Prepared in cooperation with Clarke County

Hydrogeology and Groundwater Availability in Clarke County, Virginia

Scientific Investigations Report 2010–5112

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

Cover photograph. Volumetric discharge measurement at spring 46WS 22. View looking west towards Boyce, Virginia. (Photograph by David L. Nelms, U.S. Geological Survey, April 2005)

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

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KEN SALAZAR, Secretary

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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:

$$°F=(1.8×°C)+32$$

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)

Hydrogeology and Groundwater Availability in Clarke County, Virginia

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

Abstract

The prolonged drought between 1999 and 2002 drew attention in Clarke County, Virginia, to the quantity and sustainability of its groundwater resources. 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 October 2002 and October 2008 by the U.S. Geological Survey, in cooperation with Clarke County, Virginia, to describe the hydrogeology and groundwater availability in the county and to establish a long-term water monitoring network. The study area encompasses approximately 177 square miles and includes the carbonate and siliciclastic rocks of the Great Valley section of the Valley and Ridge Physiographic Province and the metamorphic rocks of the Blue Ridge Physiographic Province (Blue Ridge).

High-yielding wells generally tend to cluster along faults, within lineament zones, and in areas of tight folding throughout the county. Water-bearing zones are generally within 250 feet (ft) of land surface; however, median depths are slightly deeper for the hydrogeologic units of the Blue Ridge than for those of the Great Valley section of the county. Total water-level fluctuations between October 2002 and October 2008 ranged from 2.86 to 87.84 ft across the study area, with an average of 24.15 ft. Generally, water-level fluctuations were greatest near hydrologic divides, in isolated elevated areas, and in the Opequon Creek Basin. Seasonally, water-level highs occur in the early spring at the end of the major groundwater recharge period and lows occur in late autumn when evapotranspiration rates begin to decrease. An overall downward trend in water levels between 2003 and 2008, which closely follows a downward trend in annual precipitation over the same period, was observed in a majority of wells in the Great Valley and in some of the wells in the Blue Ridge. Water-level fluctuations in the Blue Ridge tend to follow current meteorological conditions, and seasonal highs and lows tend to shift in response to the current conditions.

Springs generally are present along faults and fold axes, and discharges for the study period ranged from dry to 10 cubic feet per second. A similar downward trend in discharges correlates with the trend in water levels and is indicative of an aquifer system that, over time, drains to a base level controlled by springs and streams. 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 in the Great Valley function as aqueducts. Springs in the Blue Ridge have relatively low discharge rates, have small drainage areas, and are susceptible to current meteorological conditions.

Estimates of effective groundwater recharge from 2001 to 2007 ranged from 6.4 to 23.0 inches per year (in/yr) in the Dry Marsh Run and Spout Run Basins with averages of 11.6 and 11.9 in/yr, respectively. Base flow accounted for between 80 and 97 percent of mean streamflow and averaged about 90 percent in these basins. The high base-flow index values (percent of streamflow from base flow) in the Dry Marsh Run and Spout Run Basins indicate that groundwater is the dominant source of streamflow during both wet and drought conditions. Between 46 and 82 percent of the precipitation that fell on the Dry Marsh Run and Spout Run Basins from 2001 to 2007 was removed by evapotranspiration, and an average of approximately 30 percent of the precipitation reached the water table as effective recharge. The high permeability of the rocks and low relief in these basins are not conducive for runoff; therefore, on average, only about 3 to 4 percent of the precipitation becomes runoff.

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 as effective recharge increases, especially in the Dry Marsh Run area. Effective recharge tends to increase as precipitation increases, but lack of precipitation, especially snow, during the critical recharge periods can have an effect on the amount of recharge. The combination of a lack of precipitation, large water-level fluctuations, depths to water-bearing zones, and hydrogeologic setting is the most probable explanation of the well failures during the recent drought.

Introduction

The Northern Shenandoah Valley is underlain by karst and fractured-rock aquifers that are increasingly being relied upon to supply water to local communities and individual residences. This is an area with an expanding economy and a growing population, and, to meet future water needs, these aquifers are likely to be developed further to supplement current withdrawals. The prolonged drought between 1999 and 2002 drew attention in Clarke County, VA, to the quantity and sustainability of the groundwater resources. More than 20 wells in Clarke County reportedly went dry during this drought, which brought into question whether these failures were related to increased demand or the result of natural fluctuations of the water table. An improved understanding of the complex aquifer systems in the county is required to effectively develop and manage them as sustainable water supplies because 54 percent of water use in the county is obtained from groundwater for domestic purposes (Hutson and others, 2004). In order to assess current and future hydrologic conditions within the county, a long-term monitoring network was established to measure water levels, streamflows, and spring discharges. Hydrogeologic information collected during this investigation has been used to 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.

Prior to this investigation, the major water-resources focus in the county had been protection of water quality. Information from this report on water availability coupled with ongoing water-quality protection efforts will assist the county in meeting requirements outlined in the county's comprehensive plan, which includes water resources, groundwater resources, and surface-water resources components. In addition, a long-term monitoring network will provide information necessary to assess future hydrologic conditions and to evaluate effects of increasing water-supply demands in the future.

Purpose and Scope

This report describes the hydrogeology and groundwater availability of the karst and fractured-rock aquifer systems in Clarke County, VA, and provides hydrogeologic information that can be used to guide the development and management of these important water resources. Water budgets that include effective groundwater recharge are presented for the Dry Marsh and Spout Run Basins for 2001–2007. This report also includes data for groundwater levels, spring discharges, and streamflows collected as part of a long-term water-resources monitoring network and data for apparent groundwater ages.

Description of Study Area

The study area includes all of Clarke County, VA (fig. 1). The county is located within the Valley and Ridge and Blue Ridge Physiographic Provinces (Valley and Ridge and Blue Ridge, respectively) of Virginia (Fenneman, 1938), at the northern end of the Shenandoah Valley, about 75 miles (mi) west of Washington, DC. Clarke County is bordered by Jefferson County, WV, to the north, Warren County to the south, Fauquier and Loudoun Counties to the east, and Frederick County to the west. Clarke County encompasses about 177 square miles (mi^2) and had a population of 12,652 in 2000. The Valley and Ridge part of the county commonly is 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 Great Valley section within the study area, locally known as the Shenandoah Valley, is predominantly underlain by soluble carbonate rocks that form karst features such as sinkholes, caves, estavelles, swallet holes, and sinking streams. Less soluble siliciclastic rocks (sandstone, siltstone, and shale) underlie the western edge of the Great Valley section of the county. The Great Valley section of the county encompasses two major basins within the Potomac River Watershed: Opequon Creek to the west and the Shenandoah River on the east. The drainage divide between these two basins is present in an area of the county that is frequently referred to as the Limestone Ridge. Formal definition of this area is necessary because of its importance to the underlying groundwater flow systems. The Limestone Ridge is delineated as the area higher than the contour for 630 ft above NGVD 1929 (fig. 1).

The most resistant to weathering and oldest rocks in the study area are the metamorphic rocks that underlie the Blue Ridge in the eastern part of Clarke County (fig. 1). The Blue Ridge is a mountainous terrain with steep slopes and the highest land-surface altitudes within the study area.

Conceptual Model of Groundwater Flow

The groundwater flow systems in the Valley and Ridge and Blue Ridge are complex. Flow through and storage within these systems are controlled by the topography and underlying geology of the respective provinces. The two hydrogeologic sections shown in figure 2 depict a conceptual model of groundwater flow through both of these systems. In both areas, the rocks are highly deformed by folding, faulting, and weathering processes. In order to depict the range in depth where most of the wells are drilled, the steepness of the geologic structures is over-exaggerated, but the difference in dip between the west and east limbs of the Massanutten synclinorium is preserved in these sections. The conceptual relations among karst features and geologic structure are illustrated in sections A–A' and B–B'. Groundwater flow directions generally follow the topography and are controlled by the geologic structure.

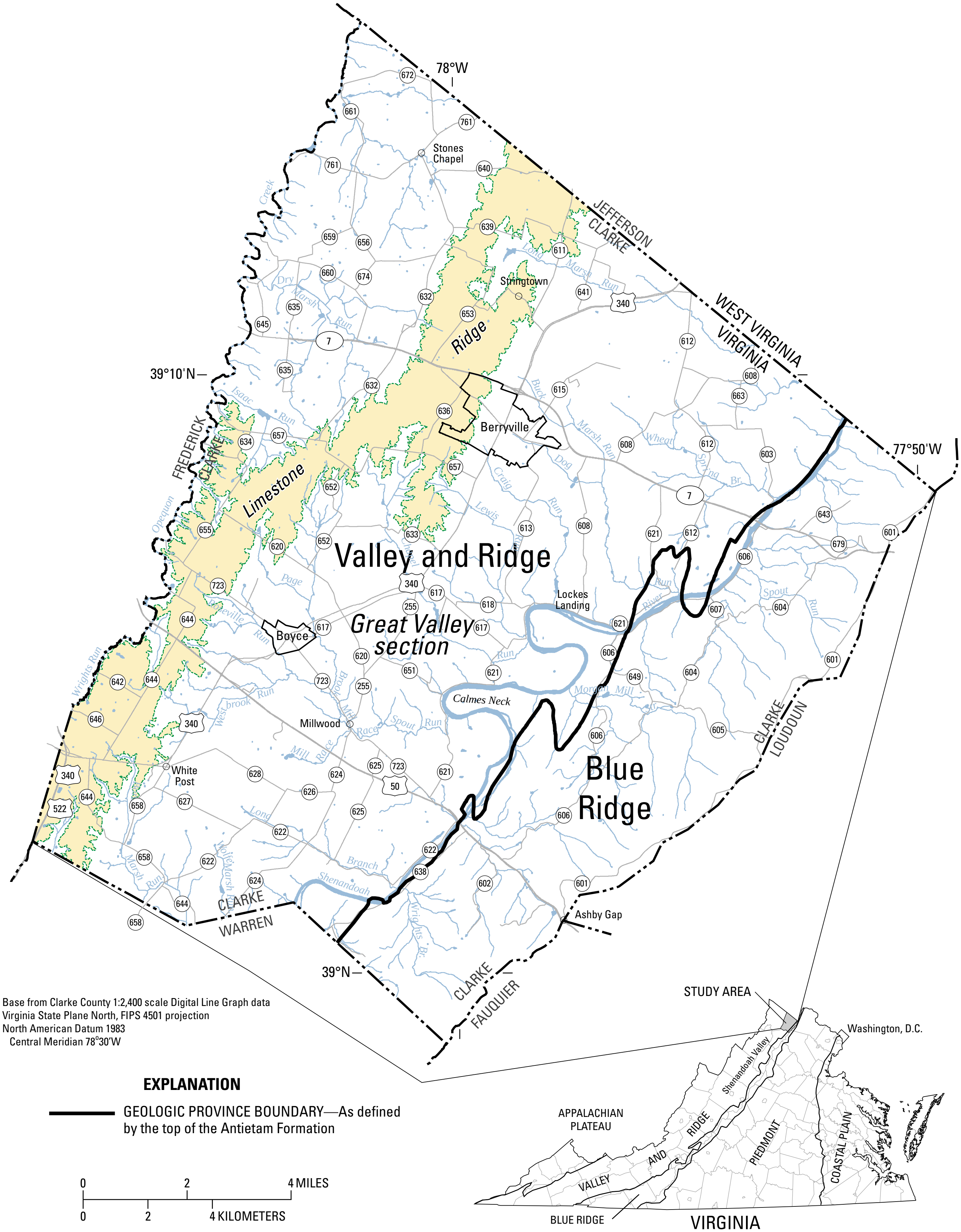


Figure 1. Generalized geologic province map of Clarke County, Virginia, and location of study area.

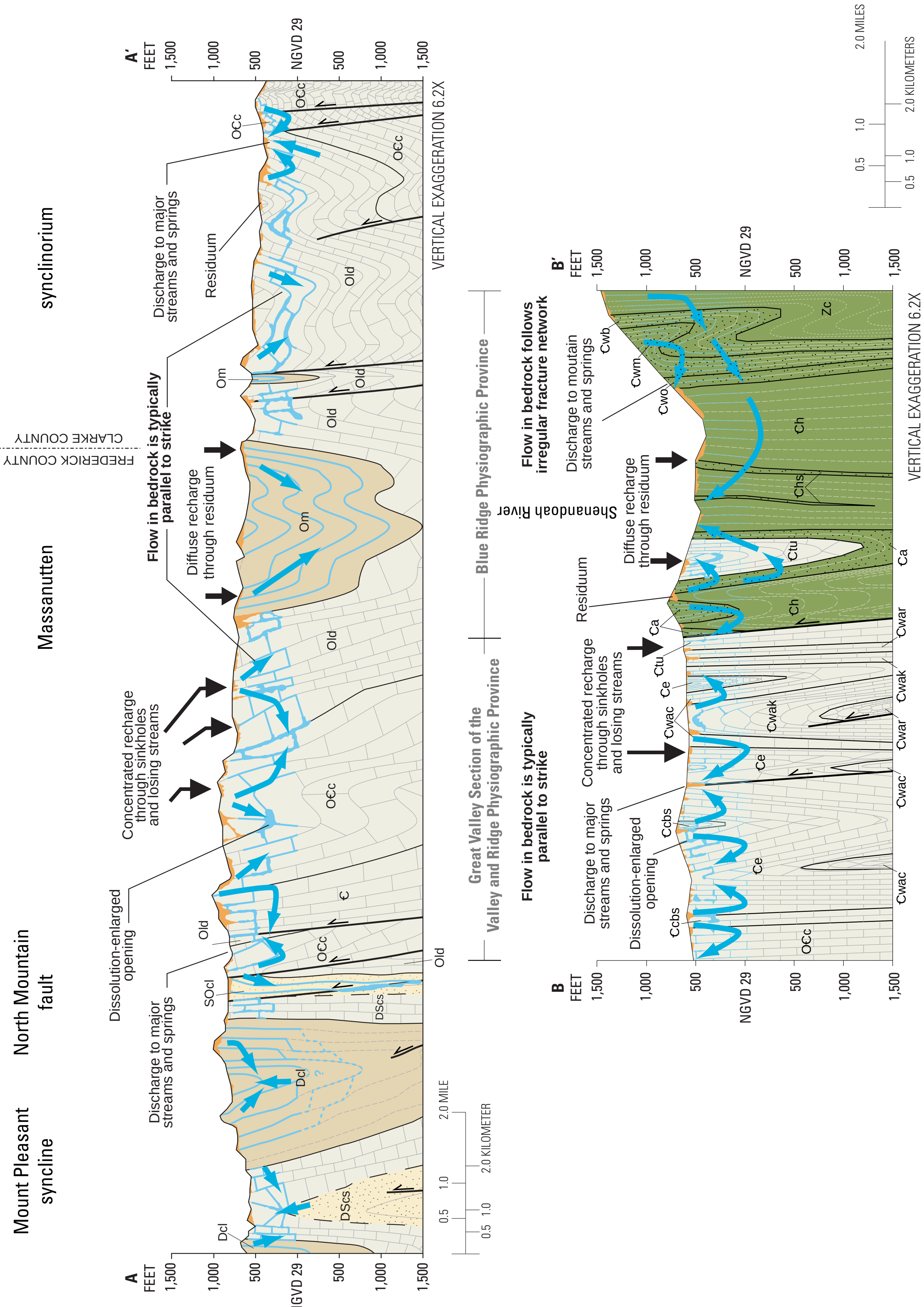


Figure 2. Generalized hydrogeologic sections across Clarke and Frederick Counties, Virginia. Section A–A′ modified from Harris and others (1994) and section B–B′ modified from Southworth and others (2002). Line section of A–A′ and B–B′ shown in figure 5.

EXPLANATION

CORRELATION OF HYDROGEOLOGIC UNITS

System	Southworth and others (2002)		Harris and others (1994)
DEVONIAN	Db	Brallier Formation	Dcl
DEVONIAN	Dms/Dm	Mahantango Formation	Dcl
DEVONIAN	Dmn	Marcellus Shale and Needmore Shale, undivided	Dcl
SILURIAN	DSow	Oriskany Sandstone through Wills Creek Formation, undivided	DScs
SILURIAN	Sbr	Bloomsburg Formation through Rose Hill Formation, undivided	SOcl
SILURIAN	St	Tuscarora Quartzite	SOcl
ORDOVICIAN	Oj	Juniata Formation	SOcl
ORDOVICIAN	Oo	Oswego Sandstone	SOcl
ORDOVICIAN	Om	Martinsburg Formation	SOcl
ORDOVICIAN	Oms	Stickley Run Member	Ocl
ORDOVICIAN	Oeln	Edinburg Formation, Lincolnshire Limestone, and New Market Limestone	Old
ORDOVICIAN	Oc	Chambersburg Limestone	Old
ORDOVICIAN	Ob	Beekmantown Group	Old
ORDOVICIAN	Op	Pinesburg Station Dolomite	Old
ORDOVICIAN	Or	Rockdale Run Formation	Old
ORDOVICIAN	Os	Stonehenge Limestone	Old
ORDOVICIAN	OЄc	Conococheague Limestone	Old
CAMBRIAN	Єcbs	Big Spring Station Member	OЄc
CAMBRIAN	Єe	Elbrook Formation	OЄc
CAMBRIAN	Єwa	Waynesboro Formation	Є
CAMBRIAN	Єwac	Chewsville Member	Є
CAMBRIAN	Єwak	Cavetown Member	Є
CAMBRIAN	Єwar	Red Run Member	
CAMBRIAN	Єtu	Tomstown Dolomite	
CAMBRIAN	Єtd	Dargan Member	
CAMBRIAN	Єtb	Benevola Member	
CAMBRIAN	Єtf	Fort Duncan Member	
CAMBRIAN	Єtbh	Bolivar Heights Member	
CAMBRIAN		Chilhowee Group	
CAMBRIAN	Єa	Antietam Formation	
CAMBRIAN	Єh	Harpers Formation	
CAMBRIAN	Єhs	Metasandstone	
CAMBRIAN	Єw	Weverton Formation	
CAMBRIAN	Єwo	Owens Creek Member	
CAMBRIAN	Єwm	Maryland Heights Member	
CAMBRIAN	Єwb	Buzzard Knob Member	
CAMBRIAN	Єlp	Loudoun Formation	
NEOPROTEROZOIC	Zc	Catoctin Formation	

Valley and Ridge Physiographic Province Great Valley Section

CARBONATE ROCKS

SILICICLASTIC ROCKS

Sandstone

Shale

Blue Ridge Physiographic Province

METAMORPHIC ROCKS

Quartzite

Phyllite

Metavolcanics

GENERAL DIRECTION OF GROUNDWATER FLOW

RECHARGE

WATER-FILLED FRACTURE OR CONDUIT

CONTACT

FAULT

Figure 2. Generalized hydrogeologic sections across Clarke and Frederick Counties, Virginia. Section A–A′ modified from Harris and others (1994) and section B–B′ modified from Southworth and others (2002). Line section of A–A′ and B–B′ shown in figure 5.—Continued

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 altitude of 1,720 ft above NGVD 29, and from NWS climatological station 449186 Winchester 7 SE, which is located to the west in Frederick County at an altitude of 680 ft above NGVD 29 (fig. 4). The periods of record for these two stations are 103 and 102 years for temperature data and 104 and 101 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. 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 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 Winchester 7 SE station is 11.7 °C with the coldest month being January (–0.9 °C) and the warmest July (23.7 °C). The colder periods of the year for air temperature also 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, average annual precipitation would be highest in May (4.5 in.) and lowest in February (2.5 in.). The average annual precipitation of 39.1 in. at the Winchester 7 SE station is about 4 in. lower than annual precipitation at the Mt. Weather station. In an average year, monthly precipitation totals are highest in June (4.1 in.) and lowest in February (2.4 in.) at the Winchester 7 SE station. Although precipitation is relatively evenly distributed throughout an average year, average monthly precipitation tends to be lower for October through April than for May through September (fig. 3).

A grid of average annual precipitation interpolated from the parameter-elevation regressions on independent slopes model (PRISM) for Clarke County, VA, is shown in figure 4. 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 38.9 to 42.6 in. across Clarke County. The higher values illustrate the orographic effect on precipitation of the elevated areas of the Blue Ridge east of the Shenandoah River. The lower values also illustrate orographic effects caused by mountain ranges to the west in western Frederick County, VA, and WV. The lowest average annual precipitation is present in the western parts of the county and just east of Berryville. These two areas are the northern extent of a rain shadow centered on Harrisonburg, VA, which is caused by the mountain ranges to the west.

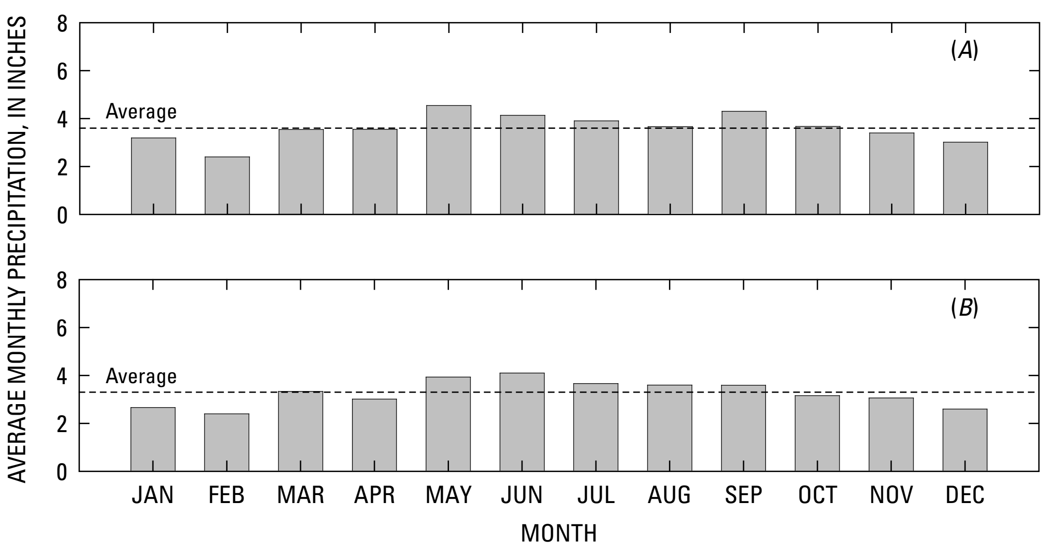
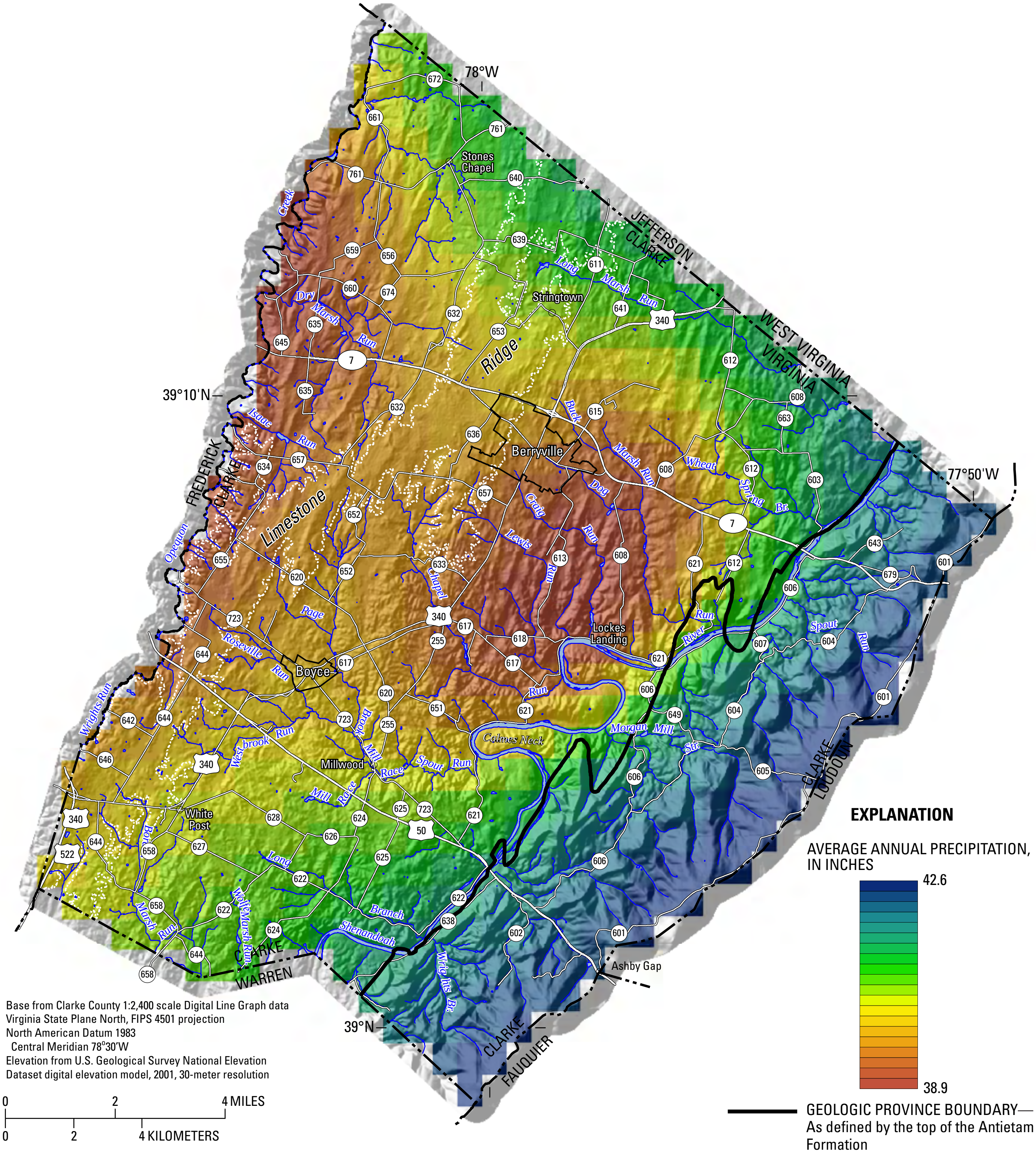


Figure 3. Average monthly precipitation for National Weather Service climatological stations *(A)* 445851 Mt. Weather located in Loudoun County, Virginia, at an altitude of 1,720 feet above NGVD 29 and *(B)* 449186 Winchester 7 SE located in Frederick County, Virginia, at an altitude of 680 feet above NGVD 29. The normal values are based on the National Weather Service's current normal climatological period from 1971 to 2000.



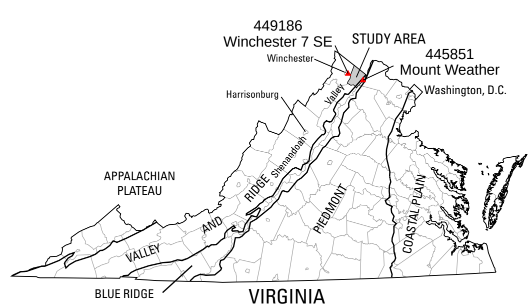


Figure 4. Average annual precipitation across Clarke County, Virginia, based on parameter-elevation regressions on independent slopes model (PRISM). The normal values are based on the National Weather Service's current normal climatological period from 1971 to 2000.

Well- and Spring-Numbering System

A unique USGS identifier was assigned to each well (appendix 1) and spring (appendix 2) for this study, for the purpose of storing well-construction and site information in the Ground-Water Site Inventory (GWSI) database 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 46W175 corresponds to the 175th well entered by the USGS in the area covered by the Boyce quadrangle, which has a Virginia coordinate grid number of 46W. Springs (appendix 2) 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; Clarke County, however, was not included. The first comprehensive investigation of the county’s groundwater resources was included in Cady (1938), in which he noted that (1) “the limestone wells are exceptionally successful,” (2) the “spring waters” were susceptible to contamination in “settled areas,” and (3) a large number of springs east of Berryville either “became weak or went dry” in the early 1930s, which was the initial period of a prolonged drought. Hack (1965) provides 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. Hubbard (1983) mapped selected karst features in the northern Valley and Ridge of Virginia. 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 Clarke County, at a 1:100,000 scale. Doctor and others (2008) provided detail 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 correspond with changes in the strike and dip of bedrock across the valley.

Several investigations specifically dealt with the geology and hydrology of Clarke County. Edmundson and Nunan (1973) mapped the geology of the Berryville, Stephenson, and Boyce quadrangles, and Gathright and Nystrom (1974) mapped the geology of the Ashby Gap quadrangle. A soil survey of the county, conducted by the U.S. Department of Agriculture, noted sinkholes (Edmonds and Stiegler, 1982). Schnabel Engineering Associates (1983) evaluated the hydrogeology of spring 46WS 3 (Prospect Hill Spring) and provided recommendations for protecting this water source by establishing land-use restriction zones and an observation-well network. Jones (1987) conducted an overview of groundwater resources in the county for the Lord Fairfax Planning District Commission, which mainly focused on the carbonate aquifers. In addition, Jones (1987) conducted dye-tracer tests to help delineate the drainage basin for spring 46WS 3 (Prospect Hill Spring). The influence of geology and agriculture on groundwater quality was studied by LoCastro (1988) as part of a Master’s Thesis at the University of Virginia. Hubbard (1990) mapped the geology, lineaments, and sinkholes in the county at a scale of 1:50,000. Wright (1990) studied the county’s groundwater hydrology and quality. Jones (1987), Hubbard (1990), and Wright (1990) noted that groundwater flow in the carbonate aquifers is a mix of diffuse- and conduit-flow conditions; flow in the Blue Ridge is along irregular fracture patterns in the rock, and rapid flow is through the overburden to springs and streams in response to the steep terrain. Wright (1990) also noted that fecal-bacteria contamination was detected at about 40 percent of the sites sampled during his study. Ross and others (1992) evaluated household water quality in the county as part of the Virginia Cooperative Extension’s water-quality testing program at Virginia Polytechnic Institute and State University. Recent studies have focused in detail on the occurrence and sources of fecal bacteria contamination in local springs and basins (Hagedorn and others, 1998).

Hydrogeology

The geology of Clarke County is the main control on the occurrence and flow of groundwater. The county is characterized by karst and fractured-rock aquifer systems. The karst terrains of the Great Valley section of the Valley and Ridge are underlain by Lower Cambrian to Middle Ordovician limestone and dolostone bedrock, which are mantled by unconsolidated regolith material of varying thickness. The bedrock is variably fractured, folded, and faulted (Harlow and others, 2005), and the regolith material consists of residuum (weathered bedrock) and alluvium (stream deposits). Jones (1987) and Wright (1990) stated that the karst aquifer systems exhibit both conduit- and diffuse-flow conditions, and the occurrence and movement of groundwater is probably controlled by both karst and fractured-rock features. A mantle of unconsolidated regolith material overlies the siliciclastic rocks of the Upper Ordovician Martinsburg Formation in the western part of the county and the Neoproterozoic to Lower Cambrian metamorphic rocks of the Blue Ridge. The regolith in these areas tends to vary less in thickness than in the karst areas. Fractured-rock aquifers in these areas control the occurrence of groundwater, and water generally moves under diffuse-flow conditions.

Geology

The rocks in Clarke County were folded and faulted during the late Paleozoic Alleghanian orogeny about 300 million years ago. The terrain is a direct reflection of the underlying geology. Generally, the Great Valley section is a gently to moderately rolling terrain with low relief. Sinkholes, sinking streams, dry stream channels, caves, and springs are common in the karst terrain (Wright, 1990; Harlow and others, 2005). The areas underlain by the low permeability shale and siltstone of the Martinsburg Formation exhibit highly dissected drainage patterns. The mountainous terrain of the Blue Ridge formed in response to the resistant nature of the underlying metamorphic rocks (Hack, 1965).

Hydrogeologic Units

Clarke County can be subdivided into hydrogeologic units based on the mapped geologic formations and hydraulic properties of the rocks (fig. 5). In general, these hydrogeologic units also can be grouped based on gross lithology or rock type:

Carbonate—limestone and dolostone;
Metamorphic—metavolcanic and metasedimentary rocks; and
Siliciclastic—sandstone, siltstone, and shale.

The hydrogeologic characteristics vary among these units and between the major rock type groupings. Descriptions of the individual hydrogeologic units are provided below. The age and major rock-type grouping are included in the respective report section, and the map symbol used to identify the respective hydrogeologic unit in figure 5 is provided in the text.

Carbonate Rock Unit

The carbonate rock unit consists of dolostone, shale, limestone, and sandstone of the Lower Cambrian Tomstown and Waynesboro Formations; 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 Formation including the Big Spring Station Member; dolostone, limestone, and chert of the Lower Ordovician Stonehenge Limestone, the Lower and Middle Ordovician Rockdale Run Formation, and Pinesburg Station Dolomite of the Beekmantown Group; and limestone and shale of the Middle Ordovician New Market Limestone, Lincolnshire Limestone, Edinburg Formation, and Chambersburg Limestone (fig. 5). The combined thickness of the carbonate rock unit is approximately 11,500 ft (Hubbard, 1990).

Tomstown Dolomite

The Lower Cambrian Tomstown Dolomite (Ct) represents the oldest carbonate unit in Clarke County and was formed in deep shelf to peritidal-type environments (Southworth and others, 2002). The Tomstown Dolomite has been divided into four members by Brezinski (1992): Bolivar Heights, Fort Duncan, Benevola, and Dargan Members (fig. 5). These members have only been mapped in the northeastern part of the county, and only the contacts of the undivided Tomstown Dolomite are shown on figure 5 for the remainder of the county. The overall thickness of the Tomstown is from 1,100 to 1,200 ft (Hubbard, 1990).

The Bolivar Heights Member (Ctbh) consists of dark-gray limestone with tan dolomitic burrows. The limestone is thin bedded and medium grained, and bioturbation is more prevalent upsection. A very light-gray to tan, mylonitic marble is present at the base and has been termed the Keedysville marble bed (Brezinski, 1992) that extends more than 60 mi from east of Berryville, VA, to south-central PA along a stratigraphically restricted fault zone (Brezinski and others, 1996). The Fort Duncan Member (Ctf) consists of a dark-gray, bioturbated dolomite that is thick bedded. *Salterella*, which is a cone-shaped fossil, is present in this member (Southworth and others, 2002). The Benevola Member (Ctb) consists of light-gray, sugary dolomite. The dolomite is of high purity, and bedding is very thick to massive (Southworth and others, 2002). The Dargan Member (Ctd) consists of alternating intervals of light-gray, bioturbated and laminated dolomite in the lower part. Interbeds of light-gray, bioturbated and oolitic dolomite and laminated limestone and silty dolomite are present in the upper part (Southworth and others, 2002).

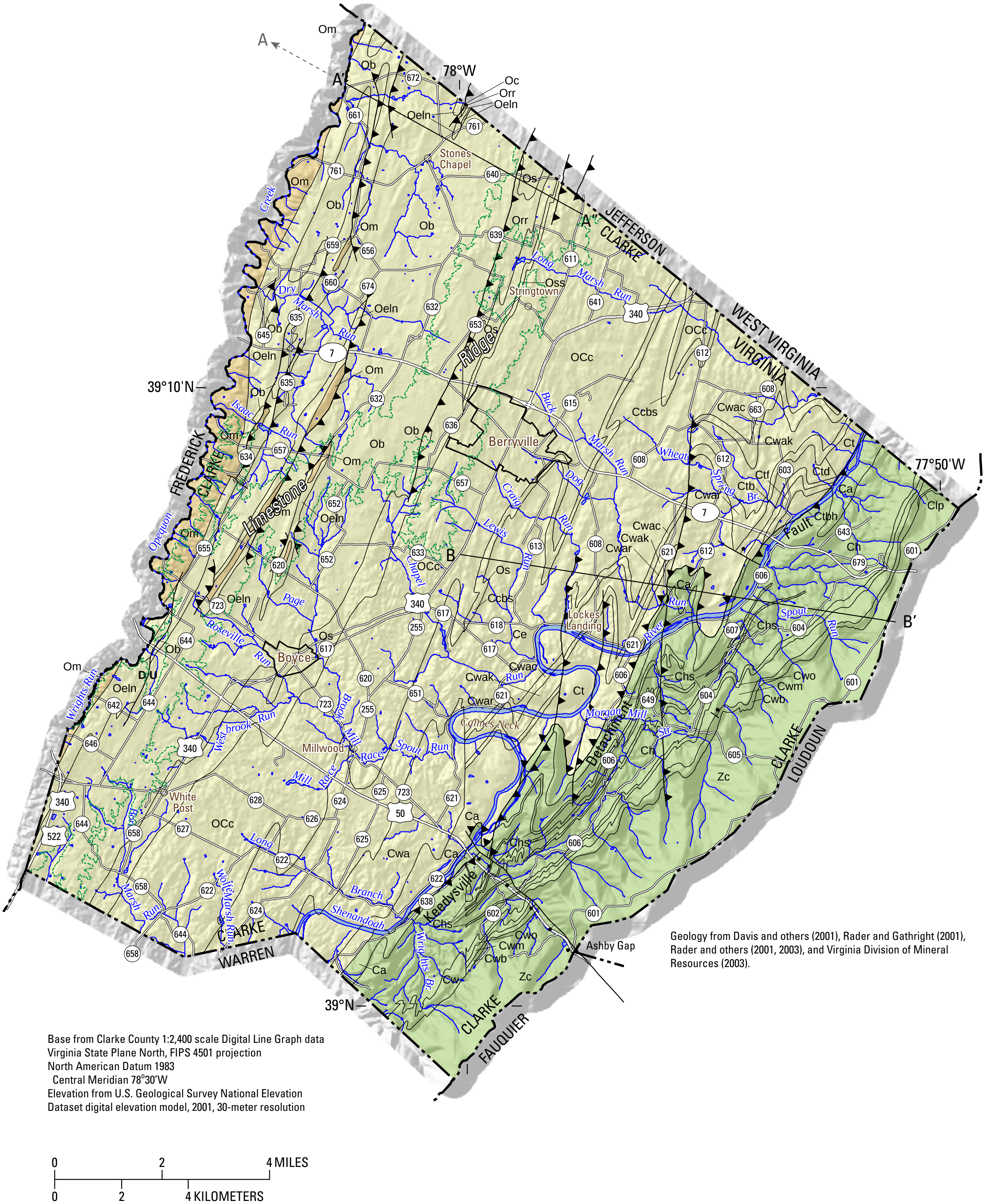


Figure 5. Generalized hydrogeologic units map of Clarke County, Virginia.

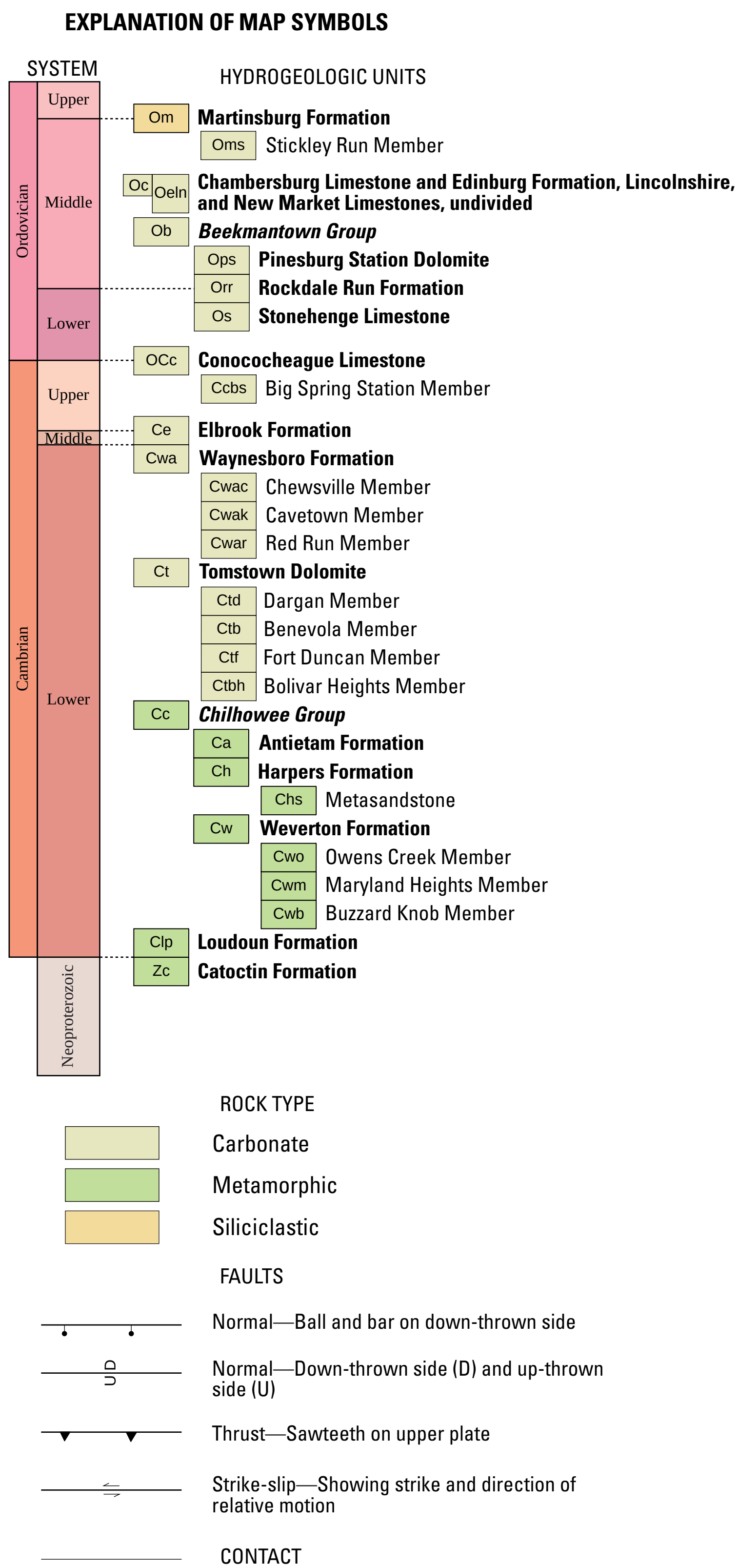


Figure 5. Generalized hydrogeologic units map of Clarke County, Virginia.—Continued

Waynesboro Formation

The Lower Cambrian Waynesboro Formation (Cwa) has been divided into three members by Brezinski (1992): Red Run, Cavetown, and Chewsville Members (fig. 5). The sandstone of the lower Red Run and upper Chewsville Members forms low hills. The carbonate rock of the Cavetown Member underlies swales between these hills (Southworth and others, 2002). These units are not mapped in the southeastern part of Clarke County, and only the contacts of the undivided Waynesboro Formation are shown in figure 5 (Virginia Division of Mineral Resources, 2003). The overall thickness of the Waynesboro Formation is 1,300 ft (Hubbard, 1990).

The Red Run Member (Cwar) consists of interbeds of light-gray, fine-grained, calcareous sandstone; medium- to dark-gray laminated, ribbony, sandy dolomitic limestone; and light-olive-gray, silty, calcareous shale (Southworth and others, 2002). The Cavetown Member (Cwak) consists of medium- to dark-gray, thick-bedded, massive limestone and bioturbated dolomite in the lower part. The middle part consists of bioturbated, dolomitic limestone and dolomite and thin calcareous sandstone and shale. The upper part consists of thick-bedded, bioturbated dolomite with laminated ribbony dolomite. Typically, the Cavetown Member is not well exposed (Southworth and others, 2002). The Chewsville Member (Cwac) consists of dark dusty-red siltstone with ripple marks and mudcracks; light-gray sandstone with cross bedding and *Skolithus* tubes; and interbeds of dolomitic limestone and dolomite (Southworth and others, 2002).

Elbrook Formation

The Middle and Upper Cambrian Elbrook Formation (Ce) consists of interbedded, medium-gray and bluish-gray limestone, light- to medium-gray dolostone, and gray shale. The dolostone and shale tend to weather to a yellowish color. The limestone is thin to thick bedded, fine- to medium-grained, and contains algal bioherms, intraformational conglomerate, and dolomite mottles. The dolostone is medium bedded and fine grained. The thickness of the Elbrook is at least 2,300 ft (Harlow and others, 2005).

Conococheague Limestone

The Upper Cambrian and Lower Ordovician Conococheague Limestone (OCc) consists of interbedded, medium-gray limestone, light-gray dolostone, and light-gray to buff sandstone. The limestone is thin to medium bedded, fine grained, and contains algal bioherms, intraformational conglomerates, oolites, and interlaminated tan dolostone and gray limestone (ribbon rock). The dolostone is medium bedded and fine grained. The sandstone is present in the lowermost and uppermost parts of the Conococheague and is medium to coarse grained and weathers to a reddish color. The thickness of the Conococheague ranges from 2,200 to 2,600 ft (Harlow and others, 2005).

The Upper Cambrian Big Spring Station Member (Ccbs) forms the basal unit of the Conococheague Limestone and consists of gray to buff, coarse-grained, calcareous sandstone interbedded with intraformational conglomerate and fine-grained dolostone. In response to the abundance of sandstone, the Big Spring Station Member tends to form prominent ridges where exposed. The thickness of the Big Spring Station Member is 300 ft (Harlow and others, 2005).

Stonehenge Limestone of the Beekmantown Group

The Lower Ordovician Stonehenge Limestone (Os) of the Beekmantown Group consists of dark-gray, thick-bedded, fine- to medium-grained, fossiliferous limestone. Other characteristic features of the Stonehenge Limestone are algal bioherms, intraformational conglomerates, bioclastic beds, crinkly siliceous laminations, minor black chert nodules, and some minor dolostone beds. The lowermost and uppermost beds of the Stonehenge were formed in a lagoon environment and, therefore, are thin-bedded. The thickness of the Stonehenge is from 600 to 650 ft (Harlow and others, 2005). The basal part of the Stonehenge Limestone consists of a light-gray, silty, laminated limestone (Southworth and others, 2002).

Rockdale Run Formation of the Beekmantown Group

The Lower and Middle Ordovician Rockdale Run Formation (Orr) of the Beekmantown Group consists of interbedded, bluish-gray, medium-gray, and dark-gray limestone and medium-gray dolostone. The limestone is thin to medium bedded, fine to medium grained, and fossiliferous, and includes intraformational conglomerates, algal bioherms, bioclastic zones, and burrow mottling. The dolostone is medium bedded, fine to medium grained, and crystalline. Nodules and large masses (2 to 4 ft in diameter) of gray chert are common in the Rockdale Run Formation. Topographic knolls with little bedrock exposures tend to form where large masses of *Cryptozoon* chert are present in the soil of the lower part of the formation. The gastropod *Lecanospira* is common in limestone beds in the lower and middle part of the Rockdale Run. The thickness of the Rockdale Run Formation is about 1,500 ft (Harlow and others, 2005).

Pinesburg Station Dolomite of the Beekmantown Group

The Middle Ordovician Pinesburg Station Dolomite (Ops) of the Beekmantown Group consists of medium- to light-gray, buff to light weathering, cherty dolostone and dololaminite. The Pinesburg Station is medium- to thick-bedded, fine-grained, and weathered dolostone that typically exhibits a distinctive “butcher-block” (cross-hatched joints) structure. The lower part of the formation is characterized by a few thin limestone beds that are medium gray and fine grained. Near the top of the formation, collapse breccias and irregular bedding are the paleokarst structures that indicate subaerial exposure during Middle Ordovician time. Thickness of the Pinesburg Station Dolomite ranges from 650 to 875 ft (Harlow and others, 2005).

New Market Limestone

The Middle Ordovician New Market Limestone, Lincolnshire Limestone, and Edinburg Formations (Oeln) usually are mapped as an undivided unit on small-scale maps because of the thin nature of these Middle Ordovician limestone units. The New Market Limestone consists of dove-gray and medium-gray, micritic, fenestral limestone. The New Market is thick-bedded, high purity limestone that can be as much as 98-percent calcium carbonate (Edmundson, 1945). Many quarries in the Shenandoah Valley have been established to extract the high calcium limestone of the New Market. The thickness of the New Market Formation is from 140 to 200 ft (Harlow and others, 2005).

Lincolnshire Limestone

The Middle Ordovician Lincolnshire Limestone consists of dark-gray to very dark-gray limestone with bedded, black, chert nodules and medium-gray, bioclastic limestone (fig. 5). The limestone is medium bedded and medium to coarse grained; however, the bioclastic limestone is thin bedded and coarse grained. The thickness of the Lincolnshire Limestone is from 75 to 105 ft (Harlow and others, 2005).

Edinburg Formation

The Middle Ordovician Edinburg Formation consists of interbedded limestone and medium-dark to very dark-gray, calcareous shale (fig. 5). The limestone is thin to thick bedded, irregularly bedded, fine to medium grained, and exhibits knobby weathering. Yellowish-brown metabentonite is present in thin beds throughout the unit and represents volcanism from an island arc system to the east during the Middle Ordovician. The thickness of the Edinburg is about 500 ft (Harlow and others, 2005).

Chambersburg Limestone

The Middle Ordovician Chambersburg Limestone (Oc) consists of a dark-gray, fine- to medium-grained, argillaceous (clay-rich) and nodular, fossiliferous limestone (Southworth and others, 2002). The Chambersburg Limestone is only present in a small area of the northwest part of the county along the border with Jefferson County, WV, and is equivalent to the Lincolnshire Limestone and Edinburg Formation to the south (fig. 5).

Metamorphic Rock Unit

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 Clarke County and are present along the eastern margin of the Shenandoah Valley on the eastern side of the county in the Blue Ridge. The metamorphic rock unit consists of metabasalt and metasedimentary rocks of the Neoproterozoic Catoctin Formation; phyllite of the Lower Cambrian Loudoun Formation, and the metasedimentary rocks of the Lower Cambrian Weverton, Harpers, and Antietam Formations of the Chilhowee Group (fig. 5).

Catoctin Formation

The Neoproterozoic Catoctin Formation (Zc) 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 plagioclase-actinolite-epidote-chlorite-magnetite, quartz-feldpspar-epidote-chlorite amygdules (Hubbard, 1990). The metabasalts are interpreted as basaltic flows and tend to form prominent ledges. Epidosite locally is present as light green, blocky masses in the metabasalt breccia (Southworth and others, 2002). The Catoctin is the oldest unit exposed in Clarke County, and Badger and Sinha (1988) determined a rubidium/strontium (Rb/Sr) age of 570±36 millions of years before present (Ma) for the metabasalt of the Catoctin Formation in Virginia. The thickness of the Catoctin Formation is greater than 1,200 ft (Hubbard, 1990).

Loudoun Formation of the Chilhowee Group

The Lower Cambrian Loudoun Formation (Clp) of the Chilhowee Group consists of a dark variegated phyllite that is amygdaloidal, vesicular, and tuffaceous. Elongated amygdules along the slaty cleavage plane indicate a volcanic origin (Southworth and others, 2002). The Loudoun Formation is only present in the northeast corner of the county along the border with Jefferson County, WV (fig. 5).

Weverton Formation of the Chilhowee Group

The Lower Cambrian Weverton Formation (Cw) of the Chilhowee Group represents the change from a volcaniclastic to predominantly fluvial environment where alluvial sediments were deposited during the initial stages of a marine transgressive sequence (Schwab, 1986). Whitaker (1955) determined from paleocurrent directions that the source of the sediments was from the west. The Weverton Formation has been divided into three members by Brezinski (1992): the Buzzard Knob, Maryland Heights, and Owens Creek Members (fig. 5). Within each of these members, fining-upward sequences are evident; however, the Owens Creek Member is coarser grained and more poorly sorted than the other members (Southworth and others, 2002). These units have not been mapped separately in the southeastern part of the county, and only the contacts of the undivided Weverton Formation are shown in figure 5 (Virginia Division of Mineral Resources, 2003). The overall thickness of the Weverton Formation ranges from 440 to 600 ft (Hubbard, 1990).

The Buzzard Knob Member (Cwb) consists of light-gray quartzite interbedded with light colored metasiltstone. The quartzite is present as two well-sorted, crossbedded, mature beds that are interbedded with a sandy metasiltstone (Southworth and others, 2002). The Maryland Heights Member (Cwm) consists of interbedded, dark-greenish-gray metasiltstone and metagraywacke with dusky-blue to greenish-gray quartzite. The quartzite is very coarse grained with granular beds that vary in thickness from 10 to 30 ft. Topographically, swales tend to form on this member between ledges of quartzite beds of the underlying Buzzard Knob Member and overlying Owens Creek Member (Southworth and others, 2002). The Owens Creek Member (Cwo) consists of green to dark-gray sandstone to pebble conglomerate. Nickelsen (1956) noted that "gunmetal blue" is a diagnostic color for this unit. The sandstone is coarse grained, and the conglomerate contains pebbles of blue and red quartz, magnetite, opaque minerals, and blue-green phyllite clasts that can be up to 6 in. long, which give rise to the dark blue color. A clean gray-green conglomeratic quartzite is present at the base of the Owens Creek Member (Southworth and others, 2002).

Harpers Formation of the Chilhowee Group

The lower part of the Lower Cambrian Harpers Formation (Ch) of the Chilhowee Group consists of greenish-brownish-gray, phyllitic metasiltstone interbedded with meta-arkose and basal pebble conglomerate. The phyllitic units are very fine grained and thick bedded (Hubbard, 1990). Bedding, however, is typically obscured by the strongly developed cleavage (Southworth and others, 2002). The upper part of the Harpers Formation consists of light-gray to brown, thin-bedded, ferruginous, magnetite-rich metasandstone (Chs), which contains trace fossils, *Skolithos* tubes, and *Arenicolites* burrows (Hubbard, 1990; Southworth and others, 2002). The thickness of the Harpers Formation ranges from 2,200 to 2,500 ft (Hubbard, 1990).

Antietam Formation of the Chilhowee Group

The lower part of the Lower Cambrian Antietam Formation (Ca) of the Chilhowee Group consists of very light-gray quartzite interbedded with green-gray, sandy metasiltstone. *Skolithos* tubes are numerous in the quartzite beds. The Antietam becomes coarser grained higher in the formation ranging 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 upper contact of the Antietam Formation delineates the boundary between the Blue Ridge to the east and the Valley and Ridge to the west. The thickness of the Antietam ranges from 200 to 800 ft (Hubbard, 1990).

Siliciclastic Rock Unit

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

Martinsburg Formation

The Middle and Upper Ordovician Martinsburg Formation (Om) consists of interbedded, medium-gray to dark-gray shale and medium-gray sandstone and siltstone. Weathered shale tends to be olive gray, grayish orange, and yellowish orange; the sandstone and siltstone weather grayish orange. The sandstone and siltstone is medium gray, is very fine grained to fine grained, and fines upward. Graywacke is more abundant and thicker bedded higher in the formation where it forms conspicuous ribs in creek beds. The Martinsburg Formation cores the Massanutten synclinorium along the western part of Clarke County and represents the deepest environment of deposition for the Cambrian and Ordovician rocks of the Shenandoah Valley. The thickness is about 2,600 ft, but Orndorff and others (1999) indicate the Martinsburg may be as much as 5,000 ft thick regionally.

The Middle Ordovician Stickley Run Member (Oms) forms the basal unit of the Martinsburg Formation and may be as thick as 900 ft (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. The Stickley Run Member is mapped as undivided from the Martinsburg in figures 2 and 5.

Structural Geology

The Great Valley section of Clarke County is located on the eastern limb of the regional Massanutten synclinorium (fig. 2), which is a complexly folded and faulted synclinal trough with numerous tight, upright, second- and third-order, disharmonic folds (anticlines and synclines) that verge up the limbs of the higher order synclinorium. The synclinorium is doubly plunging at low angles; the north end plunges to the south, and the south end plunges to the north. The Massanutten synclinorium contains about a 3-mi-thick section of siliciclastic and carbonate rocks. The axis of the synclinorium in Clarke County is underlain by the Middle and Upper Ordovician Martinsburg Formation. The eastern limb of the synclinorium is characterized by rocks with nearly vertical dips to the northwest or locally overturned beds with steep dips to the southeast (Southworth and others, 2002; Yager and others, 2008). Although Clarke and Frederick Counties are within the same structural block (the Massanutten block), the rocks in Frederick County, which are situated on the western limb of the Massanutten synclinorium, dip gently to the southeast (Harlow and others, 2005; Yager and others, 2008).

The Neoproterozoic and 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). These rocks were part of a 3-mi-thick wedge of rocks that 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 rocks of the Blue Ridge have undergone lower greenschist-facies metamorphism; however, most of the carbonate rocks of the Great Valley have not been metamorphosed (Southworth and others, 2002).

The structural deformation has created weaknesses in the competent bedrock that are of hydrologic importance 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 and Joints

Groundwater flows through, and is stored in, the secondary permeability of bedding-plane partings and joints in the bedrock that result from various processes. Bedding-plane partings (fig. 6) are separations between different layers or beds in sedimentary rocks and between basaltic flows in the metabasalt of the Catoctin Formation. The tectonic forces of the Alleghanian orogeny formed four types of joints (fractures) 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, and tension joints form along fold hinges (Harlow and others, 2005). Joint types vary with rock type. Brittle deformation is characteristic of the carbonate, sandstone, and metabasalt, and ductile deformation is characteristic of the finer-grained rocks such as the shale of the Martinsburg Formation and phyllite in the Blue Ridge. Axial planar cleavage is most evident in the shale of the Martinsburg Formation (Harlow and others, 2005). Columnar jointing is present in the Catoctin Formation as a result of shrinkage during cooling of the basalt to form hexagonal joints, but is relatively uncommon in Clarke County (Lukert and Nuckols, 1976).

Dips of bedding-plane partings and the various joint types are highly variable and range from horizontal to vertical and can be overturned, but are generally between 10 and 80° (Wright, 1990); however, steeply dipping beds are prevalent in Clarke 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 Clarke County is variable, the general strike ranges from N. 10° E to N. 20° E (Wright, 1990).

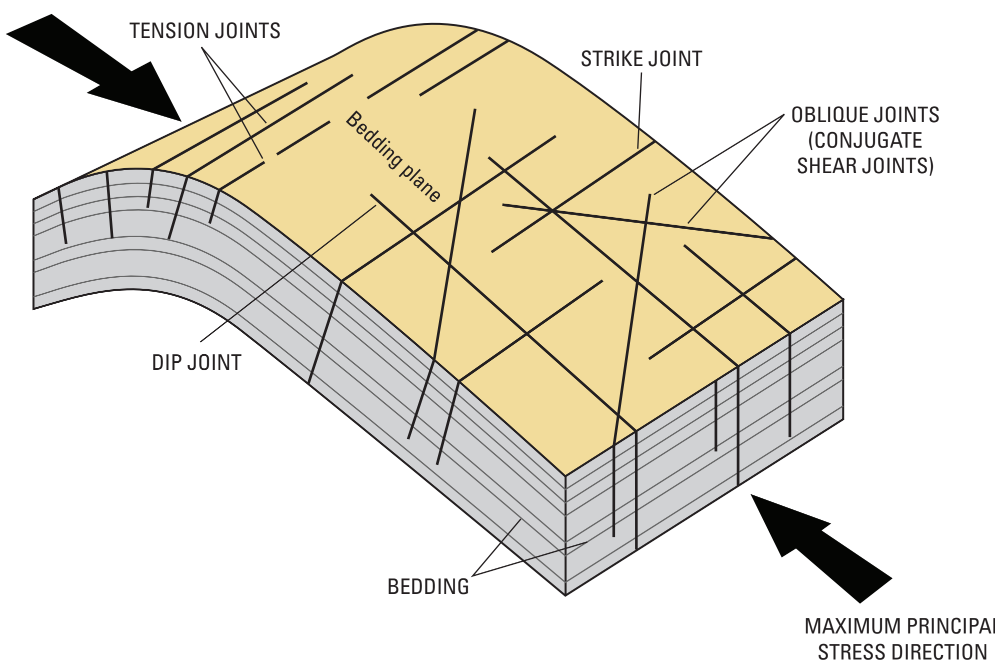


Figure 6. Graphic representation of joint types and bedding in folded rocks (modified from Earth Science Australia, 2004; Harlow and others, 2005).

Folds

Folds of various types are present in Clarke County and generally have fold axes that trend N. 15° E to N. 20° E (Wright, 1990). Folds plunge to the north-northeast generally at 10° to 20°, but can range from less than 5° to at least 35°. Deformation has the character of many subsidiary folds developed on the limbs of the major folds. Generally, the west limbs of folds have very steep dips and can be overturned. Fold amplitude and wavelength range from less than 100 ft to several thousands of feet (Gathright and Nystrom, 1974). An apparent disharmony in fold wavelength in response to rheological differences of the rock units was noted by Orndorff and others (1999). 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. The sinuous appearance of the contacts of some of the hydrogeologic units in figure 5 is indicative of folded rocks. As an example, an anticline with a fold wavelength of approximately 1,000 ft is clearly visible in the streambed just south of Calmes Neck (fig. 7) during low-flow conditions of the Shenandoah River at the time of acquisition of the aerial photography in 2002.

Faults

Several fault types have been mapped in Clarke County (fig. 5). Thrust faults strike north-northeast and dip southeast, whereas local back thrusts dip steeply to the northwest (Gathright and Nystrom, 1974; Yager and other, 2008). Most of these faults parallel the strike and generally trend N. 15° E (Edmundson and Nunan, 1973; Wright, 1990). Some of the faults along the boundary between the Great Valley section and Blue Ridge have been folded as evidenced by the sinuous trace of the Keedysville detachment fault in figure 5 (Southworth and others, 2007). Several high-angle transverse and normal faults cut across the boundary between the two geologic provinces in the county. Numerous local transverse or cross-strike faults are present in the Valley and Ridge and Blue Ridge.

Lineaments (fig. 8) are linear surface features that can reflect areas of concentrated fractures or faults. Lineaments were mapped in Clarke County by Hubbard (1990). Most of the Landsat lineament zones are nearly normal to the strike of the rocks, fault traces, and fold axes. Parts of the lineament zone that extends from Ashby Gap through Millwood, however, coincides with a near-vertical normal fault downthrown on the southwest mapped in the Blue Ridge along Route 50 (Gathright and Nystrom, 1974). Most of the lineament zones converge in the northwest part of the county. Lineament zones shown in figure 8 likely continue into and possibly through the neighboring counties.

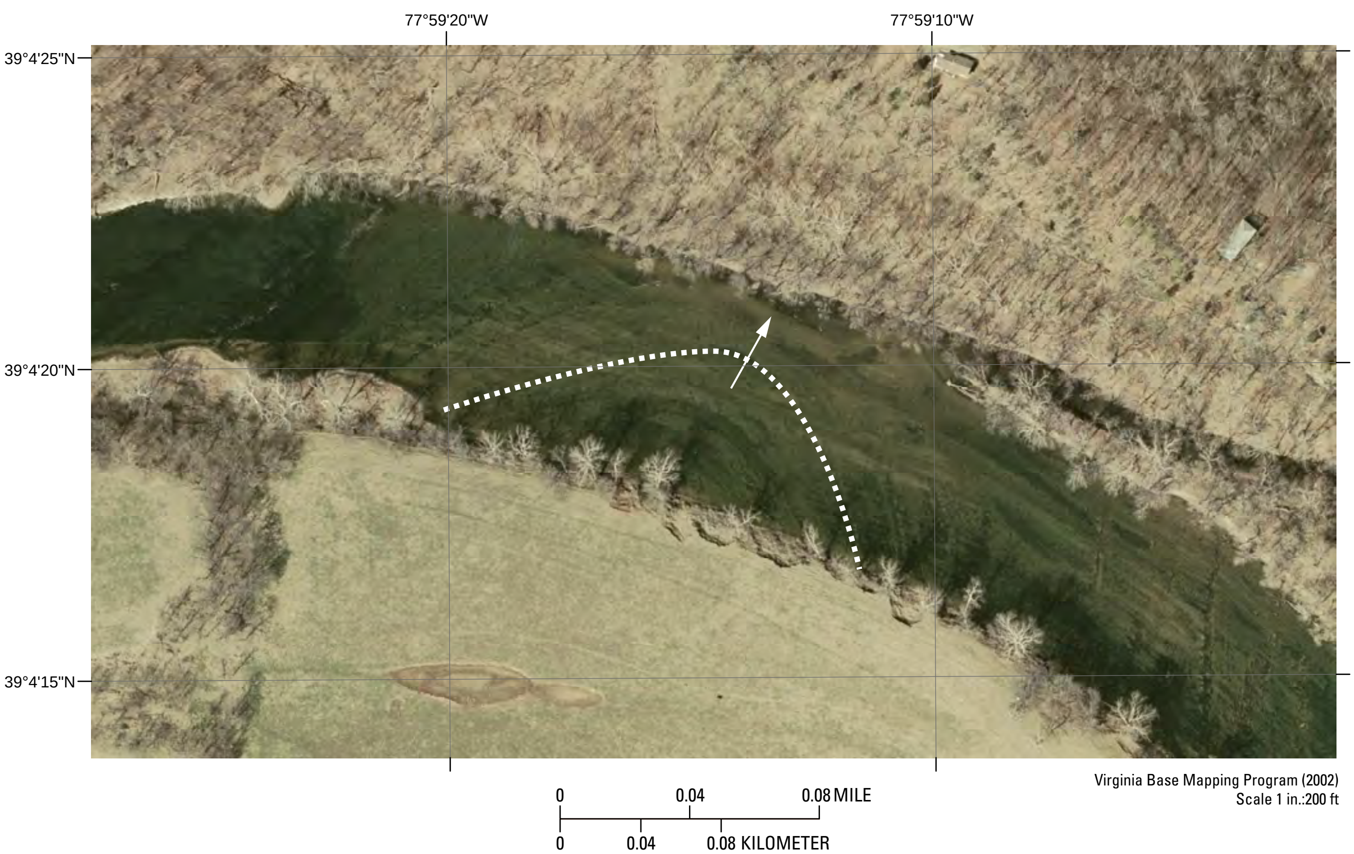


Figure 7. Large plunging fold in the Shenandoah River south of Calmes Neck in Clarke County, Virginia. Dashed line indicates bedding and arrow indicates direction of plunge.

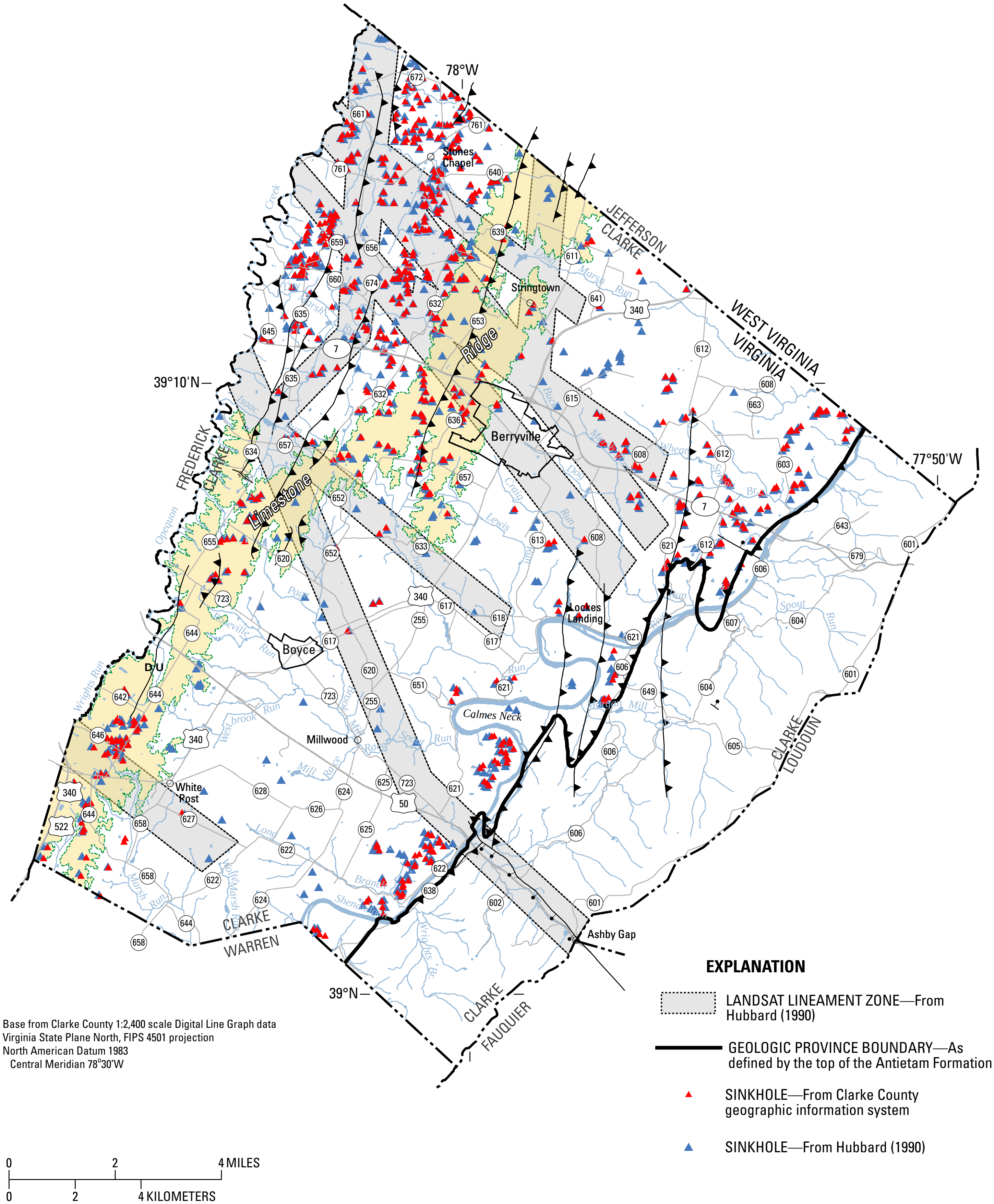


Figure 8. Location of Landsat lineament zones and sinkholes in Clarke County, Virginia.

Karst Features

Sinkholes, solution-enlarged conduits, caves and caverns, estavelles, and sinking and dry streams are characteristic features of karst terrain. Acidic precipitation infiltrates the subsurface and dissolves the very soluble carbonate rocks to form these features. Lithologic characteristics, fracture density, proximity of carbonate rock to streams, land slope, and geologic structure are controlling factors in sinkhole development (Orndorff and Goggin, 1994; Hyland and others, 2006). Sinkholes are more abundant and increase in size near incised streams like Opequon Creek and the Shenandoah River. The greater development of sinkholes near streams has been attributed to the steepened hydraulic gradient and increased rate of groundwater flow in these areas (Hubbard, 1983). The relation between sinkhole development and folds, especially noses of anticlines and synclines, is well established (Hack, 1965; Hubbard, 1983, 1990; Orndorff and Goggin, 1994; Doctor and others, 2008). Doctor and others (2008) also noted that sinkholes usually form in elevated and flat (less than 5 degree slope) areas. Hubbard (1990) and Wright (1990) documented sinkhole development during well construction and pumping. The greatest density of sinkholes is in the northwest part of the county (fig. 8).

Hydrology

Groundwater flows through bedrock- and regolith-aquifer systems in Clarke County. The bedrock systems are characterized by karst and fractured-rock aquifers that have developed in the folded and faulted rocks. Conduit- and diffuse-flow conditions are present in the karst aquifer systems in areas underlain by the carbonate rock unit. Diffuse-flow conditions are characteristic of the fractured-rock aquifer systems in areas underlain by the siliciclastic and metamorphic rocks (Jones, 1987; Hubbard, 1990; Wright, 1990). Diffuse, porous-media flow is present in the regolith material overlying bedrock. Preferential groundwater flow also is present along relict structures in the regolith. The karst and fractured-rock aquifers generally are unconfined, and groundwater gradients are controlled by topography. Confined aquifers, however, may be present locally (Harlow and others, 2005). Groundwater recharge is derived from precipitation. Recharge occurs by percolation of water through the regolith mantle to the bedrock, along partings in the rock, and by direct inflow into sinkholes and from sinking streams. Groundwater eventually discharges to streams primarily in the form of spring discharge.

Hydrogeologic Characteristics

Each of the hydrogeologic units has distinctive characteristics that are evident in the records provided by local well drillers. More than 1,800 well records from files maintained by the Virginia Department of Environmental Quality (VDEQ), the Virginia Department of Health, Clarke County, and the USGS were analyzed to determine well-construction characteristics, well yield, and water-bearing characteristics of the different hydrogeologic units. The results of this analysis are presented in tabular form (table 1) and graphical form as boxplots (fig. 9), and they are described in detail below. The blue-shaded areas in figure 9 represent the 95-percent confidence intervals. In most cases, the confidence intervals for the hydrogeologic units overlap, which indicates the characteristics of these hydrogeologic units are not significantly different statistically. This is not unusual because nearly all of the wells in the analysis were drilled for domestic use (Cederstrom, 1972). 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 and a 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 established for Clarke County. Water levels were measured quarterly in more than 40 wells, as well as discharges and field water-quality properties at 23 springs across the county, between October 2002 and October 2008. Site information for the wells and springs can be found in appendixes 1 and 2, respectively. Individual water-level measurements are listed in appendix 3, and discharge and water-quality measurements are in appendix 4. Seasonal and spatial changes in water levels and discharges are described below.

Well Depths

Well depths in Clarke County range from 23 to 1,020 feet below land surface (ft bls; table 1 and fig. 9). The shallowest wells are numerous large-diameter, hand-dug, stone-lined wells located in the Great Valley section of the county. Some of these wells have been reported to date back to the 1700s. These wells were commonly dug either adjacent to, or upgradient from, intermittent springs. Generally, median well depths are deep in the metamorphic rocks of the Blue Ridge, which is a reflection of the elevated setting, depth to water-bearing zones, and relatively low hydraulic conductivity of these hydrogeologic units. The occurrence of dissolution-enlarged openings and relatively low relief of the carbonate rock types contributes to the shallower median well depths than those in the Blue Ridge. The deepest well inventoried during this study, however, was drilled to 1,020 ft into the Beekmantown Formation.

Well Yields

Well yields in Clarke County range from 0.4 to 600 gallons per minute (gal/min; table 1 and fig. 9). Dry holes are not uncommon, and filing of well-completion reports is not required. Most of the well-yield data are from short duration, airlift tests conducted after total depth of the wells had been reached. Less than 10 of the wells had sufficient data to calculate specific capacity, which is pumped discharge divided by the amount of water-level drawdown. Tukey's multiple-comparison test, a rank transform, nonparametric analysis of variance test, was used to compare well yields from the individual hydrogeologic units. At the p-value < 0.05 significance level, the results from the Tukey's analysis indicate that the hydrogeologic units can be categorized into three groups. The Antietam, Catoctin, and Harpers Formations in the Blue Ridge and the Stonehenge Limestone of the Beekmantown Group are categorized as having low well yields. The undivided Beekmantown Group and Conococheague Limestone, Elbrook Formation, and New Market Limestone have moderate well yields. The Tomstown Dolomite and Waynesboro and Weverton Formations could not be statistically differentiated from the low and moderate groups; therefore, they are categorized as having low to moderate well yields. Wells finished in the Martinsburg Formation were categorized as having the highest yields. The latter contradicts previous conclusions 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), but is consistent with findings of Shultz and others (1995) in Berkeley County, WV. A review of the 27 wells finished in the Martinsburg Formation indicates that 40 percent of these wells are 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. The small overall sample size coupled with a large percentage of these wells being located in areas conducive to high yielding wells and the possibility that some of these wells may actually obtain water from the Stickley Run Member of the Martinsburg Formation, which is a carbonate rock, create a potential bias in the statistical analysis that may not be representative of the siliciclastic rocks of the Martinsburg Formation. A high-yielding well (130 gal/min) was recently drilled in Warren County that produced from the Stickley Run Member, which was overlain by 225 ft of shale (D.L. Nelms, U.S. Geological Survey, written commun., 2009).

A spatial analysis was conducted to identify areas where well yields tend to cluster as either low (less than 5 gal/min) or high (greater than 50 gal/min). In the Great Valley section, many of the areas with the highest density of low-yielding wells are present where lineament zones or faults have not been mapped (fig. 10). To some degree, the same is true for the Blue Ridge; however, several high density areas of low-yielding wells are present in areas underlain by tight folds and faults. High-yielding wells generally tend to cluster along faults, within lineament zones, and in areas of tight folding throughout the county (fig. 11). A comparison of density clusters 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 karst and fractured-rock aquifer systems. For example, the clusters of both low- and high-yielding wells along Route 7 about 1.5 mi east of the boundary between the provinces are located in an intensely folded and faulted area. Many of the high-yielding wells are less than 200 ft deep, whereas the low-yielding wells generally are greater than 300 ft deep.

The statistical and spatial analyses described previously should be considered a general indication of well-yield characteristics rather than 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 limit well yield. Also, 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 has not been thoroughly investigated for the metamorphic rocks. Other investigations have indicated that yields increase with depth (Cressler and others, 1983; Daniel, 1989; Swain, 1993; Hansen and Simcox, 1994; Loiselle and Evans, 1995).

Depth to Bedrock

Median depths to bedrock are less than 50 ft bls in Clarke County (table 1 and fig. 9). The metamorphic rocks of the Harpers Formation and the carbonate rocks of the Waynesboro Formation and Tomstown Dolomite in the eastern part of the county have a larger range of depths to bedrock than the other hydrogeologic units in the county (fig. 12). Numerous outcrops of carbonate rocks in the western part of the county provide evidence of shallow depths to bedrock in that area. Hack (1965), Edmundson and Nunan (1973), Gathright and Nystrom (1974), and Hubbard (1990) mapped a thick residual mantle on carbonate rocks in the eastern part of Clarke County. The deep depths to bedrock for the Waynesboro Formation are present at the base of the Blue Ridge Mountains in areas adjacent to the Shenandoah River (especially near the Route 50 bridge; fig. 1), where thick residual mantle and terrace deposits (Hubbard, 1990) are mapped. Although few of the wells inventoried in the Martinsburg Formation had depth to bedrock reported, Hack (1965) states that this formation generally lacks residuum.

Much of Clarke County has some mantle over the bedrock, but groundwater storage in this mantle is believed to be minimal (Harlow and others, 2005). The areas with a thick sequence of regolith overlying the Waynesboro Formation, however, may have considerable storage potential. Areas underlain by the Waynesboro Formation, unlike the Tomstown Dolomite, have slopes that are generally less than 5 degrees, which may reduce surface runoff and consequently facilitate downward percolation of water.

Table 1. Well-construction characteristics for the hydrogeologic units in Clarke County, Virginia.

[Fm, Formation; Lst, Limestone; Carb., carbonate; Meta., metamorphic; Sili., siliciclastic; n, number of sites; nd, not determined]

Statistic	Hydrogeologic unit											
	Tomstown Dolomite	Waynesboro Fm	Elbrook Lst	Conococheague Lst	Stonehenge Lst	Beekmantown Fm	New Market Lst	Catoctin Fm	Weverton Fm	Harpers Fm	Antietam Fm	Martinsburg Fm
	Rock type											
	Carb.	Carb.	Carb.	Carb.	Carb.	Carb.	Carb.	Meta.	Meta.	Meta.	Meta.	Sili.
Well depth, in feet below land surface												
Minimum	40	85	35	23	31	28	56	96	90	72	125	80
Mean	349	265	284	300	285	309	287	368	357	351	400	257
Median	325	250	260	280	235	280	275	340	313	305	400	225
Maximum	800	805	700	900	740	1,020	647	765	800	800	820	700
n	117	130	149	289	70	430	85	74	24	341	33	30
Well yield, in gallons per minute												
Minimum	0.5	0.8	1	1	1	0.4	1	0.75	2	0.5	1	5
Mean	24	26	25	34	18	27	29	17	15	16	19	39
Median	15	17	20	20	10	20	20	10	14	9.5	10	35
Maximum	150	300	200	600	90	240	200	100	60	465	125	100
n	111	119	143	273	63	398	71	75	23	330	33	27
Depth to bedrock, in feet below land surface												
Minimum	2	10	1	2	3	1	2	4	5	7	4	9
Mean	56	90	24	30	44	17	16	26	46	35	38	17
Median	39	40	18	25	34	12	13	25	25	30	33	17
Maximum	233	340	90	130	225	60	56	53	108	135	100	25
n	40	36	48	91	18	126	23	34	8	98	12	4
Upper water-bearing zone reported, in feet below land surface												
Minimum	48	66	70	60	50	17	30	65	219	40	70	75
Mean	256	210	199	228	232	232	219	253	287	261	280	213
Median	235	204	157	190	157	190	180	250	267	235	267	172
Maximum	584	481	550	690	550	745	550	570	400	678	540	457
n	44	45	57	113	23	149	27	35	8	109	14	6
Lower water-bearing zone reported, in feet below land surface												
Minimum	100	66	80	60	70	17	60	140	228	40	165	125
Mean	328	243	251	296	273	294	304	345	375	352	383	299
Median	282	250	240	249	201	260	297	325	316	330	350	249
Maximum	780	490	625	859	629	982	550	700	740	739	790	505
n	44	45	57	113	23	149	27	35	8	109	14	6

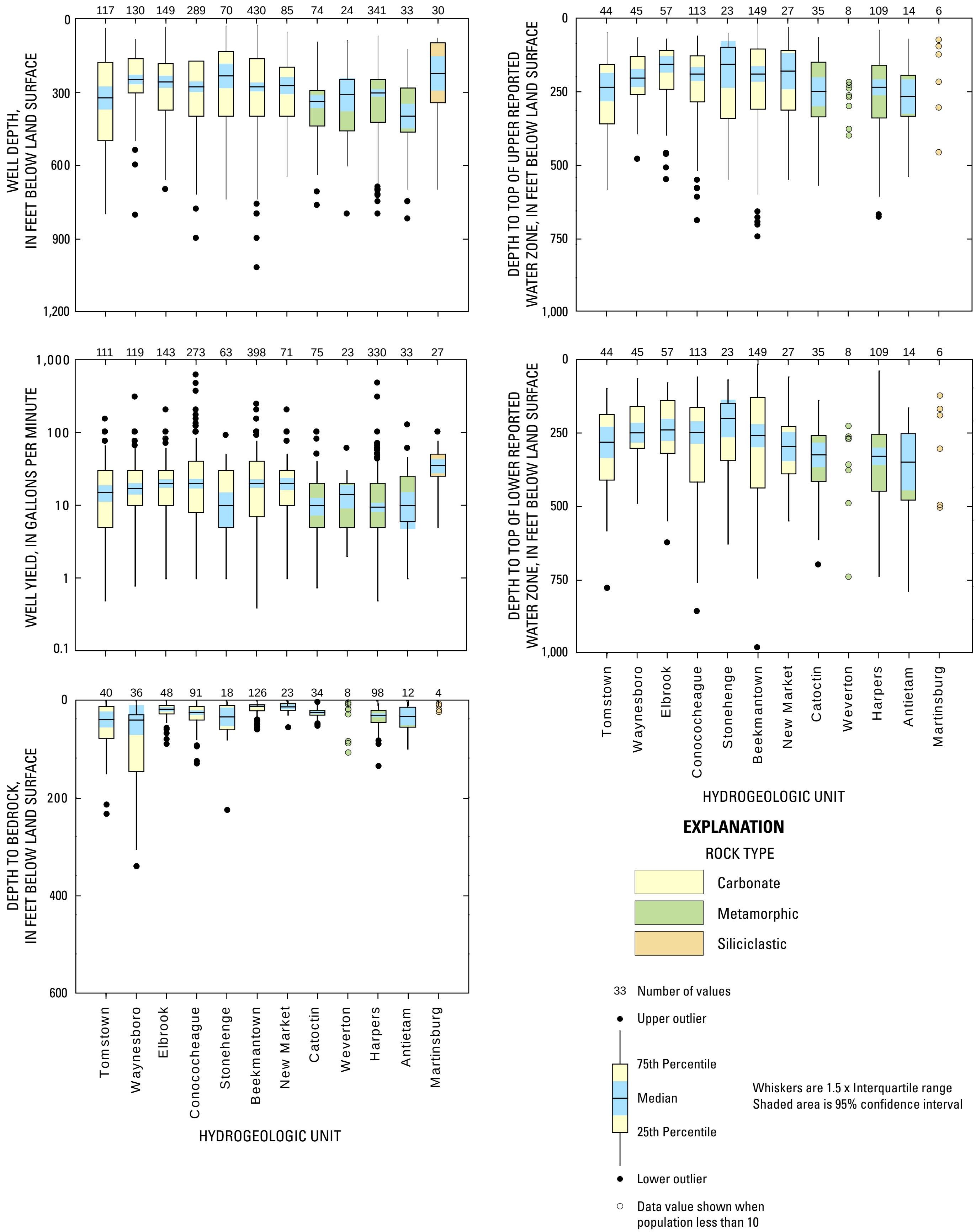


Figure 9. Summary statistics of well-construction and hydrologic characteristics of the hydrogeologic units in Clarke County, Virginia.

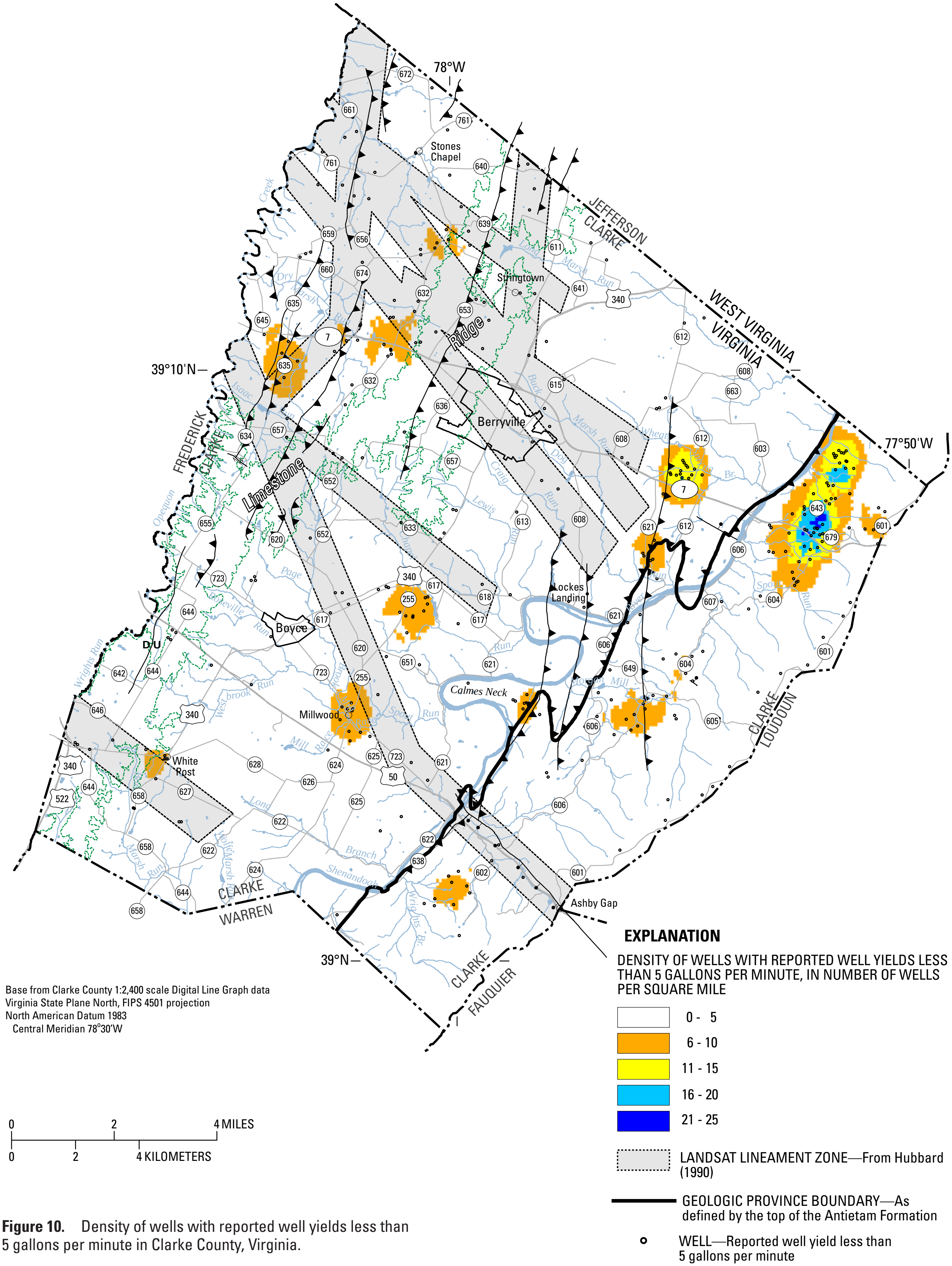


Figure 10. Density of wells with reported well yields less than 5 gallons per minute in Clarke County, Virginia.

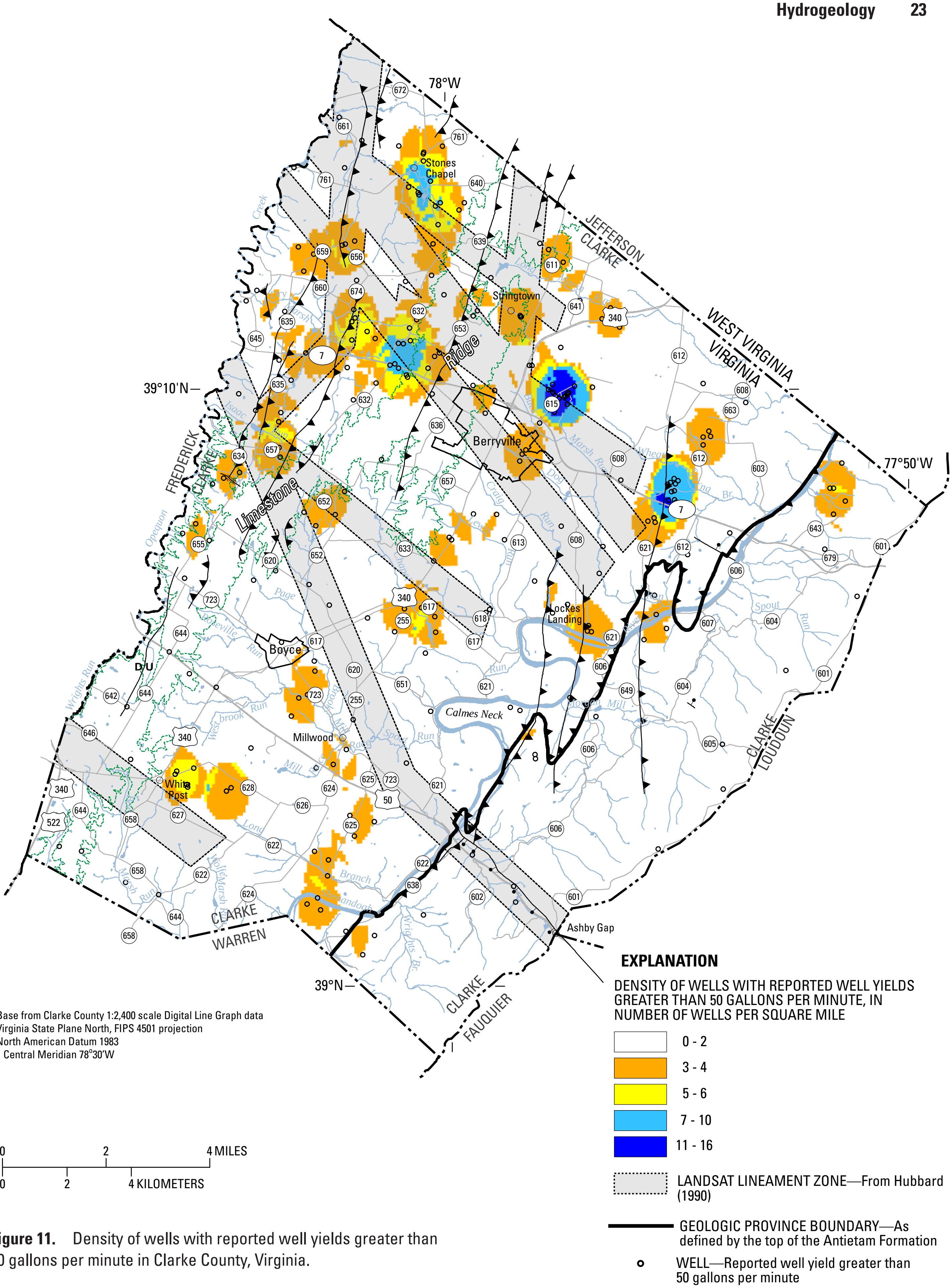


Figure 11. Density of wells with reported well yields greater than 50 gallons per minute in Clarke County, Virginia.

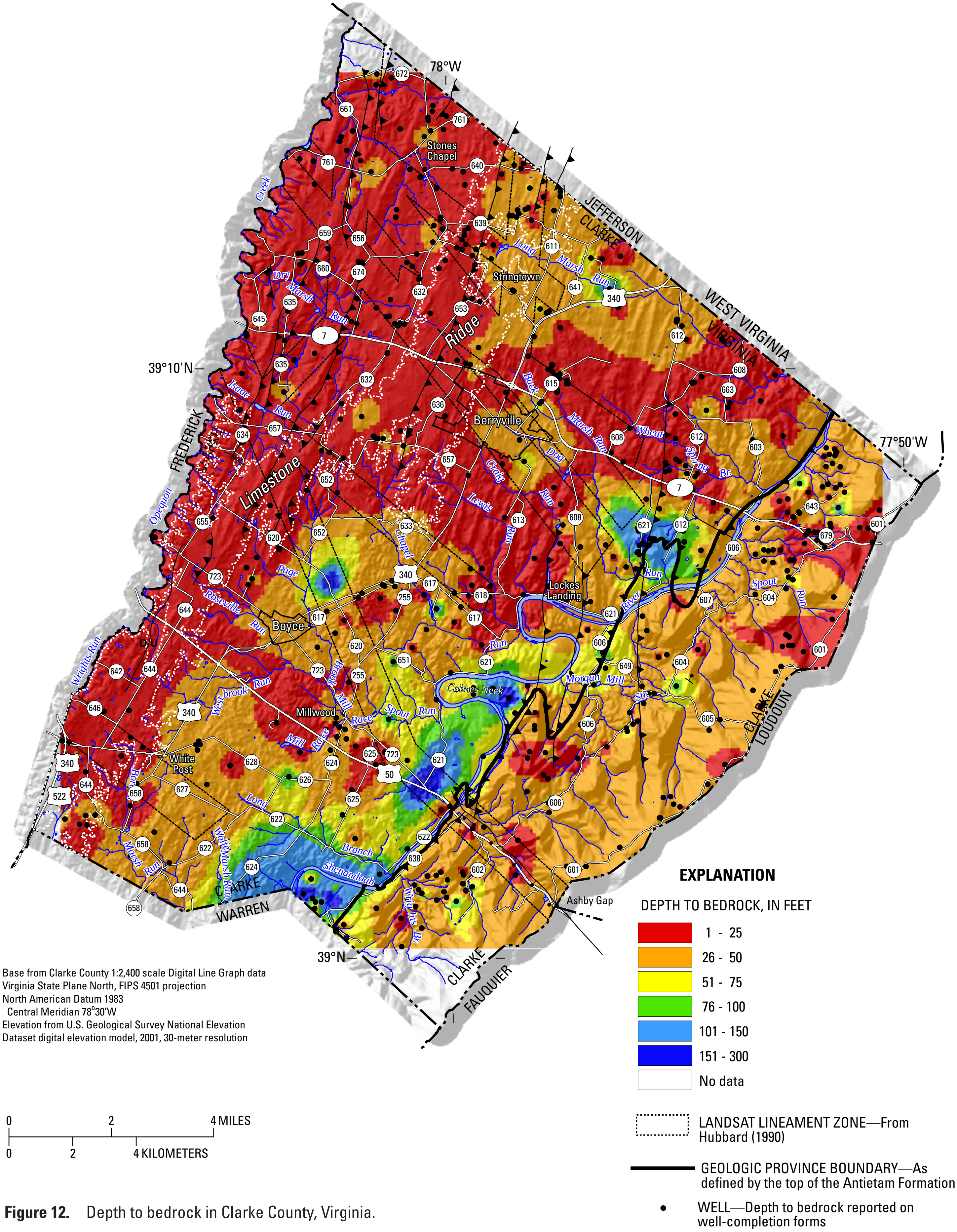


Figure 12. Depth to bedrock in Clarke County, Virginia.

Water-Bearing Zones

The depth to water-bearing zones identified on well-completion reports provides insight into where groundwater is present (table 1 and fig. 9). A well can encounter single or multiple water-bearing zones. Often, zones bearing small amounts of water are encountered but are not reported, and only the major water-bearing zones are recorded. Median depths of the upper water-bearing zones reported indicate that water generally is first encountered in about the upper 250 ft below land surface. However, median depths are slightly deeper for the hydrogeologic units of the Blue Ridge. A similar distribution of depth to the top of the lower water-bearing zones reported also is evident (table 1 and fig. 9).

Spatial distribution of the depths to the top of the upper water-bearing zones in Clarke County provides insight into the topographic and geologic controls on the occurrence of groundwater (fig. 13). In general, several spatial characteristics are evident.

Shallow depths (less than 250 ft bls) are present

- beneath basin boundaries or divides in the upper reaches of basins, especially where divides converge;
- in the Westbrook Run Basin southwest of Boyce;
- along the Shenandoah River where the geologic structure is tight folds and faults, and a thick mantle of residuum and terrace deposits is present (figs. 5 and 12);
- in areas of converging Landsat lineament zones;
- along the Landsat lineament zone in the southern part of the Blue Ridge along Route 50; and
- in elevated parts of faults and lineaments.

Deep depths (greater than 250 feet bls) are present

- along faults and noses of plunging folds, especially tight folds (fig. 5);
- along Landsat lineament zones;
- in the Blue Ridge and the Limestone Ridge area of the Great Valley (fig. 1); and
- in the northern part of the county along the Shenandoah River and the lower reaches of the Opequon Creek Basin.

A similar spatial pattern exists for the depth to the top of the lower water-bearing zones (fig. 14), but the majority of the depths reported are greater than 250 ft bls. About 43 percent of these lower water-bearing zones are between 400 and 1,000 ft bls and are present throughout the county. Cady (1936) and Hack (1965) suggest that water-bearing zones in carbonate rocks may be present at depths as great as 2,000 ft. A recently drilled well in Frederick County yielded more than 100 gal/min from a single water zone at 1,339 ft, possibly associated with the Apple Pie Ridge fault (G.E. Harlow, Jr., U.S. Geological Survey, written commun., 2005). In fact, Wright (1990) reported that a well located on a ridgetop in the Blue Ridge section of the county encountered freshwater at about 5,000 ft bls. All of these examples indicate the possibility of encountering water-bearing zones at substantial depths.

The spatial distribution of the depth of water-bearing zones is consistent with the conceptual idea that the groundwater flow systems are topographically driven and controlled by geologic structure. The shallow water-bearing zones beneath the basin divides are consistent with the idea that recharge occurs in or near these areas. In lower topographic areas, water-bearing zones are deeper because groundwater flows from the elevated areas along geologic structures, which commonly have steep dips. The deep water-bearing zones along faults and lineament zones are the result of high permeability that extends to depth along these features. It should be noted that many of the wells in the dataset were drilled during the drought between 1999 and 2002, and data shown in figures 13 and 14 could be biased towards deeper depths than would be encountered during average or wet conditions. This is especially true in the northwest part of the county, where a majority of the dry wells are located. This potential bias, however, is believed to be slight because a sufficient number of wells drilled during other years are interspersed with those from the drought period. Future well construction may take into account that wells with water zones shallower than those shown in figure 14 may be at risk of going dry or having reduced yield during drought conditions.

Water Levels

Fluctuations in water levels are the result of natural and anthropogenic effects. The primary natural effects are precipitation, groundwater evapotranspiration, and discharge from the aquifer system to springs and streams (Harlow and others, 2005). Pumpage withdrawals for water-supply demands and surface and subsurface injection are the primary anthropogenic activities that cause water-level fluctuations. In general, recharge of precipitation to the aquifer system causes water levels to rise, and over time these levels slowly decline as water discharges to springs and streams in the area. Harlow and others (2005) state that the amount of seasonal water-level fluctuation varies and is 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; water levels in discharge areas near streams and springs and areas underlain by permeable rocks tend to fluctuate less.

A long-term water-level network was established during this investigation to quantify seasonal water-level fluctuations in Clarke County. Pressure transducers were installed in wells 46W179 and 48X 20 to monitor water levels continuously (fig. 15). Well 46W179 is a 36-ft deep, stone-lined, hand-dug well located in White Post, approximately 600 ft from the

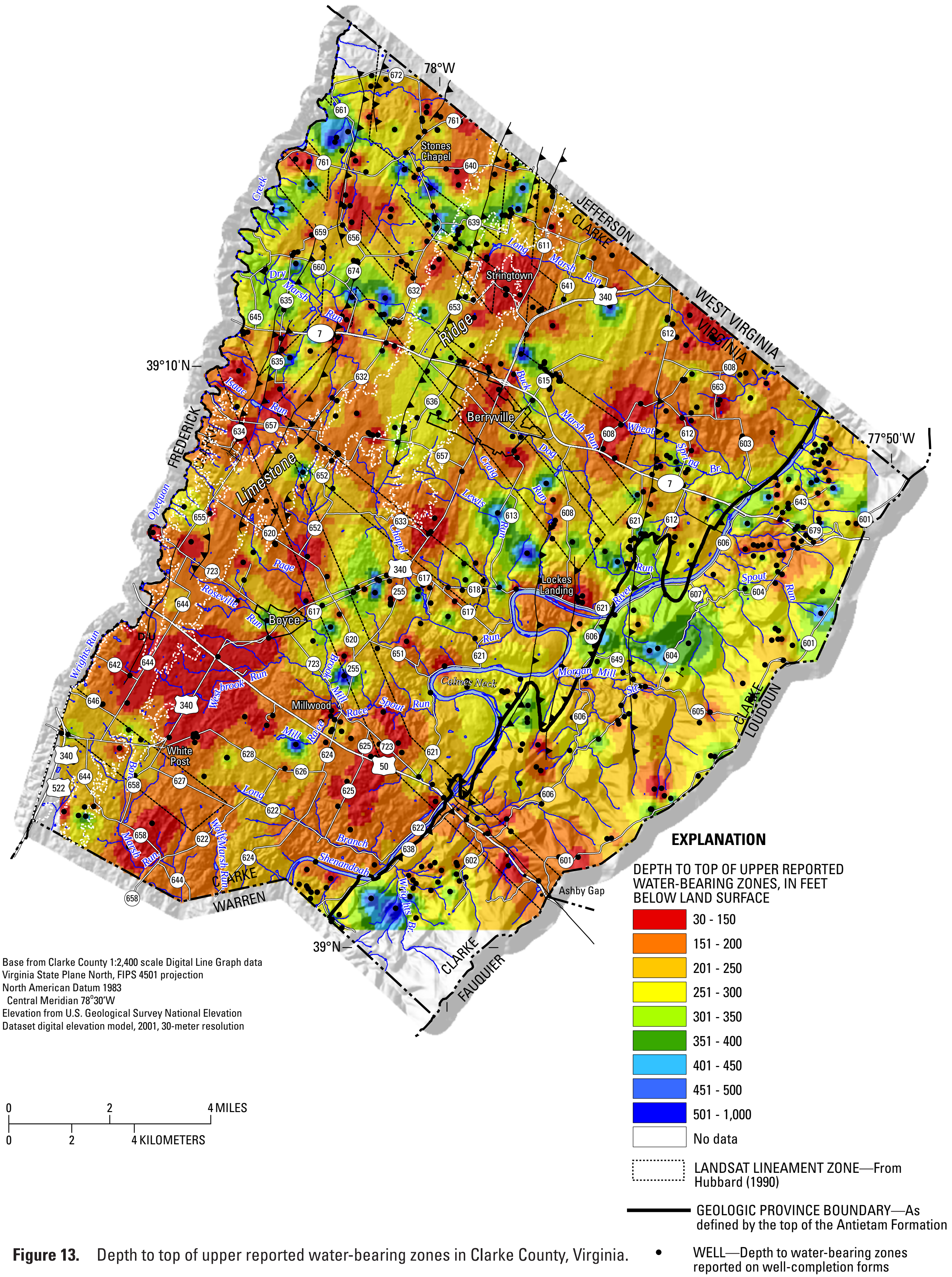


Figure 13. Depth to top of upper reported water-bearing zones in Clarke County, Virginia.

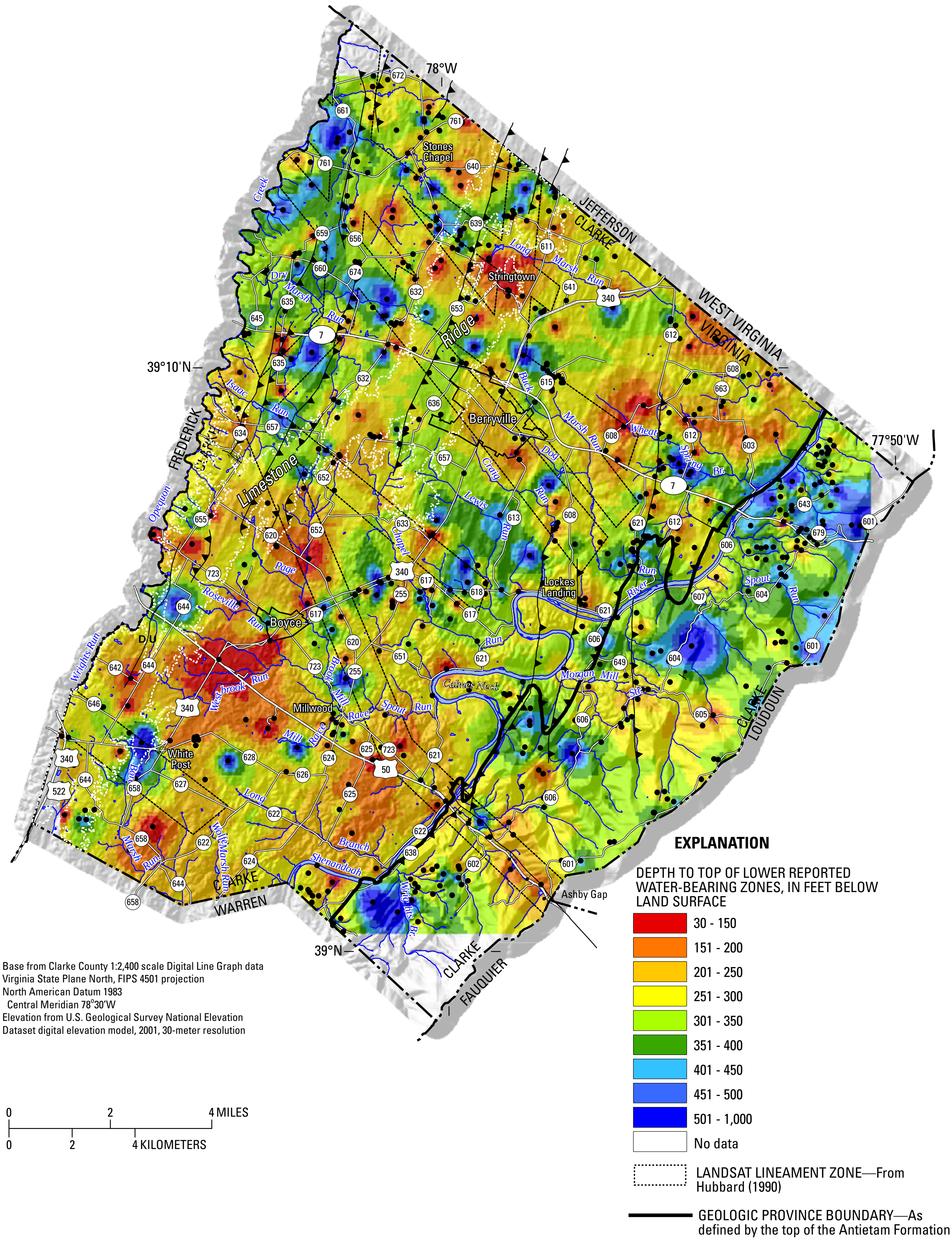


Figure 14. Depth to top of lower reported water-bearing zones in Clarke County, Virginia.

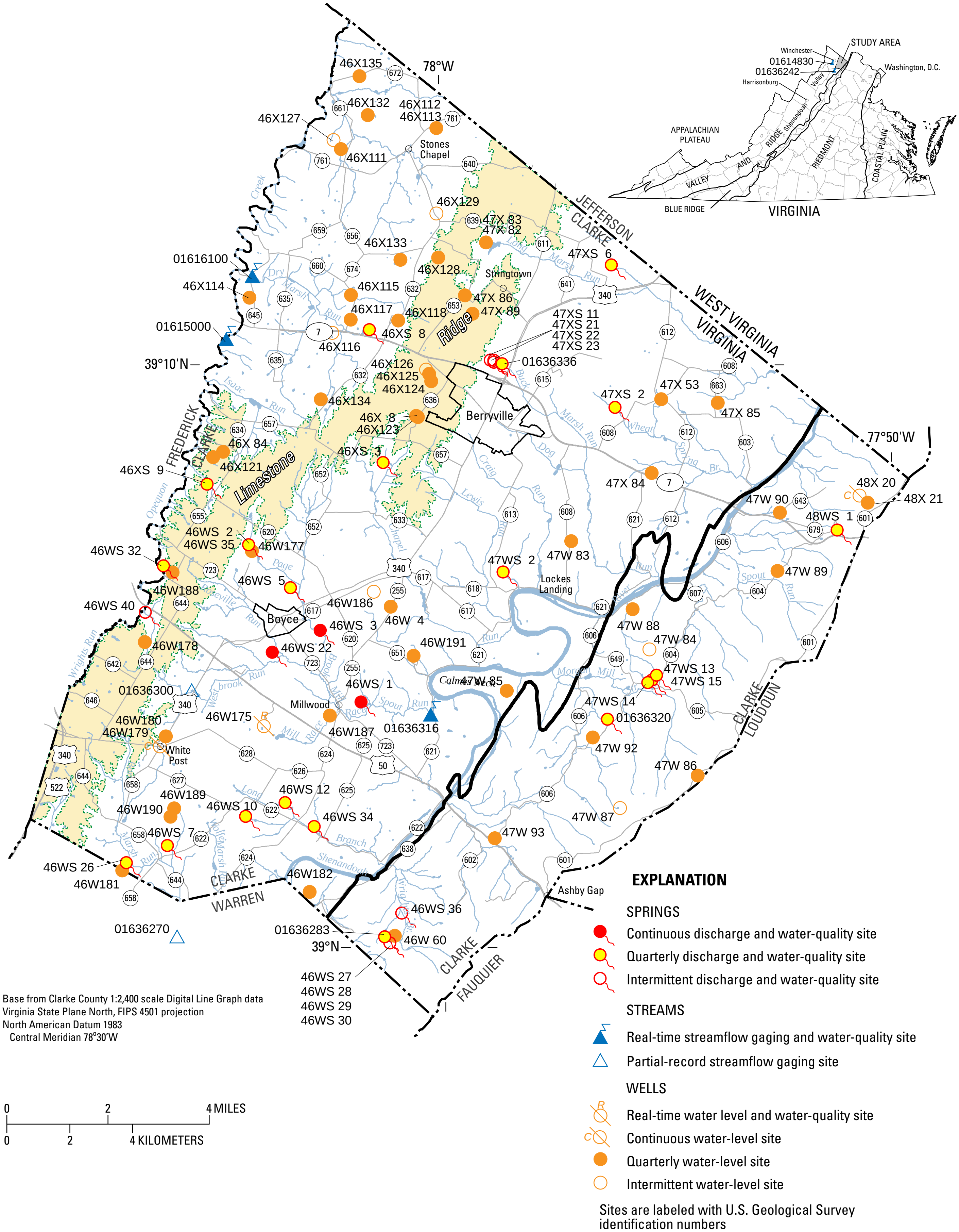


Figure 15. Location of streamflow gaging stations, springs, and wells in the long-term water monitoring network for Clarke County, Virginia.

divide between Borden Marsh Run and Spout Run Basins. This well is probably open to the residuum of the Rockdale Run Formation. Well 48X 20 is a 63-ft deep, drilled well with 16 ft of 6-in.-diameter steel casing located on a ridgetop in the northeast corner of the county in the Blue Ridge and is open to the Buzzard Knob Member of the Weverton Formation very near the contact with the Catoctin Formation. Well 46W175 located at the University of Virginia's Blandy Experimental Farm and The State Arboretum of Virginia (fig. 15) is part of the statewide observation well network maintained by the USGS and VDEQ. The depth of well 46W175 is 80 ft, and the well has 24 ft of 6-in.-diameter steel casing. Caliper logging by Wright (1990) indicates a fracture zone between 66 and 68 ft in the Conococheague Formation. Water levels have been measured continuously since July 1987 in well 46W175, which is located in the Spout Run Basin nearly equidistant from the fold axes of the Milldale syncline and Pyletown anticline of Edmundson and Nunan (1973).

Hydrographs of daily maximum water levels recorded in wells 46W175 and 46W179 (fig. 16) indicate that both of these wells are responsive to current climatic conditions. Generally, intense thunderstorms, tropical storms, or hurricanes cause sudden but temporary water-level rises during the summer and autumn. The response in well 46W179 tends to be larger than that in well 46W175 because of shallower depth, lack of available storage, and downward vertical hydraulic gradients that are probably greater than those at well 46W175. The hydrograph for well 46W175 is more subdued, and recessions are of longer duration than those in well 46W179. The two hydrographs suggest that water-level fluctuations are more dampened in the bedrock when compared to those in the regolith. The overall trend in water levels for both wells is downward between 2003 and 2008, which closely follows a downward trend in annual precipitation over the same period (fig. 16). This trend is consistent with the conceptual idea that these aquifer systems undergo a major period of recharge that is followed by a slow decline in water levels as water discharges to springs and streams. Superimposed on this overall cycle are seasonal water-level fluctuations where seasonal highs occur between April and May and lows occur in September and October.

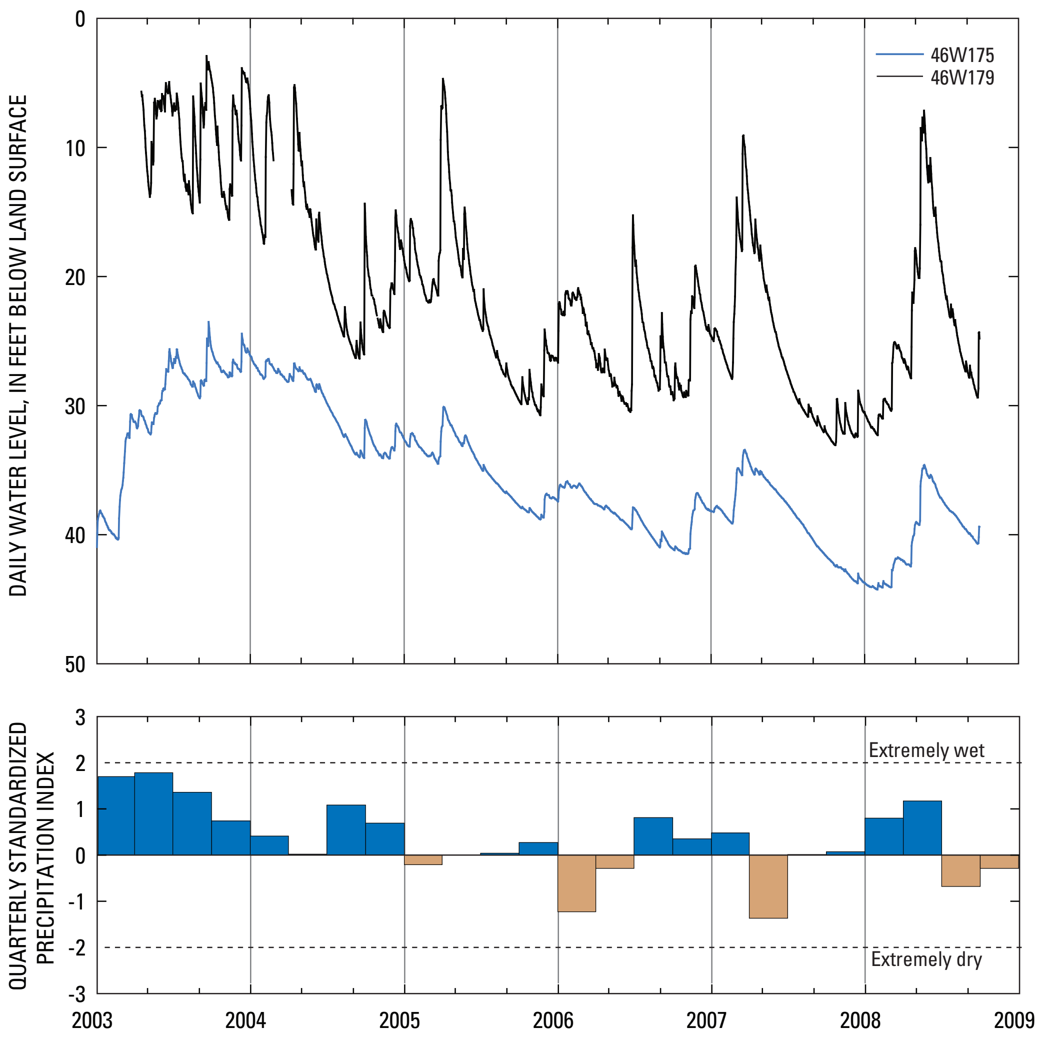


Figure 16. Relation between daily water levels in wells 46W175 and 46W179 and quarterly standardized precipitation index at National Weather Service climatological station 449186 Winchester 7 SE, Virginia.

The hydrograph for well 48X 20 is typical for a ridgetop setting where the recharge area is limited (fig. 17). Water-level rises in response to precipitation events are frequent, yet the recessions are less steep than those observed in well 46W179 and a seasonal trend is more apparent in well 48X 20. The permeability and storage capacity of the rocks at wells 46W179 and 48X 20 control the differing manners in which these systems drain. Permeability of the Buzzards Knob Member at well 48X 20 is lower than the permeability of the Rockdale Run Formation at well 46W179; therefore, water-level recessions should be less steep and have a longer period. The downward trend in water levels from 2003 to 2008 identified in the Great Valley wells is not evident in the water levels recorded in the Blue Ridge at well 48X 20. Water-level fluctuations in well 48X 20 tend to follow current climatic conditions, and seasonal highs and lows tend to shift in response to the current conditions. For example, precipitation throughout 2007 was nearly 7 in. below normal at NWS climatological station 445851 Mt. Weather resulting in a water-level recession in well 48X 20 for a majority of the year (fig. 17).

Water levels were measured quarterly in more than 40 wells from October 2002 to October 2008 (fig. 15) to document seasonal and temporal changes across the county and to provide current hydrologic conditions for drought-response planning. A majority of these wells were finished as open holes in the bedrock. Where possible, sites with a single water-bearing zone reported on well-completion reports were selected to provide hydraulic head for the respective depths and to minimize compositing of hydraulic heads from multiple zones. The seasonal water-level fluctuations measured between October 2002 and October 2008 probably represent a reasonable range for expected hydrologic conditions as indicated by record maximum and minimum water levels established at well 46W175 during this same period. Water-level fluctuations in all the wells measured during this time period ranged from 2.86 to 87.84 ft with an average of 24.15 ft (appendix 3). Generally, water-level fluctuations were greatest in recharge areas (near hydrologic divides and in isolated elevated areas) and in the Opequon Creek Basin (fig. 18). Water levels in discharge areas (near streams and springs) tend to fluctuate less (fig. 18).

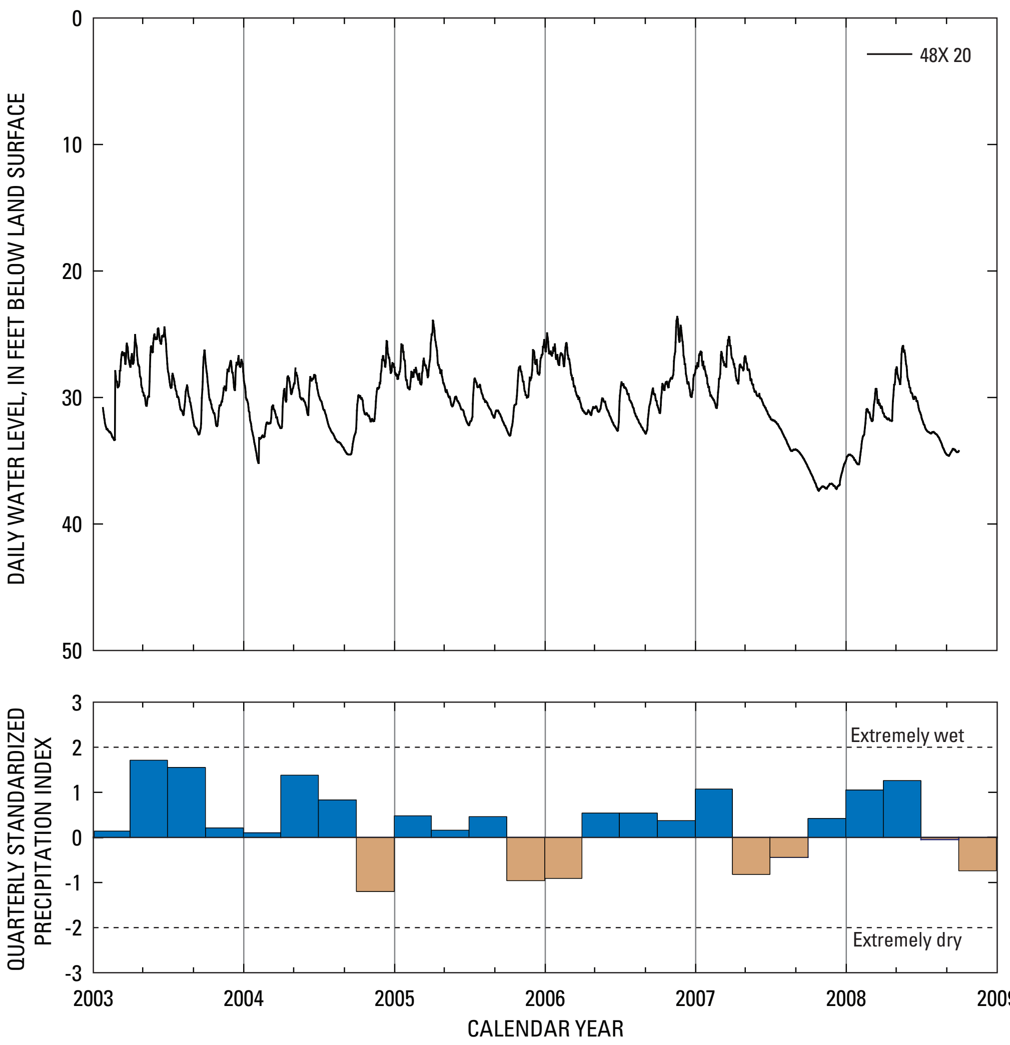


Figure 17. Relation between daily water levels in wells 48X 20 and quarterly standardized precipitation index at National Weather Service climatological station 445851 Mt. Weather, Virginia.

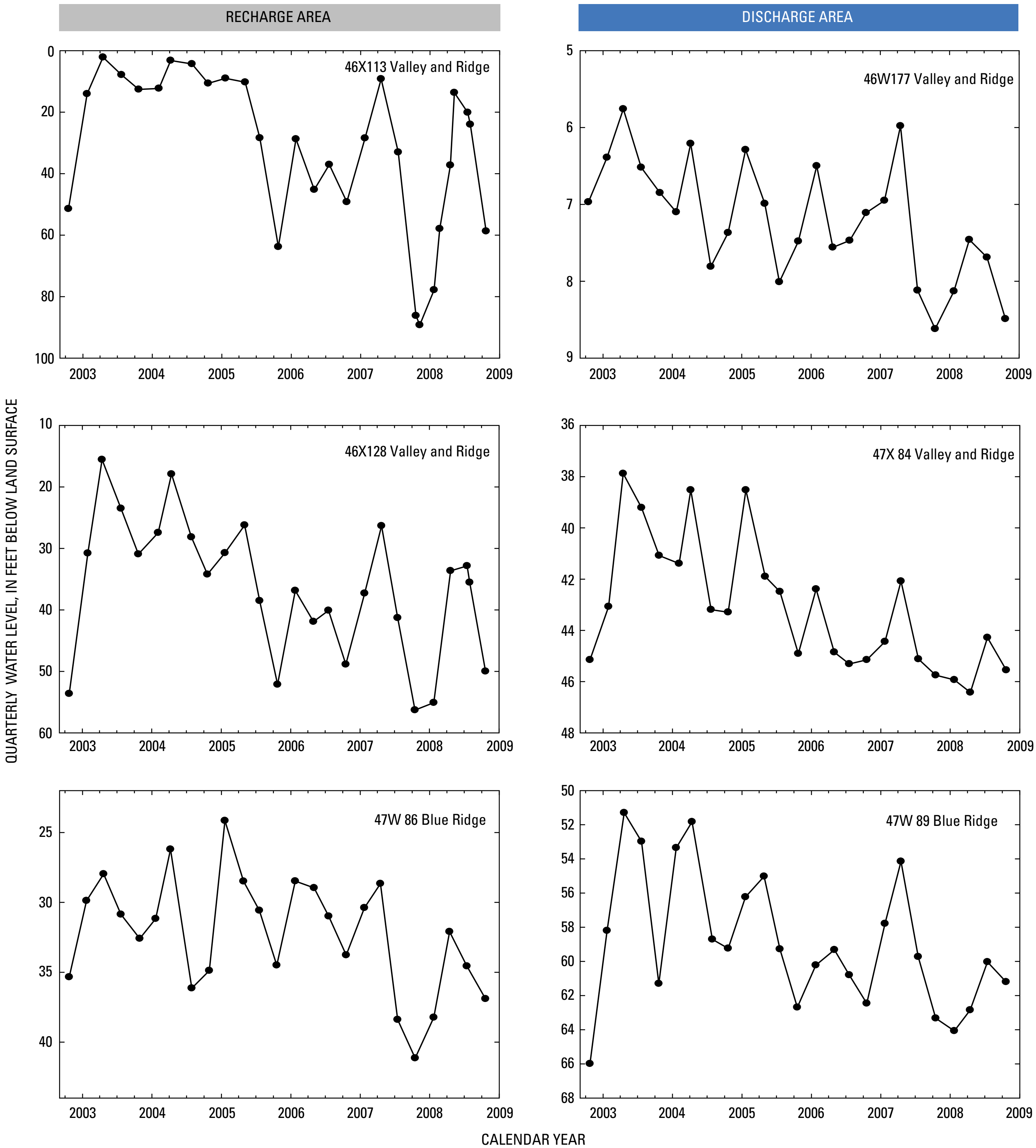


Figure 18. Quarterly water levels from selected wells located in recharge and discharge areas of the Valley and Ridge and Blue Ridge Physiographic Provinces in Clarke County, Virginia.

The very shallow water levels measured in well 46X113 during calendar years 2003–2004 suggest periods of semi-confined conditions when the height of the hydraulic head in the upgradient parts of a basin is primarily controlled by the outlets (springs) of the groundwater flow systems.

Seasonal water-level highs typically occur in the early spring at the end of the major groundwater recharge period, and lows occur in late autumn when evapotranspiration rates begin to decrease. The overall downward trend in water levels between 2003 and 2008 observed in wells 46W175 and 46W179 is evident in most of the quarterly measured wells in the Great Valley and in wells finished in the Lower Cambrian metamorphic rocks of the Blue Ridge (fig. 18). No overall downward trend was observed in the quarterly wells finished in the Catoctin Formation, but cycles similar to those described for well 48X 20 were observed.

Water-table maps were constructed from the quarterly water-level measurements and from spring and stream altitudes. Flow conditions of streams and springs were noted during quarterly measurements, and altitude values were assigned accordingly. Approximation of the water table for April 2003 (fig. 19) and October 2007 (fig. 20) were constructed to represent periods of high and low groundwater conditions, respectively. The assigned altitudes of the streams from the 10-meter (m) DEM and the spring altitudes were used to construct the water table for April 2003. The arbitrary amount of 10 ft was subtracted from the altitudes of the dry stream segments and dry springs to construct the October 2007 water-table map. The difference in configuration of the water table between these two periods is subtle. The area of the water-table high (altitudes between 600 and 750) beneath the Limestone Ridge that divides the Opequon Creek and Shenandoah River Basins is slightly smaller in October 2007 than in April 2003. In addition, water-table altitudes between 350 and 500 ft move further up in the Opequon Creek and Dry Marsh Run Basins, which can explain the numerous dry stream segments and springs in this part of the county. Changes in the water table in the Shenandoah River Basin are even more subtle because the river exerts a strong regional control on the groundwater flow system and water-level fluctuations tend to be less in both the Great Valley and Blue Ridge over the same period.

Theoretically, groundwater flows perpendicular to water-table contours (figs. 19 and 20). Wright (1990) stated that the geologic structure in the Great Valley section controls groundwater flow and directions of flow may not always be perpendicular to the water-table contours. Users of the water-table maps in this part of the county should consider that dominant flow directions are along strike; therefore, hydraulic gradients may differ with respect to strike direction. In the Great Valley section of the county, hydraulic gradients are approximately 20 and 40 feet per mile (ft/mi) along and normal to strike, respectively, which may explain the relatively slow travel times determined from dye-tracer studies (Jones, 1987; Wright, 1990). In the Opequon Creek Basin, hydraulic gradients are generally low, but steepen rapidly near streams and springs in the lower entrenched reaches of the basin. Hydraulic gradients of hundreds of feet per mile in the Blue Ridge reflect the steep terrain and low permeability of the rock.

Vertical hydraulic gradients were evaluated at three well-pair sites. The largest ranges of water-level fluctuations (87.08 and 87.84 ft) measured were from wells 46X112 and 46X113, respectively. These wells are located in the northwest part of Clarke County near Stones Chapel (fig. 15). These wells are approximately 50 ft apart, in an elevated, flat area with difference in altitude of less than 1 ft. Well 46X112 is 145 ft deep and was reported to have either diminished yield or to have been dry in early 2002. Well 46X113 is 500 ft deep and was drilled in March 2002. The reported water-bearing zone in well 46X112 is 135 ft bls, and the reported water-bearing zone in well 46X113 is 475 ft bls. Differences in hydraulic head were upward throughout the period and were generally less than 1 ft, except during low-water conditions when the magnitude of upward vertical hydraulic gradients increases (fig. 21). A similar relation is observed between wells 46X 8 and 46X123, which are approximately 120 ft apart and are located west of Berryville (fig. 15). Well 46X 8 is a 6-in.-diameter well drilled to 185 ft with no water-bearing zones reported, and well 46X123 is a 6-in.-diameter well drilled to 420 ft with a single water-bearing zone reported at 290 ft. The vertical hydraulic gradients observed in these two wells are negligible (fig. 21). Both of these well pairs indicate that hydraulic heads are similar regardless of the depths of the water-bearing zones and that vertical hydraulic gradients are extremely low. This is to be expected because of the steep dips of the different geologic structures in this part of the county. The well pair located near Stones Chapel also indicates that during dry or drought conditions hydraulic head is lowered in the upper parts of the system, which is consistent with an aquifer system that fills upward from the lower or base-level parts of the aquifer system.

Wells 47X 82 and 47X 83 are approximately at the same altitude and are 40 ft apart in an area where seeps and springs are present just north of Stringtown (fig. 15). Well 47X 82 is a 35-ft deep, stone-lined hand-dug well that reportedly was constructed in the 1700s and went dry for the first time in early 2002. Well 47X 83 was drilled in March 2002 to a depth of 340 ft, with a single water-bearing zone reported at 325 ft. The ranges in water levels for these wells (8.56 and 12.35 ft, respectively) are far less than for the other two sites. Upward vertical hydraulic gradients were observed between these two wells, especially during periods of high water levels. As water levels declined, the magnitude of the vertical hydraulic gradient decreased and occasionally reversed to become downward (fig. 21). The overall upward hydraulic gradient and relatively small range in water levels are characteristic of a discharge area. Frequently, the term “perched aquifers” is used to describe the aquifer systems in the Great Valley; however, this well pair and the nearby seeps and springs indicate that the regolith mantle and underlying bedrock are connected. Many areas that might be interpreted as perched aquifers may simply be depression storage in small ponds that may or may not be associated with sinkholes. During drought conditions, vertical hydraulic gradients can be an order of magnitude larger than the horizontal gradients described earlier.

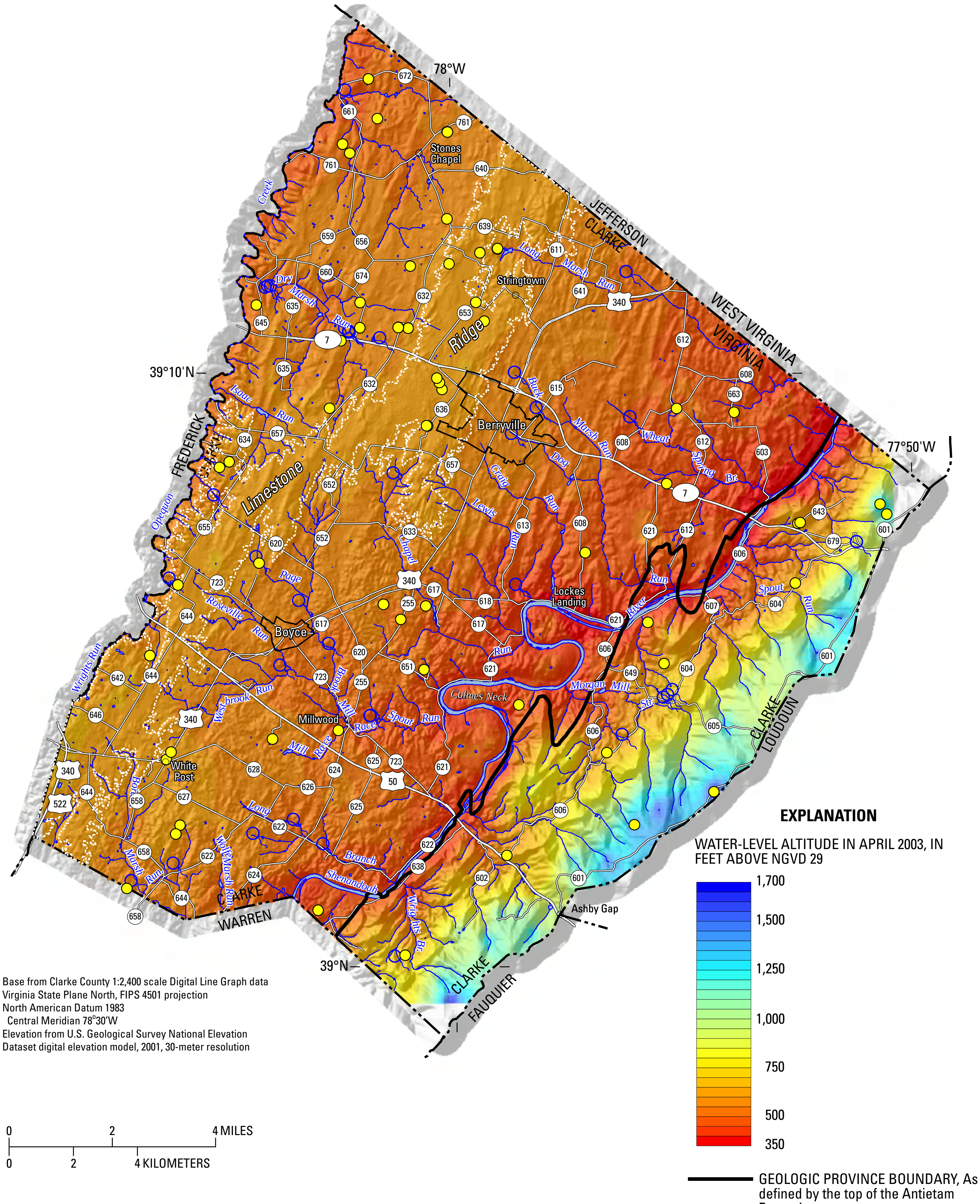


Figure 19. Approximate altitudes and configurations of the water table determined from spring altitudes and water levels measured in wells, April 2003, Clarke County, Virginia.

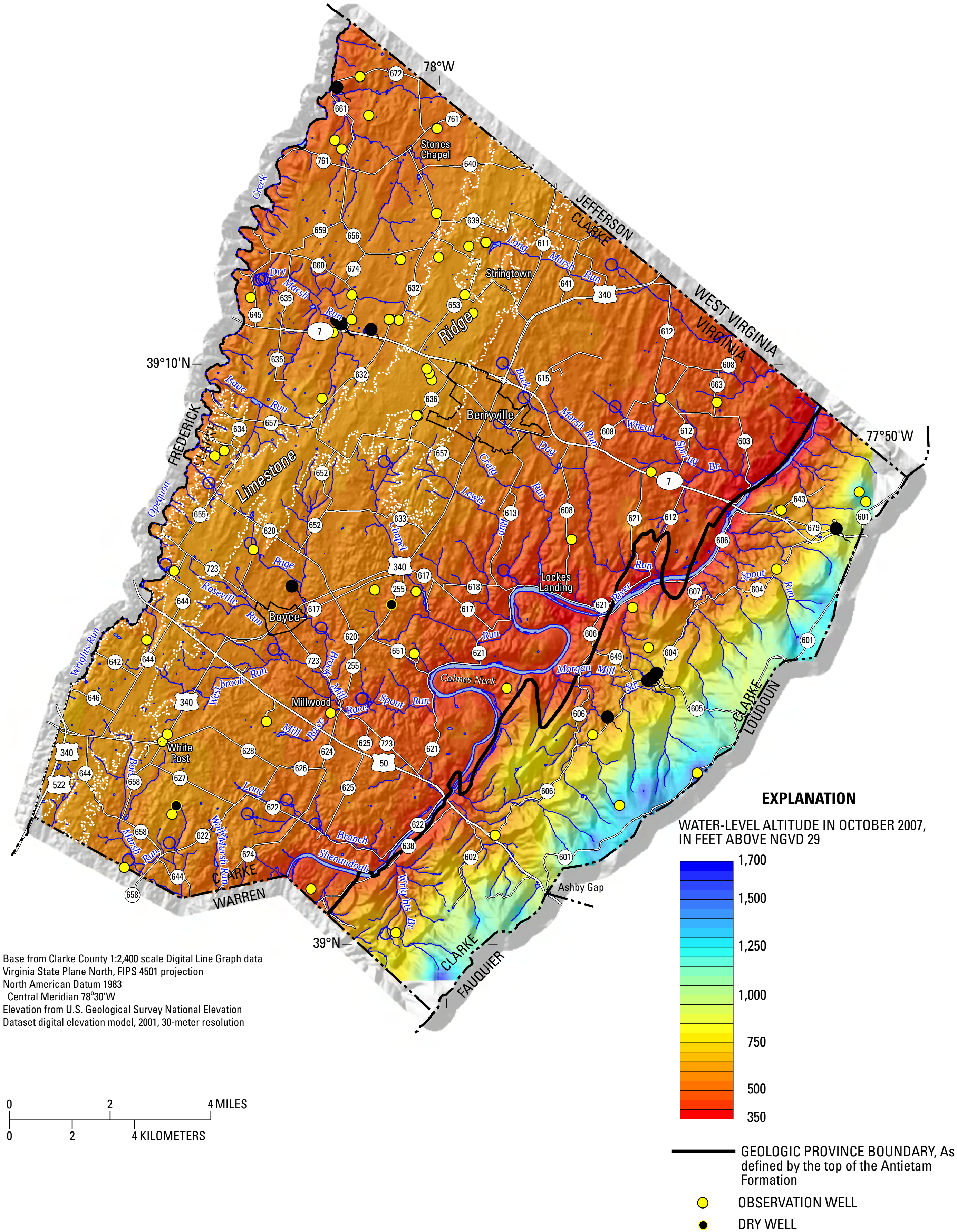


Figure 20. Approximate altitudes and configurations of the water table determined from spring altitudes and water levels measured in wells, October 2007, Clarke County, Virginia.

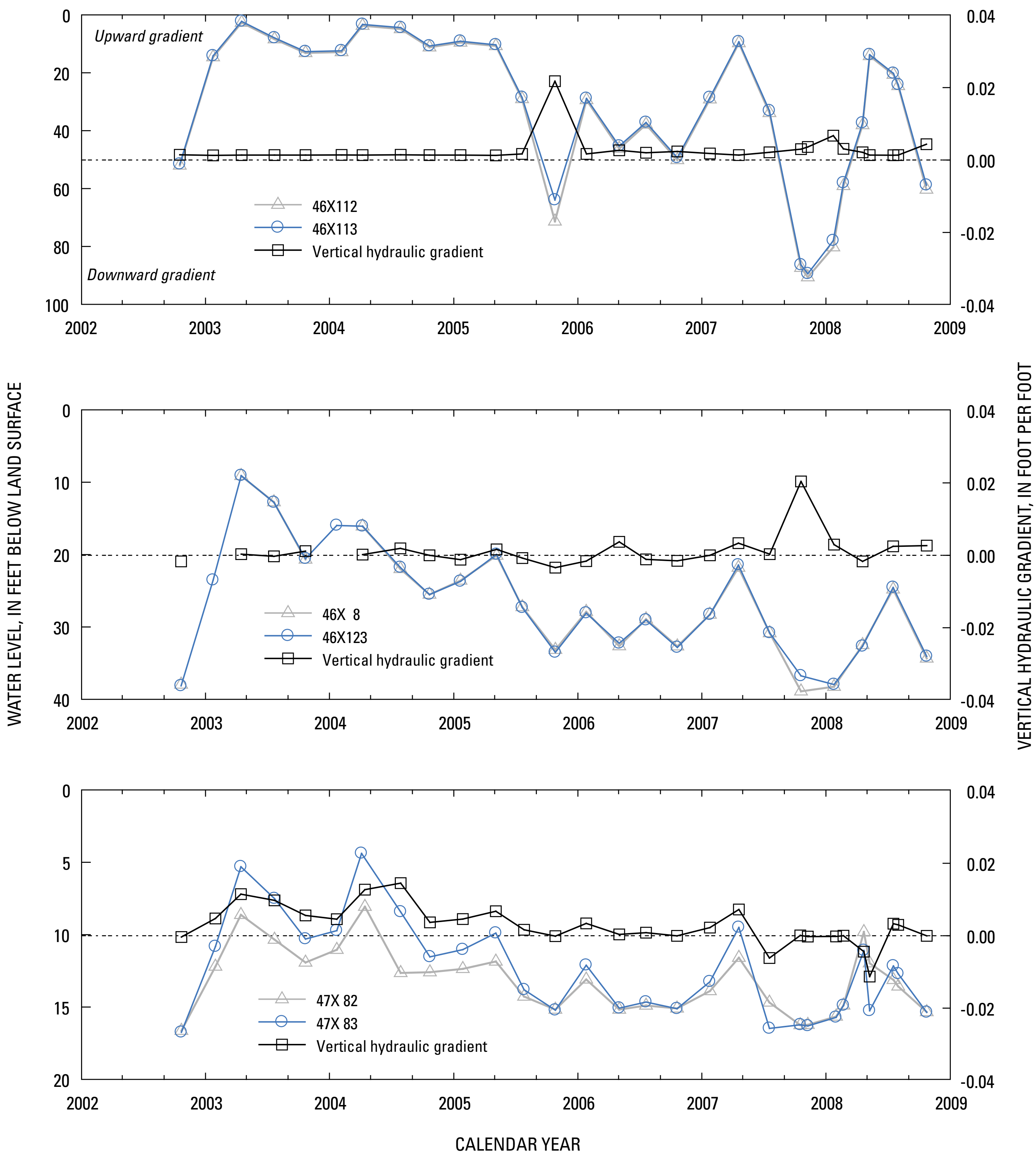


Figure 21. Vertical hydraulic gradients in the Great Valley section of Clarke County, Virginia, between October 2002 and October 2008.

Streamflow and Spring Discharge

Groundwater discharges from the aquifer systems in Clarke County as base flow to streams and as spring discharge. A large part of streamflow is groundwater discharge (base flow) during low- and high-flow conditions. Springs commonly form the headwaters of many of the streams in the county. Dry stream segments during drought conditions are usually the result of cessation of flow from an upstream spring. A long-term network to monitor streamflow and spring discharge was established during this investigation. Two streamflow gaging stations were established: 01616100 (Dry Marsh Run near Berryville) and 01636316 (Spout Run at Route 621 near Millwood; fig. 15). Flow-duration statistics, which are used to assess current hydrologic conditions, indicate that mean annual streamflow for water years 2002–2007 averaged 12.4 and 25.1 cubic feet per second (ft^3/s) at streamflow gages 01616100 and 01636316, respectively. Drainage areas for these basins are 11.0 and 21.4 mi^2, respectively. Thus, discharge averaged over these basins is about 15 percent more than the 1 ft^3/s of flow per square mile of drainage area typically observed in long-term records for basins in the mid-Atlantic region of the United States (Poff, 1999).

Pressure transducers were installed at three springs (fig. 15)—46WS 1 (Carter Hall), 46WS 3 (Prospect Hill), and 46WS 22 (Saratoga)—to estimate continuous spring discharge. Stage-discharge ratings were developed to calculate discharge for springs 46WS 1 and 46WS 22; however, a similar rating for spring 46WS 3 was unsuccessful because of water withdrawals and physical characteristics of the structure constructed over the spring. Spring 46WS 1 (fig. 22) was the largest spring measured in the county with discharges that ranged from 3.02 to 10.0 ft^3/s and a mean annual discharge of 5.16 ft^3/s, which indicates that the drainage area is approximately 5 mi^2 based on an average discharge of 1 ft^3/s of flow per 1 mi^2. Discharge at spring 46WS 22 ranged from 0.30 to 1.98 ft^3/s with a mean annual discharge of 0.85 ft^3/s, indicating that the spring probably drains an area slightly less than 1 mi^2. The average drainage area for spring 46WS 3 can be approximated from the 23 quarterly measurements that ranged from 1.16 to 3.06 ft^3/s. The mean discharge of these measurements is 2.03 ft^3/s, which indicates a drainage area of about 2 mi^2. As discussed earlier and as determined by Jones (1987), flow to springs is not controlled by surface-water divides, but probably is controlled by the geologic structure. Future efforts to delineate drainage areas for these springs, as well as for the other springs discussed below, can use mean discharge to approximate the size of the area needed to provide the respective discharge.

Spring discharge and field water-quality properties were measured quarterly at 6 and 16 sites in the Blue Ridge and Great Valley section, respectively (fig. 15). Streamflow gaging stations 01636283 (Wrights Branch Tributary below Jeep Trail near Stone Bridge) and 01636336 (Buck Marsh Run above Highway 340 at Berryville) were included in the spring monitoring network because streamflow at each of these stations is from several springs a short distance upstream from the measuring section. Wright (1990) stated that discharges from springs in the Great Valley are greater than those in the Blue Ridge because of the well-developed system of solution-enlarged fractures and less steep terrain. Discharge at the Blue Ridge springs ranged from dry to 0.41 ft^3/s with an average discharge of 0.04 ft^3/s from 2003 to 2008 (appendix 4). During the same time period, discharge at the Great Valley springs ranged from dry to 4.47 ft^3/s with an average discharge of 0.58 ft^3/s. The seasonality of discharge is evident in the hydrographs (fig. 22). The highest discharges occur in winter and early spring when *ET* is at minimum, and discharge generally declines into late autumn. An overall downward trend in spring discharge is evident in nearly every spring monitored in the Great Valley between 2003 and 2008. This downward trend correlates with the similar trend documented in water levels and is indicative of an aquifer system that drains over time to a base level controlled by springs and streams. A similar trend is not readily identifiable for the springs in the Blue Ridge because of the relatively low discharge rates, probable small drainage areas, and the susceptibility of these aquifer systems to current meteorological conditions.

As discussed earlier, review of mean discharges provides an estimate of drainage area. In the Blue Ridge, delineation of a spring's drainage area based on surface-water divides provides sufficient area to supply the mean discharge and probably represents the contributing area to the spring. In the Great Valley, mean discharge 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.

From 2003 to 2008, several springs had periods when flow ceased (fig. 22). Springs in the Blue Ridge are especially susceptible to successive periods of below-normal precipitation. Abundant precipitation during the winter/early spring recharge period, however, can cause rapid percolation through the overburden and transmission to springs (Wright, 1990). Evidence of this is shown by the nearly threefold increase in discharge at spring 01636320 in 2004. During extended dry periods, many springs in the Great Valley, especially in the upper reaches of the basins, ceased flowing. Spring 46XS 8 best illustrates the magnitude of intermittent flow observed during 2003–2008. This spring was reported to be dry during the prolonged drought between 1999 and 2002, and aerial photography collected in 2002 by the Virginia Base Mapping Program clearly shows no discharge from the spring and shows dry stream segments for approximately 1 mi downstream. Flow from spring 46XS 8 resumed sometime between November 2002 and January 2003 after nearly 9 months of above-normal precipitation, but slowly declined into late autumn of 2003. By April 2004, a discharge of 4.47 ft^3/s was measured at spring 46XS 8, which was the highest discharge at this site during 2003–2008. Dry flow conditions have prevailed for a majority of the time after April 2004 because precipitation was below normal most of the time between April 2004 and October 2008.

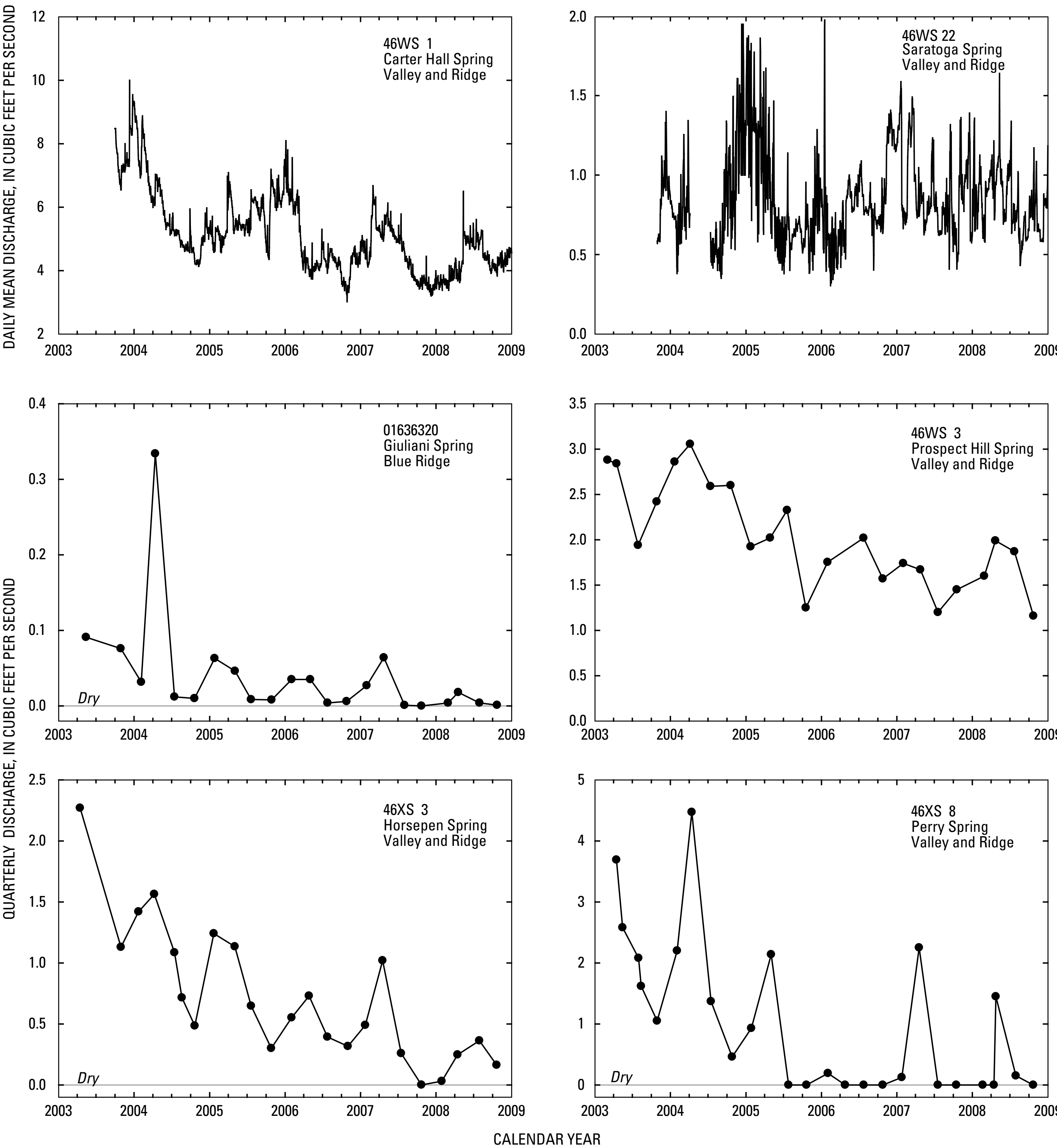


Figure 22. Daily mean and quarterly discharges from selected springs in Clarke County, Virginia, between April 2003 and October 2008.

Evaluation of intermittent flow conditions in the Great Valley section of the county provides insight into the manner in which the aquifer system recharges, stores, and discharges groundwater. Quarterly water temperature measurements at spring 46XS 8 only ranged from 12.1 to 12.8 °C during 2003–2008, which indicates that groundwater generally has equilibrated to the average annual ambient temperature of the shallow subsurface rocks and is not influenced by rapid movement of direct inflow from surface sources such as sinking streams and sinkholes. A thermister was placed at the outlet of spring 46XS 8 (fig. 15) in December 2005 after a period of nearly 6 months of no flow. An additional thermister was placed approximately 2 ft above the existing water line in a depression located 0.84 mi downstream along Dry Marsh Run that is believed to be an estavelle. The air-water temperature record for spring 46XS 8 and the estavelle are shown in figure 23 in relation to daily air temperature and precipitation at NWS climatological station 449186 Winchester 7 SE. The upward shift in water temperature on December 26, 2005, at the estavelle site is interpreted as inflow of Dry Marsh Run from several springs a few hundred feet upstream. From late December 2005 to late January 2006, daily temperature fluctuations tended to respond slightly to daily changes in air temperature and precipitation. These fluctuations oscillated around 10.5 °C, which indicates that the temperature of the water discharging from the upstream springs changes in Dry Marsh Run prior to flowing into the estavelle. The water temperature record at spring 46XS 8 nearly mimics the daily range of air temperatures at NWS climatological station 449186 until January 19, 2006, when the spring probably flowed again and the temperature at the spring increased and remained at a constant temperature of 12.8 °C. The warm temperature is characteristic of groundwater temperatures, which tend to be warmer than air temperatures in the winter months and colder than air temperatures in the summer months. Flowing conditions in early February 2006 were noted at both sites when the thermisters were retrieved, and the measured discharge at spring 46XS 8 was 0.19 ft^3/s. The nearly 1-month offset in the start of flow between these two sites indicates that the aquifer system fills from the lower to the upper reaches of the basin. However, the filling of the aquifer system follows the geologic structure and is expected to fill from the lower reaches in the north to the upper reaches in the south (fig. 5).

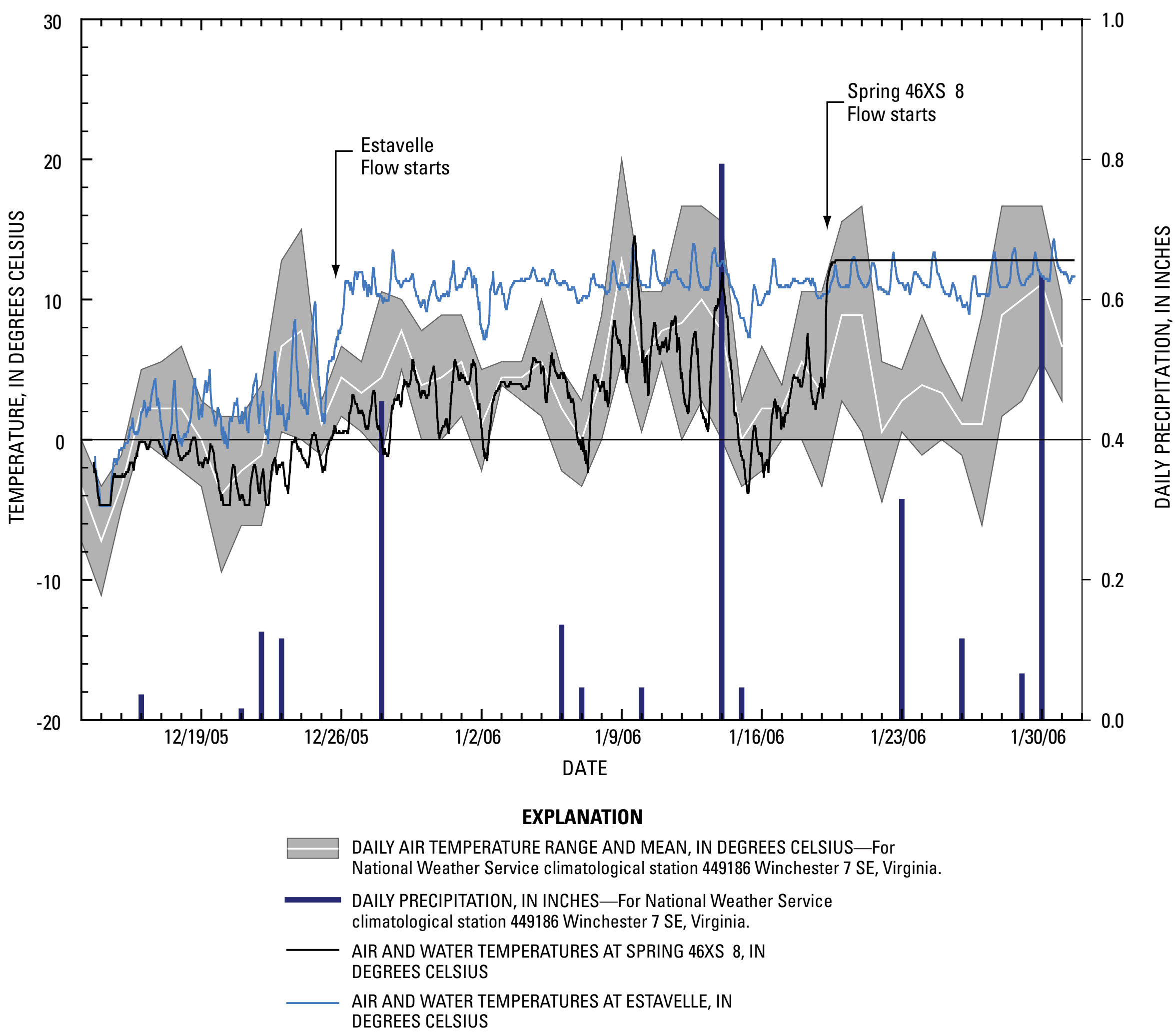


Figure 23. Relation between daily air temperature and precipitation at National Weather Service climatological station 449186 Winchester 7 SE and air and water temperatures at spring 46XS 8 and estavelle located 0.84 mi west of spring 46XS 8 in Clarke County, Virginia.

Groundwater Areas

Clarke County was divided into nine groundwater areas based on surface-water basin boundaries (fig. 24). Delineation of these groundwater areas could assist future water-management activities because each area contains similar physical, geologic, and hydrologic characteristics (table 2). In the Blue Ridge section of the county, the boundaries of the three groundwater areas may mimic the boundaries of the individual groundwater flow systems because the conceptual model for this part of the county assumes groundwater divides generally are closely related to the surface-water divides. In the Great Valley section of the county, the groundwater areas only represent areas with similar characteristics and not necessarily groundwater boundaries because flow beneath surface-water divides has been observed (Jones, 1987).

The Blue Ridge groundwater areas are characterized by high altitudes with relief greater than 1,400 ft, steep slopes,

Table 2. Physical and geologic characteristics of the groundwater areas in Clarke County, Virginia.

[Min, minimum; Max, maximum; np, not present. Shaded rows indicate Blue Ridge areas, and unshaded rows indicate Valley and Ridge areas. See figure 24 for location of groundwater areas]

Groundwater area		Area (square miles)	Altitude (feet above NGVD 29)				Slope (degrees)			Rock type (percent of area)			Sinkhole density (sinkholes per square mile)	
Number	Name		Min	Mean	Max	Relief	Min	Mean	Max	Carbonate	Metamorphic	Siliciclastic	County GIS	Hubbard (1990)
B01-BR	Raven Rocks Run	17.1	355	889	1,769	1,413	0	10.1	46.7	4.7	95.3	np	0.1	0.1
B01-VR	Long Marsh Run	39.7	359	544	710	351	0	3.1	43.2	96.7	3.3	np	3.2	4.1
B02-BR	Morgan Mill	24.9	374	917	1,919	1,545	0	11.4	46.9	13.6	86.4	np	0.4	0.5
B02-VR	Spout Run	47.8	370	571	684	314	0	3.9	47.5	99.3	0.2	0.5	2.1	3.3
B03-BR	Rock Spring Branch	0.8	408	1,072	1,925	1,517	0.01	10.6	42.6	12.5	87.5	np	0.0	0.0
B03-VR	Borden Marsh Run	9.9	409	613	715	306	0	3.6	28.8	100	np	np	2.2	2.3
B04-VR	Crooked Run	1.2	592	647	715	123	0	2.2	12.9	100	np	np	5.7	7.4
B54-VR	Dry Marsh Run	25.8	449	585	680	231	0	2.1	45.7	94.1	np	5.9	12.3	14.4
B55-VR	Opequon Creek	8.7	491	629	712	221	0	4.3	50.6	67.6	np	32.4	5.0	5.3

Groundwater area		Stream density (miles per square mile)				Annual precipitation (inches per year)			
		Area	Rock type						
Number	Name		Carbonate	Metamorphic	Siliciclastic	Min	Mean	Max	Range
B01-BR	Raven Rocks Run	1.97	0.05	1.93	np	39.0	40.9	42.4	3.4
B01-VR	Long Marsh Run	1.24	1.11	.13	np	38.9	39.3	40.3	1.4
B02-BR	Morgan Mill	2.1	0.16	1.95	np	39.1	40.9	42.6	3.5
B02-VR	Spout Run	1.78	1.76	.01	1.69	38.9	39.2	39.9	1.0
B03-BR	Rock Spring Branch	1.76	.08	1.69	np	40.6	41.6	42.5	1.9
B03-VR	Borden Marsh Run	1.81	1.81	np	np	39.1	39.3	39.5	0.4
B04-VR	Crooked Run	1.82	1.82	np	np	39.2	39.2	39.2	0.0
B54-VR	Dry Marsh Run	1.41	1.32	np	0.09	38.9	39.1	39.6	0.7
B55-VR	Opequon Creek	1.77	0.98	np	0.79	38.9	39.0	39.1	0.2

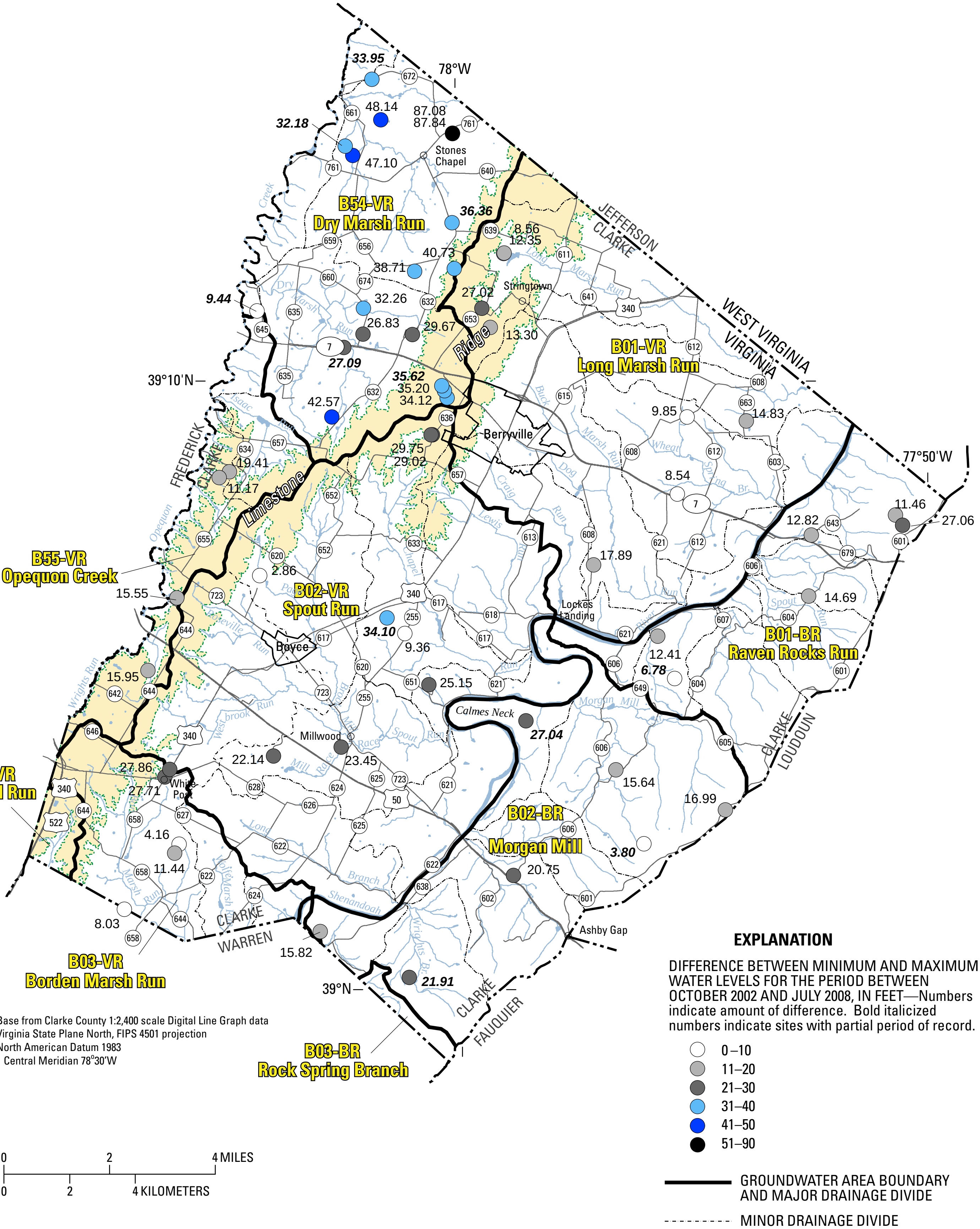


Figure 24. Location of groundwater areas and difference between minimum and maximum water levels for the period between October 2002 and July 2008 in Clarke County, Virginia.

low sinkhole density, high stream density, mean annual precipitation of about 41 inches per year (in/yr), and relatively large differences between minimum and maximum annual precipitation across the areas (table 2). The Great Valley groundwater areas are characterized by low altitudes with relief generally less than 350 ft, gentle slopes, high sinkhole density, low stream density, mean annual precipitation of about 39 in/yr, and less variability in precipitation across the areas (table 2). The difference in mean annual precipitation within and between groundwater areas, and even across the county, may seem small, but 1 in. of precipitation across 1 mi^2 is equivalent to 17.4 million gallons.

The orographic effect of the elevated areas on precipitation in Blue Ridge is evident; lower annual precipitation values (less than 40 in/yr) are present at the lower altitudes, and the higher values (greater than 40 in/yr) are present at the higher altitudes. Precipitation that percolates into the subsurface flows rapidly as interflow or subsurface stormflow along steep gradients to the relatively dense stream network (Wright, 1990). Although precipitation is generally less in the Great Valley, the combination of gentle slopes, low relief, and more permeable rock types, as indicated by the low stream density (Olmsted and Hely, 1962; Hely and Olmsted, 1963; Hack, 1965), facilitates flow of water from the surface downward to the water table. The parts of the groundwater areas in the Great Valley underlain by siliciclastic rocks, however, have characteristics that are more similar to the Blue Ridge areas.

In general, the magnitude of water-level fluctuations tends to be controlled by the topography of the groundwater areas (fig. 24). Water-level fluctuations are greatest near the groundwater area boundaries in the upper reaches, under isolated elevated areas within the groundwater areas, and in areas where the low-order streams parallel the strike of the rocks (Dry Marsh Run area). The ranges between the minimum (highest) and maximum (lowest) water levels measured between October 2002 and October 2008 are greatest in the Dry Marsh Run groundwater area (fig. 24). Numerous geologic structures (faults and lineament zones) cross and intersect in the Dry Marsh Run area. Low stream density and large water-level fluctuations suggest that the area is underlain by permeable rocks; the relatively deep water-bearing zones and the occurrence of numerous faults and lineament zones (figs. 13 and 14) suggest that permeability may be present to considerable depth. High permeability extending to depth and large water-level fluctuations can explain why the density of sinkholes in this area is more than twice the densities determined for the other Great Valley groundwater areas, numerous stream segments are dry a majority of the time, and numerous wells went dry during the prolonged drought during 1999–2002. These factors likely are the reason that this area is locally referred to as the “Arabian Plain,” and many of the old homesteads are equipped with cisterns and shallow, hand-dug wells near intermittent springs. Conversely, the Dry Marsh Run area had the largest magnitude and rate of recovery measured at the cessation of this drought. Kozar and Weary (2009) suggest that this area represents a recharge area for regional flow that ultimately discharges to the north in the vicinity of Leetown, WV.

Water-level fluctuations in the Opequon Creek groundwater area are nearly half of those in the Dry Marsh Run area (fig. 24). Possible explanations for this are (1) groundwater in the Dry Marsh area may also flow to the south towards Opequon Creek, which is opposite the topographic gradient; (2) flow out of the carbonate rocks in the Opequon Creek area may be impeded by the low permeability Martinsburg Formation, which underlies Opequon Creek (fig. 5); (3) the areas underlain by the Martinsburg Formation have low recharge rates; or (4) the Opequon Creek and Dry Marsh Run areas are independent of each other and are parts of different flow blocks. Future groundwater flow modeling efforts in this part of the county could help determine whether or not these groundwater areas are connected.

The noticeable change in drainage direction from the southerly direction in the Borden Marsh Run and Crooked Run groundwater areas to the southeast across the strike in the Long Marsh Run and Spout Run areas suggests that these areas may act as separate flow blocks. A majority of the folds in the Long Marsh Run and Spout Run areas plunge to the north-northeast, and the topographic gradient is generally in the same direction.

Relation of Geology to Groundwater Flow

In the Great Valley section, the conceptualization is that the preferred direction of groundwater flow is along strike. Therefore, the dominant direction of groundwater flow is generally from elevated areas either to the northeast or southwest along the strike of the rocks. Drainage networks in the Great Valley section of the county often follow cross joints in the rock (Hack and Young, 1959). Many of the higher order streams and creeks flow normal to strike; however, many of the low-order tributaries and the Shenandoah River and Opequon Creek generally flow parallel to the strike of the rocks especially in the northwest part of the county and the upper reaches of the Spout Run drainage. 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.

In the Blue Ridge, relict structures in the regolith material provide pathways for the flow of 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 (D.L. Nelms, U.S. Geological Survey, written commun., 2009). Groundwater flow in the bedrock of the Blue Ridge is controlled by the orientation of the foliations and joints, but dominant direction is difficult to ascertain. One possibility, suggested by Southworth (1990), is that water recharged on the western slopes of the mountains of the Blue Ridge flows down-dip and eventually discharges in springs and valleys on the eastern sides of the mountains.

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 Clarke County are present along faults and within lineament zones in both the Great Valley and Blue Ridge. Many springs, however, also are present along fold axes where joints converge. 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

Often, groundwater and surface water are discussed as if these components of the flow systems were separate entities. In Clarke County, 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 during dry periods in the late summer and early autumn. 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 start at springs. Springs 46WS 1, 46WS 3, and 46WS 22 either discharge directly to Spout Run or a tributary (fig. 15). Although discharge at these springs may vary, these springs provide a relatively continuous source of water to Spout Run (fig. 25*A*). During wet conditions, discharge from springs 46WS 1 and 46WS 22 accounted for approximately 30 percent of the streamflow measured at gaging station 01636316; during dry conditions, 50 to more than 80 percent of the streamflow was from the discharge of these two springs (fig. 25*B*). If discharge from spring 46WS 3 is included, these percentages would substantially increase, especially during periods of low flow at gage 01636316. These three springs are not the only springs contributing flow to Spout Run, which illustrates the importance of groundwater for sustaining streamflow. When managing water resources and identifying potential contaminant sources within the county, it is important to take into account that a large portion of streamflow at different flow regimes comes directly from groundwater discharge.

Field reconnaissance of spring locations throughout the county was conducted by Wright (1990), county personnel, and also during this investigation. Identification of subaqueous spring discharge in streams and creeks, especially the Shenandoah River, is difficult. A section of the Shenandoah River below Lockes Landing was evaluated as part of a pilot study by the USGS Groundwater Resources Program to demonstrate and assess a fiber-optic distributed temperature sensing (FO DTS) system as a method to identify groundwater discharge to streams. Lane and others (2008) state that the analysis of light backscattered from the propagation of a laser pulse along a fiber-optic line is a function of temperature, which is known as Raman scatter. An optical frequency-domain reflectometry analysis was used to estimate temperature every meter along a 300- and 1,300-m fiber-optic cable submerged to the bottom of the Shenandoah River just downstream from Lockes Landing in August 2006 (fig. 26). This time period coincides with the maximum thermal anomaly between groundwater and surface-water temperatures. The discharge of cold groundwater from a spring is evident by the thermal anomaly shown in figure 26*B* at approximately 200 m along the fiber-optic cable. The thermal profile shown in figure 26*B* was constructed by stacking individual traces that individually represent a time interval of approximately 1 minute. Local lore holds that “cold spots” in the river are areas where springs discharge. The subaqueous spring identified along the 300-m cable is an example where this is true. A thermal anomaly was observed along the 1,300-m cable between 1,150 and 1,200 m (fig. 27) during the late afternoon of August 8, 2006. After sunset, the temperature along the entire fiber decreased, and the anomaly was no longer evident. The thermal anomaly coincides with the area where a depression in the streambed of approximately 2 m is present, and the anomaly is the result of differential heating during the daylight hours that is depth dependent. 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 streams), and estavelles.

A similar relation between groundwater and surface water exists in the Blue Ridge section of the county, except the overburden or regolith material overlying the bedrock plays a more important role than 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 can be considered groundwater, in reality, the subsurface stormflow and, to some degree, interflow are probably representative of water in the overburden and not of water in the bedrock as evidenced by the seasonality of flow conditions and rapid response to extreme precipitation events.

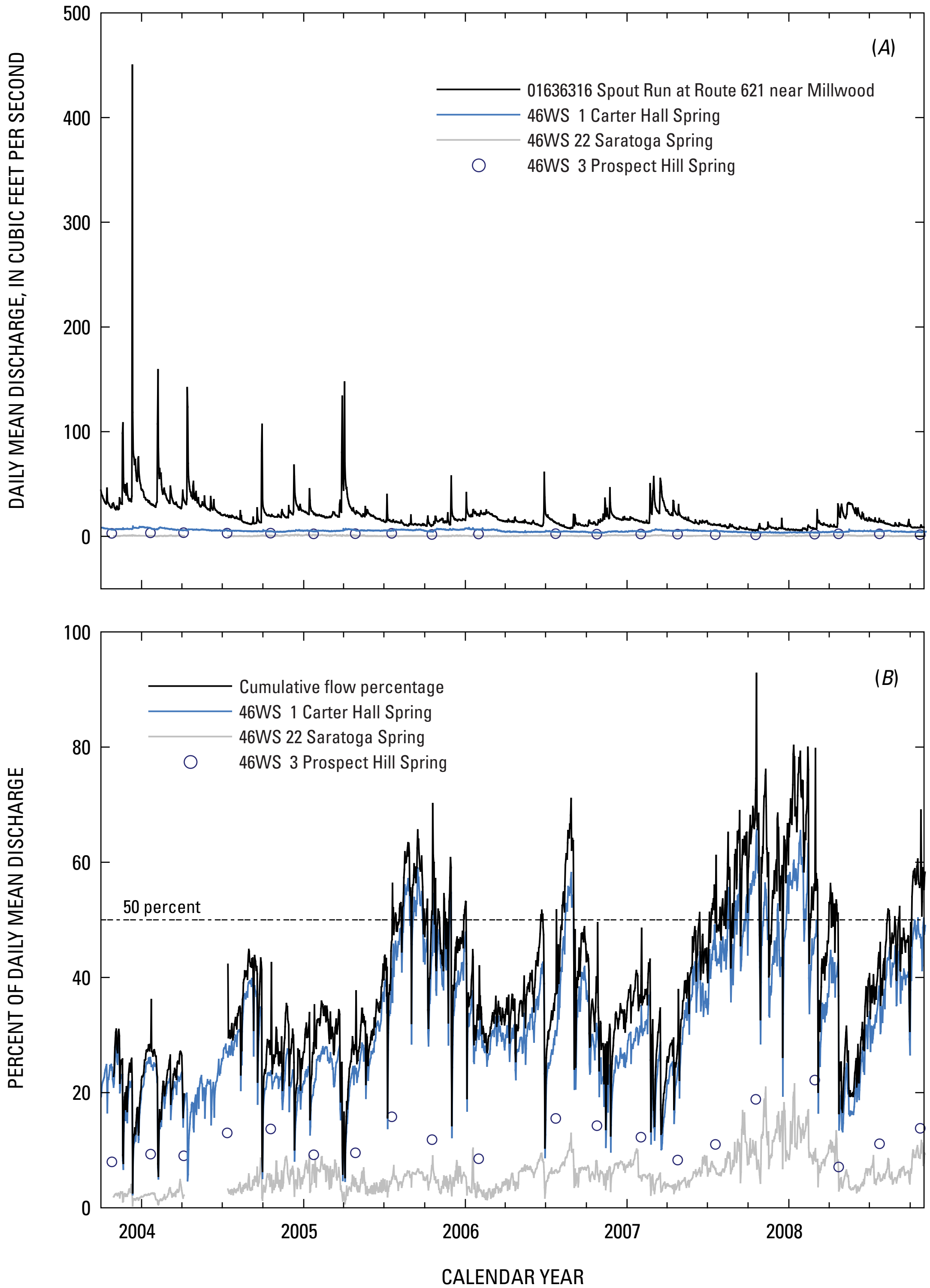


Figure 25. Relation between *(A)* daily mean discharge and *(B)* percent of daily mean discharge at streamflow gaging station 01636316 Spout Run at Route 621 near Millwood, Virginia, and 46WS 1 Carter Hall and 46WS 22 Saratoga Springs in Clarke County, Virginia. Cumulative flow percentage is based on combined daily mean discharge from springs 46WS 1 and 46WS 22 and is not shown when data are missing. Quarterly discharge measurements for 46WS 3 Prospect Hill Spring included for reference.

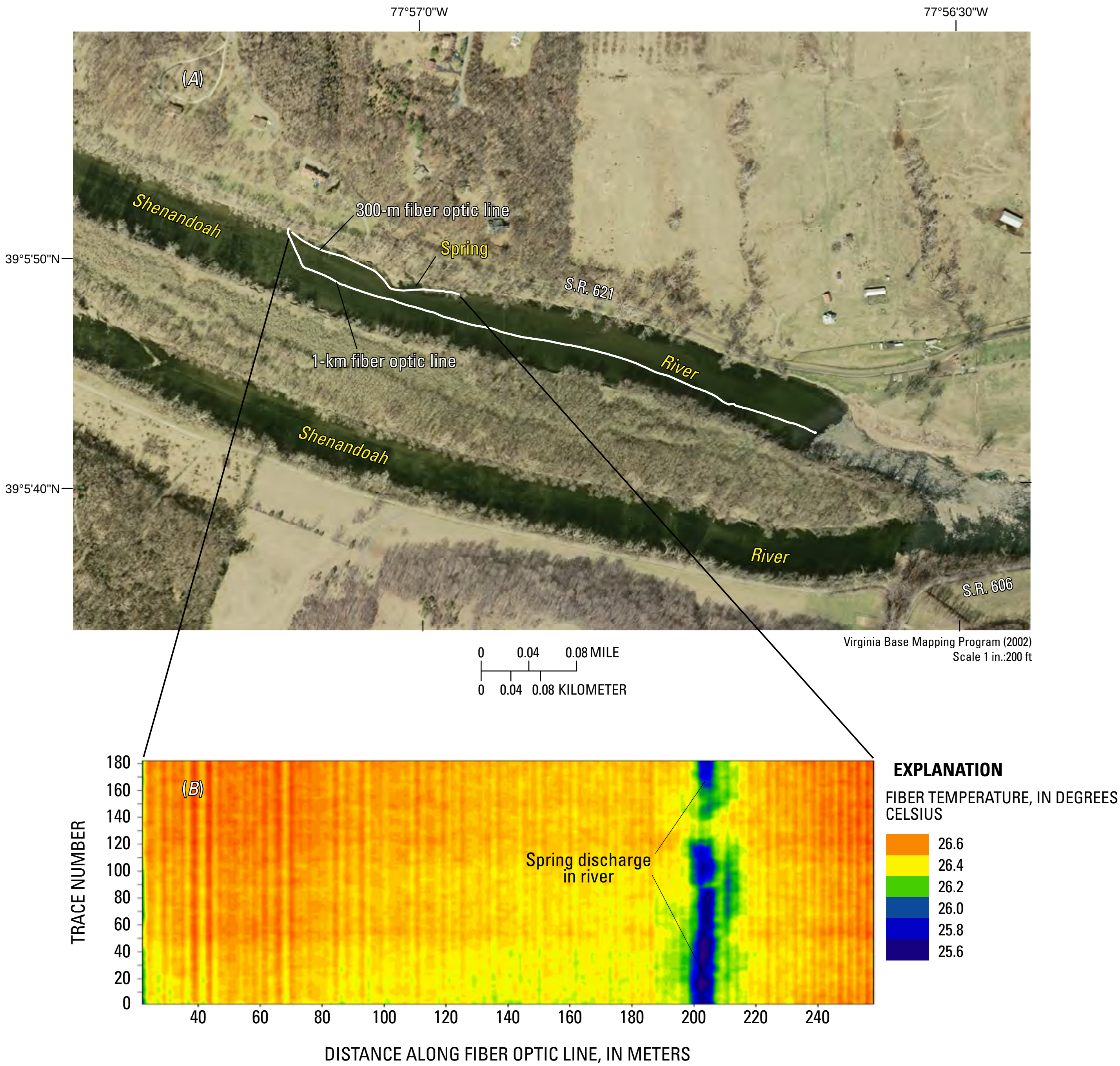


Figure 26. *(A)* Aerial photograph showing location of U.S. Geological Survey's Groundwater Resources Program fiber-optic distributed temperature sensing evaluation project site and *(B)* two-dimensional display of temperature data showing thermal anomaly, Shenandoah River, Clarke County, Virginia. Data collected with 300-meter fiber, August 10, 2006, 12:10:28 to 15:10:36. Trace interval is 59 seconds. Modified from Lane and others (2008).

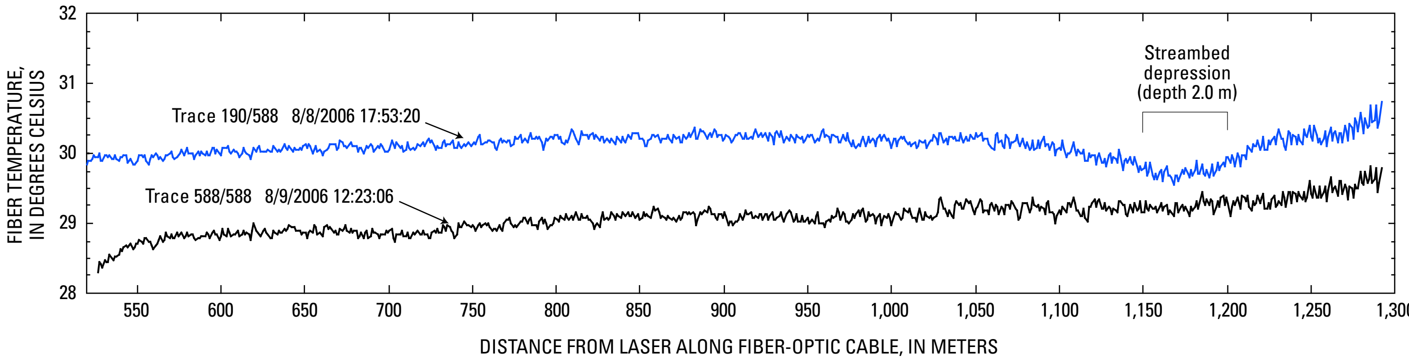


Figure 27. Fiber-optic distributed temperature sensing data showing thermal anomaly associated with streambed depression in Shenandoah River, Clarke County, Virginia.

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). A total of 15 springs located in the Great Valley section of Clarke County were sampled during the summer months of 2003–2005 (fig. 28). Timing of the sampling coincided with the period of the year when spring flows and water levels are low; therefore, estimates of apparent groundwater ages should represent the oldest ages of the young waters in the flow systems. Analytical data are presented in appendixes 5–13 at end of the report. 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 also excess air in groundwater, which is attributed to entrainment of air during recharge (Heaton, 1981; Heaton and Vogel, 1981; Heaton and others, 1983; Busenberg and others, 1993). 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. 29). This apparent age estimate assumes that the tracer (the CFC compound) is transported as a plug through the aquifer with no dispersive mixing in the direction of flow (Busenberg and Plummer, 1992). The CFC data, however, can provide an indication of whether the sample represents a binary mixture of old (which is often assumed to be pre-CFC) and young waters for which the relative proportions can be estimated. Sorption of CFCs to sediments and organic matter and biodegradation of the CFCs can decrease the concentrations of CFCs in groundwater. This decrease in concentration results in the apparent age determined from measured concentrations of one CFC appearing to be older than the ages determined from the other CFCs (Plummer and Busenberg, 2000). Contamination of the CFCs, in terms of dating methodology, is frequently detected and indicates that sources other than the atmosphere, such as sewage effluent, have introduced CFCs into the groundwater system. The use of other tracers aids in the age determinations and in the assessment of degradation and contamination of the CFCs.

The SF_6 dating method (Busenberg and Plummer, 2000) is similar to the CFC dating method (fig. 29). Unlike CFCs, SF_6 in groundwater can be derived from anthropogenic and terrigenic sources. SF_6 is generally not affected by sorption and biodegradation processes, but it can be affected by excess air in groundwater. Groundwater in areas where the flux of terrigenic SF_6 is high cannot be dated by the SF_6 method.

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). Tritium is produced naturally in the atmosphere by cosmic ray spallation, but the principal source from about 1952 to 1963 has been the atmospheric testing of thermonuclear weapons (fig. 29). The $^3H/^3He$ method is based on the radioactive decay of ^3H to helium-3 (^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 from Schlosser and others (1988, 1989):

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

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 metamorphic rocks.

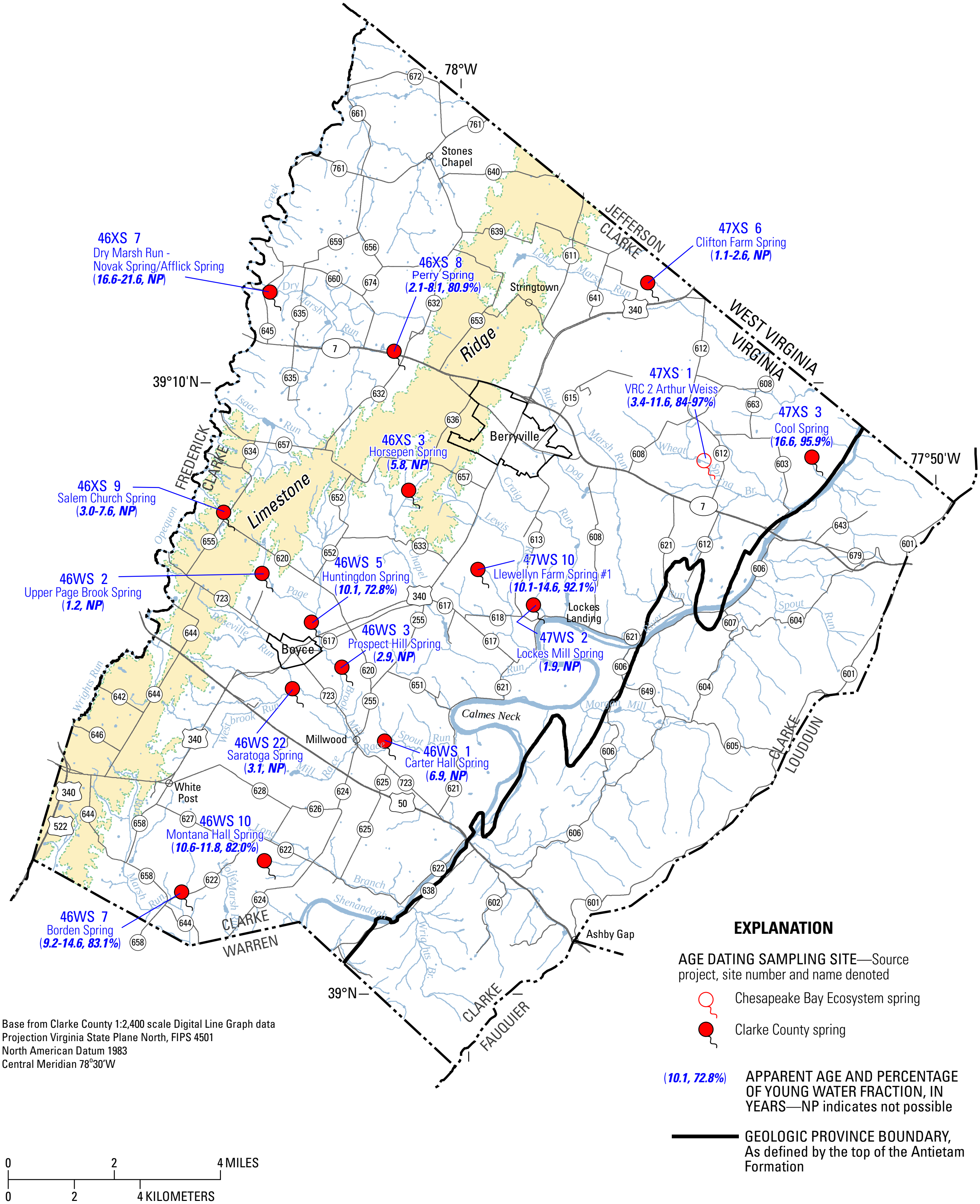


Figure 28. Apparent age and percentage of young water fraction for sampling sites in Clarke County, Virginia.

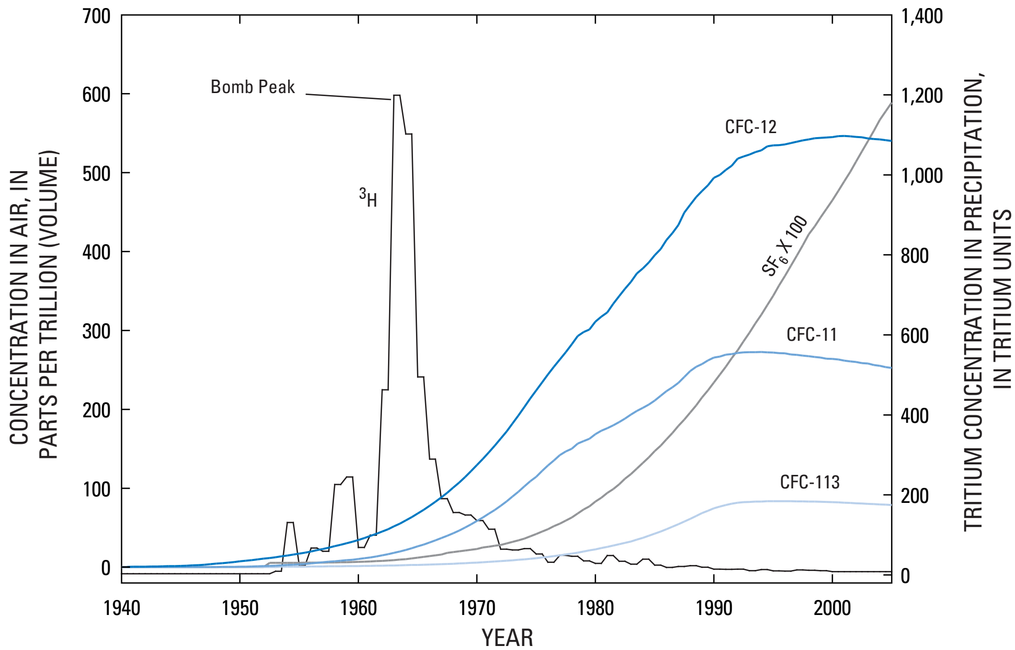


Figure 29. Atmospheric mixing ratios of chlorofluorocarbon-11 (CFC-11), chlorofluorocarbon-12 (CFC-12), chlorofluorocarbon-113 (CFC-113), and sulfur hexafluoride (SF_6) for North American air and estimated monthly concentration of tritium (^3H) in precipitation for Virginia. Tritium data derived from estimation technique of Michel (1989) and are not corrected for radioactive decay. Modified from Plummer and Busenberg (2000).

Determination of final apparent age estimates is based on the comparison of the estimates from the different tracers and whether the sample indicates piston flow or binary mixtures. The final apparent age estimates ranged from 1.1 to 21.6 years (table 3). Nearly half of the springs contained some fraction of the waters with apparent ages that were less than 5 years. Of the remaining springs, 75 percent contained waters with apparent ages greater than 10 years. Because of contamination (in terms of age determinations) of the CFCs and year of recharge, the percentage of the young fraction in some binary mixtures could not be determined. For the springs in which determination of the young fraction was possible, the young fraction ranged from approximately 73 to 96 percent. These high percentages indicate that a majority of the water discharging from the springs is young and is close to being piston flow, which would have a young fraction of 100 percent. In fact, spring 46XS 7 on Dry Marsh Run (fig. 28) indicates piston flow with apparent ages that ranged from 16.6 to 21.6 years. Water clarity even during stormflows and the presence of watercress at gaging station 01616100, which is approximately 1,000 ft downstream, indicate that streamflow is dominated by spring discharge. The relatively old piston-flow ages suggest relatively long residence times, which may explain the continuous flowing conditions present at this gage even during periods of prolonged drought conditions.

A review of apparent ages estimated for spring 47XS 1 (VRC 2 Arthur Weiss) (fig. 28) from three sampling events conducted in September and November 1996 and August 1997 provide insight into temporal changes in the distribution of apparent ages and mixing fractions under different hydrologic conditions (Focazio and others, 1998; Lindsey and others, 2003). Apparent $^3H/^3He$ ages increased from 3.4 to 8.8 years for the 1996 and 1997 samples, respectively, and the apparent CFC ages increased from 6.7 to 11.6 years during the same period. The percentage of the young fraction in the binary mixture decreased from 94 to 87 percent between 1996 and 1997. This finding indicates that as water levels decrease the amount of young water discharging from springs decreases. Therefore, under different hydrologic conditions, temporal changes in water-quality trends and flow rates determined by dye-tracer studies would be expected to occur.

Young apparent ages and binary mixtures generally are present at springs in the upper reaches of the basins, and the older ages are present in the lower reaches. This distribution and temporal changes of apparent ages and mixing fractions are consistent with the conceptual idea of a system that is topographically driven in which local flow systems with young waters are superimposed on the regional flow system with older waters. The height of hydraulic head in the upgradient parts of a basin is primarily controlled by the outlets (springs) of the groundwater flow systems. In some situations, the hydraulic head is higher than land surface, and groundwater will overflow along joints, especially along fold hinges or faults. This overflow does not represent convergence of flow lines, but simply is the result of pressure relief along partings in the bedrock in response to the backup of water caused by the “bottlenecks” created by the flow system outlets (generally springs). To some degree, during periods of overflow, these

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 springs in Clarke County, Virginia, 2003–2005.

[CFC-11, (trichlorofluoromethane, $CFC1_3$); CFC-12, (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$); SF_6, sulfur hexafluoride; $^3H/^3He$, tritium/helium-3; C, contaminated; NP, not possible; nd, not determined. Final apparent ages and percentages are shaded. Numbers in parentheses indicate possible recharge years before and after atmospheric peak concentration. See figure 28 for location of springs See figure 28 for location of springs]

USGS local no.	Date	Apparent age and uncertainty, in years											Percentage of young fraction		
		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
46WS 1	08/13/2003	C	C	12.1 ± 3.9	NP	15.1 ± 0.5	NP	NP	NP	NP	C	6.9 ± 0.5	NP	NP	NP
46WS 2	08/20/2003	24.1 ± 1.0	NP	14.6 ± 1.5	NP	14.6 ± 0.5	NP	NP	NP	NP	1.6	1.2 ± 0.2	NP	NP	NP
46WS 3	08/13/2003	C	C	C	C	14.6 ± 0.8	NP	NP	NP	NP	nd	2.9 ± 0.3	NP	NP	NP
46WS 5	08/11/2005	23.1 ± 1.3	NP	9.1 ± 4.2	NP	18.1 ± 0.5	NP	NP	NP	10.1	17.1	nd	NP	NP	72.8
46WS 7	08/11/2005	20.1 ± 1.3	NP	16.1 ± 1.8	NP	17.1 ± 0.5	NP	NP	NP	14.6	C	9.2 ± 0.7	NP	NP	83.1
46WS 10	08/11/2005	20.1 ± 1.3	NP	12.6 ± 1.8	NP	17.1 ± 0.8	NP	NP	NP	10.6 ± 0.8	4.1	11.8 ± 0.6	NP	NP	82.0
46WS 22	08/13/2003	C	C	C	C	12.6 ± 2.9	NP	NP	NP	NP	nd	3.1 ± 0.5	NP	NP	NP
46XS 3	08/19/2004	C	C	C	C	14.6 ± 1.0	NP	NP	NP	NP	0.1	5.8 ± 0.4	NP	NP	NP
46XS 7	08/11/2005	28.1 ± 0.8	NP	20.6 ± 1.0	NP	21.6 ± 0.5	NP	NP	NP	17.1 ± 0.3	16.6	19.9 ± 0.9	NP	NP	60.1
46XS 8	08/13/2003	18.1 ± 1.0	NP	C	C	15.1 ± 0.8	NP	NP	NP	8.1	5.6	2.1 ± 0.2	NP	NP	80.9
46XS 9	08/19/2004	15.1 ± 3.4	4.1 ± 6.0	C	C	15.1 ± 0.8	NP	NP	NP	NP	7.6	3.0 ± 0.3	NP	NP	NP
47WS 2	08/19/2004	Mod.	C	C	C	14.6 ± 0.8	NP	NP	NP	NP	C	1.9 ± 0.2	NP	NP	NP
47WS 10	08/12/2005	18.1 ± 1.3	NP	C	C	16.1 ± 1.0	NP	NP	NP	14.6 ± 0.3	10.1	1.8 ± 0.2	NP	NP	92.1
47XS 3	08/19/2004	21.6 ± 1.3	NP	18.1 ± 0.8	NP	17.1 ± 0.5	NP	NP	16.6 ± 0.3	11.6 ± 0.8	4.6	nd	NP	95.9	71.0
47XS 6	08/19/2004	C	C	C	C	14.1 ± 1.0	NP	NP	NP	NP	2.6	1.1 ± 0.3	NP	NP	NP

aquifer systems could be considered to be under semiconfined to confined (artesian) conditions.

Detailed groundwater dating of springs has been conducted in Blue Ridge settings similar to those located in Clarke County. Plummer and others (2001) determined that apparent $^{3}H/^{3}He$ ages for springs in Shenandoah National Park predominantly ranged between 0 and 3 years. Large precipitation events caused specific conductance and temperature to increase in these springs within a few hours of the event and then decrease to values below 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. A similar range of apparent ages for springs located in the Blue Ridge of Warren County, VA, have been estimated (D.L. Nelms, U.S. Geological Survey, written commun., 2009). Several springs sampled in Warren County, however, had apparent ages between 10 and 20 years. Both of these investigations illustrate the close relation between spring flow and precipitation in the Blue Ridge and indicate that transport of contaminants from the surface to outlets such as springs and streams can be rapid in the Blue Ridge.

Revised Conceptual Model of Groundwater Flow

Geologic sections generally are constructed normal to the strike of the rocks in order to show the overall geologic structure. Conceptually, a majority of the groundwater flow in the Great Valley is normal to these sections or along strike and cannot be depicted in figure 2. A revised conceptual hydrogeologic section that parallels the strike is shown in figure 30. Land surface depicted in figure 30 is the intersection of the strike-parallel thrust and cross-strike faults with the surface. Regional groundwater flow moves from the elevated areas along the fault planes and bedding-plane partings until it is intercepted by a stream, spring, or cross-strike fault. 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 the neighboring counties of WV. Regional flow continues along the cross-strike fault until it either is intercepted by another strike-parallel fault or eventually discharges to a base-level spring. Superimposed on the regional flow is local flow that generally follows a shorter path to intermittent streams and springs. Generally, groundwater is under unconfined or water-table conditions. During wet periods, the amount of water entering the system can exceed the amount flowing out, which causes hydraulic pressures to increase and groundwater to be become either semiconfined or possibly confined. Faults, bedding-plane partings, and joints can allow these pressures to dissipate as overflow on the land surface, which is similar to an artesian flowing well scenario. These overflow areas in the Great Valley section, which are locally referred to as “wet weather springs,” probably do not represent convergence of flow lines, but simply represent pressure release from the flow system. These overflow areas frequently are present along the axes of folds.

The conceptualization shown in figure 30 also applies to other partings in the rocks, such as bedding planes, and joints (fractures), where the direction of groundwater flow would be aligned to the dominant orientation of these features. Fault-bounded areas may act as individual flow cells or blocks that route water from elevated flow cells to downgradient cells (Allen and Michel, 1999). Local, fairly rapid flow along dissolution features may not follow a regional path if karstification has obliterated the geologic structure. Topography is the driving force behind groundwater flow, and geologic structures provide the pathways that directionally control this flow.

In the Blue Ridge, topography controls groundwater gradients, and the water-table surface closely mimics land surface (fig. 31). The high density of streams in the Blue Ridge is characteristic of areas underlain by low permeability rock. The porous nature of the regolith material (overburden) and sharp contrast in permeability with the underlying bedrock coupled with the stream density and steep terrain are more conducive for the development of local flow systems. Wright (1990) stated that subsurface stormflow through the porous overburden moves rapidly to streams and springs in the Blue Ridge because of the steep gradients. Although the terrain is steep, overland flow is believed to be a lesser component of the total runoff than subsurface stormflow (Whipkey, 1965). The presence of local flow systems developed in the unconsolidated material overlying the bedrock aquifers in the riparian areas of the Blue Ridge has been suggested (D.L. Nelms, U.S. Geological Survey, written commun., 2009). When determining the locations of potential contaminant sources in the future, it will be important to consider subsurface stormflow, especially in areas near stream valleys filled with alluvial and colluvial deposits.

Flow in the bedrock of the Blue Ridge is controlled primarily by the irregular fracture network and steep terrain (Wright, 1990). Local flow systems may be controlled by stress-relief fracturing; however, bedding plane partings in the siliciclastic rocks and partings between basalt flows in the Catoctin Formation 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 down-dip and eventually discharges in springs and valleys on the eastern sides of the mountains (fig. 31).

Conceptualization of the groundwater flow system in the siliciclastic rocks on the western edge of the county, underlain by the Martinsburg Formation, is more similar to that of the Blue Ridge than of 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 as evidenced by the high density of streams. 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. 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, whereas seeps are much more common.

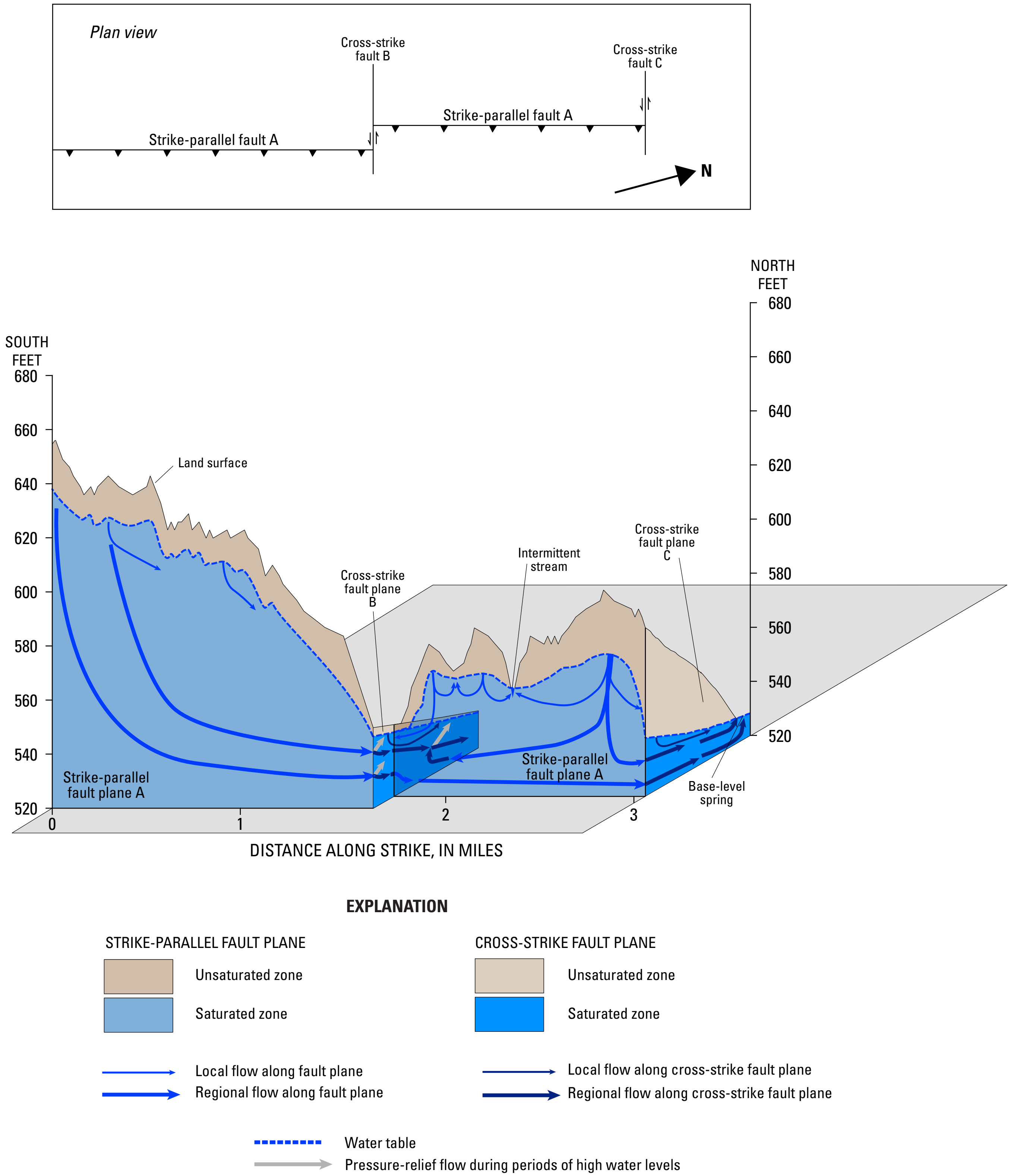


Figure 30. Generalized conceptual hydrogeologic longitudinal section of the flow system in the Valley and Ridge Physiographic Province in Clarke County, Virginia, showing strike-parallel and cross-strike flow along faults. View is of the upper footwall surfaces of the strike-parallel faults. Strike-parallel flow along bedding follows similar flowpaths.

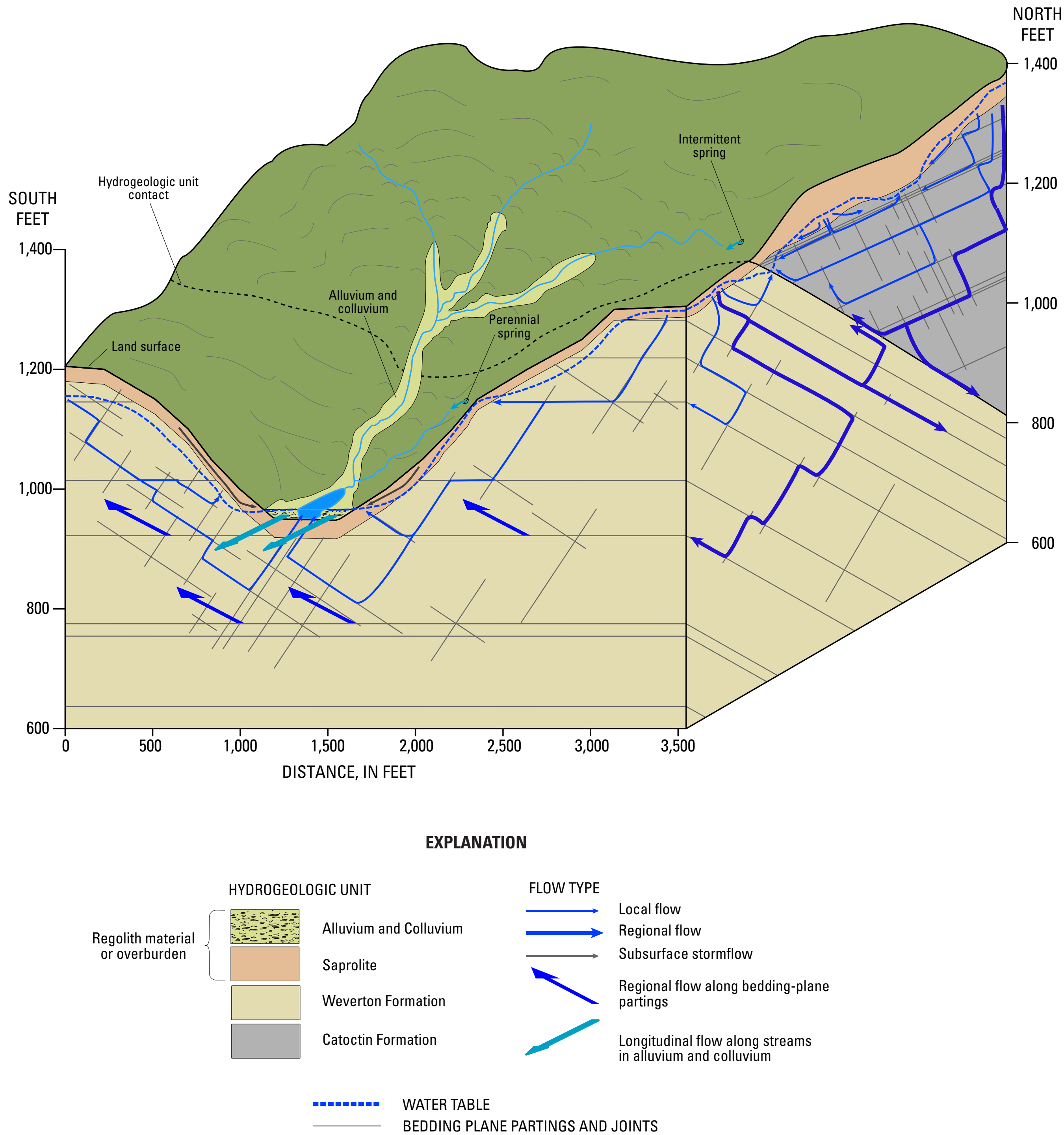


Figure 31. Generalized conceptual hydrogeologic longitudinal section of the flow system in the Blue Ridge Physiographic Province in Clarke County, Virginia.

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 (table 4). Additional rates of effective recharge for the groundwater areas were estimated by a regression equation developed by Yager and others (2008). Annual water budgets were developed for two basins (Dry Marsh and Spout Runs) in the county for the years 2001–2007. These water budgets include precipitation, mean annual streamflow, and mean annual base flow, *ET*, changes in groundwater storage (from water-level data), estimates of specific yield, and water withdrawal data (table 5).

Effective Recharge

Effective recharge 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 in/yr in the Appalachian Valley and Ridge from Alabama to New Jersey. Recharge occurs throughout a basin, but rates generally lessen towards 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), uses 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 because groundwater discharge over a long period of time approximately equals groundwater recharge (Richardson, 1982). Nelms and others (1997) used PART to estimate a median effective recharge of 8.4 in/yr from 73 basins and 11.1 in/yr in 46 basins in the northern Valley and Ridge and Blue Ridge of Virginia, respectively. PART was applied to hydrographs from two unregulated streams in the county—Dry Marsh and Spout Runs (table 4). PART assumes that the surface-water drainage basin and the recharge area coincide. Harlow and others (2005) noted that the validity of this assumption is uncertain. Groundwater flow beneath surface-water divides is well documented by dye-tracer studies in karst areas (Jones, 1987; Wil Orndorff, Virginia Department of Conservation and Recreation, oral commun., 2005). Regardless, the PART method provides a conservative estimate of effective recharge.

Streamflow gaging station 01616100, Dry Marsh Run near Berryville, VA, is in the northwestern corner of the county and has been in operation since August 2002. The drainage area of gaging station 01616100 is 11 mi^2, and is entirely within the Dry Marsh Run groundwater area (figs. 15, 24). The station is approximately 870 ft upstream from the confluence with Opequon Creek and on the contact between the New Market Limestone and Martinsburg Formation (D.J. Weary, U.S. Geological Survey, written commun., 2008). Nearly 99 percent of the drainage area above this station is underlain by carbonate bedrock. 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 01616100 and those for streamflow gaging station 01614830, Opequon Creek at Route 11 near Stephens City, VA (fig. 15), between 2003 and 2007. Estimates of effective groundwater recharge between 2001 and 2007 at the Dry Marsh Run gage ranged from 6.4 to 22.5 in/yr with an average of 11.6 in/yr (table 4). Base flow accounted for between 81 and 93 percent of mean annual streamflow and averaged 90 percent over the same period. Nelms and others (1997) correlated partial record streamflow data at gage 01616100 with continuous streamflow data and estimated an annual effective recharge rate of 15.5 in/yr. A majority of the streamflow at gaging station 01616100 between 2002 and 2007 was derived from several springs along Dry Marsh Run approximately 1,000 ft upstream from gaging station 01616100. The remainder of the upstream segments had intermittent flow that was either lost into swallet holes and estavelles or the segments were completely dry. Generally, if spring 46XS 8 had substantial flow, then the segments downstream to gage 01616100 were flowing (fig. 15). Flow upstream from gaging station 01616100 at the Route 635 crossing has been documented at times and is caused by water overflowing into Dry Marsh Run from a former marl pit, which is labeled “Shale pit” on the Stephenson 7.5-degree topographic quadrangle map.

Streamflow gaging station 01636316, Spout Run at Route 621 near Millwood, VA, is in the southeastern part of the county and has been in operation since August 2002. The drainage area of gaging station 01636316 is 21.4 mi^2 and is entirely within the Spout Run groundwater area (figs. 15, 24). The station is approximately 1,900 ft upstream from the confluence with the Shenandoah River. The entire drainage area above this station is underlain by carbonate bedrock. 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 gage 01636316 and those for streamflow gaging station 01614830 between 2003 and 2007. Estimates of effective groundwater recharge between 2001 and 2007 ranged from 6.7 to 23.0 in/yr with an average at the Spout Run gage of

Table 4. Summary of effective recharge and streamflow partitioning rates for the groundwater areas and selected streamflow gaging stations in and adjacent to Clarke County, Virginia.

[mi^2, square miles; in/yr, inches per year; nd, not determined. Base-flow index is base flow as percentage of streamflow. For the years 2001–2002, estimates at streamflow gages 01616100 and 01636316 are based on linear regression with streamflow gaging station 01614830 Opequon Creek at Route 11 near Stephens City, VA. Ranges of annual estimates are shown in parentheses. Blue-shaded rows indicate Blue Ridge areas, gray-shaded rows indicate streamflow gaging stations, and unshaded rows indicate Valley and Ridge areas. See figures 15 and 24 for location of streamflow gaging stations and groundwater areas, respectively]

Groundwater area		Streamflow gaging station	Drainage area (mi^2)	Mean base flow (effective recharge) (in/yr)		Period of record	Streamflow partitioning[c]			
Number	Name			Linear regression[a]	Nelms and others (1997)[b]		Mean base flow (in/yr)	Mean streamflow (in/yr)	Base-flow index	Period of record
B01-BR	Raven Rocks Run		17.1	9.1	nd	nd	nd	nd	nd	nd
B01-VR	Long Marsh Run		39.7	9.7	nd	nd	nd	nd	nd	nd
B02-BR	Morgan Mill		24.9	9.1	nd	nd	nd	nd	nd	nd
B02-VR	Spout Run		47.8	9.7	nd	nd	nd	nd	nd	nd
		01636300 Westbrook Run near Boyce, Virginia	1.5	9.7	12.6	nd	nd	nd	nd	nd
		01636316 Spout Run at Route 621 near Millwood, Virginia	21.4	9.7	nd	nd	11.9 (6.7–23.0)	13.4 (7.8–28.6)	91 (80–97)	2001–2007
B03-BR	Rock Spring Branch		0.8	9.1	nd	nd	nd	nd	nd	nd
B03-VR	Borden Marsh Run		9.9	9.7	nd	nd	nd	nd	nd	nd
		01636270 Borden Marsh Run at Route 624 near Boyce, Virginia	8.6	9.7	12.8	nd	nd	nd	nd	nd
B04-VR	Crooked Run		1.2	9.7	nd	nd	nd	nd	nd	nd
B54-VR	Dry Marsh Run		25.8	9.5	nd	nd	nd	nd	nd	nd
		01616100 Dry Marsh Run near Berryville, Virginia	11.0	9.6	15.5	nd	11.6 (6.4–22.5)	13.0 (7.9–26.0)	90 (81–93)	2001–2007
B55-VR	Opequon Creek		8.7	8.4	nd	nd	nd	nd	nd	nd
		01615000 Opequon Creek near Berryville, Virginia	58.2	7.3	4.9	1945–1984	5.4	10.9	51	1945–2007
				nd	nd	nd	7.1 (5.0–12.6)	13.5 (8.3–25.5)	54 (49–60)	2003–2007

[a] Effective recharge (*Rch*) estimated by the following linear regression equation developed by Yager and others (2008) for the Shenandoah Valley, VA and WVA: $Rch = 5.5 + 4.3Carb + 3.6Meta + 10.1West$, where the percentage of basin is underlain by the respective rock unit: carbonate (*Carb*), metamorphic (*Meta*), and western-toe carbonate (*West*). The percentage of siliciclastics is included implicitly (5.5).

[b] Nelms and others (1997) used the streamflow partitioning software package PART (Rutledge, 1993) to compute effective recharge.

[c] Current study used PART to compute effective recharge for the periods of record noted.

11.9 in/yr (table 4). Base flow for gage 01636316 accounted for between 80 and 97 percent of mean annual streamflow and averaged 91 percent during the same period. Earlier sections of this report discuss the effect that springs 46WS 1, 46WS 22, and 46WS 3 have on the flow at gaging station 01636316 on Spout Run.

Although no streamflow gaging stations were established in the Blue Ridge part of the county, the same linear regression method was used for gaging stations in Warren County to estimate average annual effective recharge rates of 15.3 and 14.2 in/yr between 2001 and 2007 at streamflow gaging stations 01630700, Gooney Run near Glen Echo, VA, and 0163626650, Manassas Run at Route 645 near Front Royal, VA, respectively. Base-flow discharge composed about 70 percent of mean annual streamflow at both of these gages in Warren County. These average recharge rates should not be used in water-supply planning because these rates are strongly influenced by the alluvium and colluvium in the stream valleys and may not reflect effective recharge to the bedrock system from which domestic and public-supply wells produce water (D.L. Nelms, U.S. Geological Survey, written commun., 2009).

A large part of the drainage areas for streamflow gaging stations 01636242, Crooked Run below Route 340 at Riverton, VA, and 01615000, Opequon Creek near Berryville, VA, are underlain by the Martinsburg Formation. An effective recharge rate of 5.3 in/yr with a base-flow index of 53 percent was estimated at gaging station 01636242 between 2001 and 2007 (D.L. Nelms, U.S. Geological Survey, written commun., 2009). Effective recharge rates of 4.9, 5.4, and 7.1 in/yr were estimated for gaging station 01615000 for the periods between 1945 and 1984 (Nelms and others, 1997), 1945 and 2007, and 2003 and 2007, respectively (table 4).

In order to provide effective recharge rates for each of the groundwater areas (table 4), a linear regression model developed by Yager and others (2008) was used. The equation is based on the percentage of the basin underlain by respective rock types, uses effective recharge rates estimated by Nelms and others (1997) for 20 basins in the Shenandoah Valley, and is:

$$Rech = 5.5 + 4.3Carb + 3.6Meta + 10.1West, \qquad (2)$$

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 effective recharge rates are in inches per year. Results from this method (table 4) indicate that effective recharge rates ranged from 9.5 to 9.7 in/yr for the groundwater areas underlain by carbonate rocks. Effective recharge rates were 9.1 in/yr in the Blue Ridge areas and 8.4 in/yr in the Opequon Creek area where a substantial proportion (31.6 percent) of the area is underlain by the Martinsburg Formation.

The areas underlain by the least permeable unit in the county, the Martinsburg Formation, have low effective recharge rates, low base-flow index, and large stream density, which probably is a function of the low permeability of the bedrock. The regression-derived recharge rate of 8.4 in/yr (table 4) for the Opequon Creek groundwater area is strongly influenced by the presence of carbonate rocks present under two-thirds of the area (table 2). Future management activities concerned with areas underlain by the Martinsburg Formation should rely on lower annual effective recharge rates that range from 4.9 to 7.3 in/yr (table 4). The range of regression-derived recharge rates in the Blue Ridge areas seems appropriate for fractured rock aquifers, whereas those determined by PART for the neighboring Warren County gages are high and probably not representative of recharge rates to the bedrock (D.L. Nelms, U.S. Geological Survey, written commun., 2009).

Base flow as a percentage of mean streamflow is known as base-flow index (BFI). The values for BFI indicate that groundwater is a major component of streamflow in the county. The high values of BFI for the Dry Marsh Run and Spout Run Basins indicate that groundwater is the dominant source of streamflow during wet and drought conditions. The values of BFI determined for the Blue Ridge streams in Warren County are slightly lower than those for carbonate basins, but values still indicate that groundwater is a large component of streamflow (D.L. Nelms, U.S. Geological Survey, written commun., 2009). Even basins underlain by the siliciclastic rock unit have BFI values that indicate that groundwater composes more than 50 percent of mean annual streamflow. The determination that groundwater is a major component of streamflow needs to be considered by any water-resources management activity in the county.

Analysis of data from the long-term water monitoring network and of effective recharge rates indicates a close correlation with current climatic conditions. A comparison of annual recharge rates at streamflow gaging stations 01616100 and 01636316 to annual precipitation is shown in figure 32. On average, annual effective recharge is about 30 percent of the annual precipitation with a 95-percent confidence interval of about ±8 percent. The timing and type of precipitation, however, is critical in determining the amount of water that will actually recharge the groundwater system. The majority of groundwater recharge occurs between January and April of each year when plants are dormant and evapotranspiration is at a minimum. In 2002, the effective recharge rate of about 15 percent of annual precipitation deviated from the apparent correlation because precipitation and snowfall for the winter quarter were below normal. Conversely, years 2003 and 2004 show high recharge rates of 40 percent of annual precipitation. Precipitation, especially snowfall, was above normal for the entire calendar year of 2003 and was above normal in the early spring of 2004. Normally, water levels, spring discharges, and streamflows are highest 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 momentarily increase.

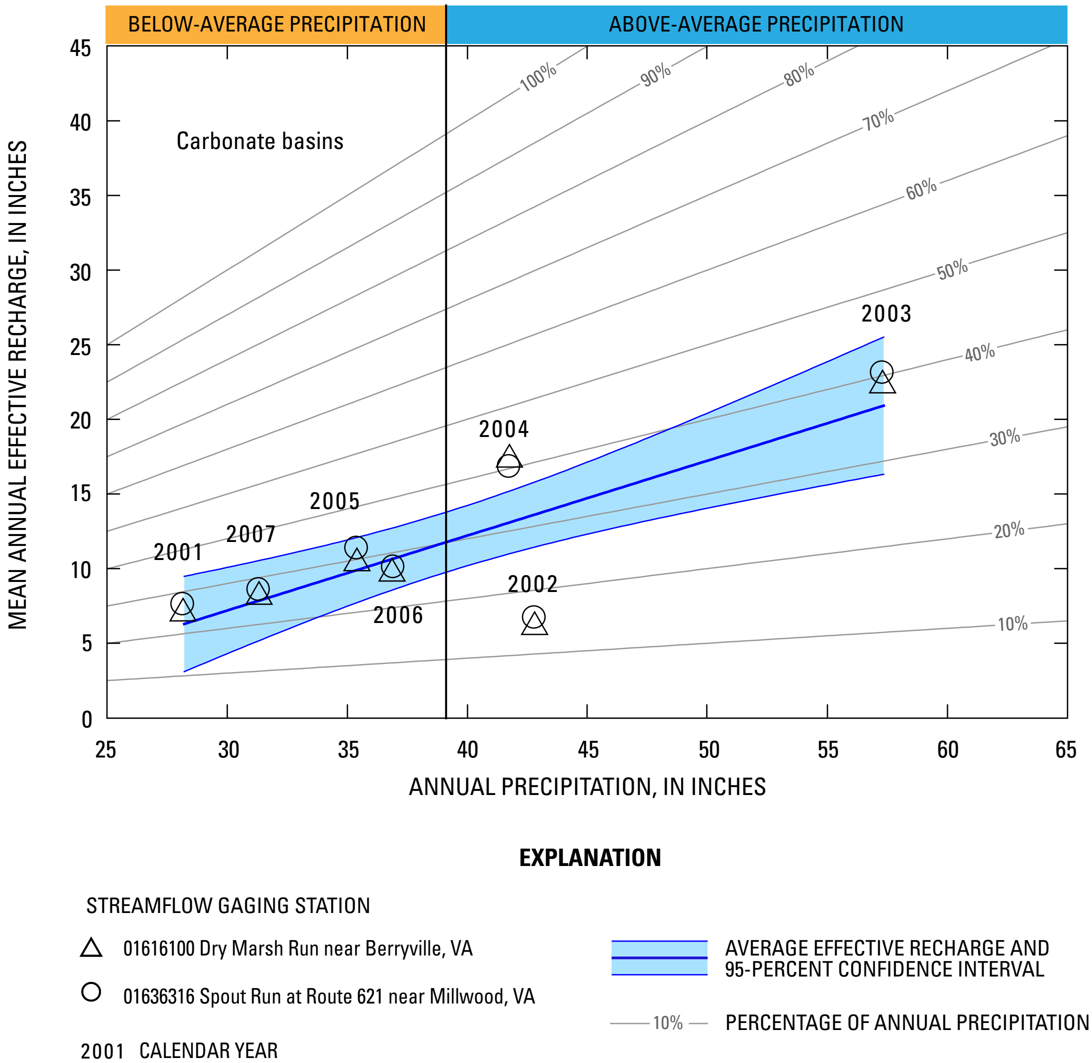


Figure 32. Relation between annual precipitation at National Weather Service climatological station 449186 Winchester 7 SE, Virginia, and effective recharge at streamflow gaging stations 01616100 Dry Marsh Run near Berryville, Virginia, and 01636316 Spout Run at Route 621 near Millwood, Virginia. Effective recharge rates for the years 2001–2002 are estimated based on linear regression with streamflow gaging station 01614830 Opequon Creek at Route 11 near Stephens City, Virginia. Effective recharge rates for the years 2003–2007 are estimated from the streamflow partitioning software package PART (Rutledge, 1993).

Water Budget

Water budgets represent an estimate of the amount of water entering and leaving a basin plus or minus changes in storage over 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:

$$P = ET + RO + \Delta S + WU + ER, \qquad (3)$$

where

- P is precipitation, in inches per year;
- ET is evapotranspiration, in inches per year;
- RO is mean surface 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*, ΔS, *WU*, and *ER* are known, measured, or estimated; therefore, solution of the water-budget equation 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 the Dry Marsh Run and Spout Run Basins (table 5).

Annual precipitation data, which includes rainfall and snowfall, were obtained from the NWS climatological station 449186 Winchester 7 SE located to the west in Frederick County, VA. Annual precipitation ranged from 28.2 to 57.4 in. between 2001 and 2007; therefore, the dominant inflow component (*P*) of the calculated water budgets nearly encompasses the entire range measured at station 449186. Also, these water budgets are almost equally distributed between above- and below-normal precipitation conditions (table 5). The average annual precipitation for the period 2001–2007 is equivalent to the long-term normal precipitation at station 449186; therefore, the averaged water budgets shown in table 5 can be considered as representative of normal precipitation conditions.

The *RO* term is estimated by subtracting effective recharge (mean base flow) from mean annual streamflow. The high permeability of the rocks and low relief in the Great Valley are not conducive for surface runoff; therefore, on average, only about 3 to 4 percent of the precipitation that falls on the basins becomes runoff. *RO* increases during above-normal conditions to between 6 and 10 percent of the precipitation (table 5). *RO* is a small component of water budgets for basins in the Blue Ridge of Warren County (D.L. Nelms, U.S. Geological Survey, written commun., 2009).

Changes in groundwater storage (ΔS) are normally negligible in water-budget calculations in karst and fractured-rock flow systems because the specific yield of these types of systems is low. Normally, ΔS is based on changes in water levels from one year to the next at a specific time of year (for example, the month of January). The difference in the yearly high water levels was used because this indicates the maximum ΔS. For the years 2001–2003, water-level changes from well 46W175 were used in both basins. For the years 2004–2007, the average change in water levels for 11 wells in the Dry Marsh Run Basin and 4 wells in the Spout Run Basin was used. In order to calculate ΔS, 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 are large in the county, changes in groundwater storage on average are small (table 5).

In both of the basins, domestic withdrawal of groundwater is the primary use of water and is assumed to be consumptive. In order to calculate total withdrawal, the number of addressed buildings in the basins was determined by intersecting the basin boundaries with a shapefile of buildings from the county's geographic information system. The number of addressed buildings was multiplied by the average family size of 2.48 people per household, and the product was multiplied by 75 gallons per day, which is the per person water-use estimate for Virginia (Hutson and others, 2004). The total daily domestic water usage of 0.1 and 0.2 million gallons (Mgal) for Dry Marsh and Spout Run, respectively, was then converted to a yearly estimate and normalized by area of each respective basin (table 5). 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 (0.5 percent). 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. The siting requirements in the county's septic ordinance help to reduce runoff and evapotranspiration of septic system outflows. Paul (2007) showed that only 1 percent of septic outflows was lost to evapotranspiration from an arid area with limited vegetative cover in Colorado. In metropolitan Atlanta, GA, base flow increased for basins with a high density of septic systems (greater than 200 systems per square mile) in response to septic outflow of municipal surface-water supplies (Landers and Ankcorn, 2008). Keyworth (2009) estimated that 85 percent of the wastewater discharged to septic systems is returned to the groundwater system. In some areas of the Spout Run Basin, water withdrawn from spring 46WS 3 (Prospect Hill) is returned to the basin either by septic system outflows or effluent discharge to Roseville Run from the sewage treatment plant located in Boyce, VA (fig. 15).

Groundwater storage in the type of aquifer systems in Clarke County is minimal; therefore, the amount of water that recharges the groundwater system (*ER*) each year is critical. For the period between 2001 and 2007, about 30 percent of the precipitation that fell in the Dry Marsh Run and Spout Run Basins reached the water table as recharge (table 5; fig. 32). Analysis of data collected by the long-term water monitoring network indicates that these systems are extremely vulnerable to 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. *ER* tends to increase as precipitation increases, but lack of precipitation, especially snow, during the critical recharge period can have a substantial effect on the amount of *ER* (fig. 32). Evaluation of the effect that future development will have on the water resources often assumes an *ER* rate of 50 percent of normal. Data in table 5 indicate that this assumption seems reasonable and that an even lower percentage could help plan for droughts in the future that may be more severe than the drought between 1999 and 2002 (fig. 32). Future water-supply planners also may consider the percentage of water withdrawals versus *ER* (table 5).

The estimation of *ET* is one of the shortcomings of any water-budget calculation. For the water budgets determined for the Dry Marsh Run and Spout Run Basins, *ET* is estimated by solution of equation 3 and also includes underflow, other losses, and errors (Harlow and others, 2005). The declines in water levels, spring discharges, and streamflows during the

Table 5. Summary of annual water budget components for the Dry Marsh Run and Spout Run Basins in Clarke County, Virginia, 2001–2007.

[mi², square miles; in/yr, inches per year; DA, drainage area; *P*, precipitation at National Weather Service station 449186 Winchester 7 SE located in Frederick County, VA; *ET*, evapotranspiration; Δ*S*, change in groundwater storage; Bldgs, number of addressed buildings in the watershed; *WU*, water usage; *SF*, mean streamflow; *RO*, surface runoff; *ER*, effective recharge estimated from streamflow partitioning program PART (Rutledge, 1993). 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. Gray shaded rows indicate average values for the period 2001–2007. See figure 15 for location of streamflow gaging stations]

Station no.	Station	DA (mi²)	Calendar year[a]	Inflow[b] (in/yr)[c]	Outflow[b] (in/yr)							Percent of normal *ER*	*WU* percent of *ER*
				P[d]	*ET*	Δ*S*[e]	Bldgs.[f]	*WU*[f]	*SF*	*RO*	*ER*		
01616100	Dry Marsh Run at Route 645 near Berryville, Virginia	11.0	2001	28.2	20.4 (*72.3*)	–0.2	437	0.2 (*0.7*)	7.9 (*28.0*)	0.6 (*2.1*)	7.2 (*25.5*)	62	2.1
			2002	42.9	35.2 (*82.1*)	–0.4	437	0.2 (*0.5*)	7.9 (*18.4*)	1.5 (*3.5*)	6.4 (*14.9*)	55	2.4
			2003	57.4	29.1 (*50.7*)	2.1	437	0.2 (*0.3*)	26.0 (*45.3*)	3.5 (*6.1*)	22.5 (*39.2*)	194	0.7
			2004	41.8	23.4 (*56.0*)	–0.7	437	0.2 (*0.5*)	18.6 (*44.5*)	1.5 (*3.6*)	17.1 (*40.9*)	147	0.9
			2005	35.5	24.7 (*69.6*)	–0.4	437	0.2 (*0.6*)	11.1 (*31.3*)	0.8 (*2.3*)	10.3 (*29.0*)	89	1.5
			2006	36.9	27.2 (*73.7*)	–0.6	437	0.2 (*0.5*)	10.2 (*27.6*)	0.7 (*1.9*)	9.5 (*25.7*)	82	1.6
			2007	31.4	21.9 (*69.7*)	0.6	437	0.2 (*0.6*)	9.0 (*28.7*)	0.7 (*2.2*)	8.3 (*26.4*)	72	1.9
			Average	39.1	26.0 (*67.7*)	0.1	437	0.2 (*0.5*)	13.0 (*32.0*)	1.3 (*3.1*)	11.6 (*28.8*)		1.3
01636316	Spout Run at Route 621 near Millwood, Virginia	21.4	2001	28.2	20.4 (*72.3*)	–0.2	855	0.2 (*0.7*)	7.8 (*27.7*)	0.3 (*1.1*)	7.6 (*27.0*)	63	2.1
			2002	42.9	35.2 (*82.1*)	–0.4	855	0.2 (*0.5*)	7.9 (*18.4*)	1.1 (*2.6*)	6.7 (*15.6*)	56	2.3
			2003	57.4	26.5 (*46.2*)	2.1	855	0.2 (*0.3*)	28.6 (*49.8*)	5.6 (*9.8*)	23.0 (*40.1*)	193	0.7
			2004	41.8	23.7 (*56.7*)	–0.4	855	0.2 (*0.5*)	18.2 (*43.5*)	1.6 (*3.8*)	16.7 (*40.0*)	140	0.9
			2005	35.5	23.4 (*65.9*)	–0.5	855	0.2 (*0.6*)	12.4 (*34.9*)	1.0 (*2.8*)	11.4 (*32.1*)	95	1.4
			2006	36.9	27.3 (*74.0*)	–0.4	855	0.2 (*0.5*)	10.1 (*27.4*)	0.5 (*1.4*)	9.6 (*26.0*)	80	1.6
			2007	31.4	21.9 (*69.7*)	0.3	855	0.2 (*0.6*)	9.1 (*29.0*)	0.5 (*1.6*)	8.6 (*27.4*)	72	1.8
			Average	39.1	25.5 (*66.7*)	0.1	855	0.2 (*0.5*)	13.4 (*33.0*)	1.5 (*3.3*)	11.9 (*29.7*)		1.3

[a] For the years 2001–2002, estimates are based on linear regression with streamflow gaging station 01614830 Opequon Creek at Route 11 near Stephens City, VA.

[b] Water-budget equation is $P = ET + RO + ER + \Delta S + WU$.

[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).

[d] Normal annual precipitation of 39.1 inches at National Weather Service station 449186 Winchester 7 SE is based on the current normal climatological period 1971–2000.

[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 and a specific yield of 0.01. For the calendar years 2001–2003, Δ*S* was calculated using water-level data from well 46W175. For the calendar years 2004–2007, Δ*S* was calculated by averaging the Δ*S* in 11 and 4 wells in the Dry Marsh and Spout Run watersheds, respectively.

[f] Source is the buildings shapefile from the Clarke County geographic information system. WU was estimated by multiplying the number of addressed buildings by the average family size of 2.48 people per household, and the product was multiplied by 75 gallons per day, which is the per person water-use estimate for Virginia (Hutson and others, 2004). The total daily domestic water usage of 0.1 and 0.2 million gallons (Mgal) for Dry Marsh and Spout Run, respectively, was then converted to a yearly estimate and normalized by area of each respective basin.

spring and summer months indicate that *ET* is probably the dominant outflow component for any water budget in the area. Between 46 and 82 percent of the precipitation that fell on the two basins between 2001 and 2007 was removed by *ET* (table 5).

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 are expected in these systems where groundwater is such a major component of streamflow. Possible changes in streamflows and groundwater levels as development continues may be assessed using data collected as part of the long-term monitoring. In addition, Bredehoeft (2002) suggests that the use of groundwater models is a better means of assessing sustainable development than those based solely on effective recharge.

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 karst and fractured-rock aquifer systems in the northern Shenandoah Valley. More than 20 wells went dry or had insufficient yield, with a majority of these located in the Dry Marsh Run groundwater area. Aerial photographs acquired in 1996 by the county and at the peak of the drought in 2002 by the Virginia Base Mapping Program assisted with the evaluation of drought effects during this period. The wet areas in the Dry Marsh Run groundwater area that are clearly visible in the 1996 photographs, when spring 46XS 8 is flowing, are completely dry in 2002 (fig. 33). In fact, the 2002 aerial photograph indicates that a majority of the stream segments in the Dry Marsh Run groundwater area were dry. During this investigation, this phenomenon was observed on numerous occasions, and the intermittent nature of the streams is directly related to the flow conditions of the springs. Similar conditions are evident along Route 620 just west of Boyce, VA (fig. 34). During wet conditions, groundwater flows along joints and bedding-plane partings, and can overflow in areas where the water table is elevated above land surface (figs. 19 and 20). The concept that over-pressurization of water along these joints and bedding-plane partings in response to increased hydraulic head caused by backup of water by the limited number of outlets (springs and streams) in the immediate area is a possible explanation. During drought conditions, the hydraulic head has sufficient time to be lowered by discharge from the various outlets.

Well 46W175 has the longest continuous water-level record in the northern Shenandoah Valley of Virginia. Several daily maximum water-level records were established between 2002 and 2003. Although several quarters between 1998 and 2001 had precipitation above normal, most of the above-normal precipitation occurred when groundwater recharge was minimal, and most of the quarterly snowfall totals were below normal (fig. 35). The overall decline in water levels closely follows the below-normal and poorly timed precipitation. Beginning in April 2002, seven successive quarters of above-normal precipitation (with two of these quarters having above-normal snowfall) caused water levels in well 46W175 to rise approximately 20 ft to record daily maximum highs (fig. 35). Overall, water levels declined between 2004 and 2008 in response to below-normal precipitation, lack of snowfall, and timing of the precipitation (fig. 35). Water-level records from well 46W175 indicate that the frequency of the drought cycle is about 6 years, which is slightly less than the 10-year cycle of drought occurrence commonly observed in the mid-Atlantic area. Data from the water-level record from well 46W175 in conjunction with other data collected during this investigation indicate that the flow systems are highly susceptible to changes in climatic conditions.

Assessment of drought severity is important in understanding groundwater availability and in water-supply planning. The statistical distribution of daily water levels in well 46W175 grouped by calendar year can be one component in the assessment of drought severity (fig. 36). Normal water-level conditions, which are between the 25th and 75th percentiles for the period of 1988–2008, are shown as the gray-shaded area in figure 36. For 2002, all daily water levels were below the normal range, and the majority of these water levels are the lowest ever recorded in well 46W175. The statistical distribution of water levels in the following year (2003) illustrates how quickly these systems can recover (fig. 36). Continuation of the collection of these data may allow water-resources managers to assess drought severity and to determine if conditions are in a declining period in the future.

Plots of precipitation versus annual estimates of mean streamflow, runoff, and effective recharge (base flow) can indicate drought severity and overall trends. Figure 37 shows the close relation between precipitation and the different flow characteristics for the Dry Marsh Run and Spout Run Basins. The small separation between the annual values of mean streamflow and base flow graphically shows that these basins on average are dominated by groundwater discharge and that surface runoff is only a small component of streamflow. As the period of record increases, the individual mean annual flow characteristics can be plotted against the respective range of normal conditions to assess drought severity and overall trends.

More than 20 wells went dry or had diminished sustainable yields during the drought between 1999 and 2002. A majority of these wells were located in the Dry Marsh Run groundwater area, and these failures may be attributed to the low relief (231 ft) between drainage divide and stream outlet and to the large range of water-level fluctuations (9.44 to 87.84 ft) when compared to the other areas of the county (table 2). During drought conditions, the volume of water available for withdrawal from the upper parts of the aquifer system is greatly reduced as the water table declines. These declines tend to be greatest beneath the elevated parts of each area. Declines in water levels can drain water-bearing zones and can limit the available drawdown in wells. For example,

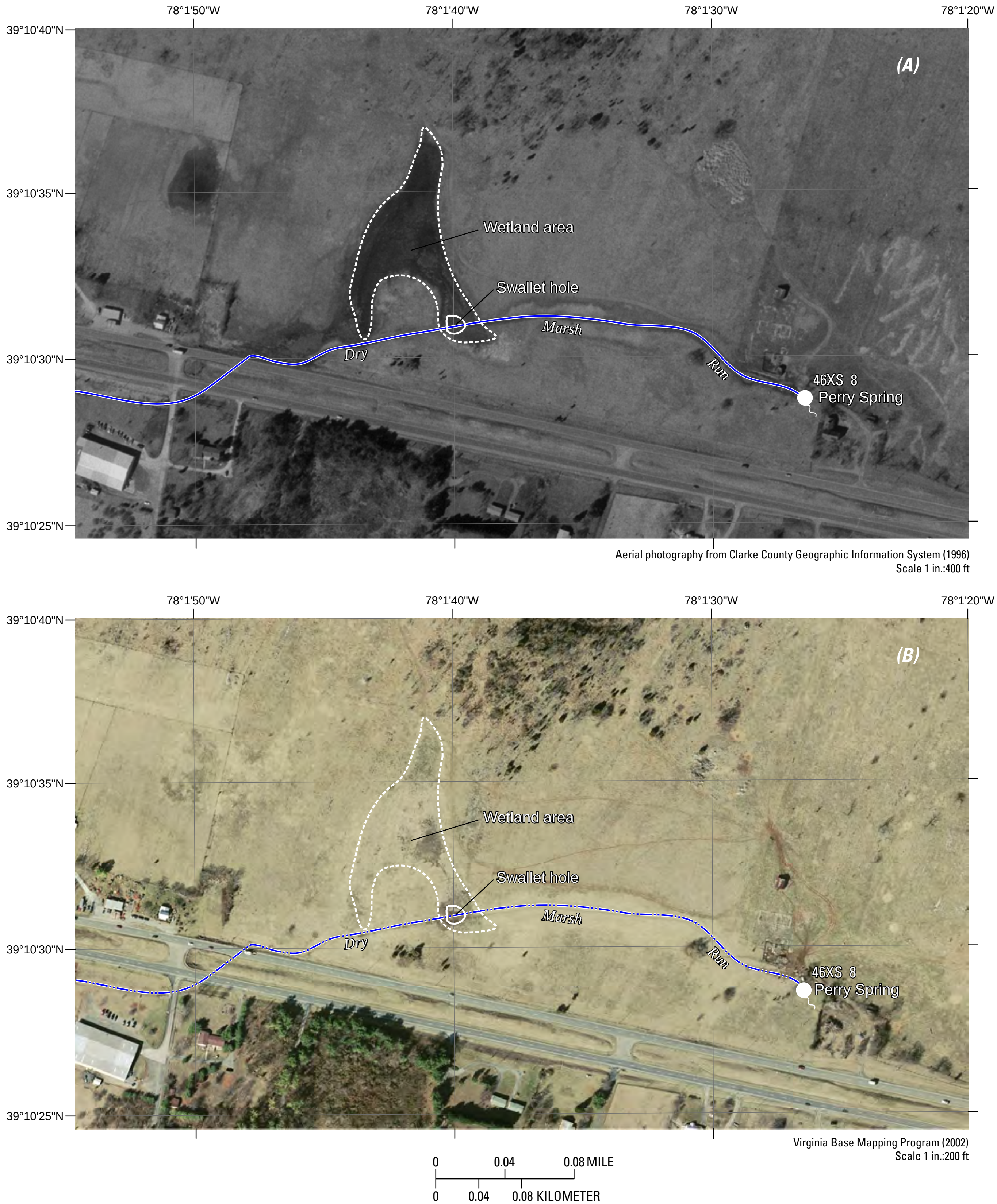


Figure 33. *(A)* Wet and *(B)* drought conditions in 1996 and 2002, respectively, for the area along Route 7 west of Berryville, Virginia, where Dry Marsh Run flows from spring 46XS 8 into a swallet hole and wetland area.

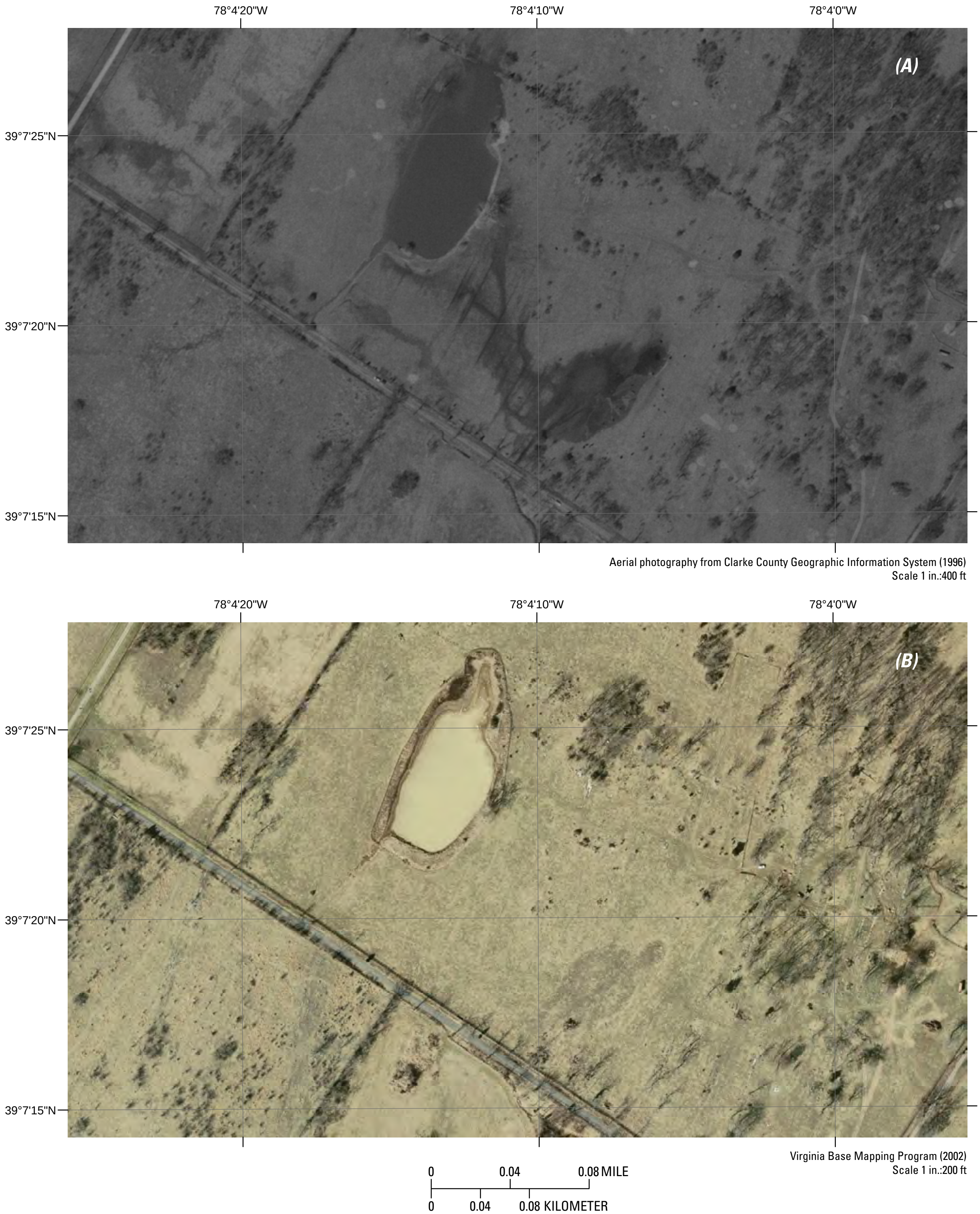


Figure 34. *(A)* Wet and *(B)* drought conditions in 1996 and 2002, respectively, for an area along Route 620 in Clarke County, Virginia, where groundwater overflows along bedding and joints (darker tones) in the carbonate rock during wet periods. Strike of the bedding is in northeast-southwest direction.

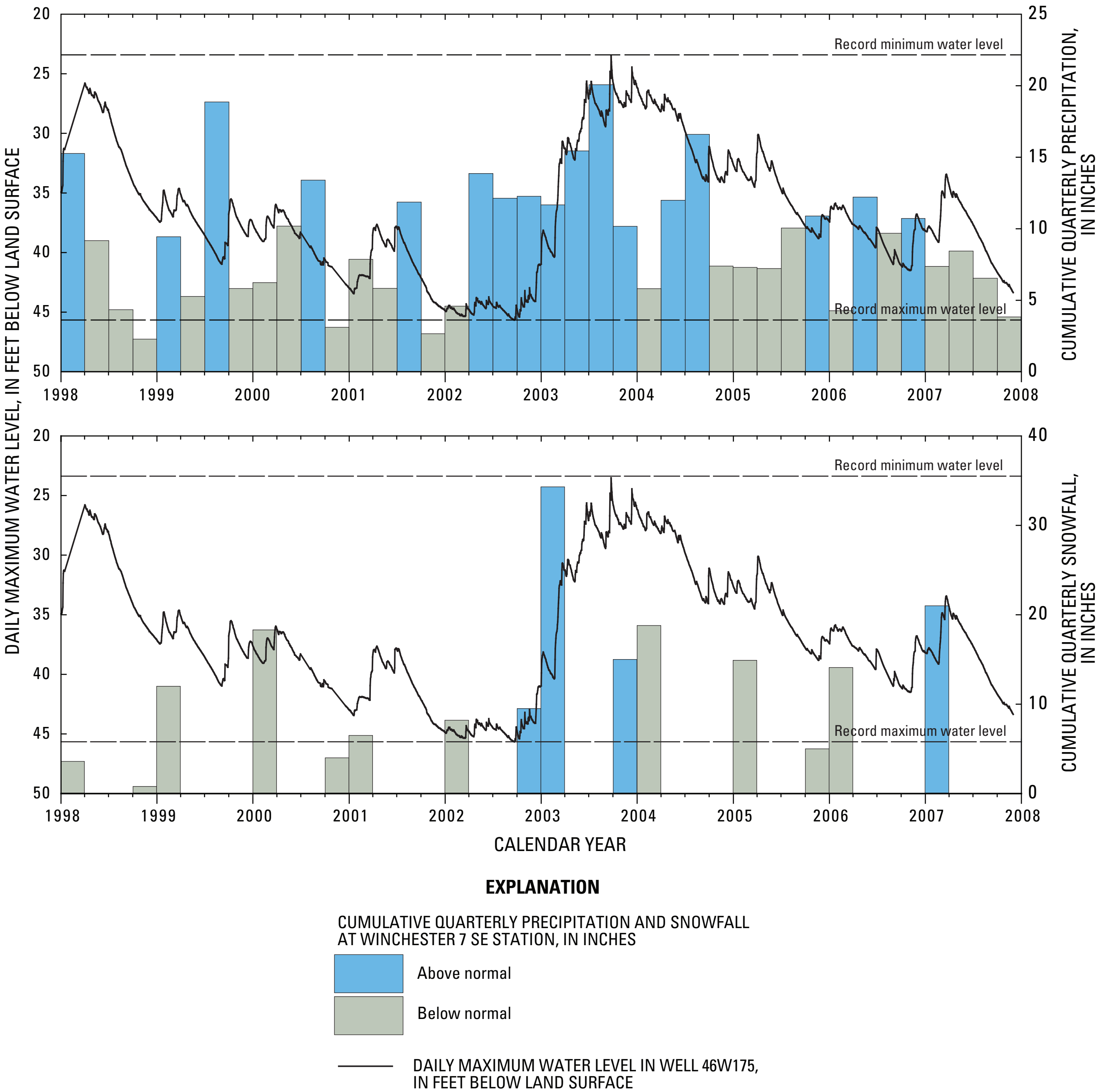


Figure 35. Relation between daily maximum water levels in well 46W175 and cumulative quarterly precipitation and snowfall at National Weather Service climatological station 449186 Winchester 7 SE, Virginia, 1998–2007.

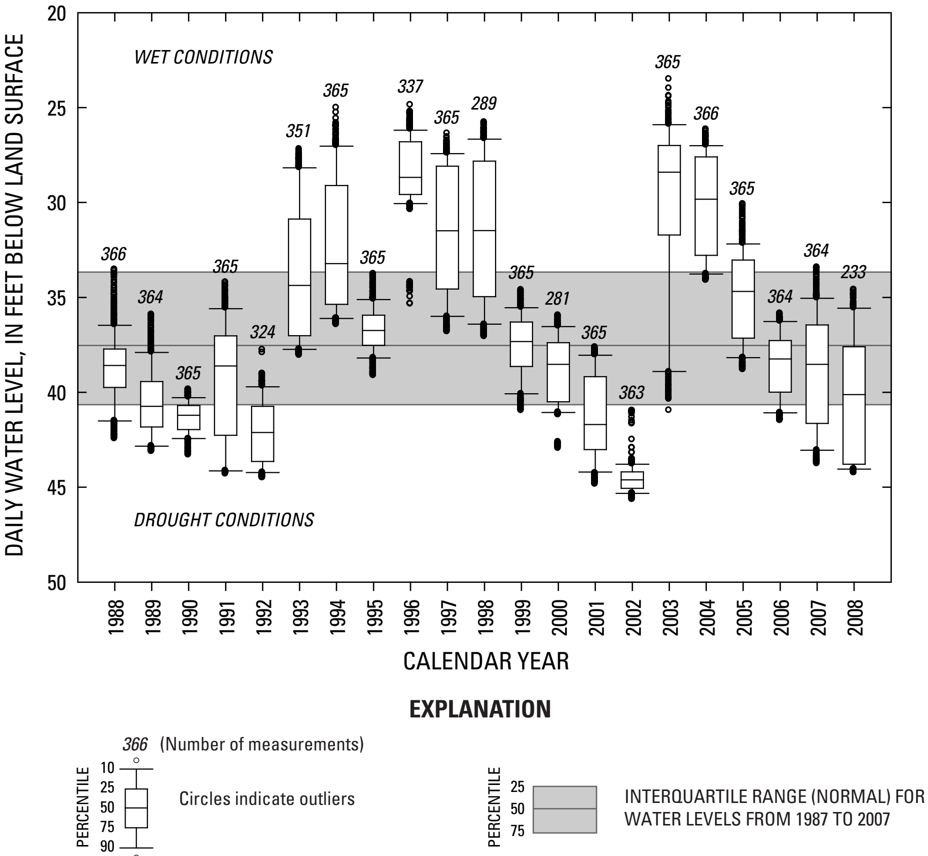


Figure 36. Statistical distribution of daily maximum water levels in well 46W175 by calendar year, 1988–2008.

figure 38 illustrates the relation between the altitude of the outlet at streamflow gaging station 01616100 and the Dry Marsh Run drainage basin, where relief is 177 ft. During dry conditions, the flow in Dry Marsh Run comes only from the springs approximately 1,000 ft upstream from the gage. Calculations of gravity drainage of the volume of the aquifer above the base level of the gage indicate that a large portion of this volume could be drained during prolonged drought conditions. Wells in the elevated parts of the basin that are either less than 177 ft deep or obtain water from zones that are less than 177 ft bls are therefore susceptible to failure during prolonged drought conditions as indicated by large water-level declines. The basin relief values for the Great Valley groundwater areas (table 2) could possibly be used to predict which wells may be affected by prolonged drought conditions. In the Blue Ridge, the use of basin relief values as indicators of well-failure susceptibility during prolonged drought conditions seems unreasonable because of the large basin relief values, which would equate to large aquifer volumes with low drainage rates.

Several wells that were reported to be dry in early 2002 had recovered by October 2002. The combination of a lack of precipitation, large water-level fluctuations, shallow depth of water-bearing zones, and overall hydrogeologic setting is the most probable explanation for the well failures during the recent drought. The cessation of meteorological drought conditions does not necessarily mean that groundwater conditions are normal. Water-resource managers need knowledge about the average rates of water-level recovery to anticipate the end of hydrologic drought conditions. Between October 2002 and April 2003, median rates of water-level recovery (table 6) were greatest in the Borden Marsh, Dry Marsh, and Spout Runs groundwater areas (0.14, 0.19, and 0.11 ft/d, respectively), and the largest recovery rates were observed in the elevated parts of these areas. Interestingly, the median rates of recovery in the remaining Great Valley and Blue Ridge groundwater areas were similar. In these areas, the changes in water levels were less than in the Dry Marsh Run area, possibly in response to the regional influence of the Shenandoah River.

The extent of drought conditions is difficult to forecast, and usually these conditions are not identified until an area has been in a drought for some period of time. Generally, water levels, spring discharges, and streamflows at the end of the critical recharge period can be used as initial guides for what the seasonal low conditions will be in late summer and early autumn. The seasonal high conditions determine the seasonal lows.

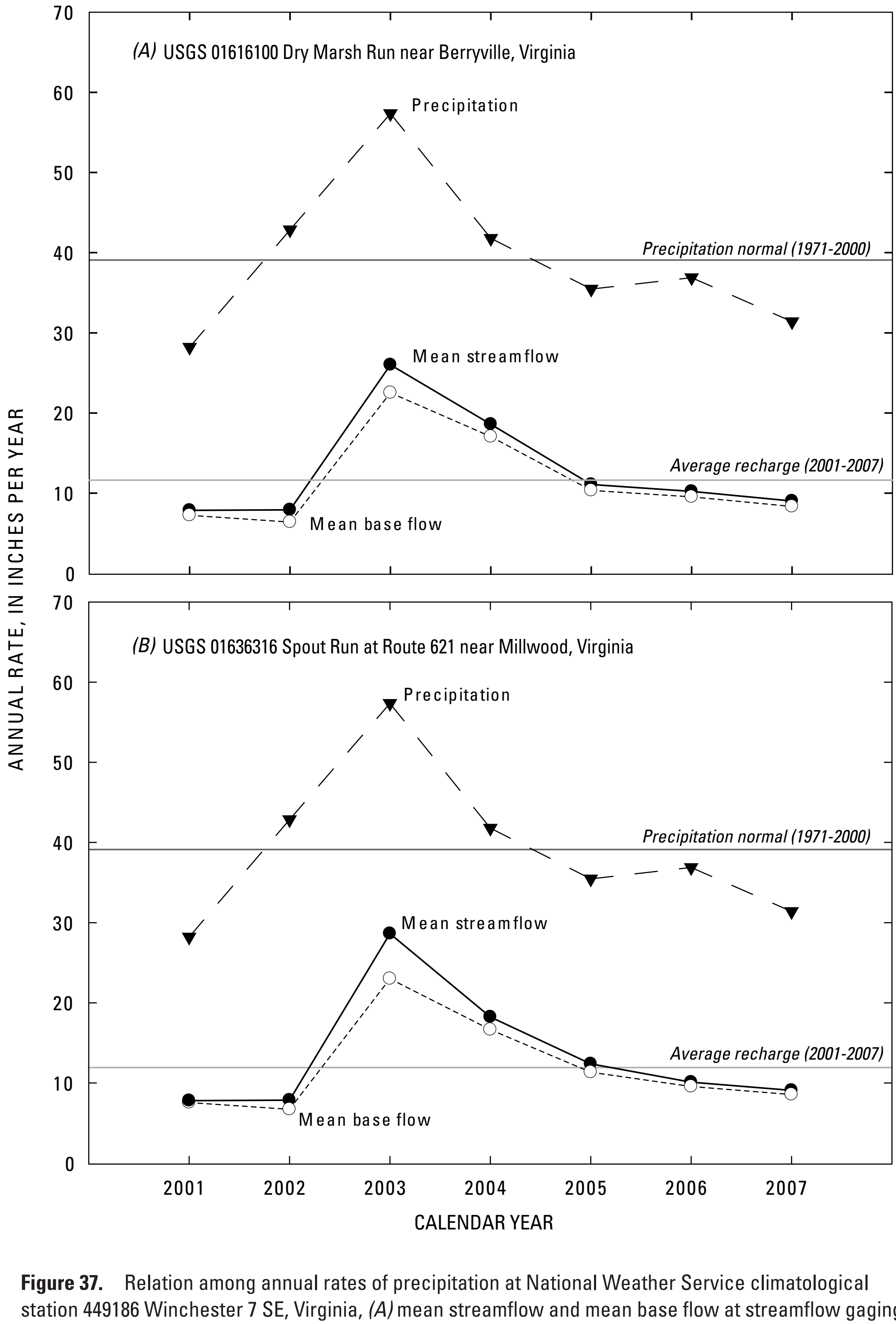


Figure 37. Relation among annual rates of precipitation at National Weather Service climatological station 449186 Winchester 7 SE, Virginia, *(A)* mean streamflow and mean base flow at streamflow gaging stations 01616100 Dry Marsh Run near Berryville, Virginia, and *(B)* 01636316 Spout Run at Route 621 near Millwood, Virginia. Mean streamflow and mean base-flow rates for the years 2001–2002 were estimated based on linear regression with streamflow gaging station 01614830 Opequon Creek at Route 11 near Stephens City, Virginia. Mean streamflow and mean base-flow rates for the years 2003–2007 were estimated from the streamflow partitioning software package PART (Rutledge, 1993).

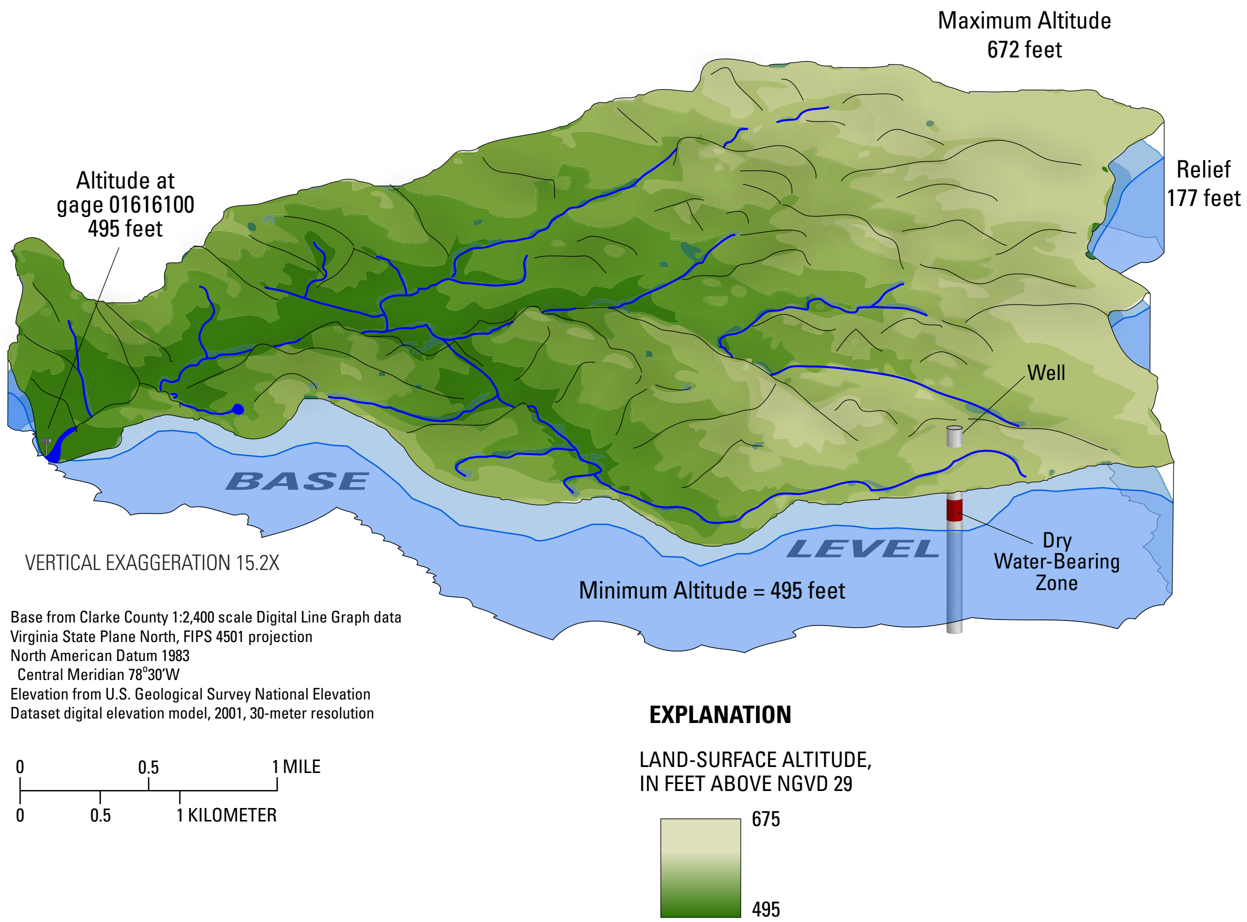


Figure 38. Schematic showing relation between watershed volume above the altitude of streamflow gaging station 01616100 Dry Marsh Run near Berryville in Clarke County, Virginia, and occurrence of dry wells.

Table 6. Median rates of quarterly water-level recovery from the 1999–2002 drought for the groundwater areas in Clarke County, Virginia.

[Water-level recovery rates are in feet per day. n, number of wells; nd, not determined; Shaded columns indicate Blue Ridge areas, and unshaded columns indicate Valley and Ridge areas. See figure 24 for location of groundwater areas]

Time period	Groundwater area									County
	B01-BR	B01-VR	B02-BR	B02-VR	B03-BR	B03-VR	B04-VR	B54-VR	B55-VR	
	Raven Rocks Run	Long Marsh Run	Morgan Mill	Spout Run	Rock Spring Branch	Borden Marsh Run	Crooked Run	Dry Marsh Run	Opequon Creek	
Oct. 2002 to Jan. 2003	0.03	0.04	0.06	0.04	nd	0.16	nd	0.25	0.08	0.09
Jan. 2003 to Apr. 2003	0.06	0.08	0.04	0.12	nd	0.13	nd	0.13	0.05	0.08
Oct. 2002 to Apr. 2003	0.06	0.07	0.04	0.11	nd	0.14	nd	0.19	0.06	0.12
n	6	7	3	6	nd	3	nd	17	4	46

Summary

A study was conducted between October 2002 and October 2008 by the U.S. Geological Survey (USGS), in cooperation with Clarke County, VA, to describe the hydrogeology and groundwater availability in the county and to establish a long-term water monitoring network. The study area encompasses approximately 177 square miles and includes the carbonate and siliciclastic rocks of the Great Valley section of the Valley and Ridge and the metamorphic rocks of the Blue Ridge. The groundwater flow systems are complex and are controlled by the extremely folded and faulted geology that underlies the county. Increasing growth and the prolonged drought between 1999 and 2002 drew attention in the county to the quantity and sustainability of the groundwater resources.

The hydrogeologic units, which are based on mapped geologic units, are grouped into three major rock types: (1) carbonate—limestone and dolostone; (2) metamorphic—metavolcanic and metasedimentary rocks; and (3) siliciclastic—sandstone, siltstone, and shale. The hydrogeologic characteristics vary among these units and among the major rock-type groupings. In the Great Valley, the dominant flow direction is along the strike of the bedding-plane partings and thrust faults, which strike from N. 10° E to N. 20° E. Groundwater movement normal to the strike, however, follows dip and oblique joints and cross-strike faults. Dips of bedding-plane partings and the various joint types are highly variable, range from horizontal to vertical, and can be overturned, but are generally between 10 and 80° to the northwest or southeast. Steeply dipping beds are prevalent in the county because of their location on the highly deformed eastern limb of the Massanutten synclinorium.

In the Blue Ridge, topography is the driving force behind groundwater flow, and water levels more closely mimic land surface. Flow in the bedrock in the Blue Ridge is controlled primarily by the irregular fracture network and steep terrain. The high density of streams in the Blue Ridge is characteristic of areas underlain by low permeability rocks. The porous nature of the regolith material or overburden and sharp contrast in permeability with the underlying bedrock coupled with numerous streams and steep terrain are conducive for the development of local-flow systems. Subsurface stormflow through the porous overburden moves rapidly to streams and springs in the Blue Ridge because of the steep terrain. Conceptualization of the groundwater flow system in the siliciclastic rocks on the western edge of the county, underlain by the Martinsburg Formation, is more similar to the Blue Ridge than the carbonate rocks of the Great Valley. Subsurface stormflow is probably a minor factor because of the lack of regolith material overlying the Martinsburg Formation and less steep terrain. Evapotranspiration, and to a lesser extent, runoff, may be greater because of the low permeability of the rock and the absence of regolith material.

Sinkholes, caves, caverns, estavelles, and sinking and dry streams are characteristic features of karst terrain. Lithologic characteristics, fracture density, proximity of carbonate rock to streams, land slope, and geologic structure are controlling factors in sinkhole development. Steep hydraulic gradients and increased rate of groundwater flow near incised streams may contribute to the abundance and increased size of sinkholes in areas near Opequon Creek and Shenandoah River. Sinkholes frequently develop in the noses of anticlines and synclines, and usually form in elevated and flat (less than 5-degree slope) areas. Sinkhole development during well construction and pumping is well documented. The greatest density of sinkholes in the county is in the northwest part in the Dry Marsh Run area.

Conduit- and diffuse-flow conditions are present in the karst aquifer systems, and the diffuse-flow conditions are present in areas underlain by the siliciclastic and metamorphic rocks. Generally, groundwater is under unconfined or water-table conditions. During wet periods, however, semiconfined to confined conditions can exist, and hydraulic head is dissipated as overflow on the land surface. These overflow areas in the Great Valley section, which are locally referred to as wet weather springs, do not represent convergence of flow lines, but simply represent pressure release from the flow system that frequently occurs along the axes of folds.

High-yielding wells generally tend to cluster along faults, within lineament zones, and in areas of tight folding throughout the county. 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 with karst and fractured-rock aquifer systems. Water-bearing zones are generally encountered within 250 feet (ft) of land surface. However, median depths are slightly deeper for the hydrogeologic units of the Blue Ridge than those in the Great Valley section of the county. A large number of water-bearing zones are present between 400 and 1,000 ft below land surface.

Between October 2002 and October 2008, water-level fluctuations ranged from 2.86 to 87.84 ft with an average of 24.15 ft. Seasonal water-level highs occur in the early spring at the end of the major groundwater recharge period, and lows occur in late autumn when evapotranspiration rates begin to decrease. Intense thunderstorms, tropical storms, or hurricanes generally cause sudden, but temporary, water-level rises during the summer and autumn. Water-level fluctuations generally were greatest near hydrologic divides, in isolated elevated areas, and in the Opequon Creek Basin. An overall downward trend in water levels between 2003 and 2008, which closely follows a downward trend in annual precipitation over the same period, was observed in a majority of wells in the Great Valley and in some of the wells in the Blue Ridge. Current meteorological conditions affect water-level fluctuations in the Blue Ridge, and seasonal highs and lows tend to shift in response to the current conditions.

Discharges from springs ranged from dry to 10 cubic feet per second (ft^3/s) between March 2003 and October 2008. Springs in the Great Valley, and to a lesser degree in the Blue Ridge, generally are associated with faults and fold axes.

A downward trend in discharges for the Great Valley springs correlates with the trend documented in water levels and is indicative of an aquifer system that over time drains to a base level that is controlled by springs and streams. 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 in the Great Valley function as aqueducts. Springs in the Blue Ridge have relatively low discharge rates and small drainage areas and are susceptible to current meteorological conditions. Movement of water through the porous regolith to springs is predominantly controlled by subsurface stormflow rather than by discharge from the bedrock.

Nine groundwater areas were delineated based on basin boundaries in Clarke County. High altitudes with relief greater than 1,400 ft, steep slopes, low sinkhole density, high stream density, mean annual precipitation of more than 40 inches per year (in/yr), and relatively large differences between minimum and maximum annual precipitation across the areas are characteristic of groundwater areas in the Blue Ridge. Low altitudes with relief less than 350 ft, gentle slopes, high sinkhole density, low stream density, mean annual precipitation of about 39 in/yr, and less areal variability in precipitation are characteristic of the Great Valley groundwater areas. The greatest range between the minimum and maximum water levels measured between October 2002 and October 2008 occurred in the Dry Marsh Run groundwater area, where numerous geologic structures (faults and lineament zones) cross and intersect. Low stream density and large water-level fluctuations indicate that this area is underlain by permeable rocks. The relatively deep water-bearing zones with large water-level fluctuations indicate that permeability maybe present to considerable depth. The combination of all of these factors can explain the high density of sinkholes, numerous dry stream segments during the majority of the study period, and the high occurrence of dry wells during the prolonged drought between 1999 and 2002 in the Dry Marsh Run area.

Apparent groundwater ages from 15 springs ranged from 1.1 to 21.6 years. Apparent ages of the young fraction that were less than 5 years were estimated in nearly half of the springs sampled. Of the remaining springs, 75 percent contained waters with apparent ages greater than 10 years. The percentage of the young fraction in binary mixtures ranged from approximately 73 to nearly 96 percent. These high percentages indicate that a majority of the water discharging from the springs is young and is close to being piston flow. Springs in the upper reaches of the basins tend to have young apparent ages and binary mixtures, and the older ages are present in the lower reaches.

Estimates of effective groundwater recharge for 2001–2007 ranged from 6.4 to 22.5 in/yr in the Dry Marsh Run Basin with an average of 11.6 in/yr. Base flow accounted for between 81 and 93 percent of mean streamflow with an average of 90 percent during the same period. Effective recharge rates for 2001–2007 in the Spout Run Basin ranged from 6.7 to 23.0 in/yr with an average of 11.9 in/yr. Base flow accounted for between 80 and 97 percent of mean streamflow with an average of 91 percent during the same period. The high base-flow index values (percentage of streamflow from base flow) in the Dry Marsh Run and Spout Run Basins indicate that groundwater is the dominant source of streamflow during wet and drought conditions.

Water-budget data indicate that between 46 and 82 percent of the precipitation that fell on the Dry Marsh Run and Spout Run Basins between 2001 and 2007 was removed by evapotranspiration, and approximately 30 percent of the precipitation reached the water table as effective recharge. The high permeability of the rocks and low relief in these basins are not conducive for runoff; therefore, on average, only about 3 to 4 percent of the precipitation becomes runoff. Current water use is a small component of the overall budget.

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 as effective recharge increases, especially in the Dry Marsh Run area. Effective recharge tends to increase as precipitation increases, but lack of precipitation, especially snow, during the critical recharge periods can have a substantial effect on the amount of recharge. Daily water levels recorded in well 46W175 in 2002 were below the normal range, and the majority of these water levels were the lowest recorded since 1987. The combination of a lack of precipitation, large water-level fluctuations, depths to water-bearing zones, and hydrogeologic setting is the most probable explanation for the well failures during the recent drought.

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Appendixes

Appendix 1. Record of selected wells in Clarke County, Virginia.

[USGS, U.S. Geological Survey; dms, degrees, minutes, and seconds in North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; gal/min, gallons per minute; nd, no data. Topographic setting: D, depression; H, hilltop; S, hillside; V, valley. See figure 15 for location of wells]

USGS local no.	Latitude (dms)	Longitude (dms)	Land-surface altitude above NGVD 29 (feet)	Topographic setting	Hydrogeologic unit	Year drilled	Depth of well (feet)	Depth of casing (feet)	Well diameter (inches)	Depth to bedrock (feet)	Depth of water-bearing zones (feet)	Well yield (gal/min)	Water-level range from Oct. 2002 to Oct. 2008 (feet below land surface)	
													Minimum	Maximum
46W 4	39 05 49	78 01 07	595	H	Conococheague	1905	80.5	nd	6	nd	nd	nd	48.38	57.74
46W 60	39 00 10	78 01 04	775	W	Hampton	1981	530	91	6	29	nd	6.5	36.95	58.86
46W175	39 03 49	78 03 54	600	W	Conococheague	1940	80.4	24	6	nd	66	nd	0.00	0.00
46W177	39 06 47	78 04 11	607	S	Beekmantown	2000	340	101	6	12	320	100	5.76	8.62
46W178	39 05 14	78 06 33	628	S	Beekmantown	1905	240	nd	6	nd	nd	nd	20.95	36.90
46W179	39 03 28	78 06 12	625	D	Stonehenge	nd	36.3	nd	nd	nd	nd	nd	5.03	32.74
46W180	39 03 36	78 06 06	625	D	Stonehenge	nd	38.61	nd	nd	nd	nd	nd	7.96	35.82
46W181	39 01 18	78 07 04	636	H	Conococheague	nd	nd	nd	6	nd	nd	nd	50.35	58.38
46W182	39 00 56	78 02 56	538	S	Waynesboro	2001	400	105	6	36	310	12	112.94	128.76
46W186	39 06 04	78 01 30	593	S	Conococheague	1997	600	63	6	6	581	6	38.06	72.16
46W187	39 03 57	78 02 29	500	V	Elbrook	1998	150	80	6	17	93	30	11.78	35.23
46W188	39 06 25	78 05 56	639	H	New Market	nd	nd	nd	6	nd	nd	nd	18.01	33.56
46W189	39 02 22	78 05 55	632	S	Conococheague	nd	23	23	nd	nd	23	nd	18.84	23.08
46W190	39 02 13	78 06 00	647	H	Conococheague	nd	29.95	29.95	nd	nd	29.95	nd	3.31	14.75
46W191	39 04 58	78 00 37	510	W	Elbrook	nd	34.62	34.62	nd	nd	34.62	nd	7.49	32.64
46X 8	39 09 04	78 00 31	635	H	Stonehenge	1968	185	40	6	nd	nd	24	9.04	38.79
46X 84	39 08 29	78 04 49	662	H	New Market	1985	145	50	6	nd	nd	50	10.87	30.28
46X111	39 13 41	78 02 10	541	S	Beekmantown	1999	300	62	6	4	280	75	13.69	60.79
46X112	39 14 02	78 00 04	566	H	Beekmantown	1994	145	57	6	12	135	50	2.63	90.47
46X113	39 14 01	78 00 03	565	H	Beekmantown	2002	500	63	6	10	475	5	2.17	89.25
46X114	39 11 08	78 04 13	600	H	New Market	nd	nd	nd	6	nd	nd	nd	71.43	80.87
46X115	39 11 10	78 01 58	574	V	Beekmantown	1999	550	63	6	15	545	100	3.66	35.92
46X116	39 10 31	78 02 23	585	S	New Market	2002	300	84	6	2	260	30	27.90	54.99
46X117	39 10 44	78 01 58	588	S	Beekmantown	2002	1020	63	6	2	nd	0.4	21.27	48.10
46X118	39 10 44	78 00 56	624	S	Beekmantown	1999	165	74	6	15	140	50	17.84	47.51
46X121	39 08 24	78 05 01	655	H	Martinsburg	nd	nd	nd	6	nd	nd	nd	24.95	36.12
46X123	39 09 05	78 00 33	635	H	Stonehenge	2002	420	63	6	13	290	30	9.01	38.03
46X124	39 09 41	78 00 12	660	H	Stonehenge	nd	nd	nd	6	nd	nd	nd	16.58	50.70
46X125	39 09 48	78 00 16	645	H	Stonehenge	2001	600	nd	nd	nd	nd	10	10.23	45.43
46X126	39 09 53	78 00 19	645	H	Stonehenge	2001	400	60	nd	nd	340	90	8.64	44.26

Appendix 1. Record of selected wells in Clarke County, Virginia.—Continued

[USGS, U.S. Geological Survey; dms, degrees, minutes, and seconds in North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; gal/min, gallons per minute; nd, no data. Topographic setting: D, depression; H, hilltop; S, hillside; V, valley. See figure 15 for location of wells]

USGS local no.	Latitude (dms)	Longi-tude (dms)	Land-surface altitude above NGVD 29 (feet)	Topo-graphic setting	Hydrogeologic unit	Year drilled	Depth of well (feet)	Depth of casing (feet)	Well diameter (inches)	Depth to bedrock (feet)	Depth of water-bearing zones (feet)	Well yield (gal/min)	Water-level range from Oct. 2002 to Oct. 2008 (feet below land surface)	
													Minimum	Maximum
46X127	39 13 50	78 02 20	545	S	Beekmantown	1998	700	57	6	8	680	25	26.63	58.81
46X128	39 11 48	78 00 02	649	W	Beekmantown	2000	120	59	6	19	102	45	15.56	56.29
46X129	39 12 34	78 00 05	595	W	Beekmantown	1997	200	84	6	3	189	10	5.19	41.55
46X132	39 14 16	78 01 34	591	H	New Market	2002	500	80	6	nd	135, 473	19	48.28	96.42
46X133	39 11 46	78 00 52	609	S	Beekmantown	1998	165	80	6	5	140	100	10.27	48.98
46X134	39 09 23	78 02 38	651	H	Beekmantown	1993	225	80	6	nd	nd	8	32.13	74.70
46X135	39 14 56	78 01 45	568	H	New Market	nd	nd	nd	6	nd	nd	nd	68.53	102.48
47W 83	39 06 56	77 57 08	520	H	Chewsville	1999	450	60	6	34	395	20	69.97	87.86
47W 84	39 05 03	77 55 26	740	H	Harpers	1998	520	77	6	20	480	5	88.84	95.62
47W 85	39 04 22	77 58 35	520	S	Tomstown	2001	180	84	6	34	175	10	66.78	93.82
47W 86	39 02 53	77 54 23	1676	H	Catoctin	1998	400	63	6	26	259	5	24.15	41.14
47W 87	39 02 20	77 56 06	1456	S	Catoctin	nd	nd	nd	6	nd	nd	nd	58.30	62.10
47W 88	39 05 45	77 55 47	554	S	Harpers	1995	320	62	6	45	308	50	11.72	24.13
47W 89	39 06 23	77 52 35	721	H	Harpers	2000	550	120	6	77	400	5	51.30	65.99
47W 90	39 07 24	77 52 32	670	S	Harpers	nd	nd	nd	6	nd	nd	nd	65.16	77.98
47W 91	39 07 24	77 52 29	680	S	Harpers	2002	380	58	6	15	320	15	84.56	88.36
47W 92	39 03 33	77 56 41	700	S	Harpers	nd	nd	nd	6	nd	nd	nd	22.67	38.88
47W 93	39 01 50	77 58 51	724	S	Owens Creek	nd	nd	nd	6	nd	nd	nd	47.23	73.43
47X 53	39 09 21	77 55 08	527	H	Chewsville	nd	nd	nd	6	nd	nd	nd	58.45	68.30
47X 82	39 12 03	77 58 59	620	S	Rockdale Run	nd	35	nd	nd	nd	nd	nd	8.00	16.56
47X 83	39 12 03	77 58 59	618	S	Rockdale Run	2002	340	68	6	15	325	15	4.32	16.67
47X 84	39 08 05	77 55 21	508	W	Chewsville	2000	240	203	6	20	210	12	37.88	46.42
47X 85	39 09 17	77 53 53	516	H	Chewsville	2000	300	80	6	10	105	20	48.90	63.73
47X 86	39 11 09	77 59 28	643	S	Rockdale Run	1999	500	75	6	10	340	5	10.80	37.82
47X 89	39 10 50	77 59 17	641	S	Stonehenge	nd	30.9	30.9	nd	nd	30.9	nd	16.69	29.99
48X 20	39 07 43	77 50 45	1353	H	Buzzard Knob	nd	63	16	6	nd	nd	nd	25.70	37.16
48X 21	39 07 33	77 50 36	1275	S	Catoctin	nd	423.6	17	6	nd	nd	nd	38.14	65.20

Appendix 2. Record of selected springs in Clarke County, Virginia.

[USGS, U.S. Geological Survey; dms, degrees, minutes, and seconds in North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; ft^3/s, cubic feet per second (1 ft^3/s equals 448.8 gallons per minute); ºC, degrees Celsius; µS/cm microsiemens per centimeter; mg/L, milligrams per liter. See figure 15 for location of springs]

USGS local no.	Latitude (dms)	Longitude (dms)	Land-surface altitude above NGVD 29 (feet)	Hydrogeologic unit	Ranges from April 2003 to October 2008									
					Discharge (ft^3/s)		Water temperature (ºC)		Specific conductance (µS/cm at 25 °C)		Dissolved oxygen (mg/L)		pH (standard units)	
					Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
01636283	39 00 04	78 01 11	710	Harpers	0.0004	0.411	11.0	nd	21	nd	6.1	nd	6.0	nd
01636320	39 03 47	77 56 15	640	Harpers	0	0.334	7.6	13.0	19	134	1.2	9.7	5.0	7.1
01636336	39 09 53	77 58 32	575	Conococheague	0.34	1.74	9.2	23.4	600	685	7.7	10.5	7.3	8.0
46WS 1	39 04 06	78 01 41	470	Conococheague	3.63	9.59	12.5	13.0	543	589	6.7	7.9	6.8	7.4
46WS 2	39 06 52	78 04 15	615	Beekmantown	nd	nd	13.6	nd	533	nd	0.9	nd	6.3	nd
46WS 3	39 05 19	78 02 35	535	Conococheague	1.16	3.06	12.0	12.7	550	651	4.7	7.6	6.6	7.1
46WS 5	39 06 04	78 03 13	557	Beekmantown	0	1.29	11.8	13.7	521	690	1.9	6.6	6.7	7.5
46WS 7	39 01 39	78 05 57	570	Conococheague	0.74	1.32	12.5	12.8	493	522	6.6	7.3	7.0	7.3
46WS 10	39 02 09	78 04 14	579	Elbrook	0.002	0.14	10.1	14.2	508	644	3.3	7.1	6.6	7.7
46WS 12	39 02 23	78 03 22	527	Elbrook	0.008	0.17	12.6	13.6	522	572	3.5	8.0	6.8	7.6
46WS 22	39 04 58	78 03 38	536	Stonehenge	0.43	0.99	11.5	16.6	532	675	2.7	8.2	6.8	7.3
46WS 26	39 01 22	78 06 52	581	Conococheague	0.006	0.23	9.8	15.0	469	546	4.1	7.2	6.4	7.6
46WS 27	39 00 02	78 01 08	744	Harpers	nd	nd	9.6	16.0	17	25	6.3	9.2	4.4	6.2
46WS 28	39 00 03	78 01 11	715	Harpers	nd	nd	5.7	17.7	15	26	2.2	12.5	4.2	6.6
46WS 29	39 00 02	78 01 11	739	Harpers	nd	nd	7.9	16.2	18	34	2.2	9.8	4.0	6.5
46WS 30	39 00 03	78 01 12	731	Harpers	nd	nd	5.2	14.5	26	32	1.9	11.0	5.0	6.5
46WS 32	39 06 26	78 06 02	585	New Market	0.06	0.70	12.6	12.9	560	677	3.1	10.1	6.7	7.1
46WS 34	39 01 58	78 02 44	501	Elbrook	0.01	0.28	12.4	13.0	454	608	3.4	7.2	6.8	7.7
46WS 35	39 06 48	78 04 09	601	Beekmantown	0.03	0.25	11.8	13.5	561	672	1.1	5.3	6.7	7.1
46WS 36	39 00 30	78 00 55	620	Harpers	0.008	nd	11.7	nd	39	nd	10.9	nd	6.3	nd
46WS 40	39 05 44	78 06 33	580	Beekmantown	0.14	nd	12.6	nd	629	nd	3.1	nd	7.0	nd
46S 3	39 08 12	78 01 10	600	Stonehenge	0.001	2.27	11.3	12.5	577	706	3.6	12.3	6.5	7.2
46XS 7	39 11 28	78 04 03	505	New Market	nd	nd	0.0	0.0	0	0	0.0	0.0	0.0	0.0
46XS 8	39 10 29	78 01 27	590	Beekmantown	0	4.47	12.1	12.8	626	765	4.8	8.1	6.7	7.3
46XS 9	39 07 51	78 05 03	592	New Market	0.08	1.7	12.3	13.2	523	634	2.4	6.0	6.8	7.4
47WS 2	39 06 19	77 58 33	442	Elbrook	0.65	2.17	11.2	12.6	540	624	6.1	9.4	6.6	7.7
47WS 10	39 06 54	77 59 43	540	Conococheague	0.17	0.17	12.5	nd	638	nd	5.8	nd	6.8	nd
47WS 13	39 04 34	77 55 17	735	Harpers	0.0001	0.12	8.5	12.6	28	67	1.1	10.7	4.7	8.0
47WS 14	39 04 24	77 55 21	702	Harpers	0.002	0.09	10.7	13.5	76	147	1.4	9.1	4.8	6.0
47WS 15	39 04 27	77 55 17	725	Harpers	0	0.07	10.7	13.4	46	144	8.3	10.5	4.8	6.6
47XS 1	39 08 39	77 54 57	460	Tomstown	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
47XS 2	39 09 08	77 56 03	494	Elbrook	0.17	2.45	12.0	12.3	521	573	7.1	9.7	5.7	7.4
47XS 3	39 08 43	77 52 41	425	Tomstown	nd	nd	12.9	nd	420	nd	7.6	nd	7.2	nd
47XS 6	39 11 35	77 56 06	532	Conococheague	0.01	1.92	9.4	12.7	510	587	6.1	9.3	6.5	7.6
47XS 11	39 10 02	77 58 53	591	Conococheague	nd	nd	11.2	13.9	560	594	0.9	8.1	6.9	7.2
47XS 21	39 10 00	77 58 46	589	Conococheague	nd	nd	11.4	14.2	594	645	5.6	7.2	6.8	7.2
47XS 22	39 10 00	77 58 47	590	Conococheague	nd	nd	10.7	13.4	608	671	5.5	7.3	6.8	7.2
47XS 23	39 10 04	77 58 48	600	Conococheague	nd	nd	11.0	12.6	597	632	6.3	7.7	6.7	7.3
48WS 1	39 07 00	77 51 10	978	Weverton	0.0001	0.07	11.4	13.2	94	213	7.2	10.8	5.3	7.0

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46W 4	390548078010801	10/24/2002	1335		Dry	Steel tape
		01/31/2003	0820		Dry	Steel tape
		04/24/2003	1430	54.24		Steel tape
		07/30/2003	1435	48.38		Steel tape
		10/23/2003	1305	50.05		Steel tape
		01/21/2004	1605	49.04		Steel tape
		04/05/2004	1550	52.14		Steel tape
		07/27/2004	1322	56.57		Steel tape
		10/18/2004	1546	57.61		Electric tape
		01/25/2005	1643	57.74		Electric tape
		05/02/2005	1709	55.14		Electric tape
		07/18/2005	1342		Dry	Electric tape
		10/26/2005	1405		Dry	Electric tape
		01/25/2006	1340		Dry	Electric tape
		04/28/2006	0837		Dry	Electric tape
		07/24/2006	1331		Dry	Electric tape
		10/24/2006	1426		Dry	Electric tape
		01/25/2007	1222		Dry	Electric tape
		04/16/2007	1514		Dry	Electric tape
		07/16/2007	1548		Dry	Steel tape
		10/18/2007	1350		Dry	Electric tape
		01/25/2008	1002		Dry	Electric tape
		04/14/2008	1340		Dry	Electric tape
		07/14/2008	1408		Dry	Electric tape
		10/20/2008	1543		Dry	Electric tape
46W 60	390021078005301	01/31/2003	1230	50.53		Steel tape
		04/22/2003	0945	40.29		Steel tape
		07/31/2003	1113	47.24		Steel tape
		11/05/2003	1330	46.02		Steel tape
		02/05/2004	1041	46.20		Steel tape
		04/13/2004	1212	36.95		Steel tape
		07/15/2004	1351	47.63	Recently pumped	Steel tape
		10/25/2004	1412	49.99		Steel tape
		01/25/2005	1422	41.60		Steel tape
		05/04/2005	0949	46.29	Recently pumped	Steel tape
		07/21/2005	1349	48.61	Recently pumped	Steel tape
		11/04/2005	1212	58.86	Recently pumped	Steel tape
		02/03/2006	1000	53.20	Recently pumped	Electric tape
		05/03/2006	0956	54.53		Steel tape
46W177	390647078041101	10/16/2002	1430	6.97		Steel tape
		01/22/2003	1505	6.39		Steel tape
		04/18/2003	1015	5.76		Steel tape
		07/21/2003	1325	6.52		Steel tape
		10/28/2003	0935	6.85		Steel tape
		01/22/2004	1130	7.10		Steel tape
		04/07/2004	1335	6.21		Steel tape
		07/22/2004	0957	7.81		Steel tape
		10/21/2004	1110	7.37		Steel tape
		01/21/2005	1100	6.29		Electric tape
		05/02/2005	1517	6.99		Steel tape
		07/18/2005	1445	8.01		Steel tape
		10/26/2005	1244	7.48		Steel tape
		01/31/2006	0913	6.50		Steel tape
		04/26/2006	1643	7.56		Steel tape
		07/24/2006	1418	7.47		Steel tape
		10/18/2006	1459	7.11		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46W177 (cont.)		01/23/2007	1132	6.95		Steel tape
		04/17/2007	1114	5.98		Steel tape
		07/16/2007	1342	8.12		Steel tape
		10/17/2007	1101	8.62		Steel tape
		01/24/2008	1345	8.13		Steel tape
		04/14/2008	1512	7.46		Steel tape
		07/16/2008	0950	7.69		Steel tape
		10/21/2008	1124	8.49		Steel tape
46W178	390514078063301	10/22/2002	1145	29.51		Steel tape
		01/28/2003	1250	25.76		Steel tape
		04/23/2003	1545	20.95		Steel tape
		07/21/2003	1255	24.15		Steel tape
		10/28/2003	1040	26.69		Steel tape
		02/04/2004	1345	30.31		Steel tape
		04/05/2004	1340	23.62		Steel tape
		07/19/2004	1328	33.39		Steel tape
		07/28/2004	1550	33.54		Steel tape
		10/25/2004	1504	31.44		Steel tape
		01/18/2005	1447	21.98		Steel tape
		05/02/2005	1420	27.49		Steel tape
		07/18/2005	1407	31.12		Steel tape
		10/26/2005	1228	28.64		Steel tape
		01/31/2006	0944	23.07		Steel tape
		05/02/2006	0926	31.89		Steel tape
		07/18/2006	1416	28.78		Steel tape
		10/24/2006	1515	31.42		Steel tape
		01/30/2007	1113	30.28		Steel tape
		04/16/2007	1401	24.85		Steel tape
		07/19/2007	1117	34.58		Steel tape
		10/18/2007	1127	36.90		Steel tape
		01/24/2008	1308	32.30		Steel tape
		04/14/2008	1418	30.00		Steel tape
		07/14/2008	1613	31.92		Steel tape
		10/20/2008	1337	33.66		Steel tape
46W179	390328078061201	10/23/2002	1220	30.30		Steel tape
		01/24/2003	1132	15.86		Steel tape
		04/16/2003	1403	5.03		Steel tape
		07/28/2003	1345	12.73		Steel tape
		10/28/2003	1115	13.48		Steel tape
		01/21/2004	1130	14.66		Steel tape
		04/06/2004	1355	12.95		Steel tape
		07/12/2004	1224	21.36		Steel tape
		10/18/2004	1324	21.42		Steel tape
		01/18/2005	1020	15.72		Electric tape
		04/26/2005	1455	14.50		Steel tape
		07/18/2005	1219	23.64		Steel tape
		10/17/2005	1536	29.44		Steel tape
		01/23/2006	1452	20.92		Steel tape
		04/28/2006	0911	26.27		Steel tape
		07/17/2006	1506	22.14		Steel tape
		10/23/2006	1431	28.86		Steel tape
		01/29/2007	1548	25.83		Steel tape
		04/16/2007	1333	15.30		Steel tape
		04/24/2007	1547	18.13		Steel tape
		07/16/2007	1252	28.85		Steel tape
		10/15/2007	1358	32.74		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46W179 (cont.)		01/25/2008	1035	31.99		Steel tape
		04/16/2008	0912	27.46		Steel tape
		07/14/2008	1518	21.42		Steel tape
		10/20/2008	1416	28.48		Steel tape
46W180	390336078060601	10/23/2002	1244	33.44		Steel tape
		01/24/2003	1130	19.02		Steel tape
		04/16/2003	1428	7.96		Steel tape
		07/21/2003	1050	13.77		Steel tape
		10/28/2003	1100	16.63		Steel tape
		02/04/2004	1055	20.06		Steel tape
		04/05/2004	1405	15.64		Steel tape
		07/12/2004	1215	24.62		Steel tape
		10/18/2004	1301	24.89		Steel tape
		01/18/2005	1530	18.80		Steel tape
		04/26/2005	1416	17.81		Steel tape
		07/18/2005	1203	27.24		Steel tape
		10/17/2005	1524	33.65		Steel tape
		01/23/2006	1441	23.72		Steel tape
		04/28/2006	0900	29.59		Steel tape
		07/17/2006	1525	25.54		Steel tape
		10/18/2006	1435	31.48		Steel tape
		01/23/2007	1234	28.23		Steel tape
		04/16/2007	1321	18.56		Steel tape
		07/16/2007	1316	32.24		Steel tape
		07/16/2007	1448	32.25		Steel tape
		10/15/2007	1425	35.82		Steel tape
		01/24/2008	1224	34.94		Steel tape
		04/14/2008	1358	30.14		Steel tape
		07/14/2008	1507	24.80		Steel tape
		10/20/2008	1351	31.78		Steel tape
46W181	390118078070401	10/25/2002	1400	58.38		Steel tape
		01/31/2003	1425	52.55		Steel tape
		04/21/2003	1458	50.35		Steel tape
		07/30/2003	1045	50.61		Steel tape
		10/28/2003	1330	50.39		Steel tape
		02/04/2004	1310	51.34		Steel tape
		04/07/2004	0922	52.63		Steel tape
		07/12/2004	1314	53.49	Recently pumped	Steel tape
		10/18/2004	1350	55.33		Steel tape
		01/26/2005	1115	54.85		Electric tape
		04/27/2005	1458	53.37	Recently pumped	Electric tape
		07/18/2005	1402	55.31	Recently pumped	Electric tape
		10/20/2005	0903	56.59		Steel tape
		01/31/2006	1019	56.65	Recently pumped	Electric tape
		04/27/2006	1555	57.10		Electric tape
		07/18/2006	0801	57.62		Electric tape
		11/02/2006	1306	57.69	Recently pumped	Electric tape
		01/30/2007	1342	57.65	Recently pumped	Electric tape
		04/23/2007	1335	54.88	Recently pumped	Electric tape
		07/18/2007	0955	57.29		Electric tape
		10/26/2007	1200	57.68	Recently pumped	Electric tape
		01/31/2008	1043	58.23	Recently pumped	Electric tape
		04/21/2008	1425	57.81	Recently pumped	Electric tape
		07/18/2008	0939	56.11	Recently pumped	Electric tape
		10/24/2008	1036	57.38		Electric tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46W182	390056078025601	10/23/2002	1325	119.52		Steel tape
		01/22/2003	0925	117.29		Steel tape
		04/22/2003	1015	112.94		Steel tape
		07/22/2003	0840	114.57		Steel tape
		10/20/2003	1540	114.74		Steel tape
		01/21/2004	1025	114.77		Steel tape
		04/05/2004	1210	115.15		Steel tape
		07/19/2004	1144	116.96		Steel tape
		10/18/2004	1226	116.74		Steel tape
		01/18/2005	1333	115.81		Steel tape
		05/02/2005	1325	115.64		Steel tape
		07/18/2005	1229	117.43		Steel tape
		10/17/2005	1328	118.61		Steel tape
		01/23/2006	1305	116.09		Steel tape
		05/01/2006	1224	117.70		Steel tape
		07/17/2006	1411	118.26		Steel tape
		10/18/2006	1317	117.85		Steel tape
		01/31/2007	1206	117.78		Steel tape
		04/16/2007	1248	115.25		Steel tape
		07/16/2007	1314	123.50		Steel tape
		10/26/2007	1126	125.81		Steel tape
		01/22/2008	1237	128.76		Steel tape
		04/14/2008	1235	118.27		Steel tape
		07/14/2008	1143	127.07		Steel tape
		10/20/2008	1307	123.75		Steel tape
46W186	390604078013001	10/23/2002	1110	72.16		Steel tape
		01/31/2003	0920	60.23		Steel tape
		04/24/2003	1415	45.74		Steel tape
		07/21/2003	1355	38.06		Steel tape
		10/23/2003	1240	40.29		Steel tape
		01/22/2004	1350	40.40		Steel tape
		04/05/2004	1525	41.84		Steel tape
		07/27/2004	1258	52.21		Steel tape
46W187	390357078022901	10/23/2002	1135	35.23		Steel tape
		01/31/2003	0950	31.10		Steel tape
		04/24/2003	1335	20.91		Steel tape
		07/21/2003	1225	11.78		Steel tape
		10/20/2003	1610	13.53		Steel tape
		01/22/2004	1310	15.35		Steel tape
		04/05/2004	1435	19.38		Steel tape
		07/19/2004	1235	27.51		Steel tape
		10/18/2004	1447	29.47		Steel tape
		01/18/2005	1426	28.10		Steel tape
		05/02/2005	1351	25.59		Steel tape
		07/18/2005	1302	29.62		Steel tape
		10/17/2005	1500	32.81		Steel tape
		01/23/2006	1351	30.85		Steel tape
		05/01/2006	1255	32.93		Steel tape
		07/24/2006	1308	33.34		Steel tape
		10/18/2006	1342	33.74		Steel tape
		01/22/2007	1423	32.17		Steel tape
		04/16/2007	1427	29.51		Steel tape
		07/16/2007	1423	33.08		Steel tape
		10/18/2007	1216	34.43		Steel tape
		01/22/2008	1306	35.18		Steel tape
		04/14/2008	1306	34.38		Steel tape
		07/14/2008	1210	31.65		Steel tape
		10/20/2008	1454	32.63		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46W188	390625078055601	10/16/2002	1630	30.74		Steel tape
		01/22/2003	1440	22.39		Steel tape
		04/18/2003	1035	18.01		Steel tape
		07/30/2003	1410	22.09		Steel tape
		10/28/2003	1005	25.60		Steel tape
		02/04/2004	1415	24.19		Steel tape
		04/07/2004	1300	23.28		Steel tape
		07/15/2004	1129	30.49	Recently pumped	Steel tape
		10/21/2004	1225	27.51		Steel tape
		01/18/2005	1512	25.34		Steel tape
		05/02/2005	1445	24.23		Steel tape
		07/18/2005	1425	28.61		Steel tape
		10/26/2005	1131	31.57		Steel tape
		01/31/2006	0929	27.08		Steel tape
		04/27/2006	1524	29.66		Steel tape
		07/24/2006	1359	31.28		Steel tape
		10/25/2006	1552	29.09		Steel tape
		01/24/2007	1443	26.81		Steel tape
		04/17/2007	1322	25.29		Steel tape
		07/19/2007	1051	32.08		Steel tape
		10/18/2007	1006	33.56		Steel tape
		01/24/2008	1324	31.38		Steel tape
		04/14/2008	1454	29.72		Steel tape
		07/16/2008	1010	27.79		Steel tape
		10/21/2008	1106	32.71		Steel tape
46W189	390222078055501	10/21/2004	1350	19.58		Steel tape
		01/26/2005	1415	18.84		Electric tape
		05/04/2005	1521	18.89		Steel tape
		07/18/2005	1508	21.80		Steel tape
		10/20/2005	1620	23.08		Electric tape
		01/31/2006	1058	22.70		Electric tape
		05/02/2006	0946		Dry	Steel tape
		07/17/2006	1439	22.73		Electric tape
		11/02/2006	1449	22.19		Electric tape
		01/30/2007	1138		Dry	Electric tape
		04/24/2007	1322	21.75		Steel tape
		08/03/2007	1114		Dry	Electric tape
		10/19/2007	1149		Dry	Electric tape
		01/31/2008	1141		Dry	Electric tape
		04/21/2008	1513	20.33		Steel tape
		07/18/2008	1024	22.75		Electric tape
		10/24/2008	1115		Dry	Electric tape
46W190	390213078060001	10/21/2004	1415	8.14		Steel tape
		01/26/2005	1417	3.55		Electric tape
		05/04/2005	1512	6.74		Steel tape
		07/18/2005	1518	12.10		Steel tape
		10/20/2005	1604	14.30		Steel tape
		01/31/2006	1106	3.31		Steel tape
		05/02/2006	0954	9.85		Steel tape
		07/17/2006	1449	8.10		Steel tape
		11/02/2006	1513	9.55		Steel tape
		01/30/2007	1146	6.47		Steel tape
		04/24/2007	1410	6.49		Steel tape
		08/03/2007	1104	13.40		Steel tape
		10/19/2007	1138	14.75		Steel tape
		01/31/2008	1133	10.86		Steel tape
		04/21/2008	1526	3.72		Steel tape
		07/18/2008	1014	8.89		Steel tape
		10/24/2008	1113	11.28		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46W191	390458078003701	10/21/2004	1502	19.40		Steel tape
		01/25/2005	1620	15.30		Steel tape
		05/02/2005	1645	7.49		Steel tape
		07/18/2005	1323	16.04		Steel tape
		10/20/2005	1408	24.40		Steel tape
		01/25/2006	1320	18.60		Steel tape
		05/01/2006	1312	22.58		Steel tape
		07/19/2006	1212	27.18		Steel tape
		10/24/2006	1439	29.02		Steel tape
		01/25/2007	1235	20.21		Steel tape
		04/16/2007	1455	12.04		Steel tape
		07/16/2007	1530	22.62		Steel tape
		10/18/2007	1336	30.08		Steel tape
		01/22/2008	1407	32.64		Steel tape
		04/14/2008	1325	30.73		Steel tape
		07/18/2008	1051	17.62		Steel tape
		10/20/2008	1527	26.12		Steel tape
46X 8	390900078003401	10/21/2002	1410	37.85		Steel tape
		04/16/2003	1140	9.04		Steel tape
		07/21/2003	1430	12.67		Steel tape
		10/22/2003	0935	20.59		Steel tape
		04/07/2004	1020	16.01		Steel tape
		07/27/2004	1356	21.89		Steel tape
		10/21/2004	1046	25.42		Steel tape
		01/20/2005	1209	23.48		Steel tape
		05/06/2005	1056	20.05		Steel tape
		07/21/2005	1310	27.15		Steel tape
		10/26/2005	1152	33.04		Steel tape
		01/25/2006	1208	27.81		Steel tape
		05/02/2006	1049	32.54		Steel tape
		07/20/2006	0918	28.82		Steel tape
		10/20/2006	1142	32.57		Steel tape
		01/24/2007	1227	28.19		Steel tape
		04/18/2007	1021	21.70		Steel tape
		07/19/2007	1518	30.75		Steel tape
		10/19/2007	1104	38.79		Steel tape
		01/24/2008	1127	38.15		Steel tape
		04/17/2008	1056	32.39		Steel tape
		07/16/2008	1108	24.71		Steel tape
		10/23/2008	1233	34.25		Steel tape
46X 84	390826078050801	10/23/2002	1035	29.14		Steel tape
		01/28/2003	1500	15.57		Steel tape
		04/18/2003	0930	10.87		Steel tape
		07/24/2003	0915	13.05		Steel tape
		10/28/2003	0845	16.68		Steel tape
		04/07/2004	0910	11.10		Steel tape
		07/28/2004	0933	19.72		Steel tape
		10/22/2004	0934	19.87		Steel tape
		01/27/2005	0930	14.38		Steel tape
		05/06/2005	0908	15.64		Steel tape
		07/22/2005	0926	21.00		Steel tape
		10/26/2005	1006	26.93		Steel tape
		01/25/2006	1119	16.78		Steel tape
		05/02/2006	0901	20.73		Steel tape
		07/20/2006	0822	21.70		Steel tape
		10/25/2006	0936	22.16		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X 84 (cont.)		01/30/2007	1046	16.90		Steel tape
		04/24/2007	1003	14.40		Steel tape
		07/19/2007	0953	23.78		Steel tape
		10/18/2007	0941	29.63		Steel tape
		01/24/2008	1013	30.28		Steel tape
		04/17/2008	0929	22.15		Steel tape
		07/16/2008	0912	19.31		Steel tape
		10/22/2008	1019	28.20		Steel tape
46X111	391341078021001	10/21/2002	1705	46.63		Steel tape
		01/30/2003	1505	19.71		Steel tape
		04/17/2003	1415	13.69		Steel tape
		07/24/2003	1130	19.25		Steel tape
		10/22/2003	1315	31.60		Steel tape
		02/04/2004	1605	29.08		Steel tape
		04/07/2004	1420	21.10		Steel tape
		07/28/2004	1129	17.79		Steel tape
		10/20/2004	1554	21.12		Steel tape
		01/20/2005	1450	23.99		Steel tape
		05/06/2005	1004	25.27		Steel tape
		07/20/2005	1505	51.16		Steel tape
		07/28/2005	1117	52.27		Steel tape
		10/26/2005	1442	55.00		Steel tape
		01/27/2006	0942	24.33		Steel tape
		05/04/2006	1424	51.18		Steel tape
		07/24/2006	1454	40.09		Steel tape
		11/03/2006	1000	45.75		Steel tape
		01/24/2007	1451	32.53		Steel tape
		04/24/2007	1200	18.58		Steel tape
		07/18/2007	1555	53.07		Steel tape
		10/19/2007	0931	60.79		Steel tape
		01/22/2008	1518	54.03		Steel tape
		04/17/2008	1603	36.19		Steel tape
		07/17/2008	1156	36.36		Steel tape
		10/22/2008	1523	57.48		Steel tape
46X112	391402078000401	10/17/2002	1310	51.93		Steel tape
		01/23/2003	1345	14.50		Steel tape
		04/17/2003	1255	2.63		Steel tape
		07/23/2003	1010	8.32		Steel tape
		10/22/2003	1230	13.05		Steel tape
		02/05/2004	1330	12.77		Steel tape
		04/07/2004	1345	3.67		Steel tape
		07/28/2004	1045	4.80		Steel tape
		10/21/2004	0953	11.11		Steel tape
		01/20/2005	1416	9.48		Steel tape
		05/04/2005	1357	10.69		Steel tape
		07/20/2005	1432	28.97		Steel tape
		10/25/2005	1047	71.21		Steel tape
		01/26/2006	1334	29.33		Steel tape
		05/02/2006	1157	46.11		Steel tape
		07/20/2006	1231	37.75		Steel tape
		10/20/2006	1041	50.01		Steel tape
		01/24/2007	1432	29.06		Steel tape
		04/19/2007	1126	9.68		Steel tape
		07/18/2007	1341	33.75		Steel tape
		10/19/2007	1030	87.22		Steel tape
		11/08/2007	1307	90.47		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X112 (cont.)		01/22/2008	1455	80.13		Steel tape
		02/21/2008	1304	58.98		Steel tape
		04/17/2008	1501	37.97		Steel tape
		05/08/2008	1637	14.13		Steel tape
		07/17/2008	1132	20.58		Steel tape
		07/31/2008	1635	24.47		Steel tape
		10/22/2008	1452	60.22		Steel tape
46X113	391401078000301	10/17/2002	1300	51.45		Steel tape
		01/23/2003	1350	14.07		Steel tape
		04/17/2003	1305	2.17		Steel tape
		07/23/2003	1020	7.86		Steel tape
		10/22/2003	1245	12.60		Steel tape
		02/05/2004	1340	12.30		Steel tape
		04/07/2004	1355	3.21		Steel tape
		07/28/2004	1055	4.32		Steel tape
		10/21/2004	0957	10.65		Steel tape
		01/20/2005	1430	9.02		Steel tape
		05/04/2005	1413	10.26		Steel tape
		07/20/2005	1444	28.40		Steel tape
		10/25/2005	1110	63.82		Steel tape
		01/26/2006	1338	28.77		Steel tape
		05/02/2006	1204	45.21		Steel tape
		07/20/2006	1237	37.07		Steel tape
		10/20/2006	1043	49.21		Steel tape
		01/24/2007	1434	28.46		Steel tape
		04/19/2007	1144	9.22		Steel tape
		07/18/2007	1345	33.03		Steel tape
		10/19/2007	1033	86.20		Steel tape
		11/08/2007	1310	89.25		Steel tape
		01/22/2008	1458	77.85		Steel tape
		02/21/2008	1308	57.94		Steel tape
		04/17/2008	1504	37.26		Steel tape
		05/08/2008	1639	13.67		Steel tape
		07/17/2008	1134	20.14		Steel tape
		07/31/2008	1637	24.02		Steel tape
		10/22/2008	1502	58.74		Steel tape
46X114	391108078041301	10/17/2002	1500	80.87		Steel tape
		01/30/2003	1545	75.45		Steel tape
		04/17/2003	1505	71.43		Steel tape
		07/21/2003	1515	78.98		Steel tape
		10/21/2003	1615	77.97		Steel tape
		01/22/2004	1550	76.12		Steel tape
		04/05/2004	1640	75.15		Steel tape
		07/20/2004	0903	76.15		Steel tape
		10/21/2004	0910	76.01		Steel tape
		01/21/2005	0932	75.45		Steel tape
		05/04/2005	1055	76.43		Steel tape
		07/20/2005	1242	78.90		Steel tape
		10/28/2005	0908	80.39		Steel tape
		01/27/2006	1013	73.86		Steel tape
		05/04/2006	1259	78.40		Steel tape
		11/03/2006	1032	77.04		Steel tape
		01/25/2007	1011	76.63		Steel tape
		04/27/2007	1439	74.38		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X115	391110078015801	10/21/2002	1213	35.92		Steel tape
		01/23/2003	1133	9.58		Steel tape
		04/16/2003	1300	3.66		Steel tape
		07/23/2003	1250	17.82		Steel tape
		10/22/2003	1020	12.03		Steel tape
		02/05/2004	1410	12.10		Steel tape
		04/08/2004	0945	8.59		Steel tape
		07/22/2004	1415	12.12		Steel tape
		10/20/2004	1527	11.92		Steel tape
		01/21/2005	0952	9.84		Steel tape
		05/04/2005	1150	11.72		Steel tape
		07/21/2005	1050	15.51		Steel tape
		10/25/2005	1002	24.32		Steel tape
		01/26/2006	1411	9.39		Steel tape
		05/02/2006	1223	16.85		Steel tape
		07/20/2006	1338	14.28		Steel tape
		10/20/2006	0957	15.75		Steel tape
		01/25/2007	1028	13.17		Steel tape
		04/24/2007	1056	9.10		Steel tape
		07/19/2007	1423	17.37		Steel tape
		10/19/2007	0910	31.24		Steel tape
		01/24/2008	1438	34.03		Steel tape
		04/17/2008	1143	14.75		Steel tape
		07/16/2008	1303	14.01		Steel tape
		10/22/2008	1328	22.08		Steel tape
46X116	391031078022301	10/21/2002	1055	54.99		Steel tape
		01/23/2003	1102	31.74		Steel tape
		04/16/2003	1235	27.90		Steel tape
		07/24/2003	1430	32.57		Steel tape
46X117	391044078015801	10/21/2002	1145	48.10		Steel tape
		01/23/2003	1117	24.39		Steel tape
		04/16/2003	1250	21.27		Steel tape
		07/23/2003	1235	24.40		Steel tape
		10/22/2003	1010	25.46		Steel tape
		02/05/2004	1430	25.24		Steel tape
		04/08/2004	0932	23.21		Steel tape
		07/22/2004	1422	25.81		Steel tape
		10/20/2004	1512	25.98		Steel tape
		01/21/2005	1005	24.83		Steel tape
		05/04/2005	1134	25.22		Steel tape
		07/21/2005	1059	27.44		Steel tape
		10/25/2005	1013	37.05		Steel tape
		01/26/2006	1420	25.50		Steel tape
		05/02/2006	1230	28.20		Steel tape
		07/20/2006	1345	27.09		Steel tape
		10/20/2006	0945	27.84		Steel tape
		01/25/2007	1038	26.49		Steel tape
		04/24/2007	1036	23.90		Steel tape
		07/19/2007	1408	28.10		Steel tape
		10/19/2007	0858	45.34		Steel tape
		01/24/2008	1414	47.53		Steel tape
		04/17/2008	1131	27.63		Steel tape
		07/16/2008	1252	26.45		Steel tape
		10/22/2008	1312	33.56		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X118	391044078005601	10/21/2002	1305	47.51		Steel tape
		01/23/2003	1325	27.31		Steel tape
		04/15/2003	1245	17.84		Steel tape
		07/23/2003	0915	21.75		Steel tape
		10/22/2003	1055	28.37		Steel tape
		02/04/2004	1445	24.73		Steel tape
		04/07/2004	1250	22.03		Steel tape
		07/28/2004	1354	27.74		Steel tape
		10/20/2004	1459	30.97		Steel tape
		01/20/2005	1259	28.47		Steel tape
		05/06/2005	0929	24.79		Steel tape
		07/22/2005	0950	33.58		Steel tape
		10/25/2005	1133	43.33		Steel tape
		01/26/2006	1316	33.37		Steel tape
		05/01/2006	1526	38.08		Steel tape
		07/19/2006	1547	33.73		Steel tape
		10/18/2006	1529	40.11		Steel tape
		01/25/2007	1146	32.91		Steel tape
		04/24/2007	1605	24.64		Steel tape
		07/18/2007	1523	36.92		Steel tape
		10/18/2007	1532	46.07		Steel tape
		01/24/2008	1543	46.74		Steel tape
		04/17/2008	1359	37.92		Steel tape
		07/17/2008	0954	29.96		Steel tape
		10/22/2008	1402	42.75		Steel tape
46X119	391044078010801	10/22/2002	1035	54.10		Steel tape
46X120	391044078010901	10/22/2002	1025	65.70		Steel tape
46X121	390824078050101	10/23/2002	0940	36.12		Steel tape
		01/28/2003	1335	28.38		Steel tape
		04/18/2003	0915	25.58		Steel tape
		07/24/2003	0845	27.26		Steel tape
		10/28/2003	0815	28.31		Steel tape
		04/07/2004	0900	24.95		Steel tape
		07/28/2004	0919	32.12		Steel tape
		10/22/2004	0914	29.85		Steel tape
		01/27/2005	0914	27.27		Steel tape
		05/06/2005	0857	28.74		Steel tape
		07/22/2005	0909	31.30		Steel tape
		10/26/2005	0950	33.76		Steel tape
		01/25/2006	1106	26.18		Steel tape
		05/02/2006	0846	31.34		Steel tape
		07/20/2006	0811	29.81		Steel tape
		10/25/2006	0921	28.54		Steel tape
		01/30/2007	1036	27.79		Steel tape
		04/24/2007	0942	26.63		Steel tape
		07/19/2007	0936	31.95		Steel tape
		10/18/2007	0916	34.98		Steel tape
		01/24/2008	0950	33.43		Steel tape
		04/17/2008	0908	29.20		Steel tape
		07/16/2008	0854	30.85		Steel tape
		10/22/2008	1007	34.13		Steel tape
46X122	390904078003101	10/22/2003	0935	20.59		Steel tape
		04/07/2004	1020	16.01		Steel tape
		07/27/2004	1356	21.89		Steel tape
		10/21/2004	1046	25.42		Steel tape
		01/20/2005	1209	23.48		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X122 (cont.)		05/06/2005	1056	20.05		Steel tape
		07/21/2005	1310	27.15		Steel tape
		10/26/2005	1152	33.04		Steel tape
		01/25/2006	1208	27.81		Steel tape
		05/02/2006	1049	32.54		Steel tape
		07/20/2006	0918	28.82		Steel tape
		10/20/2006	1142	32.57		Steel tape
		01/24/2007	1227	28.19		Steel tape
		04/18/2007	1021	21.70		Steel tape
		07/19/2007	1518	30.75		Steel tape
		10/19/2007	1104	38.79		Steel tape
		01/24/2008	1127	38.15		Steel tape
		04/17/2008	1056	32.39		Steel tape
		07/16/2008	1108	24.71		Steel tape
		10/23/2008	1233	34.25		Steel tape
46X123	390905078003301	10/21/2002	1335	38.03		Steel tape
		01/23/2003	1015	23.45		Steel tape
		04/16/2003	1130	9.01		Steel tape
		07/21/2003	1420	12.70		Steel tape
		10/22/2003	0925	20.47		Steel tape
		01/22/2004	1025	15.88		Steel tape
		04/07/2004	1008	15.99		Steel tape
		07/27/2004	1345	21.69		Steel tape
		10/21/2004	1042	25.42		Steel tape
		01/20/2005	1205	23.61		Steel tape
		05/06/2005	1048	19.88		Steel tape
		07/21/2005	1318	27.23		Steel tape
		10/26/2005	1131	33.40		Steel tape
		01/25/2006	1201	27.98		Steel tape
		05/02/2006	1041	32.15		Steel tape
		07/20/2006	0846	28.94		Steel tape
		10/20/2006	1140	32.73		Steel tape
		01/24/2007	1224	28.19		Steel tape
		04/18/2007	1012	21.35		Steel tape
		07/19/2007	1516	30.72		Steel tape
		10/19/2007	1102	36.65		Steel tape
		01/24/2008	1125	37.84		Steel tape
		04/17/2008	1054	32.57		Steel tape
		07/16/2008	1106	24.45		Steel tape
		10/23/2008	1232	33.97		Steel tape
46X124	390941078001201	10/15/2002	1240	50.70		Steel tape
		01/24/2003	0850	32.81		Steel tape
		04/16/2003	1115	16.58		Steel tape
		07/21/2003	1445	20.08		Steel tape
		10/21/2003	0845	28.75		Steel tape
		01/21/2004	1530	23.85		Steel tape
		04/05/2004	1615	24.73		Steel tape
		07/20/2004	1142	28.50		Steel tape
		10/19/2004	1027	34.56		Steel tape
		01/18/2005	1559	33.55		Steel tape
		04/27/2005	1439	27.17		Steel tape
		07/19/2005	1352	35.76		Steel tape
		10/19/2005	1531	44.40		Steel tape
		01/24/2006	1553	37.99		Steel tape
		04/28/2006	0741	41.82		Steel tape
		07/19/2006	1535	39.45		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X124 (cont.)		10/19/2006	1610	42.81		Steel tape
		01/23/2007	1634	38.45		Steel tape
		04/18/2007	0947	31.41		Steel tape
		07/17/2007	1318	40.83		Steel tape
		10/17/2007	1658	48.73		Steel tape
		01/23/2008	1604	49.91		Steel tape
		04/16/2008	0951	42.48		Steel tape
		07/14/2008	1342	37.01		Steel tape
		10/20/2008	1607	49.15		Steel tape
46X125	390948078001601	10/15/2002	1315	45.43		Steel tape
		01/29/2003	1600	27.03		Steel tape
		04/17/2003	0816	10.23		Steel tape
		07/23/2003	0825	14.14		Steel tape
		10/21/2003	0835	22.73		Steel tape
		01/22/2004	0935	17.42		Steel tape
		04/06/2004	1706	18.44		Steel tape
		07/21/2004	0915	22.75		Steel tape
		10/19/2004	1005	28.40		Steel tape
		01/19/2005	1425	27.28		Steel tape
		04/27/2005	1410	20.58		Steel tape
		07/19/2005	1332	30.19		Steel tape
		10/19/2005	1523	38.53		Steel tape
		01/24/2006	1546	32.03		Steel tape
		05/03/2006	0813	36.67		Steel tape
		07/19/2006	1528	33.30		Steel tape
		10/19/2006	1554	37.06		Steel tape
		01/23/2007	1551	31.97		Steel tape
		04/17/2007	1533	24.22		Steel tape
		07/17/2007	1309	34.46		Steel tape
		10/17/2007	1650	42.16		Steel tape
		01/23/2008	1552	43.56		Steel tape
		04/15/2008	1522	36.73		Steel tape
		04/18/2008	0912	36.86		Steel tape
		07/16/2008	1119	26.63		Steel tape
		07/22/2008	1110	27.55		Steel tape
		10/21/2008	1536	38.40		Steel tape
46X126	390953078001901	10/15/2002	1335	44.26		Steel tape
		01/29/2003	1545	25.39		Steel tape
		04/17/2003	0825	8.64		Steel tape
		07/23/2003	0810	12.60		Steel tape
		10/21/2003	0815	21.25		Steel tape
		01/22/2004	1000	15.87		Steel tape
		04/06/2004	1705	17.05		Steel tape
		07/21/2004	0957	21.26		Steel tape
		01/19/2005	1440	25.94		Steel tape
46X127	391350078022001	10/21/2002	1800	58.81		Steel tape
		01/30/2003	1445	31.31		Steel tape
		04/17/2003	1330	26.63		Steel tape
		07/24/2003	1155	31.91		Steel tape
46X128	391148078000201	10/24/2002	1240	53.63		Steel tape
		01/30/2003	1230	30.79		Steel tape
		04/15/2003	1500	15.56		Steel tape
		07/23/2003	1400	23.51		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X128 (cont.)		10/23/2003	1000	30.93		Steel tape
		02/04/2004	1530	27.45		Steel tape
		04/14/2004	1030	17.92		Steel tape
		07/28/2004	1456	28.17		Steel tape
		10/20/2004	1436	34.22		Steel tape
		01/20/2005	1351	30.73		Steel tape
		05/04/2005	1252	26.22		Steel tape
		07/22/2005	1101	38.52		Steel tape
		10/24/2005	1643	52.14		Steel tape
		01/25/2006	1526	36.86		Steel tape
		05/01/2006	1602	41.90		Steel tape
		07/19/2006	1606	40.09		Steel tape
		10/18/2006	1546	48.87		Steel tape
		01/25/2007	1125	37.31		Steel tape
		04/24/2007	1726	26.34		Steel tape
		07/18/2007	1502	41.29		Steel tape
		10/17/2007	1438	56.29		Steel tape
		01/24/2008	1524	55.09		Steel tape
		04/21/2008	1136	33.65		Steel tape
		07/17/2008	1324	32.85		Steel tape
		07/31/2008	1416	35.53		Steel tape
		10/22/2008	1429	49.99		Steel tape
46X129	391234078000501	10/17/2002	1340	41.55		Steel tape
		01/30/2003	1345	17.83		Steel tape
		04/15/2003	1335	5.19		Steel tape
		07/23/2003	1045	10.94		Steel tape
		10/29/2003	0745	17.41		Steel tape
		01/22/2004	1520	11.76		Steel tape
46X130	391422078013201	10/17/2002	1150	83.01		Steel tape
46X132	391416078013401	10/17/2002	1030	96.42		Steel tape
		01/23/2003	1445	59.03		Steel tape
		04/17/2003	1440	48.28		Steel tape
		07/24/2003	1100	55.04		Steel tape
		10/22/2003	1340	60.39		Steel tape
		02/04/2004	1630	59.54		Steel tape
		04/07/2004	1527	55.87		Steel tape
		07/28/2004	1205	57.09		Steel tape
		10/20/2004	1615	61.45		Steel tape
		01/20/2005	1513	56.82		Steel tape
		01/28/2005	0957	58.05		Steel tape
		05/03/2005	1633	57.88		Steel tape
		07/20/2005	1600	70.01		Steel tape
		10/26/2005	1518	84.25		Steel tape
		01/27/2006	0927	71.89		Steel tape
		05/04/2006	1405	75.63		Steel tape
		07/20/2006	1318	78.68		Steel tape
		11/03/2006	0945	78.16		Steel tape
		01/24/2007	1540	64.95		Steel tape
		04/25/2007	1458	59.22		Steel tape
		07/18/2007	1613	72.68		Steel tape
		10/19/2007	0947	88.47		Steel tape
		11/09/2007	1144	90.74		Steel tape
		01/22/2008	1613	90.01		Steel tape
		02/21/2008	1329	86.96		Steel tape
		04/17/2008	1658	74.76		Steel tape
		05/08/2008	1512	62.71		Steel tape
		07/17/2008	1247	64.60		Steel tape
		07/31/2008	1710	66.11		Steel tape
		10/22/2008	1541	80.65		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
46X133	391146078005201	10/17/2002	1407	44.14		Steel tape
		01/23/2003	1149	20.93		Steel tape
		04/15/2003	1600	10.27		Steel tape
		07/23/2003	1310	15.96		Steel tape
		10/22/2003	1040	22.73		Steel tape
		02/04/2004	1510	20.37		Steel tape
		04/07/2004	1325	12.90		Steel tape
		07/28/2004	1017	19.96		Steel tape
		10/20/2004	1413	24.51		Steel tape
		01/20/2005	1319	21.95		Steel tape
		05/04/2005	1212	19.46		Steel tape
		07/22/2005	1018	30.95		Steel tape
		10/24/2005	1538	45.00		Steel tape
		01/26/2006	1356	30.28		Steel tape
		05/01/2006	1545	36.08		Steel tape
		07/20/2006	1156	34.02		Steel tape
		10/20/2006	1015	39.60		Steel tape
		01/25/2007	1057	30.43		Steel tape
		04/24/2007	1120	19.10		Steel tape
		07/18/2007	1438	34.46		Steel tape
		10/18/2007	1554	48.76		Steel tape
		01/24/2008	1459	48.98		Steel tape
		04/17/2008	1430	34.07		Steel tape
		07/16/2008	1319	24.65		Steel tape
		10/22/2008	1346	40.50		Steel tape
46X134	390923078023801	10/22/2002	0805	71.42		Steel tape
		01/23/2003	1040	39.56		Steel tape
		04/16/2003	1210	32.13		Steel tape
		07/24/2003	0940	40.52		Steel tape
		10/22/2003	0845	46.79		Steel tape
		01/22/2004	1105	41.97		Steel tape
		04/07/2004	0945	41.14		Steel tape
		07/20/2004	0943	51.94		Steel tape
		10/19/2004	0942	52.63		Steel tape
		01/20/2005	1235	44.98		Steel tape
		05/04/2005	0956	42.98		Steel tape
		07/21/2005	1348	60.67		Steel tape
		10/26/2005	1105	67.54		Steel tape
		01/25/2006	1142	50.19		Steel tape
		05/02/2006	1106	60.62		Steel tape
		07/20/2006	0844	55.98		Steel tape
		10/20/2006	1108	58.09		Steel tape
		01/24/2007	1155	48.25		Steel tape
		04/18/2007	1051	39.23		Steel tape
		07/19/2007	1352	62.75		Steel tape
		10/18/2007	1513	74.70		Steel tape
		01/24/2008	1041	73.52		Steel tape
		04/17/2008	1015	59.45		Steel tape
		07/16/2008	1032	54.07		Steel tape
		10/21/2008	1152	70.49		Steel tape
46X135	391456078014501	01/27/2005	1220	74.78		Steel tape
		05/06/2005	0856	76.70		Steel tape
		07/26/2005	1606	102.44		Steel tape
		10/28/2005	0936	100.87		Steel tape
		01/27/2006	0906	71.78		Steel tape
		05/04/2006	1338	102.48		Steel tape
		07/20/2006	1300	89.77		Steel tape
		01/31/2007	1002	84.69		Steel tape
		04/25/2007	1514	68.53		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47W 83	390656077570801	10/24/2002	1115	84.57		Steel tape
		01/30/2003	1015	77.20		Steel tape
		04/17/2003	1140	69.97		Steel tape
		07/22/2003	1540	72.46		Steel tape
		10/23/2003	1155	75.97		Steel tape
		02/05/2004	1305	74.98		Steel tape
		04/06/2004	1155	75.02		Steel tape
		07/28/2004	1327	79.00		Steel tape
		10/20/2004	1109	77.41		Steel tape
		01/21/2005	1040	74.83		Steel tape
		05/03/2005	1300	74.30		Steel tape
		07/19/2005	1310	78.90		Steel tape
		10/24/2005	1352	87.86		Steel tape
		01/26/2006	1105	77.66		Electric tape
		05/01/2006	1352	81.73		Steel tape
		07/20/2006	1009	83.32		Electric tape
		10/19/2006	1353	83.42		Steel tape
		01/24/2007	1124	79.58		Steel tape
		04/25/2007	1330	77.00		Steel tape
		07/18/2007	1016	81.23		Steel tape
		10/17/2007	1409	87.11		Steel tape
		01/23/2008	1453	84.35		Steel tape
		04/16/2008	1410	82.79		Steel tape
		07/15/2008	1509	78.76		Steel tape
		10/22/2008	1140	82.46		Steel tape
47W 84	390503077552601	10/23/2002	1736	94.49	Recently pumped	Steel tape
		01/22/2003	1235	90.72	Recently pumped	Steel tape
		04/22/2003	1605	88.84	Recently pumped	Steel tape
		07/22/2003	1055	92.01	Recently pumped	Steel tape
		10/21/2003	1405	95.62	Recently pumped	Steel tape
		01/21/2004	1240	93.98	Recently pumped	Steel tape
		04/14/2004	1242	93.04		Steel tape
47W 85	390422077583501	10/23/2002	1451	93.82		Steel tape
		01/29/2003	1405	85.57		Steel tape
		04/24/2003	1045	67.54		Steel tape
		07/31/2003	1020	69.10		Steel tape
		10/29/2003	1045	76.24		Steel tape
		04/13/2004	1130	66.78		Steel tape
		07/29/2004	1100	77.50		Steel tape
		10/25/2004	1213	84.40		Steel tape
		05/04/2005	1143	73.17		Steel tape
		07/21/2005	1125	79.23		Steel tape
47W 86	390253077542301	10/23/2002	1536	35.34		Steel tape
		01/22/2003	1015	29.88		Steel tape
		04/22/2003	1320	27.97		Steel tape
		07/22/2003	0915	30.86		Steel tape
		10/29/2003	1230	32.59		Steel tape
		01/21/2004	1145	31.17		Steel tape
		04/08/2004	1310	26.20		Steel tape
		07/29/2004	1323	36.14		Steel tape
		10/29/2004	0955	34.88		Steel tape
		01/19/2005	1114	24.15		Steel tape
		04/27/2005	1116	28.49		Steel tape
		07/19/2005	1121	30.58		Steel tape
		10/19/2005	1135	34.50		Steel tape
		01/24/2006	1045	28.48		Steel tape
		05/03/2006	1439	28.96		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47W 86 (cont.)		07/19/2006	1339	30.99		Steel tape
		10/19/2006	1144	33.77		Steel tape
		01/23/2007	1139	30.39		Steel tape
		04/17/2007	1240	28.66		Steel tape
		07/17/2007	1057	38.39		Steel tape
		10/17/2007	1115	41.14		Steel tape
		01/23/2008	1232	38.23		Steel tape
		04/15/2008	1217	32.10		Steel tape
		07/15/2008	1122	34.56		Steel tape
		10/21/2008	1301	36.90		Steel tape
47W 87	390220077560601	01/31/2003	1145	61.55		Steel tape
		04/22/2003	1300	58.73		Steel tape
		07/31/2003	1253	61.80		Steel tape
		10/29/2003	1630	59.99		Steel tape
		04/08/2004	1400	58.30		Steel tape
		07/29/2004	1349	62.10		Steel tape
47W 88	390545077554701	10/15/2002	1500	20.84		Steel tape
		01/29/2003	1320	18.63		Steel tape
		04/22/2003	1635	13.51		Steel tape
		07/22/2003	1315	12.35		Steel tape
		10/21/2003	1455	13.45		Steel tape
		02/05/2004	1100	12.91		Steel tape
		04/06/2004	1435	11.72		Steel tape
		07/29/2004	0944	13.49		Steel tape
		10/19/2004	1331	14.96		Steel tape
		01/19/2005	1353	16.36		Steel tape
		04/27/2005	1004	12.22		Steel tape
		07/19/2005	0947	14.73		Steel tape
		10/19/2005	1044	18.85		Steel tape
		01/24/2006	1306	16.43		Steel tape
		05/03/2006	1149	16.53		Steel tape
		07/19/2006	0932	20.01		Steel tape
		10/19/2006	1043	21.65		Steel tape
		01/24/2007	0930	15.65		Steel tape
		04/17/2007	1125	14.07		Steel tape
		07/17/2007	0945	18.29		Steel tape
		10/17/2007	1010	22.16		Steel tape
		01/23/2008	1115	24.13		Steel tape
		04/15/2008	1113	20.68		Steel tape
		07/15/2008	1012	17.36		Steel tape
		10/23/2008	1346	22.07		Steel tape
47W 89	390623077523501	10/24/2002	0841	65.99		Steel tape
		01/22/2003	1155	58.20		Steel tape
		04/22/2003	1440	51.30		Steel tape
		07/22/2003	1125	52.98		Steel tape
		10/21/2003	1330	61.30		Steel tape
		01/21/2004	1330	53.35		Steel tape
		04/13/2004	1403	51.83		Steel tape
		07/29/2004	0906	58.71		Steel tape
		10/20/2004	0936	59.24		Steel tape
		01/19/2005	1029	56.23		Steel tape
		04/27/2005	1039	55.02		Steel tape
		07/19/2005	1023	59.28		Steel tape
		10/19/2005	1109	62.69		Steel tape
		01/24/2006	1512	60.22		Steel tape
		05/02/2006	1321	59.32		Steel tape
		07/19/2006	1014	60.80		Steel tape
		10/19/2006	1115	62.46		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47W 89 (cont.)		01/23/2007	1110	57.79		Steel tape
		04/17/2007	1205	54.15		Steel tape
		07/17/2007	1020	59.73		Steel tape
		10/17/2007	1035	63.33		Steel tape
		01/23/2008	1152	64.07		Steel tape
		04/15/2008	1141	62.85		Steel tape
		07/15/2008	1048	60.03		Steel tape
		10/21/2008	1235	61.20		Steel tape
47W 90	390724077523201	10/22/2002	1309	77.98		Steel tape
		01/29/2003	1255	70.26		Steel tape
		04/16/2003	1400	65.16		Steel tape
		07/22/2003	1155	69.40		Steel tape
		10/21/2003	1140	72.15		Steel tape
		01/21/2004	1425	72.30		Steel tape
		04/06/2004	1005	68.48		Steel tape
		07/29/2004	0828	69.48		Steel tape
		10/20/2004	0910	70.38		Steel tape
		01/19/2005	1327	69.62		Electric tape
		04/27/2005	1221	76.56		Steel tape
		07/19/2005	1149	67.70		Steel tape
		10/19/2005	1500	74.75		Steel tape
		01/24/2006	1526	68.78		Steel tape
		05/02/2006	1351	69.90		Steel tape
		07/19/2006	1441	73.76		Steel tape
		10/19/2006	1221	74.16		Steel tape
		01/23/2007	1418	68.14		Steel tape
		04/17/2007	1319	65.99		Steel tape
		07/17/2007	1153	69.86		Steel tape
		10/17/2007	1157	77.65		Steel tape
		01/23/2008	1317	73.26		Steel tape
		04/16/2008	1135	67.60		Steel tape
		07/15/2008	1325	66.16		Steel tape
		10/21/2008	1438	74.05		Steel tape
47W 91	390724077522901	01/29/2003	1235	88.36		Steel tape
		04/16/2003	1350	84.56		Steel tape
47W 92	390333077564101	01/30/2003	1730	27.08		Steel tape
		04/24/2003	1755	26.61		Steel tape
		07/22/2003	1000	28.41		Steel tape
		10/29/2003	1145	27.58		Steel tape
		02/05/2004	1040	26.53		Steel tape
		04/13/2004	1205	22.67		Steel tape
		07/29/2004	1145	34.34		Steel tape
		10/25/2004	1301	30.13		Steel tape
		01/25/2005	1222	25.34		Steel tape
		05/04/2005	1209	26.04		Steel tape
		07/21/2005	1002	33.20		Steel tape
		10/28/2005	1039	33.88		Steel tape
		01/24/2006	1327	26.93		Steel tape
		05/03/2006	1054	26.43		Steel tape
		10/26/2006	1219	27.61		Steel tape
		01/26/2007	1057	28.26		Steel tape
		04/24/2007	1133	25.27		Steel tape
		08/02/2007	1154	31.03		Steel tape
		10/23/2007	1558	35.14		Steel tape
		01/31/2008	1339	34.44		Steel tape
		04/18/2008	1224	38.31		Steel tape
		07/17/2008	1404	32.21		Steel tape
		10/23/2008	1238	38.88		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47W 93	390150077585101	04/22/2003	1705	47.23		Steel tape
		07/21/2003	1025	53.55		Steel tape
		10/20/2003	1425	59.57		Steel tape
		01/21/2004	1105	50.56		Steel tape
		04/05/2004	1130	48.93		Steel tape
		07/27/2004	1131	57.43		Steel tape
		10/18/2004	1157	60.02		Steel tape
		01/18/2005	1358	51.54		Steel tape
		05/02/2005	1151	49.44		Steel tape
		07/18/2005	1142	57.72		Steel tape
		10/17/2005	1207	63.55		Steel tape
		01/23/2006	1236	52.68		Steel tape
		05/01/2006	1157	57.81		Steel tape
		07/17/2006	1351	58.86		Steel tape
		10/18/2006	1248	60.82		Steel tape
		01/22/2007	1325	51.81		Steel tape
		04/16/2007	1208	49.32		Steel tape
		07/16/2007	1221	59.85		Steel tape
		10/26/2007	1151	67.98		Steel tape
		01/22/2008	1207	67.28		Steel tape
		04/14/2008	1208	58.04		Steel tape
		07/14/2008	1116	64.41		Steel tape
		10/20/2008	1305	73.43		Steel tape
47X 53	390921077550801	10/24/2002	1004	67.44		Steel tape
		01/30/2003	0905	64.90		Steel tape
		04/17/2003	1045	58.45		Steel tape
		07/22/2003	1410	60.50		Steel tape
		10/21/2003	1530	62.12		Steel tape
		01/21/2004	1455	60.60		Steel tape
		04/06/2004	1055	63.28		Steel tape
		07/22/2004	1113	63.98		Steel tape
		10/19/2004	1434	64.35		Steel tape
		01/25/2005	0936	62.93		Steel tape
		05/03/2005	1158	62.45		Steel tape
		07/19/2005	1232	65.43		Steel tape
		10/24/2005	1240	67.10		Steel tape
		01/26/2006	1022	65.05		Steel tape
		05/01/2006	1444	66.59		Steel tape
		07/20/2006	1047	66.69		Steel tape
		10/19/2006	1313	68.30		Steel tape
		01/23/2007	1523	66.04		Steel tape
		04/17/2007	1414	64.82		Steel tape
		07/18/2007	0919	66.67		Steel tape
		10/17/2007	1331	67.28		Steel tape
		01/23/2008	1405	67.42		Steel tape
		04/16/2008	1238	67.36		Steel tape
		07/15/2008	1417	65.76		Steel tape
		10/21/2008	1517	67.03		Steel tape
47X 82	391203077585901	10/22/2002	1634	16.56		Steel tape
		01/30/2003	1420	12.13		Steel tape
		04/15/2003	1415	8.56		Steel tape
		07/23/2003	1115	10.27		Steel tape
		10/22/2003	1205	11.85		Steel tape
		01/22/2004	1430	10.97		Steel tape
		04/14/2004	0910	8.00		Steel tape
		07/28/2004	1427	12.57		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47X 82 (cont.)		10/22/2004	1037	12.52		Steel tape
		01/27/2005	1142	12.29		Steel tape
		05/04/2005	1332	11.78		Steel tape
		07/26/2005	1541	14.20		Steel tape
		10/26/2005	1310	15.10		Steel tape
		01/25/2006	1501	13.02		Steel tape
		05/02/2006	1132	15.10		Steel tape
		07/20/2006	1216	14.82		Steel tape
		10/19/2006	1430	15.02		Steel tape
		01/24/2007	1401	13.82		Steel tape
		04/19/2007	1044	11.52		Steel tape
		07/18/2007	1411	14.61		Steel tape
		10/17/2007	1508	16.17		Steel tape
		11/08/2007	1139	16.15		Steel tape
		01/30/2008	1452	15.58		Steel tape
		02/21/2008	1219	14.81		Steel tape
		04/21/2008	1103	9.74		Steel tape
		05/08/2008	1732	11.90		Steel tape
		07/17/2008	1040	13.05		Steel tape
		07/31/2008	1341	13.50		Steel tape
		10/23/2008	1202	15.27		Steel tape
47X 83	391203077585902	10/22/2002	1649	16.67		Steel tape
		01/30/2003	1405	10.75		Steel tape
		04/15/2003	1355	5.24		Steel tape
		07/23/2003	1105	7.44		Steel tape
		10/22/2003	1215	10.23		Steel tape
		01/22/2004	1445	9.65		Steel tape
		04/04/2004	0905	4.32		Steel tape
		07/28/2004	1417	8.36		Steel tape
		10/22/2004	1030	11.46		Steel tape
		01/27/2005	1133	10.96		Steel tape
		05/04/2005	1323	9.82		Steel tape
		07/26/2005	1535	13.73		Steel tape
		10/26/2005	1305	15.14		Steel tape
		01/25/2006	1456	12.04		Steel tape
		05/02/2006	1128	15.00		Steel tape
		07/20/2006	1212	14.58		Steel tape
		10/19/2006	1429	15.04		Steel tape
		01/24/2007	1400	13.18		Steel tape
		04/19/2007	1037	9.43		Steel tape
		07/18/2007	1414	16.40		Steel tape
		10/17/2007	1505	16.15		Steel tape
		11/08/2007	1152	16.23		Steel tape
		01/30/2008	1442	15.64		Steel tape
		02/21/2008	1202	14.82		Steel tape
		04/21/2008	1101	11.02		Steel tape
		05/08/2008	1734	15.18		Steel tape
		07/17/2008	1037	12.09		Steel tape
		07/31/2008	1339	12.63		Steel tape
		10/23/2008	1204	15.29		Steel tape
47X 84	390805077552101	10/24/2002	1026	45.15		Steel tape
		01/30/2003	0835	43.07		Steel tape
		04/17/2003	1115	37.88		Steel tape
		07/22/2003	1440	39.21		Steel tape
		10/23/2003	1125	41.08		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47X 84 (cont.)		02/05/2004	1220	41.39		Steel tape
		04/06/2004	1120	38.52		Steel tape
		07/22/2004	1131	43.19		Steel tape
		10/20/2004	1040	43.29		Steel tape
		01/21/2005	1109	38.52		Steel tape
		05/03/2005	1216	41.90		Steel tape
		07/19/2005	1248	42.49		Steel tape
		10/24/2005	1307	44.91		Steel tape
		01/26/2006	1037	42.39		Steel tape
		05/01/2006	1501	44.85		Steel tape
		07/19/2006	1454	45.31		Steel tape
		10/19/2006	1331	45.15		Steel tape
		01/23/2007	1459	44.44		Steel tape
		04/17/2007	1506	42.08		Steel tape
		07/18/2007	0947	45.12		Steel tape
		10/17/2007	1345	45.75		Steel tape
		01/23/2008	1428	45.93		Steel tape
		04/16/2008	1304	46.42		Steel tape
		07/15/2008	1438	44.28		Steel tape
		10/22/2008	1256	45.55		Steel tape
47X 85	390917077535301	10/24/2002	0935	63.48		Steel tape
		01/30/2003	0940	57.03		Steel tape
		04/17/2003	1020	48.90		Steel tape
		07/22/2003	1350	51.46		Steel tape
		10/23/2003	1055	53.86		Steel tape
		02/05/2004	1153	53.66		Steel tape
		04/06/2004	1040	53.58		Steel tape
		07/22/2004	1055	54.67		Steel tape
		10/19/2004	1417	57.68		Steel tape
		01/25/2005	0949	54.00		Steel tape
		05/03/2005	1141	52.46		Steel tape
		07/19/2005	1213	58.21		Steel tape
		10/24/2005	1222	62.12		Steel tape
		01/26/2006	1007	58.10		Steel tape
		05/01/2006	1430	61.53		Steel tape
		07/20/2006	1034	61.85		Steel tape
		10/19/2006	1245	62.02		Steel tape
		01/24/2007	1007	59.10		Steel tape
		04/17/2007	1355	55.74		Steel tape
		07/17/2007	1233	61.61		Steel tape
		10/17/2007	1314	63.73		Steel tape
		01/23/2008	1345	63.46		Steel tape
		04/16/2008	1218	61.75		Steel tape
		07/15/2008	1349	58.40		Steel tape
		10/21/2008	1502	62.51		Steel tape
47X 86	391109077592801	10/24/2002	1155	34.90		Steel tape
		01/30/2003	1125	33.56		Steel tape
		04/15/2003	1310	10.80		Steel tape
		07/23/2003	0940	16.59		Steel tape
		10/22/2003	1130	23.28		Steel tape
		02/05/2004	1445	21.13		Steel tape
		04/07/2004	1132	18.19		Steel tape
		07/27/2004	1423	22.94		Steel tape
		10/20/2004	1349	26.75		Steel tape
		01/27/2005	1056	25.95		Steel tape
		05/03/2005	1515	24.06		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
47X 86 (cont.)		07/20/2005	1358	29.78		Steel tape
		10/24/2005	1439	34.45		Steel tape
		01/25/2006	1421	32.40		Electric tape
		05/02/2006	1243	32.17		Steel tape
		07/20/2006	1105	33.66		Steel tape
		10/19/2006	1457	32.96		Steel tape
		01/24/2007	1311	28.82		Steel tape
		04/18/2007	1451	23.88		Steel tape
		07/18/2007	1253	31.52		Steel tape
		10/17/2007	1552	37.82		Electric tape
		01/23/2008	1518	34.30		Steel tape
		04/15/2008	1608	32.09		Steel tape
		07/16/2008	1337	26.79		Steel tape
		10/23/2008	1040	34.36		Steel tape
47X 87	391159077592201	10/21/2002	1520	41.03		Steel tape
47X 89	391050077591701	10/21/2004	1205	21.21		Steel tape
		01/27/2005	1120	19.98		Steel tape
		05/03/2005	1555	16.89		Steel tape
		07/20/2005	1340	23.72		Steel tape
		10/24/2005	1502	28.11		Steel tape
		01/25/2006	1434	21.36		Steel tape
		05/02/2006	1253	27.76		Steel tape
		07/20/2006	1116	25.85		Steel tape
		10/19/2006	1537	27.54		Steel tape
		01/24/2007	1325	23.90		Steel tape
		04/18/2007	1523	16.69		Steel tape
		07/18/2007	1306	26.66		Steel tape
		10/17/2007	1613	29.99		Steel tape
		01/23/2008	1535	29.48		Steel tape
		04/15/2008	1631	26.62		Steel tape
		07/16/2008	1421	21.54		Steel tape
		10/23/2008	1056	28.24		Steel tape
48X 20	390743077504501	10/22/2002	1355	32.41		Steel tape
		01/24/2003	1029	30.59		Steel tape
		04/15/2003	0839	25.74		Steel tape
		07/28/2003	1120	30.24		Steel tape
		10/29/2003	1330	31.97		Steel tape
		01/22/2004	1500	32.73		Steel tape
		04/06/2004	1532	29.56		Steel tape
		07/14/2004	0925	30.97		Steel tape
		10/19/2004	0829	31.01		Steel tape
		01/19/2005	1021	25.70		Electric tape
		04/26/2005	1642	28.33		Steel tape
		07/20/2005	0850	29.12		Steel tape
		10/19/2005	1204	30.57		Steel tape
		01/24/2006	1128	25.80		Steel tape
		05/03/2006	1510	30.71		Steel tape
		07/19/2006	1420	29.67		Steel tape
		10/23/2006	1551	28.73		Steel tape
		01/26/2007	1016	28.33		Steel tape
		04/26/2007	1539	27.83		Steel tape
		07/20/2007	1009	32.15		Steel tape
		07/25/2007	1507	32.50		Steel tape
		10/16/2007	1021	36.63		Steel tape
		10/22/2007	1407	37.16		Steel tape
		11/07/2007	1444	37.10		Steel tape

Appendix 3. Water-level measurements from wells in Clarke County, Virginia, 2002–2008.—Continued

[ft blsd, feet below land surface datum. See figure 15 for location of wells]

USGS local no.	USGS site no.	Date	Time	Water level (ft blsd)	Water-level status	Measurement method
48X 20 (cont.)		11/09/2007	1250	37.14		Steel tape
		01/25/2008	1158	35.13		Steel tape
		02/20/2008	1512	30.81		Steel tape
		04/15/2008	1327	31.76		Steel tape
		07/15/2008	1211	32.63		Steel tape
		07/31/2008	0951	32.72		Steel tape
		10/21/2008	1344	34.72		Steel tape
48X 21	390733077503601	10/22/2002	1519	59.98		Steel tape
		01/24/2003	0950	58.11		Steel tape
		04/15/2003	0919	45.90		Steel tape
		07/28/2003	1145	49.02		Steel tape
		11/06/2003	1140	48.14		Steel tape
		01/21/2004	1400	48.59		Steel tape
		04/06/2004	0930	38.14		Steel tape
		07/14/2004	0957	50.63		Steel tape
		10/19/2004	0855	54.54		Steel tape
		01/19/2005	1047	44.13		Electric tape
		04/26/2005	1611	50.78		Steel tape
		07/20/2005	0912	51.76		Steel tape
		10/19/2005	1224	56.56		Steel tape
		01/24/2006	1110	48.08		Steel tape
		05/02/2006	1335	53.82		Steel tape
		07/19/2006	1401	54.56		Steel tape
		10/19/2006	1204	52.81		Steel tape
		01/26/2007	1001	45.68		Steel tape
		04/26/2007	1521	52.74		Steel tape
		07/18/2007	1120	53.62		Steel tape
		10/16/2007	1003	61.71		Steel tape
		10/22/2007	1603	62.90		Steel tape
		11/07/2007	1342	63.86		Steel tape
		01/25/2008	1309	65.20		Steel tape
		02/20/2008	1552	59.99		Steel tape
		04/15/2008	1244	59.79		Steel tape
		07/15/2008	1145	54.87		Steel tape
		07/31/2008	1039	55.62		Steel tape
		10/21/2008	1321	59.55		Steel tape

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.

[ft³/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (ºC)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft³/s	gal/min	Method					
01636283	Wrights Branch tributary below jeep trail near Stone Bridge	04/22/2003	1047	0.095	42.6	F	nd	nd	nd	nd	nd
		07/31/2003	1140	0.018	8.1	F	nd	nd	nd	nd	nd
		11/06/2003	1200	0.035	15.7	F	nd	nd	nd	nd	nd
		02/05/2004	1100	0.022	9.9	F	nd	nd	nd	nd	nd
		04/13/2004	1258	0.411	184.5	F	nd	nd	nd	nd	nd
		07/15/2004	1415	0.011	4.9	F	nd	nd	nd	nd	nd
		10/25/2004	1445	0.011	4.9	F	nd	nd	nd	nd	nd
		01/25/2005	1436	0.063	28.3	F	nd	nd	nd	nd	nd
		05/04/2005	1000	0.035	15.7	F	nd	nd	nd	nd	nd
		07/21/2005	1415	0.015	6.7	F	nd	nd	nd	nd	nd
		11/04/2005	1144	0.004	1.8	F	nd	nd	nd	nd	nd
		02/03/2006	1025	0.040	18.0	F	nd	nd	nd	nd	nd
		05/03/2006	1005	0.022	9.9	F	nd	nd	nd	nd	nd
		07/26/2006	1345	0.002	0.9	F	nd	nd	nd	nd	nd
		10/26/2006	1000	0.007	3.1	F	nd	nd	nd	nd	nd
		01/31/2007	1036	0.020	9.0	V	nd	nd	nd	nd	nd
		04/25/2007	1000	0.051	22.9	F	nd	nd	nd	nd	nd
		08/02/2007	1145	0.0004	0.2	F	nd	nd	nd	nd	nd
		02/28/2008	1245	0.001	0.3	F	nd	nd	nd	nd	nd
		04/22/2008	1515	0.278	124.8	ADV	nd	nd	nd	nd	nd
		07/30/2008	0910	0.0060	2.7	F	nd	nd	nd	nd	nd
		10/27/2008	1330	0.006	2.7	F	nd	11.0	21	6.1	6.0
01636320	Giuliani Spring near Ashby Gap	05/14/2003	1345	0.091	40.8	V	nd	10.1	19	8.1	5.0
		10/29/2003	1110	0.076	34.1	V	nd	12.0	35	7.6	5.6
		02/05/2004	1256	0.032	14.2	V	nd	9.9	23	9.3	5.9
		04/13/2004	1405	0.334	149.9	V	nd	9.5	29	9.1	5.4
		07/15/2004	1514	0.012	5.4	V	nd	12.0	24	9.3	5.3
		10/20/2004	1018	0.010	4.5	V	nd	12.3	50	4.2	5.8
		01/25/2005	1148	0.063	28.3	V	nd	10.3	32	9.7	5.6
		05/04/2005	1221	0.046	20.7	V	nd	10.2	42	6.5	6.0
		07/21/2005	1045	0.009	3.8	V	nd	12.0	27	8.3	5.1
		10/28/2005	1108	0.008	3.6	V	nd	12.1	37	7.9	6.0
		02/02/2006	1048	0.035	15.7	V	nd	10.7	23	8.4	5.4
		05/03/2006	1200	0.035	15.7	V	nd	nd	nd	nd	nd
		07/26/2006	1030	0.004	1.8	V	nd	12.6	nd	nd	6.5
		10/26/2006	1200	0.006	2.7	V	nd	11.7	30	7.6	5.8
		01/31/2007	1430	0.027	12.1	V	nd	9.8	38	9.4	6.3
		04/24/2007	1110	0.064	28.7	V	nd	10.1	23	8.2	5.7
		08/02/2007	1139	0.001	0.4	V	nd	13.0	129	9.0	6.3
		10/23/2007	1543	0.000	0.0		nd	nd	nd	nd	nd
		02/29/2008	1200	0.004	1.8	Vl	nd	7.6	34	8.1	7.1
		04/18/2008	1230	0.018	8.1	V	nd	10.3	134	1.2	6.4
		07/30/2008	1035	0.0040	1.8	V	nd	12.9	31	6.4	6.0
		10/23/2008	1200	0.001	0.5	V	nd	11.5	24	8.5	6.1
01636336	Buck Marsh Run above Highway 340 at Berryville	05/14/2003	1020	1.390	623.8	P	4.43	nd	nd	nd	nd
		07/30/2003	1200	1.470	659.7	P	nd	18.0	nd	nd	nd
		10/29/2003	1430	1.480	664.2	P	4.48	nd	nd	nd	nd
		02/05/2004	1520	1.740	780.9	P	4.45	nd	nd	nd	nd
		04/08/2004	1300	1.625	729.3	P	4.47	nd	nd	nd	nd
		07/14/2004	1535	1.325	594.7	P	4.44	nd	nd	nd	nd
		10/20/2004	1440	0.977	438.5	ADV	4.42	nd	nd	nd	nd
		01/19/2005	1542	1.170	525.1	ADV	4.42	nd	nd	nd	nd

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft³/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft³/s	gal/min	Method					
01636336	Buck Marsh Run above Highway 340 at Berryville (cont.)	05/03/2005	1503	1.330	596.9	ADV	4.44	nd	nd	nd	nd
		07/22/2005	1015	0.929	416.9	ADV	4.40	nd	nd	nd	nd
		10/27/2005	1127	0.776	348.3	ADV	4.39	nd	nd	nd	nd
		02/01/2006	1535	0.875	392.7	ADV	4.40	12.1	nd	nd	nd
		04/27/2006	1027	0.625	280.5	ADV	4.31	nd	nd	nd	nd
		07/25/2006	1500	0.554	248.6	ADV	4.35	nd	nd	nd	nd
		10/27/2006	1016	0.706	316.9	ADV	4.37	10.0	666	9.4	7.8
		04/16/2007	1442	1.420	637.3	ADV	4.48	10.4	600	10.0	7.3
		01/23/2007	1610	0.837	375.6	ADV	4.39	9.2	647	10.5	8.0
		07/18/2007	1633	0.547	245.5		4.37	23.4	649	8.0	7.9
		10/16/2007	1636	0.339	152.1	ADV	4.36	nd	nd	nd	nd
		01/29/2008	1700	0.531	238.3	ADV	4.50	nd	nd	nd	nd
		04/15/2008	1636	0.526	236.1	ADV	4.37	20.1	685	9.4	8.0
		07/29/2008	1630	0.7190	322.7	ADV	4.40	23.2	663.0	7.7	7.8
		10/22/2008	1000	0.411	184.5	ADV	4.36	9.3	656	9.4	8.0
46WS 1	Carter Hall Spring	04/17/2003	1318	8.353	3748.8	AA	4.30	12.6	589	7.9	6.8
		07/29/2003	1231	9.587	4302.6	AA	4.37	nd	nd	nd	nd
		08/13/2003	1228	8.373	3757.8	C	4.35	13.0	569	7.8	6.8
		10/28/2003	0907	6.881	3088.2	P	4.31	12.9	547	7.4	7.1
		10/28/2003	nd	9.815	4405.0	AA	nd	nd	nd	nd	nd
		01/21/2004	1418	8.036	3606.6	P	4.32	12.5	556	7.5	6.9
		04/05/2004	1642	6.792	3048.2	P	4.35	12.5	543	7.3	7.1
		07/13/2004	0910	5.364	2407.4	P	4.21	12.7	554	6.7	7.2
		10/19/2004	1040	5.040	2262.0	ADV	4.20	12.7	560	7.0	7.1
		10/19/2004	nd	4.686	2103.1	P	nd	nd	nd	nd	nd
		01/18/2005	1530	5.670	2544.7	ADV	4.24	12.7	579	7.5	7.4
		04/25/2005	1220	5.950	2670.4	ADV	4.28	12.7	580	7.1	7.1
		07/20/2005	1320	5.971	2679.8	ADV	4.21	12.7	565	7.7	6.9
		10/18/2005	1155	5.450	2446.0	ADV	4.18	12.7	560	6.9	7.0
		01/30/2006	1320	5.560	2495.3	ADV	4.16	12.7	551	6.8	7.0
		04/26/2006	1153	4.900	2199.1	P	4.20	12.8	571	7.9	7.1
		07/24/2006	1229	4.400	1974.7	ADV	4.15	12.9	567	6.8	7.1
		10/24/2006	1045	3.630	1629.1	ADV	4.13	12.8	548	6.9	7.0
		01/23/2007	1400	4.740	2127.3	ADV	4.17	12.7	552	6.8	7.1
		04/26/2007	1127	5.320	2387.6	ADV	4.22	12.7	579	7.4	7.1
		07/19/2007	1115	5.130	2302.3	ADV	4.16	12.8	570	6.8	7.1
		10/18/2007	1351	3.720	1669.5	ADV	4.12	12.8	563	7.6	7.0
		01/30/2008	1150	3.707	1663.7	ADV	4.13	12.6	554	7.2	7.1
		04/23/2008	1530	4.380	1965.7	ADV	4.17	12.7	578	6.7	7.1
		07/24/2008	1120	4.850	2176.7	ADV	4.17	12.8	581	7.1	7.0
		10/24/2008	1130	4.140	1858.0	ADV	4.13	12.8	570	6.8	7.1
46WS 3	Prospect Hill Spring	03/03/2003	1235	2.880	1292.5	P	4.90	12.0	nd	nd	nd
		04/16/2003	1600	2.840	1274.6	P	4.96	12.2	572	7.1	6.6
		05/15/2003	nd	nd	nd	nd	4.95	nd	nd	nd	nd
		07/29/2003	0945	1.940	870.7	P	5.02	12.0	nd	nd	nd
		10/01/2003	nd	nd	nd	nd	4.90	nd	nd	nd	nd
		10/27/2003	1530	2.420	1086.1	P	4.95	12.5	570	5.8	7.0
		01/22/2004	1155	2.860	1283.6	P	4.87	12.5	550	5.9	6.9
		04/06/2004	1131	3.056	1371.5	P	4.92	12.2	561	5.9	6.8
		07/13/2004	1313	2.590	1162.4	P	4.69	12.2	568	4.8	7.1
		10/19/2004	1415	2.600	1166.9	P	4.75	12.4	588	5.5	7.0
		01/24/2005	1348	1.924	863.5	ADV	4.69	12.5	553	5.8	6.9

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft³/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft³/s	gal/min	Method					
46WS 3	Prospect Hill Spring (cont.)	04/28/2005	1245	2.021	907.0	ADV	4.77	12.3	595	7.6	7.0
		07/19/2005	1322	2.326	1043.9	ADV	nd	nd	nd	nd	nd
		07/25/2005	nd	nd	nd		4.71	12.2	586	6.1	6.9
		10/18/2005	1536	1.250	561.0	ADV	4.53	12.4	605	6.8	6.8
		01/31/2006	1433	1.753	786.7	ADV	4.81	12.6	591	6.5	6.8
		04/28/2006	nd	nd	nd	nd	4.63	12.4	620	4.7	6.8
		07/24/2006	1547	2.020	906.6	ADV	4.89	12.4	621	6.3	6.8
		10/25/2006	1351	1.570	704.6	ADV	4.67	12.6	615	5.6	6.8
		02/01/2007	1219	1.740	780.9	ADV	nd	12.7	632	5.4	6.9
		04/25/2007	1200	1.670	749.5	ADV	nd	12.4	601	6.5	6.9
		07/19/2007	1409	1.200	538.6	ADV	nd	12.3	613	5.1	6.9
		10/18/2007	1545	1.450	650.8	ADV	nd	12.5	611	7.4	6.8
		02/28/2008	1540	1.600	718.1	ADV	4.40	12.6	651	6.9	7.0
		04/22/2008	1030	1.990	893.1	ADV	nd	12.5	641	6.9	6.9
		07/23/2008	1105	1.870	839.3	ADV	4.70	12.4	623	5.8	6.8
		10/23/2008	1408	1.160	520.6	ADV	nd	12.5	603	5.4	6.9
46WS 5	Huntingdon Spring	05/13/2003	1435	1.040	466.8	P	nd	12.2	542	5.1	6.9
		02/04/2004	1110	1.030	462.3	P	nd	12.3	521	5.6	7.0
		04/14/2004	1225	1.291	579.4	P	nd	11.8	524	5.2	7.2
		07/13/2004	1115	0.536	240.6	P	nd	12.9	552	4.6	7.0
		10/21/2004	1350	0.435	195.2	ADV	nd	13.7	571	6.1	7.0
		01/26/2005	0939	0.524	235.2	ADV	nd	12.8	592	5.2	7.5
		05/02/2005	1224	0.613	275.1	ADV	nd	12.2	585	5.7	7.0
		07/20/2005	1455	0.422	189.4	ADV	nd	12.5	587	4.6	6.7
		08/11/2005	1345	0.293	131.5	ADV	nd	12.7	592	3.1	6.9
		10/26/2005	1420	0.055	24.7	ADV	nd	12.4	599	1.9	7.0
		02/02/2006	1256	0.834	374.3	ADV	nd	12.9	570	5.8	7.0
		04/26/2006	1550	0.284	127.5	P	nd	12.5	604	5.9	7.0
		07/25/2006	1321	0.510	228.9	ADV	nd	12.8	599	4.8	7.0
		11/01/2006	1255	0.423	189.8	ADV	nd	13.4	605	4.7	6.9
		01/24/2007	1123	0.600	269.3	ADV	nd	12.1	581	5.4	7.1
		04/17/2007	1405	0.698	313.3	ADV	nd	12.3	545	4.0	7.0
		07/17/2007	1121	0.323	145.0	ADV	nd	12.9	598	4.1	7.0
		10/17/2007	1130	0.000	0.0		nd	nd	nd	nd	nd
		01/29/2008	1015	0.000	0.0		nd	nd	nd	nd	nd
		04/15/2008	1314	0.371	166.5	ADV	nd	12.4	690	6.6	7.0
		07/29/2008	1207	0.5080	228.0	ADV	nd	12.7	595	5.2	7.2
		10/21/2008	1320	0.000	0.0		nd	nd	nd	nd	nd
46WS 7	Borden Spring	08/11/2005	1000	1.306	586.1	ADV	4.14	12.6	507	6.7	7.0
		10/20/2005	1110	1.315	590.2	ADV	4.14	12.7	513	7.1	7.1
		02/01/2006	1115	1.050	471.2	ADV	4.17	12.8	493	7.1	7.3
		04/26/2006	1506	1.100	493.7	P	4.14	12.7	518	6.6	7.1
		07/18/2006	0933	0.905	406.2	ADV	4.17	12.7	496	7.3	7.1
		11/02/2006	1400	0.945	424.1	ADV	4.15	12.8	507	7.0	7.1
		01/30/2007	1500	1.030	462.3	ADV	4.14	12.5	505	7.1	7.3
		04/23/2007	1426	1.260	565.5	ADV	4.17	12.7	511	7.1	7.2
		07/18/2007	1341	0.946	424.6	ADV	4.14	12.8	514	6.8	7.1
		10/17/2007	1513	0.745	334.4	ADV	4.12	nd	nd	nd	nd
		01/29/2008	1515	0.906	406.6	ADV	4.14	12.7	504	6.8	7.0
		04/17/2008	1709	0.929	416.9	ADV	nd	12.8	514	7.1	7.2
		07/29/2008	1435	1.2200	547.5	ADV	4.16	12.7	515	6.9	7.2
		10/20/2008	1620	1.210	543.0	ADV	nd	12.7	522	6.9	7.2

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft^3/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
46WS 10	Montana Hall Spring	04/21/2003	1715	0.135	60.6	P	4.63	11.7	534	6.3	6.8
		07/30/2003	1200	0.105	47.1	P	4.70	12.9	508	6.3	6.6
		10/28/2003	1430	0.144	64.6	P	4.57	13.2	516	6.1	7.0
		02/04/2004	1415	0.075	33.7	P	4.48	10.1	515	5.1	7.0
		04/07/2004	1100	0.104	46.7	P	4.50	11.2	547	5.7	7.1
		07/12/2004	1456	0.075	33.7	F	4.48	13.0	568	4.0	7.2
		10/26/2004	1050	0.046	20.6	F	4.39	13.5	570	5.1	7.1
		01/26/2005	1224	0.051	22.9	F	4.35	12.2	589	6.2	7.7
		04/27/2005	1130	0.051	22.9	F	4.30	11.8	584	6.4	7.2
		07/18/2005	1445	0.026	11.7	F	4.17	12.8	560	5.5	6.8
		10/20/2005	1242	0.018	8.1	F	4.26	13.6	612	5.5	7.1
		02/01/2006	1227	0.051	22.9	F	4.27	12.1	592	5.4	7.2
		04/26/2006	1430	0.043	19.3	P	4.28	12.0	632	6.1	7.0
		07/18/2006	1105	0.046	20.6	F	4.30	12.9	622	5.8	7.0
		11/02/2006	1530	0.026	11.7	F	4.27	13.2	620	5.4	7.0
		01/30/2007	1400	0.035	15.7	F	4.30	12.6	621	5.2	7.2
		04/23/2007	1520	0.051	22.9	F	nd	11.8	594	6.1	7.1
		07/18/2007	1118	0.018	8.1	F	nd	12.8	603	6.0	7.0
		10/17/2007	1430	0.002	0.9	F	4.17	14.2	588	3.3	nd
		01/29/2008	1322	0.006	2.6	F	4.14	11.0	606	6.0	7.0
		04/14/2008	1527	0.011	4.9	F	4.15	11.5	644	4.2	7.1
		07/21/2008	1650	0.035	15.7	F	4.28	13.0	593	7.1	7.0
		10/20/2008	1515	0.018	8.1	F	nd	13.3	628	5.7	7.1
46WS 12	Longbranch Spring	05/16/2003	1200	0.120	53.9	P	nd	12.9	570	7.1	6.8
		10/28/2003	1455	0.168	75.4	P	nd	13.1	542	6.5	7.0
		02/04/2004	1540	0.117	52.5	P	nd	12.6	522	6.6	7.0
		04/07/2004	1530	0.114	51.2	P	nd	12.8	540	6.9	7.0
		07/12/2004	1538	0.097	43.5	P	nd	13.1	545	5.0	7.2
		10/26/2004	1221	0.039	17.5	P	nd	13.1	540	6.1	7.1
		01/26/2005	1337	0.037	16.6	ADV	nd	12.8	554	6.0	7.6
		04/27/2005	1103	0.043	19.3	ADV	nd	12.9	559	7.5	7.1
		07/19/2005	1535	0.055	24.7	ADV	nd	13.2	541	6.6	7.0
		10/20/2005	1530	0.026	11.7	ADV	nd	13.1	548	6.1	7.1
		02/01/2006	1330	0.052	23.3	ADV	nd	12.9	538	6.0	7.2
		04/26/2006	1345	0.156	70.0	P	nd	13.0	554	6.8	7.0
		07/18/2006	1338	0.022	9.9	ADV	nd	13.5	559	6.2	7.0
		11/01/2006	1445	0.037	16.6	ADV	nd	13.3	560	5.4	7.0
		01/31/2007	1336	0.050	22.4	ADV	nd	12.9	572	6.0	7.3
		04/24/2007	1426	0.082	36.8	ADV	nd	13.0	560	6.4	7.0
		07/17/2007	1600	0.081	36.4	ADV	nd	13.5	561	6.0	7.0
		10/17/2007	1350	0.010	4.5	ADV	nd	13.6	526	3.5	nd
		01/28/2008	1440	0.008	3.6	ADV	nd	12.6	543	6.1	7.0
		04/14/2008	1442	0.051	22.9	ADV	nd	13.0	567	5.6	7.1
		07/21/2008	1606	0.099	44.4	ADV	nd	13.1	553	8.0	7.0
		10/20/2008	1423	0.060	26.9	ADV	nd	13.2	572	5.6	7.1
46WS 22	Saratoga Spring	04/17/2003	1540	0.950	426.4	V	4.79	11.5	532	8.2	6.9
		07/29/2003	1505	0.816	366.2	V	4.79	16.6	nd	nd	nd
		08/13/2003	1442	0.842	377.9	V	4.78	12.3	604	2.7	6.8
		10/28/2003	1128	0.667	299.3	V	4.76	12.8	584	2.9	7.0
		01/22/2004	0946	0.720	323.1	V	4.77	12.5	575	3.3	7.1
		04/05/2004	nd	0.985	442.1	V	4.78	11.9	577	4.1	7.0
		07/13/2004	1000	0.645	289.5	V	4.76	12.1	614	3.1	7.1

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft^3/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
46WS 22	Saratoga Spring (cont.)	10/18/2004	nd	0.867	389.1	V	4.77	12.5	623	4.6	6.9
		01/18/2005	1436	0.990	444.1	V	4.79	12.6	601	nd	7.3
		04/27/2005	1645	0.912	409.1	V	4.77	12.0	597	5.2	7.1
		07/19/2005	1045	0.717	321.9	V	4.75	12.2	626	5.0	6.8
		10/19/2005	1640	0.701	314.6	V	4.76	12.5	639	3.8	6.9
		01/30/2006	1549	0.918	412.0	V	4.78	12.6	587	5.9	6.9
		04/27/2006	1720	0.736	330.3	V	4.76	12.3	641	4.2	6.9
		07/24/2006	1350	0.713	320.0	V	4.76	12.4	628	4.8	6.9
		10/24/2006	1330	0.759	340.6	V	4.77	12.7	622	4.9	6.8
		01/24/2007	1530	0.956	429.1	V	4.77	12.7	609	3.8	7.0
		04/18/2007	1345	0.863	387.3	V	4.78	12.2	571	4.1	7.0
		07/18/2007	1530	0.587	263.4	V	nd	12.3	628	4.5	6.9
		10/18/2007	1122	0.434	194.8	V	4.73	12.5	632	7.0	6.9
		02/28/2008	1649	0.744	333.9	V	4.75	12.6	675	5.6	7.0
		04/23/2008	1315	0.883	396.3	V	4.78	12.3	610	5.7	7.0
		07/24/2008	1630	0.702	315.1	V	nd	12.4	650	4.3	7.1
		10/27/2008	1500	0.676	303.4	V	4.75	12.6	648	4.4	7.0
46WS 26	Farnley Farm Spring	04/21/2003	1542	0.215	96.5	P	nd	12.6	539	5.6	6.6
		07/30/2003	1105	0.173	77.6	P	nd	nd	nd	nd	nd
		10/28/2003	1330	0.159	71.4	P	nd	12.6	505	5.5	7.1
		02/04/2004	1320	0.234	105.0	P	nd	9.8	469	6.4	7.1
		04/07/2004	0943	0.175	78.5	P	nd	11.8	495	5.4	7.0
		07/12/2004	1406	0.122	54.8	P	nd	13.5	483	6.6	7.1
		10/26/2004	0935	0.026	11.7	F	nd	12.5	510	5.4	7.1
		01/26/2005	1120	0.057	25.6	F	nd	12.8	507	7.1	7.6
		04/27/2005	1532	0.075	33.7	F	nd	12.4	472	7.2	7.1
		07/18/2005	1520	0.051	22.9	F	nd	14.6	534	5.1	6.4
		10/20/2005	1026	0.026	11.7	F	nd	13.4	534	4.1	7.0
		02/01/2006	1030	0.036	16.2	ADV	nd	10.4	528	5.9	7.3
		04/27/2006	1556	0.026	11.7	P	nd	12.3	546	5.6	7.1
		07/18/2006	0830	0.015	6.7	ADV	nd	15.0	nd	nd	nd
		11/02/2006	1335	0.022	9.9	F	nd	nd	nd	nd	nd
		01/30/2007	1416	0.022	9.9	F	nd	nd	nd	nd	nd
		04/23/2007	1400	0.040	18.1	F	nd	nd	nd	nd	nd
		07/18/2007	1015	0.015	6.7	F	nd	nd	nd	nd	nd
		01/31/2008	1100	0.006	2.6	F	nd	nd	nd	nd	nd
		04/24/2008	0925	0.022	9.9	F	nd	nd	nd	nd	nd
		07/29/2008	1355	0.018	8.1	F	nd	nd	nd	nd	nd
		10/24/2008	1020	0.018	8.1	F	nd	nd	nd	nd	nd
46WS 27	Lions Club Spring #1	04/22/2003	1052	nd	nd	QW	nd	10.5	20	7.2	4.4
		07/31/2003	1145	nd	nd	QW	nd	16.0	17	9.2	5.0
		02/05/2004	1105	nd	nd	QW	nd	10.7	23	6.3	6.2
		04/13/2004	1303	nd	nd	QW	nd	9.6	22	8.3	5.2
		07/15/2004	1420	nd	nd	QW	nd	12.3	22	7.4	6.0
		10/25/2004	1450	nd	nd	QW	nd	13.1	23	7.1	5.2
		01/25/2005	1441	nd	nd	QW	nd	11.5	25	7.4	5.5
		05/04/2005	1005	nd	nd	QW	nd	10.6	22	6.9	5.4
		07/21/2005	1420	nd	nd	QW	nd	12.4	23	6.3	4.9
46WS 28	Lions Club Spring #2	04/22/2003	1057	nd	nd	QW	nd	10.9	19	9.5	4.2
		07/31/2003	1150	nd	nd	QW	nd	16.5	19	2.2	5.4
		11/06/2003	1205	nd	nd	QW	nd	13.5	15	nd	5.5
		02/05/2004	1110	nd	nd	QW	nd	5.7	17	12.0	6.6

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft^3/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
46WS 28	Lions Club Spring #2 (cont.)	04/13/2004	1308	nd	nd	QW	nd	9.3	26	9.1	5.1
		07/15/2004	1425	nd	nd	QW	nd	13.8	24	6.8	5.7
		10/25/2004	1455	nd	nd	QW	nd	12.7	20	10.1	5.8
		01/25/2005	1446	nd	nd	QW	nd	6.1	23	12.5	6.1
		05/04/2005	1010	nd	nd	QW	nd	10.7	19	10.7	6.0
		07/21/2005	1425	nd	nd	QW	nd	17.7	18	8.7	5.5
46WS 29	Lions Club Spring #3	04/22/2003	1102	nd	nd	QW	nd	10.2	19.6	8.5	4.0
		11/05/2003	1210	nd	nd	QW	nd	13.2	34	2.2	5.3
		02/05/2004	1115	nd	nd	QW	nd	7.9	20	6.7	6.0
		04/13/2004	1313	nd	nd	QW	nd	8.6	23	9.8	5.3
		07/15/2004	1430	nd	nd	QW	nd	16.2	18	9.2	6.5
		10/25/2004	1500	nd	nd	QW	nd	12.8	22	7.3	5.0
		01/25/2005	1451	nd	nd	QW	nd	10.0	24	9.1	5.5
		05/04/2005	1015	nd	nd	QW	nd	10.9	21	8.3	5.3
		07/21/2005	1430	nd	nd	QW	nd	12.8	22	7.9	4.7
46WS 30	Lions Club Spring #4	04/22/2003	1107	nd	nd	QW	nd	10.1	27	9.6	5.0
		11/06/2003	1215	nd	nd	QW	nd	14.5	26	1.9	6.0
		02/05/2004	1120	nd	nd	QW	nd	5.2	27	8.4	6.5
		01/25/2005	1456	nd	nd	QW	nd	5.6	32	11.0	6.3
		05/04/2005	1020	nd	nd	QW	nd	9.8	29	10.8	6.5
46WS 32	Caveland Farm Spring	04/18/2003	1028	0.703	315.5	P	nd	12.6	591	5.3	6.9
		07/30/2003	1200	0.531	238.3	P	nd	12.6	568	4.0	6.7
		10/30/2003	0930	0.392	175.9	P	nd	12.7	568	3.2	7.0
		02/02/2004	1311	0.429	192.5	P	nd	12.7	570	3.1	7.0
		04/07/2004	1230	0.573	257.2	P	nd	12.6	565	3.1	6.9
		07/15/2004	1048	0.318	142.7	P	nd	12.6	572	10.1	7.0
		10/21/2004	1100	0.297	133.3	P	nd	12.6	587	4.0	6.9
		10/21/2004	1130	0.214	96.0	ADV	nd	nd	nd	nd	nd
		01/20/2005	1024	0.489	219.5	ADV	nd	12.7	604	4.1	7.0
		05/03/2005	1104	0.333	149.5	ADV	nd	12.6	588	3.9	7.0
		07/25/2005	1451	0.106	47.6	ADV	nd	12.6	603	4.6	7.0
		10/26/2005	1050	0.131	58.8	ADV	nd	12.6	667	4.4	6.9
		02/01/2006	0922	0.332	149.0	ADV	nd	12.8	609	4.5	7.1
		04/27/2006	1438	0.311	139.6	P	nd	12.8	624	4.7	6.9
		07/25/2006	0958	0.158	70.9	ADV	nd	12.7	608	4.7	6.9
		10/25/2006	1510	0.063	28.3	ADV	nd	12.8	624	4.2	6.9
		01/24/2007	1342	0.253	113.5	ADV	nd	12.9	594	3.9	7.0
		04/17/2007	1255	0.410	184.0	ADV	nd	12.8	560	3.8	6.9
		07/17/2007	1330	0.177	79.4	ADV	nd	12.8	576	4.2	6.9
		10/18/2007	1012	0.066	29.6	ADV	nd	12.7	630	6.6	6.8
		02/29/2008	0945	0.195	87.5	ADV	nd	12.8	677	4.7	7.0
		04/15/2008	1049	0.200	89.8	ADV	nd	12.8	586	4.3	7.0
		07/25/2008	1225	0.311	139.6	ADV	nd	12.7	604	4.9	7.1
		10/21/2008	1015	0.104	46.7	ADV	nd	12.7	627	4.4	7.0
46WS 34	Hickey Spring	05/16/2003	1106	0.283	127.0	P	nd	12.5	565	5.7	6.8
		02/04/2004	1635	0.141	63.3	P	nd	12.5	509	3.9	7.0
		04/07/2004	1555	0.176	79.0	P	nd	12.4	530	3.9	7.1
		07/15/2004	1244	0.115	51.6	P	nd	12.6	525	7.2	7.1
		10/26/2004	1145	0.133	59.7	F	nd	12.9	535	3.8	7.1
		01/26/2005	1300	0.133	59.7	F	nd	12.7	540	4.6	7.7
		04/27/2005	1018	0.110	49.4	F	nd	12.5	546	5.1	7.2
		07/19/2005	1614	0.075	33.7	F	nd	12.7	543	4.0	6.9

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft^3/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
46WS 34	Hickey Spring (cont.)	10/20/2005	1451	0.046	20.6	F	nd	12.8	548	3.4	7.1
		04/27/2006	1637	0.186	83.5	P	nd	12.7	555	4.8	7.1
		07/18/2006	1252	0.046	20.6	F	nd	12.8	550	4.7	7.0
		11/01/2006	1410	0.026	11.7	F	nd	12.9	584	5.3	7.0
		01/31/2007	1155	0.095	42.6	F	nd	12.8	582	5.5	7.3
		04/24/2007	1320	0.117	52.5	F	nd	12.7	531	5.3	7.1
		07/17/2007	1503	0.051	22.9	F	nd	12.8	551	4.6	7.1
		10/17/2007	1300	0.011	4.9	F	nd	13.0	454	5.0	nd
		01/29/2008	1401	0.011	4.9	F	nd	12.5	570	5.2	7.0
		04/14/2008	1345	0.035	15.7	F	nd	12.7	608	5.5	7.1
		07/21/2008	1505	0.102	45.8	F	nd	12.9	549	4.9	6.9
		10/20/2008	1325	0.046	20.6	F	nd	12.9	575	4.9	7.1
46WS 35	Lower Pagebrook Spring	04/18/2003	1134	0.249	111.8	P	nd	11.9	565	4.3	6.9
		10/28/2003	nd	0.135	60.6	P	nd	13.5	574	1.2	6.9
		01/23/2004	1235	0.116	52.1	P	nd	12.6	591	1.7	7.0
		04/07/2004	1320	0.146	65.5	P	nd	11.8	586	1.6	7.0
		07/15/2004	1524	0.109	48.9	P	nd	12.6	585	1.1	7.1
		10/21/2004	1018	0.106	47.6	P	nd	13.3	600	2.9	6.8
		01/21/2005	1057	0.147	66.0	P	nd	12.7	623	3.2	7.0
		05/02/2005	1606	0.116	52.1	P	nd	12.1	602	3.0	7.0
		07/20/2005	1553	0.109	48.9	P	nd	12.7	600	3.3	6.7
		10/26/2005	1220	0.053	23.8	ADV	nd	13.0	603	3.0	6.9
		01/31/2006	1130	0.028	12.6	ADV	nd	12.8	599	4.1	6.8
		04/26/2006	1626	0.043	19.3	P	nd	12.8	618	4.8	6.9
		07/25/2006	1240	0.056	25.1	ADV	nd	12.9	619	4.0	6.9
		10/25/2006	1121	0.055	24.7	ADV	nd	13.4	627	3.8	6.9
		01/23/2007	1152	0.052	23.3	ADV	nd	13.0	602	3.3	7.0
		04/17/2007	1106	0.054	24.2	ADV	nd	12.1	561	3.3	7.1
		07/16/2007	1421	0.068	30.5	ADV	nd	12.7	608	3.5	6.8
		10/17/2007	1047	0.033	14.8	ADV	nd	12.9	575	2.6	nd
		02/28/2008	1740	0.035	15.7	ADV	nd	12.6	672	5.3	7.0
		04/15/2008	1200	0.082	36.8	ADV	nd	12.4	647	4.4	6.9
		07/23/2008	1300	0.069	31.0	ADV	nd	12.9	620	3.7	6.9
		10/21/2008	1135	0.026	11.7	ADV	nd	13.0	609	3.6	7.0
46WS 36	Hamilton Mtn Spring	01/25/2005	nd	0.009	3.8	F	nd	11.7	39	10.9	6.3
46WS 40	Sprouse Spring	07/29/2005	nd	0.138	61.9	ADV	nd	12.6	629	3.1	7.0
46XS 3	Horsepen Spring	04/15/2003	1215	2.270	1018.8	P	nd	11.9	626	9.1	6.5
		10/30/2003	1036	1.130	507.1	P	nd	12.4	637	4.4	6.8
		01/23/2004	1100	1.420	637.3	P	nd	12.0	642	5.0	6.9
		04/08/2004	0935	1.564	701.9	P	nd	12.0	616	4.8	6.9
		07/15/2004	0933	1.085	486.9	P	nd	12.1	629	12.3	7.0
		08/20/2004	1455	0.715	320.9	P	nd	12.2	577	3.7	6.9
		10/21/2004	1502	0.485	217.7	ADV	nd	12.3	642	4.0	6.8
		01/21/2005	0948	1.241	557.0	ADV	nd	12.4	669	4.9	6.9
		05/03/2005	0855	1.134	508.9	ADV	nd	12.1	652	5.9	6.9
		07/21/2005	1620	0.648	290.8	ADV	nd	12.1	663	5.7	6.6
		10/26/2005	1550	0.301	135.1	ADV	nd	12.3	691	4.6	6.8
		02/02/2006	1400	0.552	247.7	ADV	nd	12.4	656	5.5	6.9
		04/27/2006	1338	0.730	327.6	P	nd	12.3	699	5.7	6.8
		07/25/2006	1100	0.394	176.8	ADV	nd	12.2	693	9.8	6.8
		11/01/2006	1542	0.317	142.3	ADV	nd	12.4	696	5.3	6.8
		01/24/2007	1003	0.490	219.9	ADV	nd	12.5	669	5.5	6.9

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft³/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge ft³/s	Discharge gal/min	Discharge Method	Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
46XS 3	Horsepen Spring (cont.)	04/18/2007	1050	1.020	457.8	ADV	nd	12.4	662	3.6	7.2
		07/17/2007	0957	0.259	116.2	ADV	nd	12.3	691	6.0	6.7
		10/23/2007	1055	0.001	0.4	F	nd	12.3	705	9.3	6.7
		01/29/2008	1147	0.031	13.9	ADV	nd	11.3	698	5.4	6.8
		04/15/2008	1525	0.248	111.3	ADV	nd	12.4	706	6.1	6.8
		07/29/2008	1033	0.3630	162.9	ADV	nd	12.2	688	6.0	6.8
		10/21/2008	1425	0.163	73.2	ADV	nd	12.4	680	5.4	6.9
46XS 8	Perry Spring	04/15/2003	1405	3.690	1656.1	P	nd	12.3	695	7.4	6.8
		05/15/2003	0900	2.580	1157.9	P	nd	12.3	681	6.9	6.7
		07/31/2003	0745	2.080	933.5	P	nd	12.5	659	8.1	6.7
		08/13/2003	1730	1.620	727.1	P	nd	12.5	660	5.2	6.7
		10/29/2003	0815	1.050	471.2	P	nd	12.8	656	4.8	6.9
		02/03/2004	1500	2.200	987.4	P	nd	12.6	657	4.8	7.0
		04/14/2004	0925	4.472	2007.0	P	nd	12.1	666	5.3	6.9
		07/16/2004	0925	1.370	614.9	P	nd	12.3	661	6.9	7.0
		10/26/2004	1709	0.461	206.9	ADV	nd	12.7	656	4.9	7.0
		01/27/2005	1306	0.930	417.4	ADV	nd	12.7	677	5.3	7.3
		05/03/2005	1624	2.139	960.0	ADV	nd	12.2	677	6.6	6.9
		07/26/2005	nd	0.000	0.0		nd	nd	nd	nd	nd
		10/21/2005	1000	0.000	0.0		nd	nd	nd	nd	nd
		02/02/2006	1508	0.192	86.2	ADV	nd	12.8	693	6.6	6.8
		04/26/2006	1755	0.000	0.0		nd	nd	nd	nd	nd
		07/25/2006	1536	0.000	0.0		nd	nd	nd	nd	nd
		10/25/2006	1711	0.000	0.0		nd	nd	nd	nd	nd
		01/25/2007	1424	0.124	55.7	ADV	nd	12.8	681	6.0	6.9
		04/19/2007	1106	2.250	1009.8	ADV	nd	12.5	626	6.6	6.8
		07/19/2007	1700	0.000	0.0		nd	nd	nd	nd	nd
		10/16/2007	1728	0.000	0.0		nd	nd	nd	nd	nd
		02/21/2008	1455	0.000	0.0		nd	nd	nd	nd	nd
		04/15/2008	1715	0.000	0.0		nd	nd	nd	nd	nd
		04/24/2008	1151	1.450	650.8	ADV	nd	12.6	765	7.4	6.9
		07/30/2008	1515	0.1520	68.2	ADV	nd	12.7	697	6.2	6.8
		10/22/2008	1630	0.000	0.0		nd	nd	nd	nd	nd
46XS 9	Salem Church Spring	05/13/2003	1325	1.700	763.0	P	nd	12.3	547	4.2	6.8
		02/02/2004	1429	0.674	302.5	P	nd	12.7	570	2.9	7.0
		04/07/2004	1415	1.209	542.6	P	nd	12.3	565	3.0	6.8
		07/13/2004	1430	0.367	164.7	P	nd	12.5	573	2.4	7.0
		08/19/2004	1705	0.090	40.4	V	nd	12.7	523	2.6	7.0
		10/21/2004	0855	0.421	188.9	V	4.01	13.0	587	4.5	7.0
		01/20/2005	0903	0.902	404.8	ADV	4.12	12.8	597	4.9	7.0
		05/03/2005	1015	1.182	530.5	ADV	4.16	12.4	587	4.8	7.0
		07/25/2005	1424	0.245	109.8	V	3.96	12.6	595	4.1	7.0
		10/26/2005	0943	0.221	99.2	V	3.91	13.1	634	3.6	6.9
		01/31/2006	1012	0.588	263.9	ADV	4.03	12.8	588	5.7	6.9
		04/26/2006	1710	0.326	146.3	P	nd	12.6	626	5.5	6.9
		07/25/2006	0851	0.557	250.0	ADV	4.01	12.8	537	5.2	6.9
		10/25/2006	1028	0.563	252.7	ADV	4.02	13.2	608	5.0	6.9
		01/23/2007	1000	0.881	395.4	ADV	4.02	13.0	592	4.4	7.0
		04/17/2007	0953	1.460	655.2	ADV	4.21	12.5	536	4.7	7.4
		07/16/2007	1536	0.356	159.8	ADV	nd	12.7	610	4.5	6.9
		10/17/2007	0915	0.084	37.7	ADV	3.79	13.2	603	5.4	6.9
		01/30/2008	1025	0.242	108.6	ADV	3.87	12.9	618	4.5	6.9
		04/23/2008	1145	1.500	673.2	ADV	4.25	12.6	567	6.0	7.0
		07/25/2008	1015	0.788	353.7	ADV	4.07	12.8	613	4.8	7.0
		10/21/2008	1430	0.149	66.9	ADV	nd	13.1	612	4.1	7.0

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft³/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft³/s	gal/min	Method					
47WS 2	Lockes Mill Spring	04/23/2003	1448	1.740	780.9	P	nd	12.1	600	8.1	6.6
		02/05/2004	1615	2.170	973.9	P	nd	12.3	583	6.6	7.4
		04/08/2004	1050	1.750	785.4	P	nd	12.0	580	6.7	7.1
		07/14/2004	1540	1.462	656.1	P	nd	12.3	596	7.4	7.1
		08/19/2004	1305	0.649	291.3	ADV	nd	12.3	540	6.1	7.0
		10/26/2004	1550	0.808	362.6	ADV	nd	12.5	592	6.4	7.4
		01/26/2005	1615	1.268	569.1	ADV	nd	11.2	610	6.9	7.7
		05/03/2005	1230	1.564	701.9	ADV	nd	12.3	604	7.8	7.0
		07/20/2005	1154	0.978	438.9	ADV	nd	12.4	609	9.4	6.8
		10/27/2005	1423	nd	nd	nd	nd	12.4	611	6.7	7.1
		02/01/2006	1424	nd	nd	nd	nd	12.1	597	6.8	7.1
		04/27/2006	1148	nd	nd	nd	nd	nd	nd	nd	nd
		07/26/2006	1511	nd	nd	nd	nd	12.4	624	6.7	7.0
		10/26/2006	1439	1.088	488.3	ADV	nd	12.5	605	6.7	6.9
		01/22/2007	1532	1.534	688.5	ADV	nd	12.5	621	6.4	7.0
		04/18/2007	1500	1.964	881.5	ADV	nd	11.6	587	7.3	7.2
		07/19/2007	1630	1.370	614.9	ADV	nd	12.4	623	6.4	7.0
		10/23/2007	1430	1.057	474.4	ADV	nd	12.5	622	9.2	6.9
		01/31/2008	1253	0.982	440.7	ADV	nd	12.2	608	6.4	6.9
		04/17/2008	1515	1.235	55.2	ADV	nd	12.4	622	6.8	7.1
		07/22/2008	1436	1.900	852.7	ADV	nd	12.6	600	7.1	7.0
		10/22/2008	1445	1.239	22.9	ADV	nd	12.4	610	7.8	7.1
47WS 10	Llewellyn Spring	08/12/2005	1130	0.168	75.4	ADV	nd	12.5	638	5.8	6.8
47WS 13	Lee's Spring	04/22/2003	1209	0.051	22.9	F	nd	11.8	33	8.9	4.7
		10/29/2003	1224	0.022	9.9	F	nd	12.4	50	8.4	5.5
		02/05/2004	1411	0.026	11.7	F	nd	11.6	32	9.4	6.0
		04/13/2004	1538	0.117	52.5	F	nd	11.5	50	9.4	5.6
		07/15/2004	1616	0.011	4.9	F	nd	12.1	32	9.8	5.4
		10/20/2004	1000	0.006	2.7	F	nd	12.4	36	8.4	5.5
		01/25/2005	1121	0.035	15.7	F	nd	12.3	41	9.4	5.6
		05/04/2005	1512	0.026	11.7	F	nd	11.7	31	9.8	5.5
		07/21/2005	0954	0.011	4.9	F	nd	12.1	35	8.7	5.1
		10/27/2005	1705	0.008	3.6	F	nd	12.6	59	9.0	5.7
		02/02/2006	0944	0.026	11.7	F	nd	12.3	34	8.8	5.6
		05/03/2006	1405	0.011	4.9	F	nd	nd	nd	nd	nd
		07/26/2006	1000	0.006	2.7	F	nd	12.3	33	8.7	5.5
		10/26/2006	1121	0.003	1.3	F	nd	11.8	49	1.1	5.8
		01/31/2007	1515	0.011	4.9	F	nd	12.0	46	9.0	6.0
		04/24/2007	1035	0.051	22.9	F	nd	11.9	33	9.5	5.5
		08/02/2007	1045	0.002	0.9	F	nd	12.3	28	8.3	5.5
		10/23/2007	1533	0.000	0.0	F	nd	nd	nd	nd	nd
		02/29/2008	1144	0.001	0.3	F	nd	8.5	67	10.7	8.0
		04/18/2008	1157	0.015	6.7	F	nd	11.9	66	8.6	5.7
		07/30/2008	1110	0.004	1.8	F	nd	12.5	33	8.2	5.8
		10/23/2008	1125	0.002	0.9	F	nd	11.2	39	9.1	6.2
47WS 14	Morgan Mill Spring	04/22/2003	1145	0.035	15.7	F	nd	11.2	105	8.4	4.8
		10/29/2003	1136	0.026	11.7	F	nd	13.5	147	7.8	5.9
		02/05/2004	1322	0.011	4.9	F	nd	11.9	89	8.7	6.0
		04/13/2004	1447	0.095	42.6	F	nd	10.7	128	9.1	5.7
		07/15/2004	1534	0.006	2.7	F	nd	12.4	76	3.0	5.4
		10/20/2004	0858	0.002	0.9	F	nd	13.4	90	3.8	5.5
		01/25/2005	1103	0.018	8.1	F	nd	12.6	98	8.7	5.7
		05/04/2005	1425	0.015	6.7	F	nd	11.3	88	9.1	5.6
		07/21/2005	0930	0.009	3.8	F	nd	12.5	86	6.0	5.0
		10/27/2005	1630	nd	nd	QW	nd	13.3	114	1.4	5.8

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft^3/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
47WS 15	Radfords Spring	04/22/2003	1247	0.018	8.1	F	nd	10.9	50	8.9	4.8
		10/29/2003	1200	0.011	4.9	F	nd	13.1	105	8.5	5.6
		02/05/2004	1345	0.006	2.7	F	nd	11.6	49	9.7	6.2
		04/13/2004	1519	0.069	31.0	F	nd	10.7	89	9.5	5.5
		07/15/2004	1552	0.004	1.8	F	nd	12.0	69	9.6	5.7
		10/20/2004	0930	0.002	0.9	F	nd	13.2	54	8.8	5.8
		01/25/2005	1033	0.011	4.9	F	nd	12.3	51	9.9	5.8
		05/04/2005	1445	0.009	3.8	F	nd	11.0	52	10.5	5.6
		07/21/2005	1021	0.006	2.7	F	nd	12.0	107	8.9	5.6
		10/27/2005	1538	0.004	1.8	F	nd	13.4	144	9.2	6.6
		02/02/2006	1015	0.009	3.8	F	nd	12.2	52	9.2	5.8
		05/03/2006	1325	0.006	2.7	F	nd	nd	nd	nd	nd
		07/26/2006	0925	0.002	0.9	F	nd	12.6	55	8.8	5.9
		10/26/2006	1040	0.002	0.9	F	nd	13.3	82	9.0	6.2
		01/31/2007	1543	0.006	2.7	F	nd	12.3	76	9.8	6.2
		04/24/2007	0940	0.015	6.7	F	nd	11.1	52	9.7	5.6
		08/02/2007	1008	0.0006	0.3	F	nd	nd	nd	nd	nd
		10/23/2007	1525	0.000	0.0		nd	nd	nd	nd	nd
		02/29/2008	1130	0.000	0.0		nd	nd	nd	nd	nd
		04/18/2008	1130	0.001	0.3	F	nd	11.1	63	9.5	5.8
		07/30/2008	1145	0.001	0.4	F	nd	12.6	46	8.3	5.7
		10/23/2008	1015	0.001	0.4	F	nd	nd	nd	nd	nd
47XS 2	Morgan Spring	04/23/2003	1143	2.270	1018.8	P	nd	12.1	535	8.4	6.7
		10/30/2003	1230	1.870	839.3	P	nd	nd	nd	nd	nd
		02/03/2004	1630	1.840	825.8	P	nd	nd	nd	nd	nd
		04/14/2004	1100	2.454	1101.4	P	nd	12.0	521	7.4	7.3
		07/14/2004	1110	2.030	911.1	P	4.85	12.1	526	7.2	5.7
		10/20/2004	1113	1.344	603.2	P	4.95	12.2	545	7.3	6.5
		01/19/2005	1406	1.654	742.3	ADV	5.24	12.1	562	8.0	7.1
		05/03/2005	1327	1.606	720.8	ADV	5.08	12.1	546	8.4	7.1
		07/20/2005	1018	0.740	332.1	ADV	5.43	12.1	547	9.7	6.8
		10/27/2005	0921	0.479	215.0	ADV	4.73	12.2	560	7.3	7.0
		04/27/2006	1107	0.775	347.8	P	nd	nd	nd	nd	nd
		07/26/2006	1600	0.521	233.8	ADV	5.16	12.3	559	7.9	7.1
		11/03/2006	1115	0.468	210.0	ADV	5.39	12.3	544	7.1	7.1
		02/01/2007	1025	0.858	385.1	ADV	5.59	12.2	573	7.5	7.1
		04/25/2007	1350	1.320	592.4	ADV	nd	12.2	549	7.9	7.1
		07/20/2007	1209	0.533	239.2	ADV	nd	12.3	552	7.5	7.1
		10/16/2007	1443	0.169	75.8	ADV	4.80	nd	nd	nd	nd
		01/29/2008	1643	0.295	132.4	ADV	4.85	12.1	545	7.4	7.0
		04/17/2008	1122	0.424	190.3	ADV	4.86	12.2	539	7.6	7.1
		07/22/2008	1535	1.020	457.8	ADV	nd	12.2	537	7.2	7.4
		10/22/2008	1250	0.239	107.3	ADV	4.81	12.2	530	8.3	7.2
47XS 3	Cool Spring	08/19/2004	1140	nd	nd	QW	nd	12.9	420	7.6	7.2
47XS 6	Clifton Farm Spring	04/23/2003	1018	1.920	861.7	P	nd	12.3	551	8.5	6.5
		10/29/2003	1625	0.938	421.0	P	nd	12.4	554	7.4	7.0
		02/04/2004	0940	0.840	377.0	P	nd	12.4	536	7.3	7.0
		04/08/2004	1432	0.942	422.8	P	nd	12.3	542	7.4	7.0
		07/14/2004	1305	0.863	387.3	P	nd	12.2	549	6.8	6.5
		08/20/2004	1015	0.745	334.4	P	nd	12.3	510	6.6	7.0
		10/20/2004	1350	0.599	268.8	ADV	nd	12.5	569	6.9	6.9
		01/19/2005	1430	0.472	211.8	ADV	nd	12.5	587	7.6	7.1
		05/03/2005	1415	0.715	320.9	ADV	nd	12.2	574	8.5	7.0

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft^3/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft^3/s	gal/min	Method					
47XS 6	Clifton Farm Spring (cont.)	07/22/2005	0932	0.510	228.9	ADV	nd	12.3	576	7.6	6.8
		10/27/2005	1030	0.245	110.0	ADV	nd	12.5	570	6.7	7.1
		02/01/2006	1551	0.334	149.9	ADV	nd	12.6	554	6.8	7.2
		04/27/2006	0932	0.331	148.6	P	nd	12.4	578	6.1	7.0
		07/25/2006	1421	0.235	105.5	ADV	nd	12.5	571	6.9	7.0
		10/27/2006	0929	0.109	48.9	ADV	nd	12.6	556	6.4	7.0
		01/25/2007	1108	0.300	134.6	ADV	nd	12.7	557	6.8	7.1
		01/25/2007	nd	0.296	132.8	P	nd	nd	nd	nd	nd
		04/16/2007	1325	0.449	201.5	ADV	nd	12.5	536	6.3	7.0
		07/25/2007	1706	0.254	114.0	ADV	nd	12.5	574	6.9	6.9
		10/16/2007	1545	0.108	48.5	ADV	nd	nd	Nd	nd	nd
		02/29/2008	1100	0.013	5.8	ADV	nd	9.4	585	9.3	7.6
		04/17/2008	1015	0.073	32.8	ADV	nd	12.5	571	6.8	7.1
		07/30/2008	1405	0.346	155.3	ADV	nd	12.5	580	7.1	7.0
		10/22/2008	1115	0.178	79.9	ADV	nd	12.6	564	6.3	7.1
47XS 11	Trapp Hill Spring	07/14/2004	nd	nd	nd	QW	nd	13.9	594	2.8	6.9
		10/20/2004	nd	nd	nd	QW	nd	nd	nd	nd	nd
		01/19/2005	nd	nd	nd	QW	nd	11.4	560	0.9	7.0
		05/03/2005	nd	nd	nd	QW	nd	11.2	573	8.1	7.2
		07/22/2005	nd	nd	nd	QW	nd	nd	nd	nd	nd
47XS 21	Byrd Spring #1	05/14/2003	nd	nd	nd	QW	nd	12.7	645	6.5	6.8
		10/29/2003	nd	nd	nd	QW	nd	13.6	622	5.8	6.9
		02/05/2004	nd	nd	nd	QW	nd	12.5	596	7.2	7.2
		04/08/2004	nd	nd	nd	QW	nd	11.7	594	7.2	7.0
		07/14/2004	nd	nd	nd	QW	nd	14.1	595	5.6	6.8
		10/20/2004	nd	nd	nd	QW	nd	13.8	597	6.3	6.9
		01/19/2005	nd	nd	nd	QW	nd	11.4	630	6.4	7.1
		05/03/2005	nd	nd	nd	QW	nd	12.1	613	6.8	7.0
		07/22/2005	nd	nd	nd	QW	nd	14.2	606	nd	6.8
47XS 22	Byrd Spring #2	05/14/2003	nd	nd	nd	QW	nd	13.0	671	6.5	6.8
		10/29/2003	nd	nd	nd	QW	nd	13.1	654	6.6	7.0
		02/05/2004	nd	nd	nd	QW	nd	11.0	608	5.5	7.2
		04/08/2004	nd	nd	nd	QW	nd	12.1	637	7.3	7.1
		07/14/2004	nd	nd	nd	QW	nd	13.2	615	6.7	6.9
		10/20/2004	nd	nd	nd	QW	nd	13.4	619	5.5	6.9
		01/19/2005	nd	nd	nd	QW	nd	10.7	646	6.4	7.1
		05/03/2005	nd	nd	nd	QW	nd	12.3	646	6.5	7.0
		07/22/2005	nd	nd	nd	QW	nd	nd	nd	nd	nd
47XS 23	Byrd Spring #3	05/14/2003	nd	nd	nd	QW	nd	12.6	631	7.7	6.7
		10/29/2003	nd	nd	nd	QW	nd	12.5	610	7.7	6.8
		01/19/2004	nd	nd	nd	QW	nd	12.5	632	7.7	7.0
		02/05/2004	nd	nd	nd	QW	nd	11.0	601	6.3	7.3
		04/08/2004	nd	nd	nd	QW	nd	12.5	597	7.3	7.1
		07/14/2004	nd	nd	nd	QW	nd	12.5	598	7.0	7.0
		10/20/2004	nd	nd	nd	QW	nd	12.5	610	7.0	6.9
		05/03/2005	nd	nd	nd	QW	nd	12.5	625	7.7	7.0
		07/22/2005	nd	nd	nd	QW	nd	12.5	618	nd	6.7
48WS 1	Horseshoe Curve Spring	05/14/2003	1500	0.043	19.3	V	nd	11.6	107	9.2	5.3
		10/30/2003	1200	0.028	12.6	V	nd	12.6	152	9.2	6.4
		01/22/2004	1545	0.013	5.8	V	nd	11.7	125	8.9	7.0
		04/06/2004	1200	0.067	30.1	V	nd	11.4	94	9.3	5.9
		07/14/2004	1015	0.011	4.9	V	nd	12.4	147	8.1	6.7
		10/19/2004	0925	0.002	1.0	V	nd	12.9	190	8.5	6.7

Appendix 4. Discharge and water-quality field properties from streams and springs in Clarke County, Virginia, 2003–2008.—Continued

[ft³/s, cubic feet per second; gal/min, gallons per minute; ft, feet; Temp., water temperature; ºC, 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: F, flume; ADV, acoustic doppler velocimeter; AA, standard AA velocity meter; P, pygmy velocity meter; V, volumetric. See figures 15 and 28 for location of stream and spring measurement sites]

USGS local no.	Name	Date	Time	Discharge			Gage height (ft)	Temp (°C)	Sp. Cond (µS/cm)	O_2 (mg/L)	pH
				ft³/s	gal/min	Method					
48WS 1	Horseshoe Curve Spring (cont.)	01/19/2005	1209	0.067	30.1	V	nd	12.0	104	10.2	5.9
		05/04/2005	1330	0.027	12.2	V	nd	11.6	120	10.8	6.0
		07/20/2005	0948	0.011	5.0	V	nd	12.3	146	9.4	5.6
		10/19/2005	1425	0.010	4.5	V	nd	13.2	213	7.2	6.2
		02/02/2006	1124	0.018	8.1	V	nd	12.0	130	8.9	6.0
		05/03/2006	nd	0.021	9.4	V	nd	nd	nd	nd	nd
		07/26/2006	1100	0.002	0.9	V	nd	12.8	111	8.6	6.3
		10/26/2006	nd	0.001	0.4	V	nd	nd	nd	nd	nd
		01/31/2007	1506	0.007	3.3	V	nd	nd	nd	nd	nd
		04/18/2007	1530	0.049	21.9	V	nd	nd	nd	nd	nd
		07/19/2007	1630	0.001	0.5	V	nd	nd	nd	nd	nd
		10/16/2007	1130	0.000	0.0	V	nd	nd	nd	nd	nd
		03/07/2008	1230	0.030	13.3	V	nd	nd	nd	nd	nd
		04/16/2008	1105	0.017	7.6	V	nd	nd	nd	nd	nd
		07/15/2008	1300	0.005	2.2	V	nd	nd	nd	nd	nd
		10/21/2008	1420	0.004	1.6	V	nd	nd	nd	nd	nd

Appendix 5. 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 springs in Clarke County, Virginia, 2003–2005.

[USGS, U.S. Geological Survey; rech. elev., recharge elevation is land surface in feet above NGVD 29; 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; ºC, 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; nd, not determined. See figure 28 for location of springs]

			USGS dissolved gases[a]									USGS[b]		Lamont-Doherty[c,d]		
USGS local no.	Date	Rech. elev. (ft)	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. (ºC)	N_2-Ar ex. air (cc_{STP}/L)	n	Neon x10^{-8} (cc_{STP}/g)	n	Neon x10^{-8} (cc_{STP}/g)	Neon ex. air (cc_{STP}/L)
46WS 1	08/13/2003	470	2	21.4	0.7	7.8	4.3	41.7	0.0000	12.0	4.4	2	30.1	1	23.13	2.02
46WS 2	08/20/2003	610	2	21.9	0.7	0.9	0.1	53.4	0.0002	11.5	4.7	1	29.3	1	26.53	3.89
46WS 3	08/13/2003	530	2	20.9	0.7	6.2	2.8	55.8	0.0000	11.4	3.7	2	27.1	1	29.20	5.32
46WS 5	08/11/2005	556	2	19.7	0.7	3.0	2.6	53.5	0.0000	11.3	2.4	1	29.1	1	22.80	1.80
46WS 7	08/11/2005	580	2	20.9	0.7	6.7	6.2	28.8	0.0000	11.1	3.6	1	29.2	1	33.37	7.61
46WS 10	08/11/2005	578	2	19.9	0.7	4.7	3.7	41.8	0.0000	11.2	2.6	1	28.7	1	6.14	–7.36
46WS 22	08/13/2003	540	2	20.7	0.7	2.6	0.7	48.7	0.0000	11.9	3.6	1	25.1	1	26.44	3.86
46XS 3	08/19/2004	599	2	20.2	0.7	3.7	0.1	72.6	0.0000	11.5	3.1	1	28.3	1	17.87	–0.87
46XS 7	08/11/2005	505	2	21.3	0.7	1.8	0.8	42.7	0.0000	11.9	4.2	1	30.2	1	25.28	3.21
46XS 8	08/13/2003	560	2	23.1	0.8	5.2	3.3	73.9	0.0000	9.5	5.2	2	27.3	1	26.58	3.69
46XS 9	08/19/2004	591	2	21.7	0.7	2.6	0.1	53.0	0.0000	12.1	4.8	1	30.7	1	26.35	3.84
47WS 2	08/19/2004	441	2	19.8	0.7	6.1	1.6	51.6	0.0000	12.2	2.8	1	26.7	1	24.32	2.68
47WS 10	08/12/2005	540	2	18.8	0.7	5.8	5.8	58.0	0.0000	11.7	1.6	1	27.8	1	20.80	0.74
47XS 3	08/19/2004	420	2	19.2	0.7	7.2	1.0	31.0	0.0000	11.3	1.9	1	26.8	1	24.32	2.58
47XS 6	08/19/2004	531	2	19.1	0.7	6.6	2.3	48.9	0.0000	12.4	2.2	1	27.0	1	22.42	1.69

[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 6. Concentrations of chlorofluorocarbons and sulfur hexafluoride in North American air, 1940–2006.

[CFC-11, (trichlorofluoromethane, $CFCl_3$); 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
1940.0	0.000	0.000	0.000	0.000
1940.5	0.000	0.396	0.000	0.000
1941.0	0.000	0.478	0.000	0.000
1941.5	0.000	0.559	0.000	0.000
1942.0	0.000	0.661	0.000	0.000
1942.5	0.000	0.762	0.000	0.000
1943.0	0.000	0.884	0.000	0.000
1943.5	0.000	1.006	0.000	0.000
1944.0	0.000	1.179	0.000	0.000
1944.5	0.000	1.342	0.000	0.000
1945.0	0.048	1.555	0.000	0.000
1945.5	0.055	1.769	0.000	0.000
1946.0	0.069	2.155	0.000	0.000
1946.5	0.081	2.531	0.000	0.000
1947.0	0.109	3.110	0.000	0.000
1947.5	0.139	3.700	0.000	0.000
1948.0	0.199	4.371	0.000	0.000
1948.5	0.248	5.041	0.000	0.000
1949.0	0.338	5.763	0.000	0.000
1949.5	0.427	6.485	0.000	0.000
1950.0	0.556	7.277	0.000	0.000
1950.5	0.676	8.070	0.000	0.000
1951.0	0.854	8.934	0.000	0.000
1951.5	1.023	9.798	0.000	0.000
1952.0	1.282	10.693	0.000	0.000
1952.5	1.530	11.597	0.000	0.054
1953.0	1.878	12.593	0.000	0.054
1953.5	2.216	13.599	0.491	0.054
1954.0	2.643	14.738	0.530	0.055
1954.5	3.060	15.876	0.579	0.055
1955.0	3.577	17.147	0.629	0.055
1955.5	4.094	18.417	0.687	0.056
1956.0	4.739	19.901	0.746	0.056
1956.5	5.375	21.385	0.805	0.057
1957.0	6.091	23.062	0.874	0.058
1957.5	6.806	24.749	0.943	0.059
1958.0	7.462	26.498	1.021	0.060
1958.5	8.108	28.256	1.110	0.061
1959.0	8.764	30.218	1.188	0.062
1959.5	9.419	32.179	1.287	0.064
1960.0	10.294	34.517	1.385	0.066
1960.5	11.168	36.855	1.493	0.069
1961.0	12.291	39.477	1.601	0.072
1961.5	13.424	42.089	1.728	0.076
1962.0	14.854	45.098	1.856	0.079
1962.5	16.275	48.096	1.994	0.084
1963.0	18.024	51.613	2.141	0.088
1963.5	19.763	55.130	2.308	0.095
1964.0	21.839	59.226	2.475	0.100
1964.5	23.906	63.312	2.661	0.110
1965.0	26.251	67.916	2.848	0.120
1965.5	28.586	72.530	3.064	0.130
1966.0	31.199	77.643	3.280	0.140
1966.5	33.802	82.755	3.526	0.150
1967.0	36.743	88.518	3.771	0.160
1967.5	39.694	94.281	4.056	0.180
1968.0	43.033	100.735	4.331	0.190
1968.5	46.371	107.179	4.655	0.200
1969.0	50.246	114.355	4.979	0.210
1969.5	54.121	121.521	5.352	0.220
1970.0	58.513	129.347	5.726	0.230
1970.5	62.895	137.163	6.148	0.250
1971.0	67.674	145.508	6.570	0.260
1971.5	72.463	153.852	7.051	0.270
1972.0	77.839	162.919	7.543	0.280
1972.5	83.214	171.995	8.102	0.300
1973.0	89.354	182.027	8.652	0.320
1973.5	95.495	192.059	9.291	0.340
1974.0	102.202	202.884	9.929	0.360
1974.5	108.908	213.698	10.666	0.390
1975.0	114.572	224.025	11.392	0.420
1975.5	122.104	234.341	12.227	0.450
1976.0	128.920	244.190	13.072	0.480
1976.5	135.130	254.039	14.024	0.520
1977.0	142.085	263.268	14.987	0.550
1977.5	146.705	272.497	16.087	0.590
1978.0	149.964	282.407	17.187	0.630
1978.5	156.502	292.855	18.444	0.680
1979.0	159.801	298.090	19.701	0.730
1979.5	162.642	301.190	21.145	0.770
1980.0	168.584	311.212	22.588	0.830
1980.5	172.807	317.422	24.150	0.880
1981.0	175.996	322.737	25.721	0.940
1981.5	179.732	333.796	27.342	0.990
1982.0	183.846	343.604	28.962	1.050
1982.5	188.347	352.721	30.759	1.120
1983.0	193.295	361.594	32.547	1.180
1983.5	198.015	372.236	34.796	1.250
1984.0	201.939	378.589	37.035	1.320
1984.5	206.023	386.232	39.696	1.390
1985.0	211.229	395.380	42.348	1.470
1985.5	217.261	403.257	45.177	1.540
1986.0	222.984	414.620	48.015	1.620
1986.5	227.912	423.463	51.128	1.700
1987.0	233.466	433.586	54.241	1.790
1987.5	241.047	449.310	57.738	1.870
1988.0	248.648	459.474	61.224	1.960
1988.5	253.964	469.089	64.868	2.050
1989.0	257.442	476.671	68.521	2.150
1989.5	261.983	484.030	71.517	2.240
1990.0	265.758	493.523	74.512	2.340
1990.5	266.861	497.131	76.633	2.440
1991.0	269.216	503.382	78.755	2.540
1991.5	270.100	508.779	80.287	2.650
1992.0	271.521	517.703	81.514	2.750
1992.5	272.217	520.468	82.300	2.860
1993.0	272.346	522.958	82.693	2.970
1993.5	272.445	526.007	82.987	3.090
1994.0	272.793	528.162	83.184	3.200
1994.5	272.187	533.305	83.528	3.320
1995.0	272.033	534.687	83.557	3.440
1995.5	271.327	534.789	83.650	3.570
1996.0	271.024	535.744	83.550	3.690
1996.5	269.514	537.406	83.500	3.820
1997.0	269.037	539.317	83.400	3.950
1997.5	268.009	540.882	83.300	4.080
1998.0	267.263	542.117	83.150	4.220
1998.5	266.310	543.728	83.000	4.320
1999.0	265.619	544.003	82.800	4.430
1999.5	264.188	544.587	82.600	4.540
2000.0	263.841	545.055	82.300	4.650
2000.5	263.234	546.269	82.100	4.770
2001.0	261.843	546.515	81.700	4.890
2001.5	260.795	546.102	81.300	5.010
2002.0	260.120	545.299	81.000	5.140
2002.5	258.569	544.724	80.600	5.270
2003.0	258.137	543.306	80.250	5.400
2003.5	256.051	542.758	79.900	5.530
2004.0	255.057	542.148	79.550	5.670
2004.5	253.467	541.233	79.100	5.780
2005.0	252.374	540.318	78.750	5.890
2005.5	250.983	539.698	78.400	6.000
2006.0	249.592	538.692	78.100	6.110
Mod.	284.000	550.000	87.000	6.200
Cont.	294.000	570.000	92.000	6.300

Appendix 7. Summary of average chlorofluorocarbon concentrations and calculated atmospheric partial pressures in water samples from springs in Clarke County, Virginia, 2003–2005.

[CFC-11, (trichlorofluoromethane, $CFC1_3$); CFC-12, (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$); pg/kg, picograms per kilogram; N_2-Ar Rech. temp., nitrogen-argon recharge temperature; ºC, degrees Celsius; rech. elev., recharge elevation in feet above NGVD 29; pptv, parts per trillion by volume; nd, not determined. See figure 28 for location of springs]

USGS local no.	Date	Average concentration in water (pg/kg)[a]			N_2-Ar rech. temp. (ºC)	Rech. elev. (ft)	Average calculated atmospheric partial pressure (pptv)		
		CFC-11	CFC-12	CFC-113			CFC-11	CFC-12	CFC-113
46WS 1	08/13/2003	1,936.4	314.0	71.9	12.0	470	757.5	516.3	65.9
46WS 2	08/20/2003	431.9	297.2	78.2	11.5	600	165.5	479.0	69.9
46WS 3	08/13/2003	873.5	359.5	79.7	11.4	530	332.6	580.3	71.2
46WS 5	08/11/2005	508.1	334.2	67.9	11.3	556	193.2	543.5	60.9
46WS 7	08/11/2005	593.0	307.3	74.4	11.1	580	222.6	490.4	65.4
46WS 10	08/11/2005	588.1	324.9	76.8	11.2	578	222.5	525.4	68.5
46WS 22	08/13/2003	1,235.6	404.4	86.4	11.9	540	484.3	669.9	79.7
46XS 3	08/19/2004	2,689.8	360.2	82.9	11.5	599	1,034.0	589.2	75.1
46XS 7	08/11/2005	376.5	243.1	42.6	11.9	505	146.9	399.4	39.0
46XS 8	08/13/2003	637.3	426.1	85.6	9.5	560	218.1	620.7	67.6
46XS 9	08/19/2004	667.5	353.8	78.8	12.1	591	263.7	585.4	72.8
47WS 2	08/19/2004	721.2	371.1	80.8	12.2	441	286.2	624.6	75.8
47WS 10	08/12/2005	629.1	477.9	78.5	11.7	540	244.7	797.2	72.5
47XS 3	08/19/2004	509.8	262.6	65.4	11.3	441	193.3	427.4	58.7
47XS 6	08/19/2004	803.8	367.0	80.2	12.4	531	324.0	629.1	76.7

[a] Water samples for the determination of chlorofluorocarbons in the U.S. Geological Survey Chlorofluorocarbon 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 8. Summary of average chlorofluorocarbon-based model piston-flow apparent recharge dates, ages, and uncertainties in water samples from springs in Clarke County, Virginia, 2003–2005.

[CFC-11, (trichlorofluoromethane, $CFC1_3$); CFC-12, (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$); C, contaminated (sample concentration higher than that of water in equilibrium with modern North American air); NP, not possible; 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 6. Numbers in parentheses indicate possible recharge years before and after atmospheric peak concentration. See figure 28 for location of springs]

USGS local no.	Date	Model piston-flow average apparent recharge date[a]						Model piston-flow average apparent age and uncertainity[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)
46WS 1	08/13/2003	C	C	1991.5	NP	1988.5	NP	C	C	12.1 ± 3.9	NP	15.1 ± 0.5	NP
46WS 2	08/20/2003	1979.5	NP	1989.0	NP	1989.0	NP	24.1 ± 1.0	NP	14.6 ± 1.5	NP	14.6 ± 0.5	NP
46WS 3	08/13/2003	C	C	C	C	1989.0	NP	C	C	C	C	14.6 ± 0.8	NP
46WS 5	08/11/2005	1982.5	NP	1996.5	2006.0	1987.5	NP	23.1 ± 1.3	NP	9.1 ± 4.2	NP	18.1 ± 0.5	NP
46WS 7	08/11/2005	1985.5	NP	1989.5	NP	1988.5	NP	20.1 ± 1.3	NP	16.1 ± 1.8	NP	17.1 ± 0.5	NP
46WS 10	08/11/2005	1985.5	NP	1993.0	NP	1988.5	NP	20.1 ± 1.3	NP	12.6 ± 1.8	NP	17.1 ± 0.8	NP
46WS 22	08/13/2003	C	C	C	C	1991.0	2004.0	C	C	C	C	12.6 ± 2.9	NP
46XS 3	08/19/2004	C	C	C	C	1990.0	NP	C	C	C	C	14.6 ± 1.0	NP
46XS 7	08/11/2005	1977.5	NP	1985.0	NP	1984.0	NP	28.1 ± 0.8	NP	20.6 ± 1.0	NP	21.6 ± 0.5	NP
46XS 8	08/13/2003	1985.5	NP	C	C	1988.5	NP	18.1 ± 1.0	NP	C	C	15.1 ± 0.8	NP
46XS 9	08/19/2004	1989.5	2000.5	C	C	1989.5	NP	15.1 ± 3.4	4.1 ± 6.0	C	C	15.1 ± 0.8	NP
47WS 2	08/19/2004	Mod.	Mod.	C	C	1990.0	NP	Mod.	C	C	C	14.6 ± 0.8	NP
47WS 10	08/12/2005	1987.5	NP	C	C	1989.5	NP	18.1 ± 1.3	NP	C	C	16.1 ± 1.0	NP
47XS 3	08/19/2004	1983.0	NP	1986.5	NP	1987.5	NP	21.6 ± 1.3	NP	18.1 ± 0.8	NP	17.1 ± 0.5	NP
47XS 6	08/19/2004	C	C	C	C	1990.5	NP	C	C	C	C	14.1 ± 1.0	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 9. Summary of average chlorofluorocarbon-based model ratio apparent recharge dates, ages, and uncertainties in water samples from springs in Clarke County, Virginia, 2003–2005.

[CFC-11, (trichlorofluoromethane, $CFC1_3$); CFC-12, (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$); ºC, degrees Celsius; C, contaminated, sample concentration higher than that of water in equilibrium with modern North American air; Apparent age uncertainties are based on changes in age resulting from uncertainty in nitrogen-argon (N_2-Ar) recharge temperature of ±1 ºC. Dates and ages are based on the North American air data in appendix 6. See figure 28 for location of 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
46WS 1	08/13/2003	NP	NP	NP	NP	NP	NP
46WS 2	08/20/2003	NP	NP	NP	NP	NP	NP
46WS 3	08/13/2003	NP	NP	NP	NP	NP	NP
46WS 5	08/11/2005	NP	NP	10.1	NP	NP	72.8
46WS 7	08/11/2005	NP	NP	14.6	NP	NP	83.1
46WS 10	08/11/2005	NP	NP	10.6 ± 0.8	NP	NP	82.0
46WS 22	08/13/2003	NP	NP	NP	NP	NP	NP
46XS 3	08/19/2004	NP	NP	NP	NP	NP	NP
46XS 7	08/11/2005	NP	NP	17.1 ± 0.3	NP	NP	60.1
46XS 8	08/13/2003	NP	NP	8.1	NP	NP	80.9
46XS 9	08/19/2004	NP	NP	NP	NP	NP	NP
47WS 2	08/19/2004	NP	NP	NP	NP	NP	NP
47WS 10	08/12/2005	NP	NP	14.6 ± 0.3	NP	NP	92.1
47XS 3	08/19/2004	NP	16.6 ± 0.3	11.6 ± 0.8	NP	95.9	71.0
47XS 6	08/19/2004	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 10. Summary of average sulfur hexafluoride data in water samples from springs in Clarke County, Virginia, 2003–2005.

[n, number of samples averaged; SF_6, sulfur hexafluoride; fmol/L, femtomoles per liter; ºC, degrees Celsius; pptv, parts per trillion by volume; cc/L, cubic centimeters per liter; ex air, excess air; C, contaminated (sample SF_6 concentration greater than that of water in equilibrium with modern air); Meas. st. dev., standard deviation of measured values; Rtemp, recharge temperature; nd, not determined; Apparent age uncertainties are based on standard deviation of measured ages, changes in recharge temperature (±1 ºC) and excess air (±1 cc/L). Apparent recharge dates and ages are based on the North American air data in appendix 6. See figure 28 for location of springs]

USGS local no.	Date	n	SF_6 concentration in water (fmol/L)[a]	Recharge temperature (ºC)	SF_6 partial pressure (pptv)	Excess air (cc/L)	Model SF_6 partial pressure remove ex 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 ºC (years)	Excess air ±1 cc/L (years)
46WS 1	08/13/2003	2	5.685	12.0	17.48	4.4	11.27	C	C	nd	nd	nd
46WS 2	08/20/2003	2	2.708	11.5	8.21	4.7	5.18	2002.0	1.6	1.1	0.7	2.1
46WS 3	08/13/2003	2	2.869	11.4	8.64	3.7	5.95	2004.5	–0.9	nd	nd	nd
46WS 5	08/11/2005	2	2.204	11.3	4.09	2.4	2.12	1988.5	17.1	2.8	0.4	0.7
46WS 7	08/11/2005	2	6.627	11.1	13.03	3.6	6.59	C	C	nd	nd	nd
46WS 10	08/11/2005	2	5.291	11.2	9.93	2.6	5.11	2001.5	4.1	0.4	0.7	1.1
46WS 22	08/13/2003	2	2.679	11.9	8.24	3.6	5.67	2004.0	–0.4	0.4	1.1	nd
46XS 3	08/19/2004	2	2.685	11.5	8.14	3.1	5.88	2004.5	0.1	nd	nd	nd
46XS 7	08/11/2005	2	2.232	11.9	4.50	4.2	2.17	1989.0	16.6	1.8	0.4	0.7
46XS 8	08/13/2003	2	2.431	9.5	6.77	5.2	4.25	1998.0	5.6	0.0	0.7	1.8
46XS 9	08/19/2004	2	2.080	12.0	6.43	4.8	4.00	1997.0	7.6	3.5	0.7	1.8
47WS 2	08/19/2004	2	8.346	12.2	25.87	2.8	19.10	C	C	nd	nd	nd
47WS 10	08/12/2005	2	3.895	11.7	6.95	1.6	3.60	1995.5	10.1	0.7	0.4	0.7
47XS 3	08/19/2004	2	1.961	11.3	5.86	1.9	4.76	2000.0	4.6	0.4	1.1	2.8
47XS 6	08/19/2004	2	2.131	12.3	6.65	2.2	5.20	2002.0	2.6	0.7	0.7	2.8

[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 11. Summary of tritium, dissolved helium, and dissolved neon data in water samples from springs in Clarke County, Virginia, 2003–2005.

[^3H, tritium; TU, tritium unit (1 TU = 1 atom of ^3H in 10^{18} atoms of hydrogen (H); 2σ, 2 standard deviations; USGS, U.S. Geological Survey Low-Level ^3H Laboratory in Menlo Park, CA; LDEO, Noble Gas Laboratory at Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY; cc_{STP}/g, cubic centimeters at standard temperature and pressure per gram; 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., terrigenic; nd, not determined. See figure 28 for location of 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 $\times 10^{-8}$ (cc_{STP}/g)[c]	ΔNe (%)[c]	Terr. He (%)
					USGS[b]	LDEO[c]					
46WS 1	08/13/2003	7.5	0.5	USGS	8.350	5.893	30.17	4.32	23.132	18.87	5.2
46WS 2	08/20/2003	8.1	0.5	USGS	7.400	6.410	42.03	0.39	26.532	36.41	nd
46WS 3	08/13/2003	8.1	0.5	USGS	6.900	7.332	61.91	2.42	29.195	49.52	nd
46WS 5	08/11/2005	7.1	0.6	USGS	7.595	5.660	25.05	–2.77	22.801	16.76	nd
46WS 7	08/11/2005	7.0	0.6	USGS	7.234	8.666	91.51	8.91	33.366	70.78	nd
46WS 10	08/11/2005	6.8	0.5	USGS	7.517	1.710	–62.20	2.18	6.141	–68.54	60.8
46WS 22	08/13/2003	7.2	0.4	USGS	8.200	6.853	51.70	–2.15	26.443	36.11	4.6
46XS 3	08/19/2004	6.9	0.4	USGS	7.310	4.390	–2.77	1.46	17.869	–8.17	7.6
46XS 7	08/11/2005	8.3	0.6	USGS	17.804	15.240	237.00	–38.90	25.279	30.00	59.3
46XS 8	08/13/2003	7.9	0.2	USGS	9.500	6.439	41.18	1.47	26.576	33.82	nd
46XS 9	08/19/2004	8.1	0.5	USGS	7.930	6.191	37.42	3.12	26.354	36.15	nd
47WS 2	08/19/2004	7.5	0.5	USGS	7.370	6.100	34.71	1.25	24.319	25.06	nd
47WS 10	08/12/2005	7.3	0.6	USGS	7.558	4.866	7.64	1.30	20.804	6.90	nd
47XS 3	08/19/2004	6.9	0.5	USGS	7.030	4.660	2.45	–2.03	24.320	23.94	nd
47XS 6	08/19/2004	6.6	0.5	USGS	7.260	5.318	17.93	–0.04	22.423	15.90	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 12. Summary of apparent tritium/helium-3 ages in water samples from springs in Clarke County, Virginia, 2003–2005.

[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; Y, yes, terrigenic helium correction needed; N, no, terrigenic helium correction not needed; nd, not determined; All apparent age calculations based on recharge temperatures determined for the respective samples. See figure 28 for location of 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)
46WS 1	08/13/2003	3.9	0.3	6.9	0.5	Y	6.9	0.5
46WS 2	08/20/2003	1.2	0.2	–0.5	0.4	N	1.2	0.2
46WS 3	08/13/2003	2.9	0.3	3.1	1.0	N	2.9	0.3
46WS 5	08/11/2005	–1.2	0.2	1.5	0.3	N	nd	nd
46WS 7	08/11/2005	9.2	0.7	10.5	0.7	N	9.2	0.7
46WS 10	08/11/2005	1.6	0.1	11.8	0.6	Y	11.8	0.6
46WS 22	08/13/2003	–1.0	0.3	3.1	0.5	Y	3.1	0.5
46XS 3	08/19/2004	1.9	0.3	5.8	0.4	Y	5.8	0.4
46XS 7	08/11/2005	nd	nd	19.9	0.9	Y	19.9	0.9
46XS 8	08/13/2003	2.1	0.2	1.4	0.5	N	2.1	0.2
46XS 9	08/19/2004	3.0	0.3	–0.7	0.5	N	3.0	0.3
47WS 2	08/19/2004	1.9	0.2	3.8	0.4	N	1.9	0.2
47WS 10	08/12/2005	1.8	0.2	1.3	0.4	N	1.8	0.2
47XS 3	08/19/2004	nd	nd	nd	nd	nd	nd	nd
47XS 6	08/19/2004	1.1	0.3	0.0	0.5	N	1.1	0.3

Appendix 13. Summary of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopic data in water samples from springs in Clarke County, Virginia, 2003–2005.

[per mil, parts per thousand; $\delta = [(R_{sample}/R_{standard}) - 1] \times 1{,}000$, where R is an isotope ratio; 2σ, 2 standard deviations; The 2σ precision of oxygen- and hydrogen-isotope results is 0.2 and 1.5 per mil, respectively; *d*, deuterium excess. See figure 28 for location of springs]

USGS local no.	Date	$\delta^{18}O$ (per mil)[a]	$\delta^{2}H$ (per mil)[a]	*d* (per mil)[b]
46WS 1	08/13/2003	–8.11	–51.3	13.6
46WS 2	08/20/2003	–8.14	–50.8	14.3
46WS 3	08/13/2003	–8.26	–51.7	14.4
46WS 5	08/11/2005	–7.59	–47.0	13.7
46WS 7	08/11/2005	–7.99	–49.6	14.3
46WS 10	08/11/2005	–7.95	–49.6	14.0
46WS 22	08/13/2003	–7.98	–50.0	13.8
46XS 3	08/19/2004	–8.14	–49.9	15.2
46XS 7	08/11/2005	–7.99	–48.6	15.3
46XS 8	08/13/2003	–8.36	–53.1	13.8
46XS 9	08/19/2004	–7.89	–48.9	14.2
47WS 2	08/19/2004	–8.11	–50.1	14.8
47WS 10	08/12/2005	–8.10	–49.2	15.6
47XS 3	08/19/2004	–8.13	–49.5	15.5
47XS 6	08/19/2004	–8.11	–50.3	14.6

[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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