8	33.6	3.53	0.34	np	3.19
PS77-VR	Passage Creek	4.1	470	704	2,387	1,917	0	8.7	59.6	3.56	np	np	3.56
PS78-VR	North Fork Shenandoah River	16.4	456	653	2,368	1,911	0	9.3	54.2	3.53	0.05	np	3.48
PS79-VR	Crooked Run	17.0	453	605	741	288	0	6.3	53.3	2.69	0.62	np	2.07
PS80-BR	Manassas Run	23.5	423	939	2,388	1,965	0	10	55.2	2.11	0.78	1.33	np
PS80-VR	Willow Brook	11.0	425	577	691	265	0	4.4	54.9	1.57	1.57	np	np
PS81-BR	Rock Spring Branch	15.8	408	1,002	2,206	1,798	0	11.4	42.9	2.09	0.12	1.97	np
PS81-VR	Borden Marsh Run	8.5	408	555	668	261	0	5.1	36.4	2.31	2	0.32	np

Table 7. Physical and geologic characteristics, estimated effective recharge rates, and estimated water use at buildout of ungaged basins in Warren County, Virginia.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; Min, minimum; Max, maximum; np, not present. Shading indicates dominant rock type: Green, metamorphic rocks in the Blue Ridge Physiographic Province; Brown, siliciclastic rocks of the Valley and Ridge Physiographic Province; Yellow, carbonate rocks of the Valley and Ridge Physiographic Province]

Basin		Annual precipitation (inches per year)				Rock unit (percent of area)			*WU* build-out[a] (inches per year)[c]	*ER*[b] (inches per year)[c]
Number	Name	Min	Mean	Max	Range	Carbonate	Metamorphic	Siliciclastic		
PS45-BR	Brown Hollow Run	39.9	41.2	45.4	5.6	19.4	53	27.6	0.14	8.2
PS45-VR	Hazard Mill	39.8	40.4	41.4	1.7	2.5	0	97.5	0.23	5.6
PS46-BR	Gooney Run	40	46.4	59.6	19.6	0.5	99.5	0	0.10	9.0
PS47-BR	Dry Run	39.4	40.4	43.1	3.7	34.7	50	15.2	0.23	8.7
PS47-VR	Cabin Run	39.4	39.8	40.9	1.5	4.3	0	95.7	0.41	5.7
PS48-BR	Happy Creek	39.4	42.2	52	12.6	21.7	78.3	0	0.22	9.2
PS70-VR	Tumbling Run	39.2	39.7	40.2	1	0	0	100	0.07	5.5
PS75-VR	Cedar Creek	38.5	38.6	38.7	0.2	3.6	0	96.4	0.14	5.6
PS77-VR	Passage Creek	39.3	39.6	40.7	1.4	0	0	100	0.28	5.5
PS78-VR	N.F. Shenandoah River	38.7	39.2	40.6	2	1.3	0	98.7	0.25	5.5
PS79-VR	Crooked Run	39.2	39.3	39.4	0.2	32.5	0	67.5	0.24	6.9
PS80-BR	Manassas Run	39.3	40.9	45.2	5.9	32.8	67.2	0	0.89	9.3
PS80-VR	Willow Brook	39.2	39.3	39.5	0.3	100	0	0	0.18	9.7
PS81-BR	Rock Spring Branch	39.7	41.2	43.9	4.2	6.8	93.2	0	1.38	9.1
PS81-VR	Borden Marsh Run	39.3	39.5	39.9	0.6	95.3	4.8	0	0.04	9.7

[a] *WU* estimate assumes one household per parcel at buildout. Number of people per household is 2.48, and daily water use is 75 gallons per day per person.

[b] Effective recharge (*Rch*) estimated by the following linear regression equation developed by Yager and others (2008) for the Shenandoah Valley, VA and WV:

$$Rch = 5.5 + 4.3Carb + 3.6Meta + 10.1West,$$

where the percentage of basin underlain by the respective rock unit is carbonate (*Carb*), metamorphic (*Meta*), and western-toe carbonate (*West*). The percentage of siliciclastics is included implicitly (5.5). Equation-derived effective recharge rates are in inches per year.

[c] To convert inches per year to cubic feet per second, divide value by 13.5837 and then multiply by drainage area (in square miles). To convert cubic feet per second to million gallons per day, multiply value by 6.46.

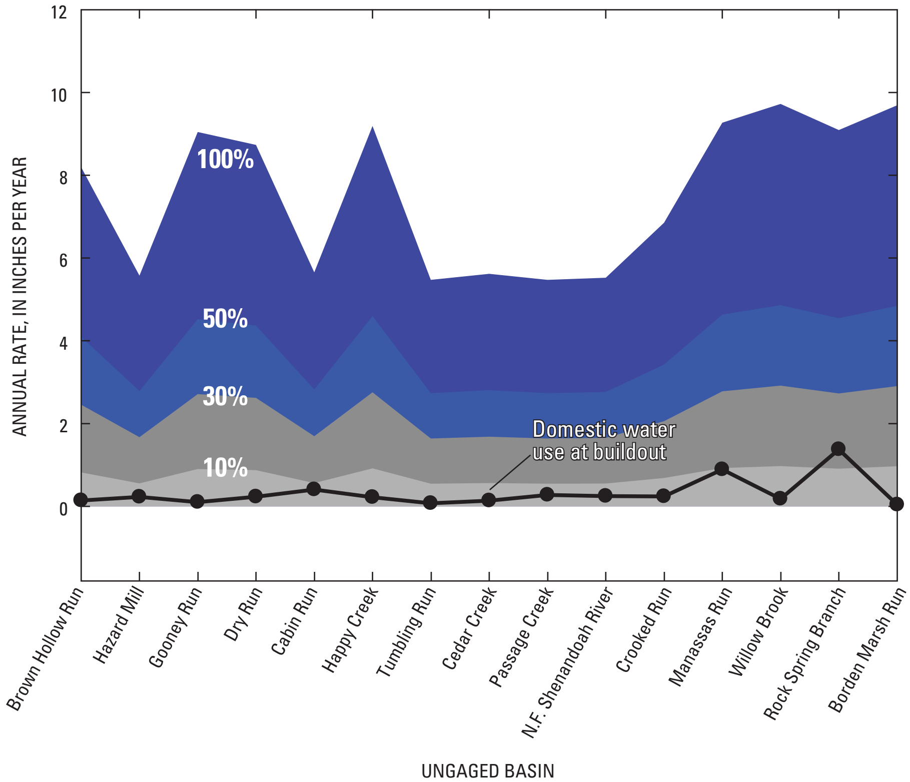

Figure 30. Relation between estimated domestic water usage at buildout and varying percentages of annual effective recharge estimated from the linear regression method of Yager and others (2008) for ungaged basins in Warren County, Virginia. Domestic usage is based on 2.48 individuals per parcel multiplied by 75 gallons per day per person normalized over the drainage basin area.

Drought Effects

Prior to the prolonged drought between 1999 and 2002, documentation of drought effects was constrained by the paucity of continuous data and limited knowledge of the fractured-rock and karst aquifer systems in the northern Shenandoah Valley. More than 20 wells went dry or had insufficient yield during this drought in Warren County. In addition, anecdotal evidence suggests that cessation of flow in streams and springs also was common. Complete evaluation of the drought effects of the 1999 to 2002 period is not feasible in the county because data were limited to gages on the larger stream basins, and no data on groundwater levels existed. Nelms and Moberg (2010) documented drought effects on groundwater levels for a long-term observation well in Clarke County that was finished in the carbonate rock unit. In addition, comparison of aerial photographs acquired prior to and during the drought in Clarke County assisted with the evaluation of drought effects on surface-water resources (Nelms and Moberg, 2010). Similar evaluation in Warren County was not feasible because resolution of the aerial photography during the drought was not sufficient for identification of surface-water effects for a large part of the county.

Streamflow data collected during this investigation may provide some insight into possible effects of droughts in the future. Mean streamflow (*SF*, table 4) and base flow (*ER*, table 4) closely follow annual precipitation (fig. 31). Recovery from the drought between 1999 and 2002 was facilitated by well-above-average precipitation for about seven successive quarters in calendar years 2002 and 2003. Of particular note was total snowfall in the first quarter of 2003, which was about three times the normal snowfall recorded at NWS climatological station 443229 Front Royal. After 2003, the general precipitation trend has been downward, and flows generally have followed this trend. In 2005, precipitation was below average during the prime groundwater recharge period,

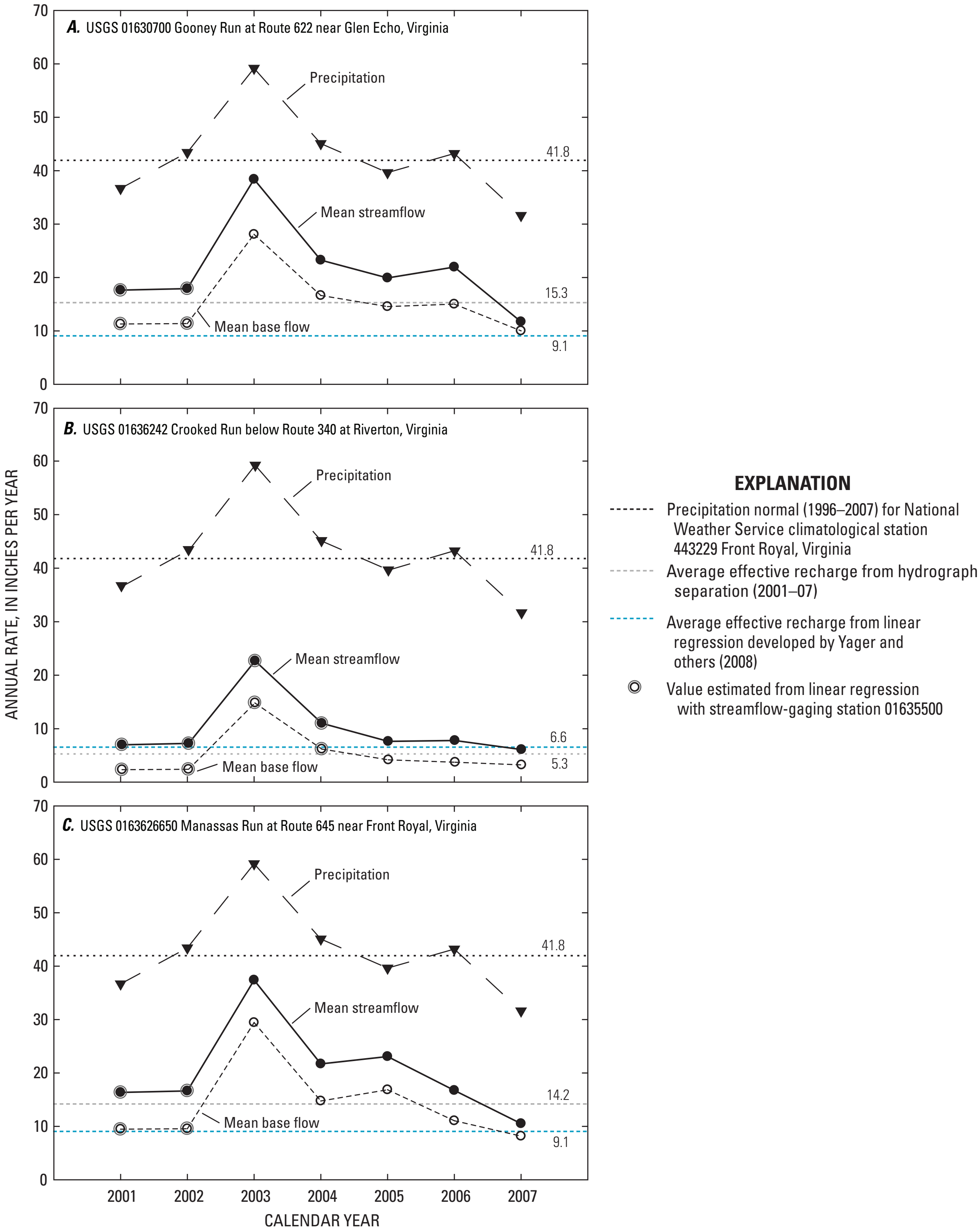

Figure 31. Relation between annual rates of precipitation at National Weather Service climatological station 443229 Front Royal, Virginia, mean streamflow and mean base flow at streamflow-gaging stations 01630700 Gooney Run at Route 622 near Glen Echo, Virginia, 01636242 Crooked Run below Route 340 at Riverton, Virginia, and 0163626650 Manassas Run at Route 645 near Front Royal, Virginia. For the years 2001–2002 at streamflow-gaging stations 01630700 and 0163626650 and for the years 2001–2004 at streamflow-gaging station 01636242, estimates are based on linear regression with streamflow-gaging station 01635500 Passage Creek above Route 55 near Buckton, Virginia. Mean streamflow and mean base-flow rates for the remaining years were estimated with the streamflow partitioning software package PART (Rutledge, 1993).

and flows declined at gages 01630700 and 01636242, but increased at gage 0163626650 (fig. 31). For 2006, the direct opposite was observed; flows increased at gages 01630700 and 01636242 with increased precipitation, but decreased at gage 0163626650. This discontinuity could result from an uneven areal distribution of precipitation across the county.

Although flows for the drought years 2001 and 2002 were estimated by linear regression from streamflow gage 01635500 Passage Creek above Route 55 near Buckton, VA, flows equal to and less than the regressed values have been measured at gages 01630700, 01636242, and 0163626650. Therefore, the values from linear regression with flows from gage 01635500 seem to be reasonable estimates during drought conditions and may actually overestimate flow. It should be noted that estimated values of mean base flow have approached the average *ER* estimated by the regression equation from Yager and others (2008). In the case of gage 01636242, however, the average *ER* is below the average *ER* estimated by the regression equation, which is indicative of groundwater systems with limited storage that are highly responsive to current meteorological conditions. Overall, precipitation during the period of this investigation is classified as average or above average, yet slight changes in annual amounts of precipitation or timing of the precipitation can affect groundwater recharge. The report of well failures during this investigation may be related to the close relation between recharge and precipitation. Kozar and others (2007) and Kozar and Weary (2009) demonstrate the utility of groundwater flow models in assessing changes in recharge with respect to groundwater levels and diminished streamflow and spring discharge.

Summary

Expanding development and the prolonged drought from 1999 to 2002 focused attention on the quantity and sustainability of the groundwater resources in Warren County, VA. The groundwater flow systems are complex, and flow paths tend to be controlled by the extremely folded and faulted geology that underlies the county. A study was conducted between May 2002 and October 2008 by the USGS, in cooperation with Warren County, VA, to describe the hydrogeology and groundwater availability of the metamorphic and siliciclastic fractured-rock aquifers in the county and to establish a long-term water monitoring network. The study area encompasses approximately 170 square miles of the county and includes the metamorphic rocks of the Blue Ridge Physiographic Province and siliciclastic rocks of the Great Valley section of the Valley and Ridge Physiographic Province.

The fractured-rock aquifer systems in the study area are characterized by diffuse-flow conditions. Well depths tend to be shallowest in the siliciclastic rock unit (predominantly in the Martinsburg Formation) where 75 percent of the wells are less than 200 ft deep. In the metamorphic rocks of the Blue Ridge, more than 75 percent of the wells are less than 400 ft deep. Median depths to bedrock are generally less than 40 ft. Depths to bedrock generally tend to be (1) relatively deep [greater than 50 ft below land surface (bls)] in the eastern part of the county, in areas where alluvial and colluvial deposits are extensive, and along faults; and (2) relatively shallow (less than 50 ft bls) in the interfluve areas, on the eastern slopes of Massanutten Mountain, and in areas underlain by the Martinsburg Formation.

The upper water-bearing zone generally is encountered in the first 200 ft bls but can be at deeper depths along faults, fold axes, and in elevated areas. Occasionally, the upper water-bearing zone is not encountered until depths of more than 400 ft bls. Median well yields for the different rock units generally range from 10 to 20 gal/min. High-yielding wells tend to cluster along faults, along the eastern contact of the Martinsburg Formation, and within potential lineament zones. A comparison of density clusters indicates that some areas contain a dense concentration of low- and high-yielding wells, which illustrates the degree of complexity inherent within karst and fractured-rock aquifer systems. Specific capacity is relatively low and ranges from 0.003 to 1.43 (gal/min)/ft with median values from 0.12 to 0.24 (gal/min)/ft. Transmissivity values derived from specific capacity data range over 4 orders of magnitude from 0.6 to 382 ft^2/d.

Groundwater levels generally are responsive to current meteorological conditions. Intense thunderstorms, tropical storms, or hurricanes cause sudden, temporary water-level rises during the summer and autumn. The prime groundwater recharge period is between January and April. Diurnal groundwater-level fluctuations in response to the combined effects of barometric pressure and earth tides, as well as oscillations caused by teleseismic wave trains from distant earthquakes of magnitude 7.0 or greater, have been observed in well 45V 3. Spring discharge in the carbonate areas tends to vary seasonally, whereas springs in the Blue Ridge are more responsive to current meteorological conditions and tend to have relatively low discharges.

Estimates of apparent groundwater age range from 0.1 to 16.1 years. About 73 percent of the samples contained some fraction of waters with apparent ages that were less than 5 years. The percentage of the young fraction in binary mixtures ranged from approximately 80 to 99.5 percent. These high percentages indicate that a majority of the water discharging from the springs is young and is close to being piston flow. Water discharging from springs in Warren County is generally younger than water from wells. The young apparent ages and binary mixtures are generally characteristic of sites in the upper reaches of the watersheds; the older ages are usually characteristic of sites in the lower reaches. This distribution and temporal changes of apparent ages and mixing fractions is consistent with an aquifer system that is topographically driven and has local flow systems containing young waters that are superimposed on a subregional to regional flow system with older waters. Therefore, under different hydrologic conditions, temporal changes in water-quality trends and dye-tracer studies would be expected to occur.

Estimates of effective groundwater recharge from hydrograph separation analyses from 2001 to 2007 range from 8.2 to 29.4 in/yr with average values of 14.2 and 15.3 in/yr for two streamflow gages in the Blue Ridge Physiographic Province. Estimates of effective groundwater recharge range from 2.4 to 14.8 in/yr with an average of 5.3 in/yr for a gage in a basin that predominantly drains a siliciclastic rock unit in the Great Valley section of the Valley and Ridge Physiographic Province. A positive correlation between effective recharge rates and current climatic conditions is evident. Analysis of diurnal streamflow signals in the Blue Ridge gages indicates median riparian evapotranspiration rates of 1.6 and 2.5 in/yr. The regression-derived recharge rate for the siliciclastic basin in the Great Valley is similar to the average value estimated from hydrograph separation, but rates for the basins predominantly underlain by the metamorphic rock unit of the Blue Ridge are about 40 percent less than the rates for basins in the Great Valley. Effective recharge rates derived from hydrograph separation in the Blue Ridge may be reflective of local riparian flow systems in the unconsolidated surficial deposits, and recharge to the fractured-rock aquifers may be overestimated. Base flow accounted for about 70 percent of mean streamflow in the Blue Ridge and 54 percent for siliciclastic rock terrain in the Great Valley. The high base-flow index values (percentage of streamflow from base flow) indicate that groundwater is the dominant source of streamflow during wet and drought conditions.

In the Blue Ridge basins, about 50 percent of annual precipitation is removed by evapotranspiration, and approximately 34 percent of the precipitation reaches the water table as effective recharge. In the siliciclastic areas of the Great Valley, evapotranspiration removes about 76 percent of annual precipitation, and only 12 percent reaches the water table as effective recharge. The amount of runoff in the Blue Ridge is about 14 percent of the amount of annual precipitation and is about 11 percent in the siliciclastic areas.

Current and projected water-use estimates are a small component of the overall water budgets in these basins and do not exceed the management threshold of 50 percent of average recharge rate for the respective basins. However, consideration of lower percentages of average rates of recharge, which would be indicative of drought conditions, indicate that water use at buildout could be a substantial percentage of recharge; in some basins, this amount of water use has been estimated to exceed groundwater recharge.

Groundwater flow systems in the county are extremely vulnerable to current meteorological conditions. Successive years of below-average effective recharge cause declines in water levels, spring discharges, and streamflows. However, these systems can recover quickly as effective recharge increases with increasing precipitation. Lack of precipitation, especially snow, during the critical recharge period (January–April) can have a substantial effect on the amount of recharge to the groundwater system and eventually on stream base flow. Estimated values of annual mean base flow have approached and have been below the average regression-derived recharge rates during a period classified as above-average precipitation. This relation is indicative of groundwater systems with limited storage that are highly responsive to current meteorological conditions. Slight changes in annual amounts of precipitation or timing of the precipitation can affect groundwater recharge.

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Appendixes

Appendix 1. Discharge and water-quality field properties from springs in Warren County, Virginia, 2003–2008.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; gal/min, gallons per minute; Gage ht., gage height; ft, feet; Temp., water temperature; °C, degrees Celsius; Sp. cond., specific conductance at 25 ºC; µS/cm, microsiemens per centimeter; O_2, dissolved oxygen; mg/L, milligrams per liter; pH in standard units; nd, not determined. Discharge measurement method: P, pygmy velocity meter; ADV, acoustic Doppler velocimeter; V, volumetric; F, flume. See figures 15 and 24 for location of springs]

USGS local no.	Name	Date	Time	Discharge			Gage ht. (ft)	Temp (°C)	Sp. cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
44US 2	PAULISCH SPRING	08/18/2004	1100	nd	nd	nd	nd	16.8	88	4.1	6.0
45US 3	CLEGG SPRING	08/18/2004	1220	nd	nd	nd	nd	13.5	82	3.8	6.0
45US 5	CHESTER GAP SPRING	08/18/2004	1515	nd	nd	nd	nd	11.4	187	7.9	5.8
45US 6	ZOO TURTLE SPRING	08/08/2005	1440	nd	nd	nd	nd	14.9	211	8.0	6.2
45VS 1	WEDDLE SPRING	08/14/2003	1030	0.281	126	P	nd	13.7	450	4.3	6.8
		12/23/2003	1445	nd	nd	nd	3.84	12.4	476	7.1	7.5
		02/25/2004	1223	1.010	453	P	3.60	10.9	471	6.3	7.2
		04/30/2004	1440	1.760	790	P	3.70	11.7	475	4.8	7.0
		06/09/2004	1200	1.090	489	P	3.52	12.8	481	4.3	7.3
		07/26/2004	1042	1.130	507	P	3.17	13.6	498	5.2	6.9
		11/05/2004	1543	0.333	149	P	2.97	13.8	503	5.9	7.0
		01/20/2005	1340	0.463	208	P	3.00	12.3	516	6.9	7.2
		04/29/2005	0945	0.429	192	P	3.20	11.8	508	7.1	7.2
		07/05/2005	1328	0.309	139	P	2.96	13.2	491	13.8	6.9
		11/03/2005	1730	0.108	48.5	ADV	2.89	13.2	514	6.9	7.0
		01/20/2006	1150	0.245	110	ADV	2.86	11.7	493	7.4	6.8
		04/28/2006	1135	0.229	103	P	2.90	12.5	510	4.7	7.0
		07/28/2006	0905	0.147	66	ADV	2.94	13.3	503	6.6	7.0
		11/02/2006	1052	0.089	39.9	ADV	2.96	13.3	508	4.7	7.0
		01/29/2007	1435	0.224	100	ADV	3.17	12.3	503	6.4	7.3
		05/02/2007	1455	0.368	165	ADV	3.34	12.1	503	6.7	7.1
		08/01/2007	1540	0.151	68	ADV	2.96	13.2	461	5.5	7.1
		12/04/2007	1155	0.001	0.4	ADV	2.75	12.2	497	7.5	7.3
		03/05/2008	1356	0.151	68	ADV	2.78	12.1	482	5.4	7.1
		04/21/2008	1424	0.280	126	ADV	3.01	12.1	514	7.6	7.2
		07/28/2008	1631	0.274	123	ADV	3.14	13.2	521	6.0	7.1
		10/28/2008	1230	0.118	53	ADV	2.98	13.2	516	5.7	7.2
45VS 2	MCKAY SPRING	08/21/2003	1140	nd	nd	nd	nd	13.3	560	5.0	6.3
45VS 3	ZOO MULE FIELD	08/09/2005	1215	nd	nd	nd	nd	12.0	103	6.7	6.0
45VS 4	ZOO GATE 4 SPRING	08/09/2005	1430	nd	nd	nd	nd	12.5	50	7.1	6.0
46V 1	HIGH KNOB WELL 1	08/14/2003	1700	nd	nd	nd	nd	11.2	120	11.0	7.1
46VS 1	HIGH KNOB SPRING 6	08/14/2003	1440	nd	nd	nd	nd	10.4	60	10.0	5.6
46VS 2	ANDREWS SPRING	08/18/2004	1715	nd	nd	nd	nd	12.1	95	4.8	6.4
46VS 6	MCAFEE SPRING	08/23/2004	1630	nd	nd	nd	nd	16.3	227	6.2	6.2
46VS 8	ROCK SPRING	08/23/2004	1300	nd	nd	nd	nd	10.0	55	8.4	6.2
46VS 12	FREEZELAND SPRING BOX 3-WEST	08/10/2005	1615	nd	nd	nd	nd	12.0	99	9.6	6.6

Appendix 1. Discharge and water-quality field properties from springs in Warren County, Virginia, 2003–2008.—Continued

[USGS, U.S. Geological Survey; ft³/s, cubic feet per second; gal/min, gallons per minute; Gage ht., gage height; ft, feet; Temp., water temperature; °C, degrees Celsius; Sp. cond., specific conductance at 25 ºC; µS/cm, microsiemens per centimeter; O_2, dissolved oxygen; mg/L, milligrams per liter; pH in standard units; nd, not determined. Discharge measurement method: P, pygmy velocity meter; ADV, acoustic Doppler velocimeter; V, volumetric; F, flume. See figures 15 and 24 for location of springs]

USGS local no.	Name	Date	Time	Discharge			Gage ht. (ft)	Temp (°C)	Sp. cond (µS/cm)	O_2 (mg/L)	pH
				ft³/s	gal/min	Method					
46VS 17	HIGH KNOB SPRING	08/14/2003	1322	0.014	6.3	V	nd	nd	nd	nd	nd
		12/22/2003	1600	0.199	89.3	V	nd	nd	nd	nd	nd
		02/25/2004	1500	0.108	48.5	V	nd	nd	nd	nd	nd
		04/30/2004	1040	0.191	85.7	V	nd	nd	nd	nd	nd
		06/09/2004	1524	0.090	40.4	V	nd	nd	nd	nd	nd
		07/26/2004	1330	0.024	10.8	V	nd	nd	nd	nd	nd
		11/05/2004	1145	0.073	32.8	V	nd	nd	nd	nd	nd
		01/20/2005	1500	0.215	96.5	V	nd	7.5	nd	nd	nd
		04/29/2005	1045	0.130	58.3	V	nd	10.0	nd	nd	nd
		06/20/2005	1600	0.083	37.3	V	nd	13.0	nd	nd	nd
		07/05/2005	1157	0.052	23.3	V	nd	15.5	nd	nd	nd
		11/04/2005	1359	0.013	5.8	V	nd	nd	nd	nd	nd
		01/20/2006	1323	0.131	58.8	V	nd	7.0	nd	nd	nd
		05/04/2006	1000	0.058	26.0	V	nd	nd	nd	nd	nd
		07/28/2006	1040	0.040	18.0	V	nd	16.0	nd	nd	nd
		11/02/2006	0920	0.050	22.4	F	nd	nd	nd	nd	nd
		01/29/2007	1235	0.077	34.6	V	nd	nd	nd	nd	nd
		05/02/2007	1130	0.149	66.9	V	nd	nd	nd	nd	nd
		08/01/2007	1200	0.007	3.1	V	nd	nd	nd	nd	nd
		12/04/2007	1400	0.000	0.0	V	nd	nd	nd	nd	nd
		03/05/2008	1230	0.032	14.4	V	nd	nd	nd	nd	nd
		04/19/2008	1050	0.000	0.0	V	nd	nd	nd	nd	nd
		07/28/2008	1335	0.0156	7.0	V	2.95	15.9	132	9.2	7.6
		10/28/2008	1530	0.008	3.5	V	2.92	10.2	128	10.2	7.8

Appendix 2. Summary of average dissolved gas compositions (nitrogen, argon, oxygen, carbon dioxide, methane, and neon), recharge temperatures, and quantities of excess air in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; Rech. elev., recharge elevation is land surface in feet above National Geodetic Vertical Datum of 1929; n, number of samples averaged; N_2, nitrogen; Ar, argon; O_2, oxygen; CO_2, carbon dioxide; CH_4, methane; mg/L, milligrams per liter; rech. temp., recharge temperature; °C, degrees Celsius; ex. air, excess air; cc_{STP}/L, cubic centimeters at standard temperature and pressure per liter; cc_{STP}/g, cubic centimeters at standard temperature and pressure per gram. See figure 24 for location of wells and springs]

USGS local no.	Date	Rech. elev. (ft)	USGS dissolved gases[a]									USGS[b]		Lamont-Doherty[c,d]		
			n	N_2 (mg/L)	Ar (mg/L)	Field O_2 (mg/l)	Lab O_2 (mg/L)	CO_2 (mg/L)	CH_4 (mg/L)	N_2-Ar rech. temp. (°C)	N_2-Ar ex. air (cc_{STP}/L)	n	Neon x 10^{-8} (cc_{STP}/g)	n	Neon x 10^{-8} (cc_{STP}/g)	Neon ex. air (cc_{STP}/L)
44US 2	08/18/2004	1305	2	15.4	0.6	4.1	0.8	68.3	0.0000	18.2	0.7	1	24.8	1	18.95	0.58
45US 3	08/18/2004	829	2	17.1	0.6	3.8	2.2	40.2	0.0000	13.7	0.8	1	23.5	1	21.57	1.46
45US 5	08/18/2004	1889	2	17.6	0.6	7.9	4.7	68.0	0.0000	13.9	2.0	1	25.9	1	20.30	1.18
45US 6	08/08/2005	1067	2	17.1	0.6	8.0	5.5	71.0	0.0000	12.1	0.4	1	25.0	1	19.66	0.34
45VS 1	08/14/2003	550	2	20.3	0.7	4.3	1.8	40.7	0.0004	12.2	3.4	2	36.5	1	24.89	3.03
45VS 2	08/21/2003	500	2	23.9	0.8	5.0	0.8	45.0	0.0000	11.7	6.8	2	41.7	1	35.72	9.04
45VS 3	08/09/2005	972	2	18.2	0.7	6.7	3.7	61.7	0.0000	11.9	1.3	1	28.2	1	20.71	0.87
45VS 4	08/09/2005	875	2	18.1	0.6	7.1	5.6	31.9	0.0000	12.8	1.5	1	30.4	1	20.43	0.77
46V 1	08/14/2003	1790	2	20.3	0.7	11.0	7.1	3.4	0.0000	7.9	2.5	1	29.8	1	32.35	7.18
46VS 1	08/14/2003	1790	2	17.5	0.7	10.0	6.9	31.9	0.0000	9.7	0.4	1	25.0	1	19.83	0.48
46VS 2	08/18/2004	803	2	18.5	0.7	4.8	2.6	41.4	0.0010	11.9	1.6	1	25.0	1	16.08	–1.74
46VS 6	08/23/2004	893	2	15.9	0.6	6.2	0.3	77.6	0.0000	15.9	0.3	1	21.1	1	19.04	0.29
46VS 8	08/23/2004	1761	2	17.5	0.7	8.4	4.8	34.5	0.0000	10.1	0.5	1	23.1	1	19.37	0.26
46VS 12	08/10/2005	1693	2	18.6	0.7	9.6	6.1	13.1	0.0000	11.0	1.9	1	26.2	1	22.40	1.99
46VS 13	08/10/2005	1669	2	17.8	0.6	8.5	5.6	52.5	0.0000	11.2	1.1	1	21.5	1	20.01	0.69

[a] Water samples for the determination of the dissolved gases (N_2, Ar, O_2, CO_2, and CH_4) in the U.S. Geological Survey Dissolved Gas Laboratory, Reston, VA, were analyzed using gas chromatography procedures (see *http://water.usgs.gov/lab/cfc/*, accessed January 6, 2010).

[b] Water samples for the determination of neon in the U.S. Geological Survey Chlorofluorocarbon Laboratory in Reston, VA, were analyzed using gas chromatography procedure with a thermal conductivity detector, which is similar to the procedure described by Sugisaki and others (1982) (see *http://water.usgs.gov/lab/cfc/*, accessed January 6, 2010).

[c] Water samples for the determination of neon in the Noble Gas Laboratory at Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, were analyzed by mass-spectrometric procedures outlined in Ekwurzel and others (1994) and Ludin and others (1998).

[d] Neon excess-air quantities are based on neon concentrations as determined by mass-spectrometric procedures.

Appendix 3. Concentrations of chlorofluorocarbons and sulfur hexafluoride in North American air, 1940–2006.

[CFC-11, (trichlorofluoromethane, $CFC1_3$); CFC-12, (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$); SF_6, sulfur hexafluoride; Mod., modern; Cont., contaminated. Concentrations in parts per trillion by volume (pptv). Data from Plummer and others (2000) and E. Busenberg, U.S. Geological Survey, written commun., 2005]

Year	CFC-11	CFC-12	CFC-113	SF_6	Year	CFC-11	CFC-12	CFC-113	SF_6	Year	CFC-11	CFC-12	CFC-113	SF_6
1940.0	0.000	0.000	0.000	0.000	1965.0	26.251	67.916	2.848	0.120	1990.0	265.758	493.523	74.512	2.340
1940.5	0.000	0.396	0.000	0.000	1965.5	28.586	72.530	3.064	0.130	1990.5	266.861	497.131	76.633	2.440
1941.0	0.000	0.478	0.000	0.000	1966.0	31.199	77.643	3.280	0.140	1991.0	269.216	503.382	78.755	2.540
1941.5	0.000	0.559	0.000	0.000	1966.5	33.802	82.755	3.526	0.150	1991.5	270.100	508.779	80.287	2.650
1942.0	0.000	0.661	0.000	0.000	1967.0	36.743	88.518	3.771	0.160	1992.0	271.521	517.703	81.514	2.750
1942.5	0.000	0.762	0.000	0.000	1967.5	39.694	94.281	4.056	0.180	1992.5	272.217	520.468	82.300	2.860
1943.0	0.000	0.884	0.000	0.000	1968.0	43.033	100.735	4.331	0.190	1993.0	272.346	522.958	82.693	2.970
1943.5	0.000	1.006	0.000	0.000	1968.5	46.371	107.179	4.655	0.200	1993.5	272.445	526.007	82.987	3.090
1944.0	0.000	1.179	0.000	0.000	1969.0	50.246	114.355	4.979	0.210	1994.0	272.793	528.162	83.184	3.200
1944.5	0.000	1.342	0.000	0.000	1969.5	54.121	121.521	5.352	0.220	1994.5	272.187	533.305	83.528	3.320
1945.0	0.048	1.555	0.000	0.000	1970.0	58.513	129.347	5.726	0.230	1995.0	272.033	534.687	83.557	3.440
1945.5	0.055	1.769	0.000	0.000	1970.5	62.895	137.163	6.148	0.250	1995.5	271.327	534.789	83.650	3.570
1946.0	0.069	2.155	0.000	0.000	1971.0	67.674	145.508	6.570	0.260	1996.0	271.024	535.744	83.550	3.690
1946.5	0.081	2.531	0.000	0.000	1971.5	72.463	153.852	7.051	0.270	1996.5	269.514	537.406	83.500	3.820
1947.0	0.109	3.110	0.000	0.000	1972.0	77.839	162.919	7.543	0.280	1997.0	269.037	539.317	83.400	3.950
1947.5	0.139	3.700	0.000	0.000	1972.5	83.214	171.995	8.102	0.300	1997.5	268.009	540.882	83.300	4.080
1948.0	0.199	4.371	0.000	0.000	1973.0	89.354	182.027	8.652	0.320	1998.0	267.263	542.117	83.150	4.220
1948.5	0.248	5.041	0.000	0.000	1973.5	95.495	192.059	9.291	0.340	1998.5	266.310	543.728	83.000	4.320
1949.0	0.338	5.763	0.000	0.000	1974.0	102.202	202.884	9.929	0.360	1999.0	265.619	544.003	82.800	4.430
1949.5	0.427	6.485	0.000	0.000	1974.5	108.908	213.698	10.666	0.390	1999.5	264.188	544.587	82.600	4.540
1950.0	0.556	7.277	0.000	0.000	1975.0	114.572	224.025	11.392	0.420	2000.0	263.841	545.055	82.300	4.650
1950.5	0.676	8.070	0.000	0.000	1975.5	122.104	234.341	12.227	0.450	2000.5	263.234	546.269	82.100	4.770
1951.0	0.854	8.934	0.000	0.000	1976.0	128.920	244.190	13.072	0.480	2001.0	261.843	546.515	81.700	4.890
1951.5	1.023	9.798	0.000	0.000	1976.5	135.130	254.039	14.024	0.520	2001.5	260.795	546.102	81.300	5.010
1952.0	1.282	10.693	0.000	0.000	1977.0	142.085	263.268	14.987	0.550	2002.0	260.120	545.299	81.000	5.140
1952.5	1.530	11.597	0.000	0.054	1977.5	146.705	272.497	16.087	0.590	2002.5	258.569	544.724	80.600	5.270
1953.0	1.878	12.593	0.000	0.054	1978.0	149.964	282.407	17.187	0.630	2003.0	258.137	543.306	80.250	5.400
1953.5	2.216	13.599	0.491	0.054	1978.5	156.502	292.855	18.444	0.680	2003.5	256.051	542.758	79.900	5.530
1954.0	2.643	14.738	0.530	0.055	1979.0	159.801	298.090	19.701	0.730	2004.0	255.057	542.148	79.550	5.670
1954.5	3.060	15.876	0.579	0.055	1979.5	162.642	301.190	21.145	0.770	2004.5	253.467	541.233	79.100	5.780
1955.0	3.577	17.147	0.629	0.055	1980.0	168.584	311.212	22.588	0.830	2005.0	252.374	540.318	78.750	5.890
1955.5	4.094	18.417	0.687	0.056	1980.5	172.807	317.422	24.150	0.880	2005.5	250.983	539.698	78.400	6.000
1956.0	4.739	19.901	0.746	0.056	1981.0	175.996	322.737	25.721	0.940	2006.0	249.592	538.692	78.100	6.110
1956.5	5.375	21.385	0.805	0.057	1981.5	179.732	333.796	27.342	0.990					
1957.0	6.091	23.062	0.874	0.058	1982.0	183.846	343.604	28.962	1.050	Mod.	284.000	550.000	87.000	6.200
1957.5	6.806	24.749	0.943	0.059	1982.5	188.347	352.721	30.759	1.120	Cont.	294.000	570.000	92.000	6.300
1958.0	7.462	26.498	1.021	0.060	1983.0	193.295	361.594	32.547	1.180					
1958.5	8.108	28.256	1.110	0.061	1983.5	198.015	372.236	34.796	1.250					
1959.0	8.764	30.218	1.188	0.062	1984.0	201.939	378.589	37.035	1.320					
1959.5	9.419	32.179	1.287	0.064	1984.5	206.023	386.232	39.696	1.390					
1960.0	10.294	34.517	1.385	0.066	1985.0	211.229	395.380	42.348	1.470					
1960.5	11.168	36.855	1.493	0.069	1985.5	217.261	403.257	45.177	1.540					
1961.0	12.291	39.477	1.601	0.072	1986.0	222.984	414.620	48.015	1.620					
1961.5	13.424	42.089	1.728	0.076	1986.5	227.912	423.463	51.128	1.700					
1962.0	14.854	45.098	1.856	0.079	1987.0	233.466	433.586	54.241	1.790					
1962.5	16.275	48.096	1.994	0.084	1987.5	241.047	449.310	57.738	1.870					
1963.0	18.024	51.613	2.141	0.088	1988.0	248.648	459.474	61.224	1.960					
1963.5	19.763	55.130	2.308	0.095	1988.5	253.964	469.089	64.868	2.050					
1964.0	21.839	59.226	2.475	0.100	1989.0	257.442	476.671	68.521	2.150					
1964.5	23.906	63.312	2.661	0.110	1989.5	261.983	484.030	71.517	2.240					

Appendix 4. Summary of average chlorofluorocarbon concentrations and calculated atmospheric partial pressures in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; pg/kg, picograms per kilogram; CFC-11, trichlorofluoromethane ($CFC1_3$); CFC-12, dichlorodifluoromethane (CF_2Cl_2); CFC-113, trichlorotrifluoroethane ($C_2F_3Cl_3$); N_2-Ar Rech. temp., nitrogen-argon recharge temperature; °C, degrees Celsius; Rech. elev., recharge elevation in feet above National Geodetic Vertical Datum of 1929; pptv, parts per trillion by volume. See figure 24 for location of wells and springs]

USGS local no.	Date	Average concentration in water (pg/kg)[a]			N_2-Ar Rech. temp. (°C)	Rech. elev. (ft)	Average calculated atmospheric partial pressure (pptv)		
		CFC-11	CFC-12	CFC-113			CFC-11	CFC-12	CFC-113
44US 2	08/18/2004	411.6	256.3	57.6	18.1	1,305	228.4	592.4	78.7
45US 3	08/18/2004	440.6	374.9	68.3	13.7	829	192.9	699.3	72.1
45US 5	08/18/2004	1,328.6	414.6	81.8	13.9	1,889	609.3	801.6	89.7
45US 6	08/08/2005	4,027.5	329.3	89.3	12.0	1,066	1,628.3	574.4	86.4
45VS 1	08/14/2003	1,673.3	320.2	81.6	12.2	550	664.3	537.2	76.4
45VS 2	08/21/2003	695.0	322.2	117.5	11.7	500	267.0	513.3	104.3
45VS 3	08/09/2005	687.5	331.2	87.7	11.9	972	274.8	567.7	83.4
45VS 4	08/09/2005	576.7	291.7	77.5	12.8	875	240.9	519.2	77.3
46V 1	08/14/2003	949.1	284.0	89.5	7.9	1,790	312.5	408.5	68.4
46VS 1	08/14/2003	642.6	314.4	97.2	9.7	1,790	235.0	503.1	84.1
46VS 2	08/18/2004	542.1	273.7	68.3	11.9	803	215.3	465.8	64.5
46VS 6	08/23/2004	561.7	302.7	154.0	15.9	893	276.0	628.5	184.9
46VS 8	08/23/2004	713.8	336.8	92.7	10.1	1,760	266.9	549.2	82.1
46VS 12	08/10/2005	658.1	333.2	82.8	11.0	1,693	257.1	559.3	76.4
46VS 13	08/10/2005	1,982.5	11,713.8	84.0	11.2	1,669	783.7	19,978.7	78.9

[a] Water samples for the determination of chlorofluorocarbons in the U.S. Geological Survey Chlorfluorocarbon Laboratory, Reston, VA, were analyzed using purge and trap gas chromatography with an electron-capture detector (Busenberg and Plummer, 1992; see *http://water.usgs.gov/lab/cfc/*, accessed January 6, 2010).

Appendix 5. Summary of average chlorofluorocarbon-based model piston-flow apparent recharge dates, ages, and uncertainties in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; CFC-11, trichlorofluoromethane ($CFCl_3$); CFC-12, dichlorodifluoromethane (CF_2Cl_2); CFC-113, trichlorotrifluoroethane ($C_2F_3Cl_3$); NP, not possible; C, contaminated (sample concentration higher than that of water in equilibrium with modern North American air); Mod., modern. Apparent age uncertainties are based on changes in age resulting from uncertainty in nitrogen-argon (N_2-Ar) recharge temperature of ±1 degree Celsius. Dates and ages are based on the North American air data in appendix 3. Numbers in parentheses indicate possible recharge years before and after atmospheric peak concentration. See figure 24 for location of wells and springs]

USGS local no.	Date	Model piston-flow average apparent recharge date [a]						Model piston-flow average apparent age and uncertainty [a] (years)					
		CFC-11 (1)	CFC-11 (2)	CFC-12 (1)	CFC-12 (2)	CFC-113 (1)	CFC-113 (2)	CFC-11 (1)	CFC-11 (2)	CFC-12 (1)	CFC-12 (2)	CFC-113 (1)	CFC-113 (2)
44US 2	08/18/2004	1986.5	NP	C	C	1990.5	2005.5	18.1 ± 0.7	NP	C	C	14.1 ± 0.4	NP
45US 3	08/18/2004	1982.5	NP	C	C	1989.5	NP	22.1 ± 0.7	NP	C	C	15.1 ± 0.7	NP
45US 5	08/18/2004	C	C	C	C	Mod.	Mod.	C	C	C	C	Mod.	C
45US 6	08/08/2005	C	C	C	C	1995.5	1995.5	C	C	C	C	10.1 ± 2.8	10.1 ± 4.2
45VS 1	08/14/2003	1985.5	NP	1991.0	NP	1990.0	NP	18.1	NP	12.6 ± 3.2	NP	13.6 ± 0.4	NP
45VS 2	08/21/2003	1990.5	1998.5	1991.5	NP	C	C	13.1 ± 1.8	5.1 ± 4.6	12.1 ± 1.4	NP	C	C
45VS 3	08/09/2005	1994.5	1994.0	Mod.	Mod.	1994.0	1997.5	11.1 ± 3.9	11.6 ± 5.7	Mod.	C	11.6 ± 3.2	8.1 ± 6.7
45VS 4	08/09/2005	1987.0	NP	1992.0	NP	1990.5	NP	18.6 ± 0.4	NP	13.6 ± 1.4	NP	15.1 ± 0.7	NP
46V 1	08/14/2003	C	C	1985.5	NP	1988.5	NP	C	C	18.1 ± 0.7	NP	15.1 ± 0.4	NP
46VS 1	08/14/2003	1987.0	NP	1990.5	NP	1995.5	1995.5	16.6 ± 1.1	NP	13.1 ± 1.1	NP	8.1 ± 3.2	8.1 ± 6.7
46VS 2	08/18/2004	1985.0	NP	1988.0	NP	1988.0	NP	19.6 ± 0.7	NP	16.6 ± 0.7	NP	16.6 ± 0.4	NP
46VS 6	08/23/2004	C	C	C	C	C	C	C	C	C	C	C	C
46VS 8	08/23/2004	1990.5	1998.5	2001.0	2001.0	1992.0	2001.0	14.1 ± 1.8	6.1 ± 4.6	3.6 ± 6.0	3.6	12.6 ± 1.1	3.6
46VS 12	08/10/2005	1988.5	2003.5	Mod.	Mod.	1990.0	NP	17.1 ± 0.7	2.1	Mod.	C	15.6 ± 0.4	NP
46VS 13	08/10/2005	C	C	C	C	1991.0	2005.0	C	C	C	C	14.6 ± 1.1	0.6

[a] Apparent chlorofluorocarbon recharge dates and ages were calculated using the chlorofluorocarbon program, version 3.0, revised February 2004 (Microsoft Excel®) by E. Busenberg and L.N. Plummer of the U.S. Geological Survey.

Appendix 6. Summary of average chlorofluorocarbon-based model ratio apparent recharge dates, ages, and uncertainties in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; CFC-11, trichlorofluoromethane ($CFC1_3$); CFC-12, dichlorodifluoromethane (CF_2Cl_2); CFC-113, trichlorotrifluoroethane ($C_2F_3Cl_3$); NP, not possible. Apparent age uncertainties are based on changes in age resulting from uncertainty in nitrogen-argon (N_2Ar) recharge temperature of ±1 degree Celsius. Dates and ages are based on the North American air data in appendix 3. See figure 24 for location of wells and springs]

USGS local no.	Date	Model ratio average apparent age [a]			Percentage of young fraction		
		CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11
44US 2	08/18/2004	NP	NP	NP	NP	NP	NP
45US 3	08/18/2004	NP	NP	NP	NP	NP	NP
45US 5	08/18/2004	NP	NP	NP	NP	NP	NP
45US 6	08/08/2005	NP	NP	NP	NP	NP	NP
45VS 1	08/14/2003	NP	NP	NP	NP	NP	NP
45VS 2	08/21/2003	NP	NP	NP	NP	NP	NP
45VS 3	08/09/2005	NP	NP	NP	NP	NP	NP
45VS 4	08/09/2005	NP	NP	10.1	NP	NP	92.4
46V 1	08/14/2003	NP	NP	NP	NP	NP	NP
46VS 1	08/14/2003	NP	NP	NP	NP	NP	NP
46VS 2	08/18/2004	NP	16.1 ± 0.4	13.1	NP	99.5	80.4
46VS 6	08/23/2004	NP	NP	NP	NP	NP	NP
46VS 8	08/23/2004	NP	NP	9.6 ± 0.7	NP	NP	98.2
46VS 12	08/10/2005	NP	NP	14.6	NP	NP	97.0
46VS 13	08/10/2005	NP	NP	NP	NP	NP	NP

[a] Apparent chlorofluorocarbon recharge dates and ages were calculated using the chlorofluorocarbon program version 3.0 revised February 2004 (Microsoft Excel®) by E. Busenberg and L.N. Plummer of the U.S. Geological Survey.

Appendix 7. Summary of average sulfur hexafluoride data in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; n, number of samples averaged; SF_6, sulfur hexafluoride; fmol/L, femtomoles per liter; °C, degrees Celsius; pptv, parts per trillion by volume; cc/L, cubic centimeters per liter; Meas. st. dev., standard deviation of measured values; Rtemp, recharge temperature; nd, not determined; C, contaminated (sample SF_6 concentration greater than that of water in equilibrium with modern air). Apparent age uncertainties are based on standard deviation of measured ages, changes in recharge temperature (±1 °C) and excess air (±1 cc/L). Apparent recharge dates and ages are based on the North American air data in appendix 3. See figure 24 for location of wells and springs]

USGS local no.	Date	n	SF_6 concentration in water (fmol/L)[a]	Recharge temperature (°C)	SF_6 partial pressure (pptv)	Excess air (cc/L)	Model SF_6 partial pressure remove excess air (pptv)	Model SF_6 apparent recharge date (years)[b]	Model SF_6 apparent age (years)[b]	Model SF_6 apparent age uncertainity		
										Meas. st. dev. (years)	Rtemp ±1 °C (years)	Excess air ±1 cc/L (years)
44US 2	08/18/2004	2	1.429	18.1	5.73	0.7	5.14	2002.0	2.6	1.1	1.1	nd
45US 3	08/18/2004	2	1.726	13.7	5.76	0.8	5.19	2002.0	2.6	1.8	1.1	3.5
45US 5	08/18/2004	2	1.268	13.9	4.44	2.0	3.45	1995.0	9.6	0.0	0.4	2.1
45US 6	08/08/2005	1	1.772	12.1	3.04	0.4	1.58	1985.5	20.1	nd	0.7	0.7
45VS 1	08/14/2003	2	2.481	12.2	7.71	3.4	5.41	2003.0	0.6	0.7	1.1	2.5
45VS 2	08/21/2003	2	4.428	11.7	13.49	6.8	7.30	C	C	nd	nd	nd
45VS 3	08/09/2005	2	1.895	11.9	3.39	1.3	1.74	1986.5	19.1	0.0	0.4	0.7
45VS 4	08/09/2005	2	1.696	12.8	3.05	1.5	1.50	1985.0	20.6	0.0	0.4	0.7
46V 1	08/14/2003	2	2.115	7.9	5.76	2.5	4.50	1999.0	4.6	0.4	0.7	2.5
46VS 1	08/14/2003	2	1.982	9.7	5.82	0.4	5.58	2003.5	0.1	0.4	1.1	nd
46VS 2	08/18/2004	2	1.029	11.9	3.19	1.6	2.66	1991.5	13.1	1.1	0.4	1.8
46VS 6	08/23/2004	2	1.450	15.9	5.28	0.4	4.98	2001.0	3.6	1.8	1.1	3.9
46VS 8	08/23/2004	2	1.369	10.1	4.09	0.6	3.81	1996.0	8.6	0.0	1.1	2.5
46VS 12	08/10/2005	2	1.583	11.0	2.99	1.9	1.55	1985.5	20.1	0.4	0.4	0.7
46VS 13	08/10/2005	2	1.910	11.2	3.47	1.1	1.82	1987.0	18.6	0.7	0.4	0.7

[a] Water samples for the determination of SF_6 in the U.S. Geological Survey Chlorofluorocarbon Laboratory, Reston, VA, were analyzed using purge and trap gas chromatographic procedures (Busenberg and Plummer, 2000).

[b] Apparent SF_6 recharge dates and ages were calculated using the SF_6 program revised February 2003 (Microsoft Excel®) by E. Busenberg of the U.S. Geological Survey.

Appendix 8. Summary of tritium, dissolved helium, and dissolved neon data in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; ^3H, tritium; TU, tritium unit (1 TU = 1 atom of ^3H in 10^{18} atoms of hydrogen (H); 2σ, 2 standard deviations; cc_{STP}/g, cubic centimeters at standard temperature and pressure per gram; USGS, USGS Low-Level ^3H Laboratory in Menlo Park, CA; LDEO, Noble Gas Laboratory at Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY; He, helium; Ne, neon; Δ^4He (%), percentage of helium-4 (^4He) greater than solubility equilibrium concentration; $\delta^3He = [(R_{sample}/R_{air}) - 1] \times 100$; R is the ratio $^3He/^4He$; $R_{air} = 1.384 \times 10^{-6}$; ΔNe (%), percentage of Ne greater than solubility equilibrium concentration; Terr. He (%), percentage of terrigenic helium; nd, not determined. See figure 24 for location of wells and springs]

USGS local no.	Date	^3H (TU)	^3H error 2σ (TU)	^3H Lab [a]	$^4He \times 10^{-8}$ (cc_{STP}/g)		Δ^4He (%) [c]	δ^3He (%) [c]	Ne x 10^{-8} (cc_{STP}/g) [c]	ΔNe (%) [c]	Terr. He (%)
					USGS [b]	LDEO [c]					
44US 2	08/18/2004	6.6	0.5	USGS	6.100	4.496	4.76	–1.38	18.951	5.89	nd
45US 3	08/18/2004	6.3	0.4	USGS	6.420	5.251	18.33	7.35	21.574	14.06	nd
45US 5	08/18/2004	6.9	0.5	USGS	6.110	4.597	7.78	0.04	20.300	11.78	nd
45US 6	08/08/2005	6.4	0.5	USGS	6.088	4.660	5.24	–0.78	19.655	3.28	nd
45VS 1	08/14/2003	7.5	0.4	USGS	9.400	6.035	33.81	1.82	24.886	28.49	nd
45VS 2	08/21/2003	8.5	0.5	USGS	16.300	16.857	272.31	–40.16	35.720	83.25	45.4
45VS 3	08/09/2005	8.4	0.6	USGS	6.560	4.893	10.04	0.55	20.708	8.28	nd
45VS 4	08/09/2005	7.3	0.6	USGS	7.054	4.795	7.87	2.83	20.431	7.38	nd
46V 1	08/14/2003	9.4	0.3	USGS	6.600	8.074	83.83	4.28	32.350	67.74	nd
46VS 1	08/14/2003	7.5	0.5	USGS	6.200	4.622	6.12	–1.75	19.828	4.66	nd
46VS 2	08/18/2004	8.5	0.6	USGS	7.070	4.003	–10.53	15.52	16.078	–16.44	11.0
46VS 6	08/23/2004	6.3	0.4	USGS	6.530	4.456	1.47	–1.60	19.039	2.83	nd
46VS 8	08/23/2004	5.0	0.4	USGS	5.780	4.522	3.89	3.26	19.366	2.50	nd
46VS 12	08/10/2005	8.1	0.6	USGS	7.062	5.458	25.56	20.11	22.396	19.23	nd
46VS 13	08/10/2005	6.8	0.6	USGS	6.401	4.677	7.60	5.26	20.010	6.65	nd

[a] Water samples for the determination of tritium (^3H) in the U.S. Geological Survey Low-Level ^3H Laboratory, Menlo Park, CA, were enriched electrolytically and analyzed by liquid scintillation counting following procedures modified from Thatcher and others (1977). Water samples for the determination of ^3H in the Noble Gas Laboratory at Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, were analyzed by the helium-3 ingrowth method (Clarke and others, 1976; Bayer and others, 1989).

[b] Water samples for the determination of helium-4 (^4He) in the U.S. Geological Survey Chlorofluorocarbon Laboratory in Reston, VA, were analyzed using gas chromatography procedure with a thermal conductivity detector, which is similar to the procedure described by Sugisaki and others (1982) (see *http://water.usgs.gov/lab/cfc/*, accessed January 6, 2010).

[c] Water samples for the determination of helium-3 (δ^3He), helium–4 (^4He), and neon (Ne) in the Noble Gas Laboratory at Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, were analyzed by mass-spectrometric procedures outlined in Ekwurzel and others (1994) and Ludin and others (1998).

Appendix 9. Summary of apparent tritium/helium-3 ages in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; Uncorr., apparent age not corrected for terrigenic helium; Uncorr. err., one standard deviation age error of uncorrected apparent age; Corr., apparent age corrected for terrigenic helium; Corr. err., one standard deviation age error of apparent age corrected for terrigenic helium; Terr. He, terrigenic helium; N, no, terrigenic helium correction not needed; Y, yes, terrigenic helium correction needed; nd, not determined. All apparent age calculations based on recharge temperatures determined for the respective samples. See figure 24 for location of wells and springs]

USGS local no.	Date	Tritium/Helium-3 ($^3H/^3He$) apparent age						
		Uncorr. (years)	Uncorr err. (years)	Corr. (years)	Corr err. (years)	Terr. He (Y/N)	Final (years)	Final error (years)
44US 2	08/18/2004	0.1	0.3	–1.4	0.9	N	0.1	0.3
45US 3	08/18/2004	6.1	0.4	6.7	0.5	N	6.1	0.4
45US 5	08/18/2004	1.0	0.2	–3.3	0.7	N	1.0	0.2
45US 6	08/08/2005	0.6	0.4	1.3	0.2	N	0.6	0.4
45VS 1	08/14/2003	2.3	0.2	1.6	0.5	N	2.3	0.2
45VS 2	08/21/2003	nd	nd	8.0	0.6	Y	8.0	0.6
45VS 3	08/09/2005	1.2	0.2	1.1	0.2	N	1.2	0.2
45VS 4	08/09/2005	2.7	0.3	2.0	0.3	N	2.7	0.3
46V 1	08/14/2003	4.0	0.2	3.3	0.3	N	4.0	0.2
46VS 1	08/14/2003	–0.1	0.2	0.1	0.3	N	–0.1	0.2
46VS 2	08/18/2004	6.8	0.4	10.0	30.3	Y	10.0	30.3
46VS 6	08/23/2004	0.0	0.3	–1.4	0.9	N	0.0	0.3
46VS 8	08/23/2004	4.0	0.4	4.5	0.5	N	4.0	0.4
46VS 12	08/10/2005	10.6	0.6	11.0	0.6	N	10.6	0.6
46VS 13	08/10/2005	4.2	0.4	3.8	0.4	N	4.2	0.4

Appendix 10. Summary of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopic data in water samples from wells and springs in Warren County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; per mil, parts per thousand; $\delta = [(R_{sample}/R_{standard}) - 1] \times 1{,}000$, where R is an isotope ratio. The 2σ precision of oxygen- and hydrogen-isotope results is 0.2 and 1.5 per mil, respectively; *d*, deuterium excess. See figure 24 for location of wells and springs]

USGS local no.	Date	$\delta^{18}O$ (per mil) [a]	$\delta^{2}H$ (per mil) [a]	*d* (per mil) [b]
44US 2	08/18/2004	–8.26	–51.7	14.4
45US 3	08/18/2004	–8.15	–50.8	14.4
45US 5	08/18/2004	–8.07	–47.9	16.7
45US 6	08/08/2005	–8.02	–49.0	15.2
45VS 1	08/14/2003	–8.03	–50.6	13.6
45VS 2	08/21/2003	–7.67	–48.8	12.6
45VS 3	08/09/2005	–8.11	–49.5	15.4
45VS 4	08/09/2005	–7.89	–48.4	14.7
46V 1	08/14/2003	–8.56	–51.8	16.7
46VS 1	08/14/2003	–8.54	–52.2	16.1
46VS 2	08/18/2004	–8.11	–49.7	15.2
46VS 6	08/23/2004	–8.28	–49.8	16.4
46VS 8	08/23/2004	–8.48	–51.0	16.8
46VS 12	08/10/2005	–8.34	–50.6	16.1
46VS 13	08/10/2005	–8.22	–50.2	15.6

[a] $\delta^{18}O$ and $\delta^{2}H$ were determined on water samples at the U.S. Geological Survey Stable Isotope Laboratory, Reston, VA. The stable isotope results are reported in per mil relative to VSMOW (Vienna Standard Mean Ocean Water; Coplen, 1996) and normalized (Coplen, 1988) on scales such that the oxygen and hydrogen isotopic values of SLAP (Standard Light Antarctic Precipitation) are –55.5 and –428 per mil, respectively.

[b] Deuterium excess is defined as $d = \delta^{2}H - 8\delta^{18}O$ by Clark and Fritz (1997).

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