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Hydrogeology and Ground-Water Availability in the Carbonate Aquifer System of Frederick County, Virginia

Scientific Investigations Report 2005-5161

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

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Gale A. Norton, Secretary

U.S. Geological Survey
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Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
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)
	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)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the North 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.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Hydrogeology and Ground-Water Availability in the Carbonate Aquifer System of Frederick County, Virginia

By George E. Harlow, Jr., Randall C. Orndorff, David L. Nelms, David J. Weary, and Roger M. Moberg

Abstract

The carbonate aquifer system of the northern Shenandoah Valley provides an important water supply to local communities, including Frederick County, Va., which depends on ground water as a source of water supply. The county and surrounding area are undergoing increased urbanization, and increased demands on the carbonate aquifer system are expected. A study was conducted between October 2000 and March 2004 by the U.S. Geological Survey (USGS), in cooperation with the County of Frederick, Va., to describe the hydrogeology and ground-water availability in the carbonate aquifer system underlying the county. The study area encompasses about 25 percent (105 square miles) of the county that is underlain by carbonate bedrock.

The carbonate aquifer system of Frederick County is in the Shenandoah Valley region of the Valley and Ridge Physiographic Province. Approximately 10,000 feet of folded and fractured Middle Cambrian to Upper Ordovician sedimentary rocks are exposed and are overlain by Pleistocene(?) and Holocene surficial deposits. All geologic units in the study area are considered to be aquifers. The geologic units are generally unconfined, fractured-rock aquifers that are recharged by precipitation and discharge locally to streams and springs, and by evapotranspiration.

Stream density in the carbonate study area is less than in the remainder of the county, which is underlain by siliciclastic rock units. Most streams flow normal to strike (from the northwest towards the southeast) across the study area. These streams are characterized by shallow incisement and are usually limited to a single stream channel. In the southern third of the study area, streams flow parallel to strike (from the northeast towards the southwest) towards the deeply intrenched Cedar Creek. Springs are commonly located at the start of flows for all streams in the carbonate study area, and spring discharges are often a large portion of the streamflow (especially during drought conditions).

The general direction of ground-water flow is from the hills in the west of the study area into and across the carbonate valley. A ground-water divide may occur north of Round Hill in the vicinity of the Apple Pie Ridge fault where the North Mountain fault zone cuts out the resistant Silurian and Devonian sandstone units and results in surface drainage from the carbonate rocks toward the west and out of the carbonate valley.

Estimates of effective ground-water recharge for 2001–02 range from 5.8 to 6.2 inches in the Cedar Creek Basin, with base flow accounting for between 60 and 64 percent of streamflow, and from 3.2 to 3.8 inches in the Opequon Creek Basin, with base flow accounting for between 86 and 92 percent of streamflow.

Water budgets calculated for 2001, a year of below-normal precipitation (33.1 inches), and 2002, a year of above-normal precipitation (41.2 inches), include a streamflow of 9.0 inches in 2001 and 9.2 inches in 2002 in Cedar Creek. Evapotranspiration ranged from 25.9 to 30.7 inches, and ground-water storage decreased 1.8 inches in 2001 and increased 1.3 inches in 2002. Streamflow was 3.7 inches in 2001 and 2002 in Opequon Creek. Evapotranspiration ranged from 29.8 to 37.5 inches, and ground-water storage decreased 0.4 inch in 2001 and did not change in 2002.

Introduction

Frederick County, Va., depends on ground water as a source of water supply. The county and surrounding area are undergoing increased urbanization as part of development around the City of Winchester and along U.S. Route 11 and Interstate 81. Ground water is a major source of supply in the surrounding area as well, and increased demands on the aquifer system are expected in the future. The amount of ground water available to meet these future demands, however, is not quantified. Consequently, the U.S. Geological Survey (USGS), in cooperation with the County of Frederick, Va., began a long-term (approximately 5-year) investigation of the hydrogeology and ground-water availability in the carbonate aquifer system of Frederick County in October 2000.

Purpose and Scope

This report describes the hydrogeology and ground-water availability in the carbonate aquifer system of Frederick County, Va., and provides hydrogeologic information that can be used to guide the development and management of this important water resource. Water budgets that include effective ground-water recharge are presented for both the Cedar and Opequon Creek Basins for 2001–02.

This report also includes recent geologic mapping of the study area and a description of geologic units that form the aquifer system. All references that could be identified on the geology and hydrology of the carbonate aquifer system of Frederick County through 2003 were consulted.

Description of Study Area

Frederick County is within the Valley and Ridge Physiographic Province of Virginia (Fenneman, 1938, p. 691), at the northern end of the Shenandoah Valley, about 75 mi west of Washington, D.C. It is bordered by West Virginia to the north and west, Shenandoah and Warren Counties to the south, and Clarke County to the east. Frederick County encompasses about 425 mi^2 (including the independent City of Winchester) and in 2000 had a population of about 59,200. The study area encompasses the 25 percent (105 mi^2) of the county that is underlain by carbonate rock and is bounded on the east by the Martinsburg Formation and on the west by the North Mountain fault zone (fig. 1). This is a karst area characterized by sinkholes, caves, and underground drainage that result from the dissolution of the soluble carbonate bedrock.

Conceptual Model of Ground-Water Flow

The ground-water-flow system in the Valley and Ridge region of Virginia is complex. The region is underlain by sedimentary rocks that were originally deposited as flat-lying layers separated by planar surfaces (bedding planes). However, over time the rocks have been bent (folded), cracked (fractured), sheared (faulted), and weathered, resulting in a highly deformed bedrock overlain by a variably thick layer of unconsolidated rock material (regolith). The deformed bedrock is composed of limestone and dolostone (carbonate rock), and sandstone, siltstone, and shale (siliciclastic rock).

Water (precipitation) that enters the regolith flows through spaces between the grains, pebbles, and rocks to recharge the water table. When bedrock is encountered, water flows through the fractures, faults, and open bedding planes that are the result of deformation. The orientation and connections between these features control the ground-water-flow path. In areas underlain by deformed carbonate bedrock, these features can be enlarged/enhanced by dissolution of the rock by the water flowing through.

Wolfe and others (1997, p. 27) developed a conceptual model of ground-water flow in the Valley and Ridge karst region of Tennessee that can also be applied to the carbonate aquifer system underlying Frederick County (fig. 2). They note that geologic structure—major folds and thrust faults—controls the spatial arrangement of the various rock units and may allow dissolution openings and active karst development to moderate depths.

The carbonate aquifer system in Frederick County is recharged by infiltration of precipitation across the area. In areas with appreciable accumulations of regolith, substantial quantities of ground water can be stored in the regolith and the dominant direction of ground-water flow may be normal to strike toward adjacent valley bottoms and streams (Bailey and Lee, 1991). However, relict bedding structures in regolith and open bedding planes in bedrock may result in a dominant direction of ground-water flow that is parallel to strike in some areas. Burton and others (2002, p. 256) studied ground-water flow in moderately dipping siliciclastic rocks in a local watershed in the Valley and Ridge of Pennsylvania and concluded that "ground-water flow paths parallel to the dip direction in well-developed bedding-plane partings in fractured bedrock result in higher proportions of young water than that for flowpaths opposite the dip direction." This result may also apply to the moderately dipping fractured carbonate bedrock in the study area.

Geomorphic Features

Stream morphology is affected by the underlying geology and the aquifer system. Stream density in the carbonate study area is less than in the remainder of the county, which is underlain by siliciclastic rock units (fig. 1). Most streams flow normal to strike (from the northwest towards the southeast) across the study area. These streams are characterized by shallow incisement and are usually limited to a single stream channel. In the southern third of the study area, streams flow parallel to strike (from the northeast towards the southwest) towards the deeply intrenched Cedar Creek. Springs are commonly located at the start of flows for these streams, and spring discharges often provide a substantial part of the streamflow (especially during drought conditions). Travertine-marl deposits form when carbonate minerals precipitate after ground water discharges from some of these springs to the streams. These deposits normally occur as extensive low-relief deposits or form bluffs or falls in active stream channels (Hubbard and Herman, 1990, p. 1). The low-relief marl deposits located just north of Winchester, along Redbud Run, have been mined for agricultural lime (Sweet and Hubbard, 1990, p. 135), and a large travertine deposit is located on the northeast bank of Cedar Creek at the mouth of Fawcett Run (fig.1). This deposit has formed about 2,700 ft downstream from Marlboro Spring and where Fawcett Run drops approximately 15 ft at a waterfall into Cedar Creek (Orndorff and Goggin, 1994).

Subsidence sinkholes dot the landscape of the study area and are larger and more abundant in the southernmost part, near the intrenched channel of Cedar Creek northwest of Middletown (Orndorff and Goggin, 1994). The few mapped cave entrances in the study area are also located here.

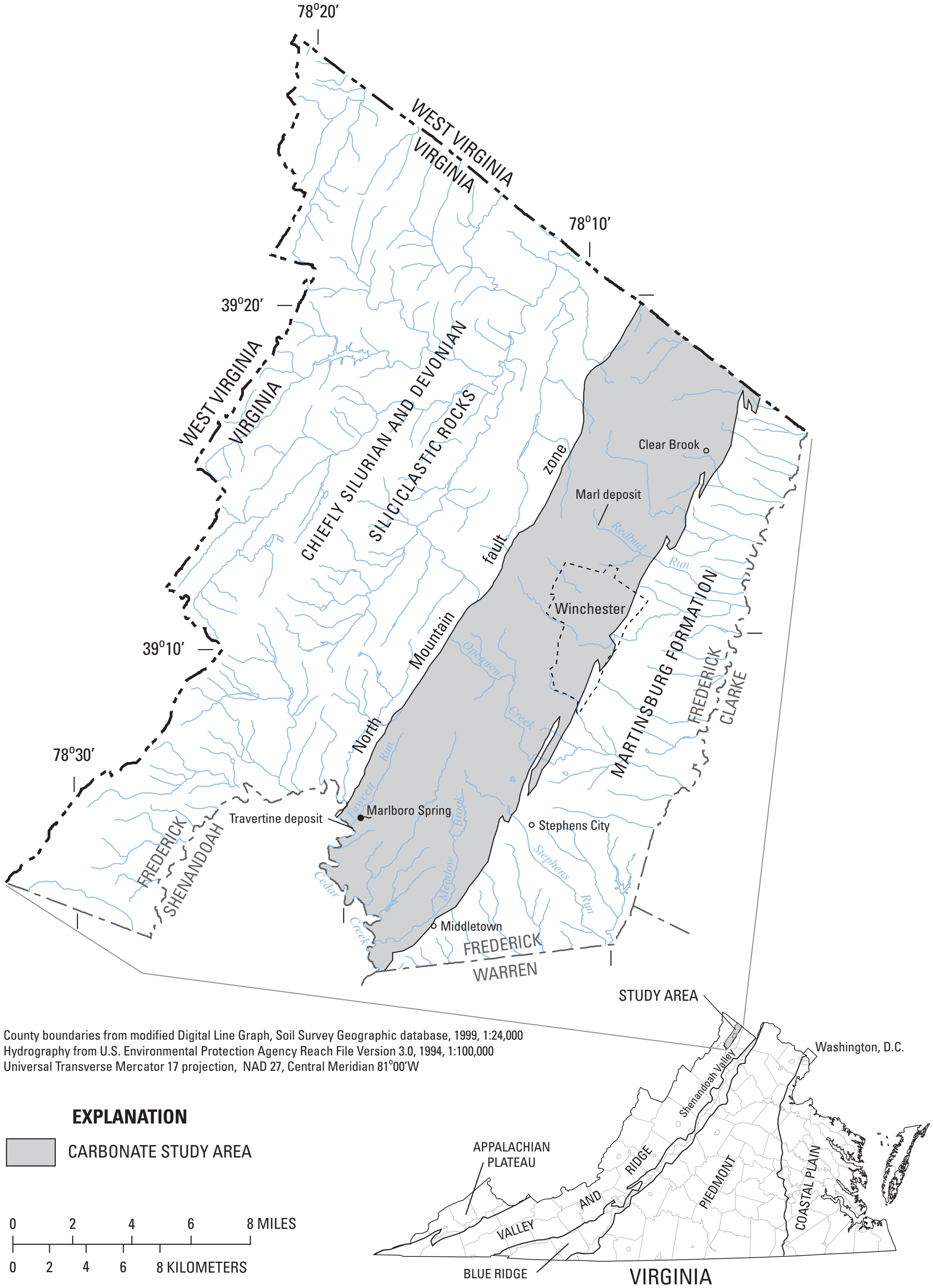

Figure 1. Generalized geologic province map of Frederick County, Va., showing geomorphic features and location of study area.

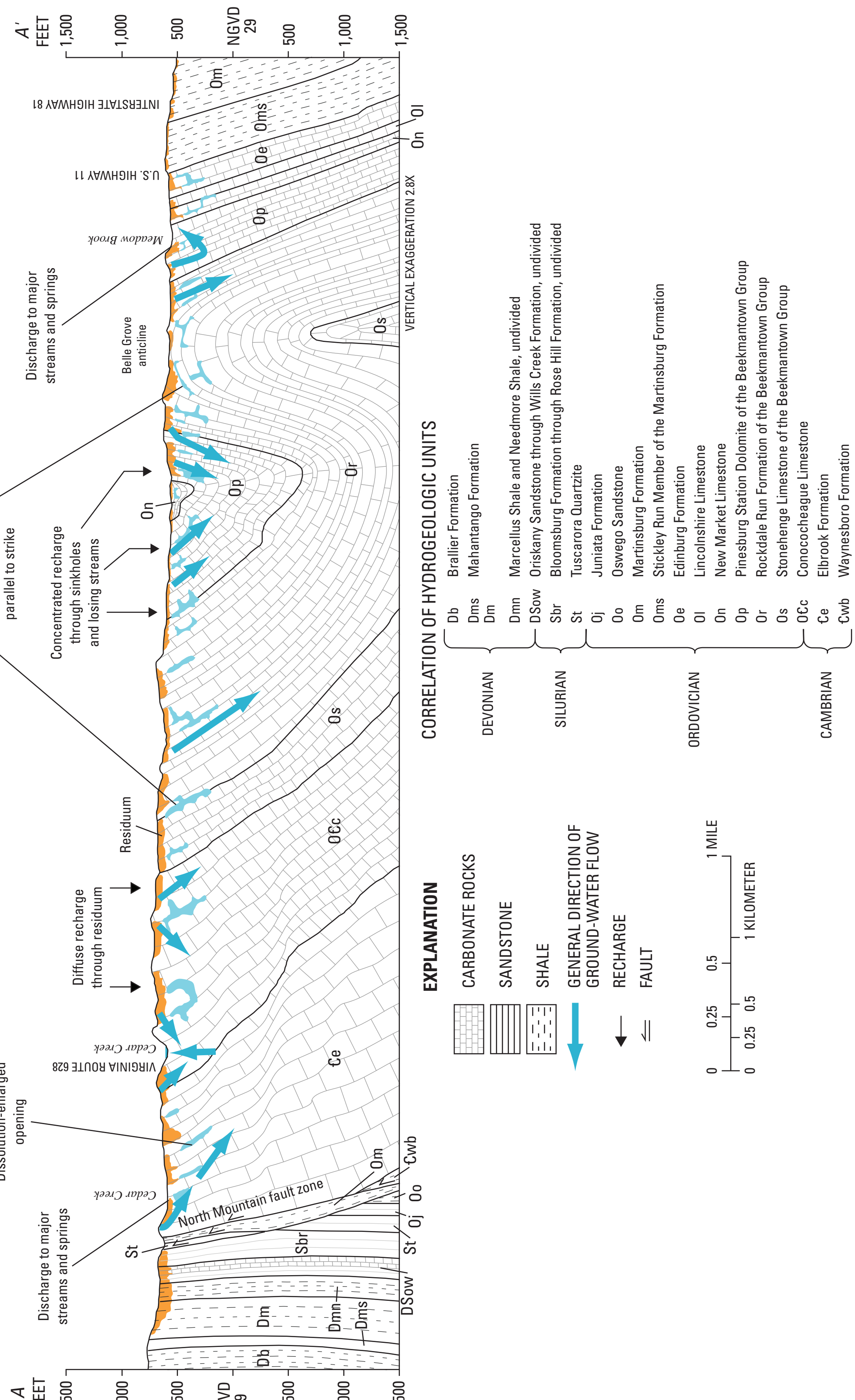

Figure 2. Generalized hydrogeologic section across the Frederick County, Va., carbonate aquifer system. Modified from Orndorff and others (1999) and Wolfe and others (1997). Line section of A–A′ shown on figure 4.

Climate

Climatic data for the region were obtained from the National Weather Service station 449263 located approximately 2 mi northeast of Woodstock, Va. (table 1), in neighboring Shenandoah County. The period of record is 105 years for temperature data and 111 years for precipitation data (National Oceanic and Atmospheric Administration, 2002, p. 18). The normal values are based on the National Weather Service's current normal climatological period from 1971 to 2000. The mean annual air temperature in the region is 11.8° C with the colder periods of the year between November and March and the warmer periods between April and October. The coldest month is January (-0.5°C) and the warmest is July (23.6°C). Precipitation is fairly evenly distributed throughout an average year with an average annual value of 35.20 in/yr. Precipitation in an average year would be highest in May, 3.82 in., and lowest in February, 2.42 in. Annual precipitation at this station was 33.27 in. in 1999, 25.87 in. in 2000, 30.59 in. in 2001, and 39.21 in. in 2002. This temporal precipitation distribution reflects the drought that affected the Shenandoah Valley and most of Virginia from 1999 through the middle of 2002 and that was followed by above-normal precipitation.

Well-Numbering System

A unique USGS identifier was assigned to each well for this study (table 2), for the purpose of storing well information in the Ground-Water Site Inventory data base 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 44W 10 corresponds to the 10th well entered by the USGS in the area covered by the Middletown quadrangle, which has a Virginia coordinate grid number of 44W.

Previous Investigations

In 1938, R.C. Cady described the occurrence and quality of ground water in northern Virginia, including Frederick County. On the basis of geology, Cady described the groundwater conditions of the "Martinsburg shale belt," "belt of Cambrian and Ordovician limestone," and "area west of Little North Mountain" in the county. Cady (1938, p. 2) noted that wells in the limestone were generally deeper and on average were higher yielding than those in the Martinsburg shale and also noted the presence of many large springs in the limestone belt, "especially near the western boundary of the shale." Butts and Edmundson (1966) mapped the geology of Frederick County at a scale of 1:62,500. Cederstrom (1972) evaluated the yields of wells in consolidated rocks from Virginia to Maine and noted that the "yields of industrial and municipal wells are the most reliable indicators of the water-yielding potential of consolidated rocks" and that "substantially greater than average sustained yields are possible in structurally deformed areas or in areas where recharge potential is especially favorable" (p.1). Trainer and Watkins (1975) conducted a geohydrologic reconnaissance of the upper Potomac River Basin. They noted three geohydrologic terrains: fractured rock having a thin regolith, fractured rock having a thick regolith, and carbonate rock, and also described their aquifer characteristics and base-flow characteristics. Rader and others (1996, 2001) compiled the geology of the northern Virginia area, including Frederick County, at a 1:100,000 scale, which included the 1:24,000-scale geologic map of the Middletown quadrangle (Orndorff and others, 1999) in the southernmost part of the study area. Orndorff and others (2003) mapped the Winchester quadrangle at a scale of 1:24,000, and are currently (2005) mapping the Stephens City Quadrangle at a scale of 1:24,000.

Science Applications International Corporation (SAIC) (2000a, 2000b, 2000c, 2000d, 2000e, 2001, 2004) has conducted a number of hydrogeologic evaluations in the study area for the Frederick County Sanitation Authority (FCSA) to develop additional sources of water supply.

Table 1. Total precipitation data (1999-2002) and average annual precipitation for the current climatological period (1971-2000) at three National Weather Service climatological stations in and near Frederick County, Va.

[in., inches; ft, feet; *, indicates partial data with 1-9 daily values missing; –, indicates insufficient data]

Climatological station	Station number	1999 precipitation (in.)	2000 precipitation (in.)	2001 precipitation (in.)	2002 precipitation (in.)	Station elevation (ft)	Average annual precipitation (1971-2000) (in.)
Winchester	9181	34.91	36.35*	33.09	41.18	720	36.40
Winchester 7 SE	9186	39.39*	32.92*	[1]28.21	42.85*	680	–
Woodstock 2 NE	9263	33.27	–	30.59	39.21*	680	35.20

[1]Reported value from Southeast Regional Climate Center station 9186, Winchester 3 ESE (2003).

Table 2. Record of selected wells, Frederick County, Va.

[USGS, U.S. Geological Survey; dms, degrees, minutes, and seconds; nd, no data; Use of site: U, unused; W, withdrawal; O, observation; T, test; Z, destroyed. Use of water: U, unused; H, domestic; T, institutional; C, commercial; I, irrigation; S, stock. Topographic setting: H, hilltop; S, hillside; V, valley; F, flat; W, upland draw; C, stream channel. Hydrogeologic unit codes: 371ELBK, Elbrook Formation; 371CCCG, Conococheague Formation; 367BKMN, Beekmantown Group; 361MRBG, Martinsburg Shale; 364EDBG, Edinburg Formation; 350SLRN, Silurian System.

USGS well number	Latitude (dms)	Longitude (dms)	Quadrangle	Year drilled	Use of site	Use of water	Land-surface altitude, above NGVD 29 (feet)	Topographic setting	Hydrogeologic unit	Depth of well (feet)	Depth of casing (feet)	Diameter of casing (inches)	Depth of water-bearing zone(s) (feet)	March 2002 water-level altitude, above NGVD 29 (feet)	March 2003 water- level altitude, above NGVD 29 (feet)	Reported yield (gal/min)	Pumping period (hours)
44W 2	39 05 46	78 19 17	Middletown	nd	U	U	827.78	H	371ELBK	300	nd	nd	nd	780.13	805.00	nd	nd
44W 3	39 05 46	78 19 17	Middletown	2001	W	H	826.98	H	371ELBK	600	80	6.25	475	nd	nd	2.5	4
44W 4	39 05 58	78 18 60	Middletown	1993	W	H	845	H	371ELBK	300	60	6.25	90/150/238/280	738.41	794.93	8	nd
44W 5	39 05 14	78 19 19	Middletown	1974	W	T	730	S	371ELBK	98	24	6	nd	672.01	703.88	30	nd
44W 6	39 04 56	78 19 15	Middletown	nd	W	T	725	S	371CCCG	nd	nd	nd	nd	686.44	693.28	nd	nd
44W 7	39 04 21	78 19 17	Middletown	nd	W	T	765	S	371CCCG	nd	nd	nd	nd	698.98	719.42	nd	nd
44W 8	39 02 26	78 17 06	Middletown	nd	W	T	735	H	367BKMN	155	81.5	6	nd	667.12	700.53	nd	nd
44W 9	39 02 28	78 17 03	Middletown	nd	W	H	730	S	367BKMN	nd	nd	nd	nd	669.45	703.19	nd	nd
44W 10	39 03 59	78 16 32	Middletown	nd	W	H	835	H	367BKMN	136	45	6	nd	737.56	781.47	nd	nd
44W 11	39 04 44	78 15 46	Middletown	nd	W	H	780	V	367BKMN	nd	nd	nd	nd	743.06	779.21	nd	nd
44W 12	39 06 31	78 15 53	Middletown	nd	W	T	835	V	367BKMN	nd	nd	nd	nd	774.09	817.65	nd	nd
44W 13	39 06 47	78 17 02	Middletown	nd	W	T	930	H	371CCCG	nd	nd	nd	nd	768.41	821.67	nd	nd
44W 14	39 01 01	78 17 48	Middletown	1991	W	H	730	H	361MRBG	515	55	nd	510	698.38	721.24	100	2
44W 15	39 03 43	78 15 44	Middletown	1996	W	C	775	S	367BKMN	120	84	6	99	nd	nd	50	3
44W 16	39 04 05	78 15 11	Middletown	2000	W	H	765	F	367BKMN	240	72	6.25	168/183/220	705.80	739.22	60	4
44W 17	39 01 34	78 17 47	Middletown	1992	W	H	645	F	367BKMN	145	60	6.25	140	623.22	636.90	35	nd
44W 18	39 05 51	78 15 58	Middletown	1998	W	H	875	S	371CCCG	140	79	6.25	112/132	771.34	791.22	30	4
44W 19	39 04 22	78 19 18	Middletown	nd	W	H	760	S	371CCCG	nd	nd	nd	nd	702.39	724.04	nd	nd
44X 2	39 07 30	78 16 08	Hayfield	1997	W	H	950	S	371CCCG	360	99	6.25	128/136/286/332/357	799.91	823.92	22	4
44X 3	39 08 47	78 15 53	Hayfield	nd	W	H	930	F	371ELBK	nd	nd	nd	nd	nd	nd	nd	nd
44X 4	39 08 40	78 15 32	Hayfield	nd	W	I	940	H	371CCCG	nd	nd	nd	nd	nd	nd	nd	nd
44X 5	39 08 49	78 15 42	Hayfield	2001	W	I	920	S	371CCCG	1200	40	6.25	237/507/764/957/1070	862.14	867.52	15	4
44X 6	39 08 46	78 16 42	Hayfield	2000	W	I	920	S	371ELBK	160	99	6.25	129/144	874.49	904.10	150	4
45W 16	39 05 42	78 14 59	Stephens City	nd	W	H	835	H	371CCCG	nd	nd	nd	nd	764.22	785.10	nd	nd
45W 17	39 06 05	78 13 47	Stephens City	1997	W	H	785	H	367BKMN	400	60	6.25	114/284/368	716.76	736.45	30	nd
45W 18	39 05 07	78 13 49	Stephens City	2000	W	C	727.72	S	364EDBG	308.5	300	16	300	567.20	679.20	1,000	nd
45W 19	39 05 16	78 13 44	Stephens City	nd	O	U	741.02	S	364EDBG	nd	nd	nd	nd	565.40	nd	nd	nd
45W 20	39 06 36	78 13 14	Stephens City	1993	O	U	744.14	F	367BKMN	300	60	6.62	155	697.50	735.90	50	nd
45W 21	39 06 18	78 13 53	Stephens City	1993	O	U	781.1	W	367BKMN	300	40	6.62	80/170/264/297	731.70	752.60	13	nd
45W 22	39 05 52	78 13 36	Stephens City	1993	O	U	760.07	F	364EDBG	300	54	6.62	192	648.10	666.60	1	nd
45W 23	39 05 27	78 13 53	Stephens City	nd	O	U	752.21	S	364EDBG	nd	nd	6	nd	638.20	707.00	nd	nd
45W 24	39 05 12	78 13 25	Stephens City	1990	O	U	716.02	S	364EDBG	225	50	6.25	85/107/144	nd	688.40	60	nd
45W 25	39 06 09	78 13 29	Stephens City	nd	O	U	744.57	F	367BKMN	nd	nd	6	nd	654.70	678.20	nd	nd
45W 26	39 06 11	78 13 07	Stephens City	1985	O	U	735.45	F	367BKMN	41.5	21	6.62	90	nd	726.00	4	2
45W 27	39 05 17	78 12 55	Stephens City	nd	O	U	779.28	S	361MRBG	nd	nd	6	nd	754.90	770.50	nd	nd
45W 28	39 04 42	78 14 08	Stephens City	2000	O	U	775	S	364EDBG	705	32	8.62	72/110/120/390	nd	nd	19	nd
45W 29	39 06 21	78 12 59	Stephens City	2001	W	U	728	W	367BKMN	705	424	8	457/502/507.5/513/520/530	nd	nd	1,000	nd
45W 30	39 06 33	78 12 52	Stephens City	2000	W	S	720	V	367BKMN	87	36	8.62	49	nd	nd	100	nd
45W 31	39 06 17	78 12 45	Stephens City	2000	T	U	755	F	364EDBG	585	22	6.62	141/215/235/248/258/304/495	nd	nd	50	nd
45W 32	39 06 16	78 12 50	Stephens City	2001	T	U	745	W	364EDBG	340	23	8	208/330	nd	nd	120	nd
45W 33	39 06 25	78 12 55	Stephens City	2000	O	U	720	W	367BKMN	52	26	6	50	nd	nd	4	nd

Table 2. Record of selected wells, Frederick County, Va.—Continued

[USGS, U.S. Geological Survey; dms, degrees, minutes, and seconds; nd, no data; Use of site: U, unused; W, withdrawal; O, observation; T, test; Z, destroyed. Use of water: U, unused; H, domestic; T, institutional; C, commercial; I, irrigation; S, stock. Topographic setting: H, hilltop; S, hillside; V, valley; F, flat; W, upland draw; C, stream channel. Hydrogeologic unit codes: 371ELBK, Elbrook Formation; 371CCCG, Conococheague Formation; 367BKMN, Beekmantown Group; 361MRBG, Martinsburg Shale; 364EDBG, Edinburg Formation; 350SLRN, Silurian System.

USGS well number	Latitude (dms)	Longitude (dms)	Quadrangle	Year drilled	Use of site	Use of water	Land-surface altitude, above NGVD 29 (feet)	Topographic setting	Hydrogeologic unit	Depth of well (feet)	Depth of casing (feet)	Diameter of casing (inches)	Depth of water-bearing zone(s) (feet)	March 2002 water-level altitude, above NGVD 29 (feet)	March 2003 water- level altitude, above NGVD 29 (feet)	Reported yield (gal/min)	Pumping period (hours)
45W 34	39 06 25	78 12 50	Stephens City	2001	T	U	730	F	367BKMN	720	90	6	132	nd	nd	150	nd
45W 35	39 06 17	78 12 48	Stephens City	2001	T	U	755	W	364EDBG	820	50	7	167	nd	nd	2	nd
45W 36	39 06 40	78 12 35	Stephens City	2000	T	U	715	F	364EDBG	930	42	6.62	73/123/125	nd	nd	35	nd
45W 37	39 06 31	78 12 39	Stephens City	2001	T	U	745	V	364EDBG	900	25	7	34	nd	nd	15	nd
45X 1	39 14 42	78 11 35	Winchester	1986	W	H	960	S	361MRBG	341	319	6	196/260/324/339	nd	nd	120	1
45X 2	39 07 31	78 11 09	Winchester	1966	W	C	750	F	364EDBG	103	50	5	65/78	nd	nd	15	0.5
45X 3	39 09 27	78 14 48	Winchester	nd	W	T	834.48	V	371CCCG	nd	nd	nd	nd	826.51	829.72	nd	nd
45X 4	39 11 39	78 14 15	Winchester	nd	W	T	920	H	361MRBG	nd	nd	nd	nd	902.05	912.65	nd	nd
45X 5	39 11 44	78 13 49	Winchester	nd	W	T	940	F	371ELBK	nd	nd	nd	nd	nd	nd	nd	nd
45X 6	39 11 32	78 13 16	Winchester	nd	W	T	945	H	371CCCG	nd	nd	nd	nd	nd	nd	nd	nd
45X 7	39 11 38	78 11 19	Winchester	nd	U	U	800	S	371ELBK	nd	nd	nd	nd	771.25	784.35	nd	nd
45X 8	39 11 22	78 10 24	Winchester	1999	W	I	825	S	371CCCG	280	23	6	145/206/275	720.65	745.45	30	4
45X 9	39 13 39	78 12 07	Winchester	nd	W	T	925	S	371CCCG	nd	nd	nd	nd	889.32	919.11	nd	nd
45X 10	39 12 33	78 08 58	Winchester	nd	U	U	700	F	367BKMN	100	nd	nd	nd	nd	nd	nd	nd
45X 11	39 12 33	78 13 38	Winchester	1992	W	H	945	H	350SLRN	300	59	6	120/275	910.96	924.92	20	3
45X 12	39 07 54	78 13 32	Winchester	1998	W	H	800	S	371CCCG	180	59	6.25	125/172	753.56	759.60	50	4
45X 13	39 07 48	78 14 33	Winchester	1994	W	I	840	S	371CCCG	250	30	6.25	77/213/226	783.46	815.17	50	nd
45X 14	39 09 30	78 13 46	Winchester	1998	W	H	850	S	371CCCG	250	84	6.25	142/173/212	790.36	809.02	50	nd
45X 15	39 09 28	78 13 60	Winchester	1997	W	H	865	S	371CCCG	120	99	6.25	110	790.43	809.54	40	4
45X 16	39 11 17	78 13 07	Winchester	1991	Z	U	860	S	371CCCG	600	nd	nd	nd	nd	nd	0	nd
45X 17	39 08 44	78 12 31	Winchester	1993	W	H	825	F	367BKMN	60	19	6.25	45	nd	nd	60	4
45X 18	39 11 01	78 12 10	Winchester	nd	U	U	805	S	371CCCG	nd	nd	nd	nd	nd	793.79	nd	nd
45X 19	39 11 01	78 12 11	Winchester	2002	U	U	790	C	371CCCG	170	120	8	155	nd	782.51	600	3
45X 20	39 11 07	78 12 08	Winchester	2002	U	U	815	F	371CCCG	440	120	8	250	nd	787.11	800	3
45Y 1	39 16 05	78 08 36	White Hall	nd	W	H	820	S	371CCCG	24.22	nd	nd	dug well	801.93	803.35	nd	nd
45Y 2	39 15 24	78 08 07	White Hall	1999	W	H	730	F	367BKMN	100	19	6	88/95/100	675.54	714.14	60	4
45Y 3	39 15 50	78 08 03	White Hall	nd	W	T	750	F	367BKMN	nd	nd	nd	nd	696.74	733.86	nd	nd
45Y 4	39 17 57	78 09 54	White Hall	nd	U	U	770	F	371CCCG	20.47	nd	nd	dug well	750.58	763.53	nd	nd
45Y 5	39 17 57	78 09 54	White Hall	nd	U	U	770	F	361MRBG	200	40	6.5	nd	746.55	757.23	nd	nd
45Y 6	39 17 38	78 08 55	White Hall	nd	W	T	905	S	371ELBK	nd	nd	nd	nd	790.08	866.86	nd	nd
45Y 7	39 17 35	78 08 46	White Hall	1988	W	H	905	S	371ELBK	700	21	6	480	nd	nd	1	6
45Y 8	39 18 58	78 07 56	White Hall	1997	W	H	845	H	371ELBK	220	19	6.12	217	814.17	815.48	100	nd
46X108	39 14 13	78 06 39	Stephenson	nd	U	U	625	F	367BKMN	120	20	6	nd	601.99	611.31	nd	nd
46X110	39 14 13	78 07 12	Stephenson	nd	U	U	665	F	367BKMN	nd	nd	nd	nd	nd	nd	nd	nd
46Y 1	39 17 16	78 07 09	Inwood	nd	W	T	735	F	371CCCG	nd	nd	nd	nd	687.59	708.38	nd	nd
46Y 2	39 15 14	78 06 14	Inwood	2000	O	U	641.3	F	367BKMN	500	20	6	85	nd	nd	0.25	nd
46Y 3	39 16 16	78 04 48	Inwood	2000	O	U	620.19	F	367BKMN	383	20	6	348	nd	nd	10	nd
46Y 4	39 15 39	78 04 50	Inwood	2000	O	U	635.14	F	361MRBG	200	45	6	70	nd	nd	25	24
46Y 5	39 15 33	78 05 24	Inwood	2000	O	U	624.88	F	367BKMN	180	20	6	123	nd	nd	5	nd
46Y 6	39 15 30	78 05 15	Inwood	2000	O	U	620.77	F	364EDBG	355	105	8	310/495	nd	nd	500	nd

SAIC (2000a) conducted a hydrogeologic and well-siting study of approximately 34,000 acres of the valley between Stephens City and Clear Brook. A total of 179 potential well sites was identified on the basis of four rating categories: fracture trace expression, recharge potential, underlying geologic formation and structure, and drill-rig access.

SAIC (2000b) conducted a hydrogeologic evaluation of the Clear Brook quarry system as a possible additional potable water supply for Frederick County. The study assessed the hydrogeologic framework of the area, noted hydraulic connections between individual quarries, determined the topographic catchment to be 3,500 acres, assumed an average annual recharge rate of 1,000 gal/d/acre, estimated a reliable yield of 2,170,000 gal/d, and noted no adverse effects from the withdrawal on the aquifer or other ground-water users in the area.

SAIC (2000c) conducted a hydrogeologic evaluation of the Stephens City quarry system. The study assessed the hydrogeologic framework of the area, noted hydraulic connections between individual quarries, determined the potential catchment to be 12,445 acres, assumed an average annual recharge rate of 623 gal/d/acre, estimated a reliable yield of 2,200,000 gal/d (which increases to 3,200,000 gal/d if a production well in the south quarry is pumped), and noted no adverse effects from the withdrawal on the aquifer system or other ground-water users in the area.

Burbey (2003) constructed a water-management model for the Stephens City quarries. MODFLOW-2000 was used to simulate flow and changes in hydraulic heads associated with fluctuations in precipitation and pumping at the quarries. Results indicate that drawdown associated with pumping largely occurs in the immediate vicinity of the quarries, and fluctuations in water levels are largely attributed to changes in precipitation and the amount of recharge to the ground-water system.

Hydrogeology

The study area is characterized as a mantled karst terrain, composed of variably fractured, folded and faulted limestone and dolostone bedrock overlain by unconsolidated regolith material ranging from 0 to 100 ft thick.

Geology

The study area of the carbonate aquifer system of Frederick County is in the Shenandoah Valley region of the Valley and Ridge Physiographic Province. Approximately 10,000 ft of Middle Cambrian to Upper Ordovician sedimentary rocks are near the surface and are overlain by Pleistocene(?) and Holocene surficial deposits. The Shenandoah Valley can geologically be divided into two regions: (1) shale, graywacke, and limestone of the Ordovician Martinsburg Formation in the east, and (2) Cambrian and Ordovician carbonate rocks to the west (fig. 1). The carbonate rocks are bounded on the east by the Martinsburg Formation and on the west by the North Mountain fault zone. All of the rocks in the area were folded and faulted (fig. 2) during the late Paleozoic Alleghanian orogeny. The terrain of the Shenandoah Valley generally is gently to moderately rolling with low relief; sinkholes are fairly common in areas underlain by carbonate rocks.

Stratigraphy

Rocks of the carbonate aquifer system underlying Frederick County range from Middle Cambrian to Late Ordovician in age and consist of carbonate and clastic lithologies. Rocks from the Middle and Upper Cambrian Elbrook Formation through the Middle Ordovician Edinburg Formation are predominately limestone and dolostone, whereas rocks of the Middle and Upper Ordovician Martinsburg Formation contain siltstone, sandstone, shale, and minor amounts of limestone (fig. 3). These Cambrian and Ordovician rocks record the depositional environments, sedimentary basin evolution, and tectonic history of this area of the Shenandoah Valley.

Elbrook Formation

The oldest unit exposed in Frederick County is the Middle and Upper Cambrian Elbrook Formation. The Elbrook consists of interbedded limestone, dolostone, and shale. The limestone is medium gray and bluish gray, medium to fine grained, thin to thick bedded, and contains algal bioherms, intraformational conglomerate, and dolomite mottles. Dolostone of the Elbrook is light to medium gray, fine grained, and medium bedded. The shale beds are gray and dolomitic. A distinctive feature of the Elbrook is that the dolostone and shale weather to a yellowish color. The lowest or oldest beds of the Elbrook are bluish-gray, medium- to thick-bedded limestone with dolomite mottles and medium-gray, thick-bedded dolostone. The middle part of the formation contains cycles of bluish- and medium-gray limestone, light-gray dolostone, and argillaceous dolostone. Cycles of bluish-gray limestone, algal limestone and grainstone, and light-gray dolostone similar to the overlying Conococheague Limestone occur in the upper or younger part of the Elbrook. The cyclic nature of the Elbrook lithologies represent deposition in a shallow marine environment. The thickness of the Elbrook is at least 2,300 ft. The lowest or oldest part of the Elbrook occurs along the North Mountain fault zone and, therefore, is faulted out.

Conococheague Limestone

Like the Elbrook Formation, the Upper Cambrian and Lower Ordovician Conococheague Limestone is a cyclic carbonate unit of interbedded limestone and dolostone. Unlike the Elbrook, the Conococheague contains sandstone beds in its lowermost and uppermost parts. Limestone of the Conococheague is medium gray, fine grained, thin to medium bedded, and contains intraformational conglomerates, algal bioherms, ribbon rock (interlaminated tan dolostone and gray limestone),

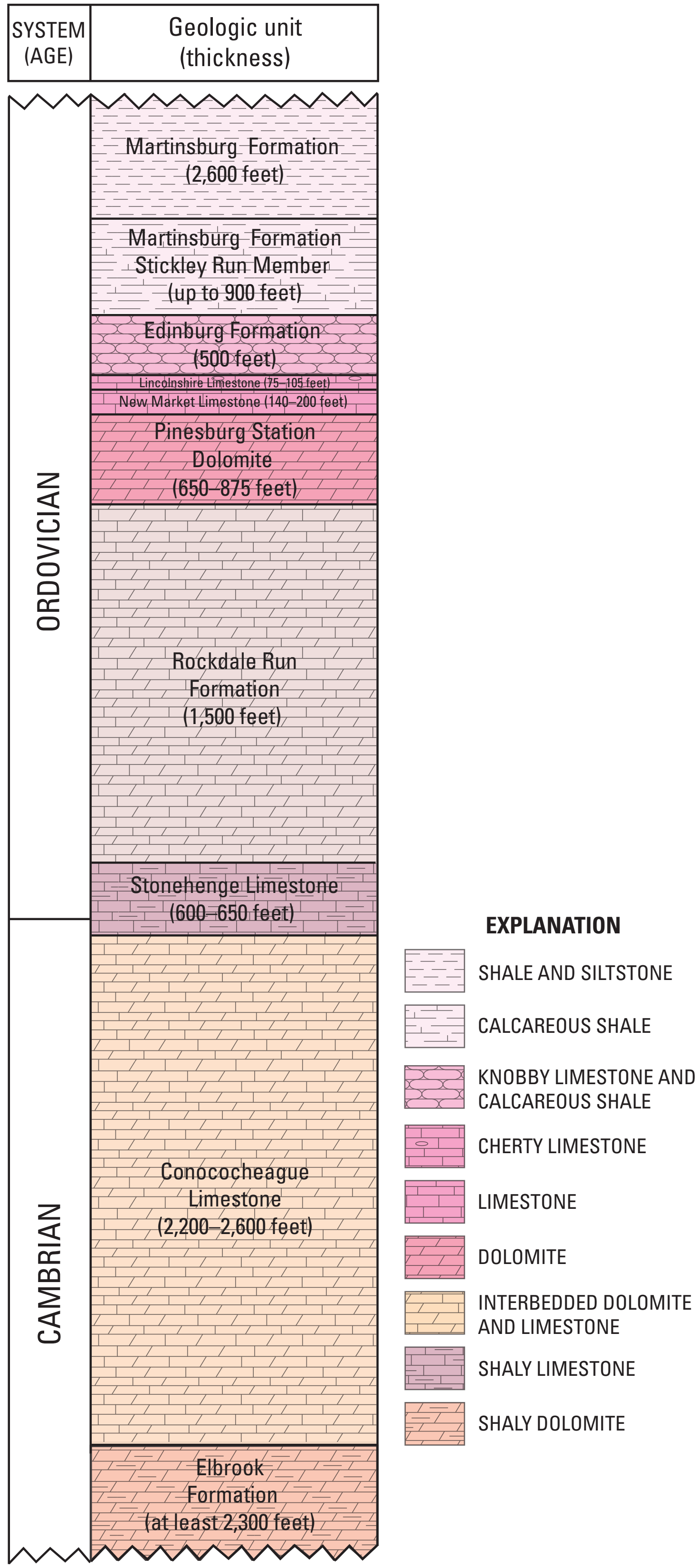

Figure 3. Stratigraphic section of geologic units and their thicknesses in the carbonate study area of Frederick County, Va.

and oolites. Dolostone and dololaminite are light gray, fine grained and medium bedded. The sandstone of the Conococheague is light gray to buff, weathers reddish, is medium to coarse grained, and calcareous in places. The lower 300 ft of the unit is a gray to buff, coarse-grained, calcareous sandstone interbedded with intraformational conglomerate and fine-grained dolostone called the Big Spring Station Member. This sandstone-rich unit generally forms a prominent ridge where exposed. The upper part of the Conococheague from the base upwards consists of cycles of intraformational conglomerate, grainstone, algal bioherm, ribbon rock, mudcracked dololaminite, and sandstone. These cycles represent subtidal to peritidal marine environments of deposition. The thickness of the Conococheague ranges from 2,200 to 2,600 ft, and the base of the unit is placed at the base of the first calcareous sandstone bed of the Big Spring Station Member.

Stonehenge Limestone of the Beekmantown Group

The Lower Ordovician Stonehenge Limestone of the Beekmantown Group consists of dark-gray, fine- to medium-grained, thick-bedded, fossiliferous limestone with crinkly siliceous laminations and minor black chert nodules. The unit also contains algal bioherms, intraformational conglomerates, bioclastic beds, and some minor dolostone beds. Although the majority of the Stonehenge is thick bedded, the lowermost and uppermost beds are thin bedded and represent a lagoon environment of deposition. The middle algal bioherm part of the formation represents the transgression of an offshore barrier complex (Taylor and others, 1992). The thickness of the Stonehenge is from 600 to 650 ft. The contact with the underlying Conococheague Limestone is gradational and is placed at the base of the first dark-gray limestone with crinkly siliceous laminations and above the highest dolostone or sandstone cap of the Conococheague carbonate cycles.

Rockdale Run Formation of the Beekmantown Group

The Lower and Middle Ordovician Rockdale Run Formation of the Beekmantown Group consists of interbedded limestone and dolostone. The limestone is bluish gray, medium gray, and dark gray, fine to medium grained, thin to medium bedded, fossiliferous, and includes intraformational conglomerates, algal bioherms, bioclastic zones, and burrow mottling. The dolostone is medium gray, fine to medium grained, medium bedded, and crystalline. Like the Elbrook and Conococheague, the lithologies in the Rockdale Run occur as shallow marine environment cycles. Gray chert is common in the Rockdale Run and occurs as nodules and large masses 2–4 ft in diameter. Large masses of *Cryptozoon* chert occur in the soil of the lower part of the formation and form topographic knolls with little bedrock exposures. The gastropod *Lecanospira* is common in limestone beds in the lower and middle part of the Rockdale Run. Based on conodont biostratigraphy, the Lower-Middle Ordovician boundary occurs in the upper part of the formation (Harris and Harris, 1978; Harris and others, 1994). The thickness of the Rockdale Run is about 1,500 ft, and the base of the unit is placed at the base of the first crystalline dolostone or dololaminite overlying dark-gray limestone of the Stonehenge Limestone.

Pinesburg Station Dolomite of the Beekmantown Group

Interbedded limestone and dolostone of the Rockdale Run Formation sharply give way upward to predominantly dolostone of the Pinesburg Station Dolomite of the Beekmantown Group. Dolostone and dololaminite of the Pinesburg Station is medium to light gray, buff to light weathering, fine grained, and medium to thick bedded. Light-gray chert nodules are common. Weathered dolostone exhibits a distinctive “butcher-block” (cross-hatched joints) structure. A few thin, medium-gray, fine-grained limestone beds occur in the lower part of the formation. Paleokarst structures, indicating subaerial exposure during Middle Ordovician time, occur as collapse breccias and irregular bedding near the top of the formation. The dolostone of the Pinesburg Station represents a restricted shallow marine environment. Thickness of the Pinesburg Station Dolomite ranges from 650 to 875 ft, and the basal contact is placed at the base of the first thick-bedded dolostone overlying dominantly limestone cycles of the Rockdale Run Formation.

New Market Limestone

The Middle Ordovician New Market Limestone consists of dove-gray and medium-gray, light-gray weathering, micritic, thick-bedded, fenestral limestone. In places, the base of the New Market is unconformable on the Pinesburg Station Dolomite. However, in places where this contact is conformable, the lower 10 ft of the New Market is medium- to light-gray, thin-bedded, dolomitic limestone interbedded with light-gray dololaminite. Excluding these lowermost beds, the New Market is a high-calcium limestone that is as much as 98-percent calcium carbonate (Edmundson, 1945) and has been quarried for the manufacture of glass, steel, and aluminum, as well as for use as a waste stream neutralizer and for agricultural lime. The New Market was deposited in a tidal flat or lagoon environment (Walker and others, 1989). The unconformity at the base of the New Market represents the first response to the Taconic orogeny and the change from a passive continental margin to an active margin of deposition (Rader and Read, 1989). The thickness of the New Market is from 140 to 200 ft, and the base of the unit is placed at the top of the last medium-gray, thick-bedded dolostone of the Pinesburg Station Dolomite and below the dolomitic limestone of the New Market.

Lincolnshire Limestone

Limestone of the Middle Ordovician Lincolnshire Limestone is dark gray to very dark gray, medium to coarse grained, medium bedded with bedded black chert nodules. The unit also contains medium-gray, coarse-grained, thin-bedded, bioclastic limestone. The Lincolnshire represents the beginning of the deepening of a Middle Ordovician basin in the central Appalachians; this is a more open marine environment than that of the New Market, possibly an inner ramp deposit (Walker and others, 1989). The thickness of the Lincolnshire is from 75 to 105 ft, and the base of the unit is placed at the base of the lowest dark-gray, medium-grained limestone above the dove-gray, micritic limestone of the New Market.

Edinburg Formation

The Middle Ordovician Edinburg Formation consists of interbedded limestone and calcareous shale. The limestone is medium to medium dark gray, fine to medium grained, thin to thick bedded, irregularly bedded, and knobby weathering. The calcareous shale is medium dark to very dark gray. Thin beds of yellowish-brown metabentonite occur throughout the unit. Weathering of the interbedded fine-grained limestone and shale creates a knobby appearance. Sediments of the Edinburg Formation were deposited in a foreland basin slope environment, deeper on the ramp than the Lincolnshire. The metabentonites represent Middle Ordovician volcanism from an island arc volcanic system to the east. The thickness of the Edinburg is about 500 ft, and the lower contact is transitional with the Lincolnshire Limestone and placed at the base of the first knobby-weathering, argillaceous limestone, very dark-gray, shaly limestone, or calcareous shale.

Martinsburg Formation

The Middle and Upper Ordovician Martinsburg Formation consists of interbedded shale and lesser graywacke siltstone and graywacke sandstone. The basal part of the formation is a calcareous shale named the Stickley Run Member. The Middle Ordovician Stickley Run Member consists of platy limestone and calcareous shale. The limestone is medium gray to grayish black, olive gray, grayish orange, very fine grained, laminated and very thin bedded, and argillaceous. Shale of the Stickley Run is medium gray to medium dark gray and calcareous. Shale of the remainder of the Martinsburg is medium gray to dark gray and weathers olive gray, grayish orange, and yellowish orange. The sandstone and siltstone is medium gray and weathers grayish orange, 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 forms the eastern edge of Frederick County and cores the Massanutten synclinorium; therefore, the top of the formation is not exposed in the study area. The Martinsburg is also exposed along the North Mountain fault zone on the western edge of the Shenandoah Valley. The Martinsburg represents the deepest environment of deposition for the Cambrian and Ordovician rocks of the Shenandoah Valley. This further deepening of the foreland basin starved carbonate deposition and allowed the increase in clastic sedimentation to form the shales and sandstones of the Martinsburg. The Stickley Run Member may be as much as 900 ft thick in this area (Epstein and others, 1995). The thickness of the Martinsburg is about 2,600 ft but may be as much as 5,000 ft thick regionally (Orndorff and others, 1999).

Structural Geology

Rocks of the carbonate valley of Frederick County are folded and faulted and lie on the west limb of the Massanutten synclinorium, a regional fold that extends from central Pennsylvania to just south of Staunton, Va. Rocks of the siliciclastic Martinsburg Formation are generally tightly folded and have prominent cleavage. Carbonate rocks generally have wider folds that plunge southwest. The western edge of the carbonate valley is defined by the North Mountain fault zone, a regional thrust fault zone that also extends from Pennsylvania to central Virginia. Various other thrust faults and strike-slip faults occur in the carbonate valley (fig. 4). Also, systematic joints are present throughout the rock units.

The structural features in the deformed rocks of the carbonate valley are important hydrologically, as they create weaknesses in the competent bedrock that enhance weathering and provide pathways for ground-water flow. Additionally, some features, such as relict bedding structure, provide pathways for ground-water flow in the regolith that overlies bedrock.

Folds

Folds range from northeast-trending, tight chevron and curvilinear folds in the Martinsburg Formation to upright, northwest verging folds in the Cambrian and Ordovician carbonate rocks (fig. 4). Bedding in the Cambrian and Ordovician carbonate rocks and Martinsburg Formation shows a general southeast dip consistent with these rocks being on the west limb of the Massanutten synclinorium. The regional orientation of folds is about N. 30^{o}–35^{o} E. as estimated from poles to bedding (fig. 5). Most folds plunge gently to the southwest toward the center of the Massanutten synclinorium. Examples of these southwest-plunging folds include the Belle Grove anticline, Marsh Brook syncline, Ridings Hill anticline, and Buffalo Marsh Run syncline (fig. 4). Orndorff and others (1999) noted a disharmony in fold wavelength between the Martinsburg Formation and Cambrian and Ordovician carbonate rocks. Cambrian and Lower Ordovician carbonate rocks have folds with longer wavelengths, whereas folds in the Martinsburg have shorter wavelengths. Folds in the Middle Ordovician limestone are intermediate between the two extremes. This disharmonic folding may be due to rheological differences of the rock units.

Faults

Most faults in the Shenandoah Valley region are northeast-trending thrust faults that place older rocks transported from the southeast over younger rocks to the northwest. The northwestern boundary of the Shenandoah Valley including the carbonate aquifer system of Frederick County is a

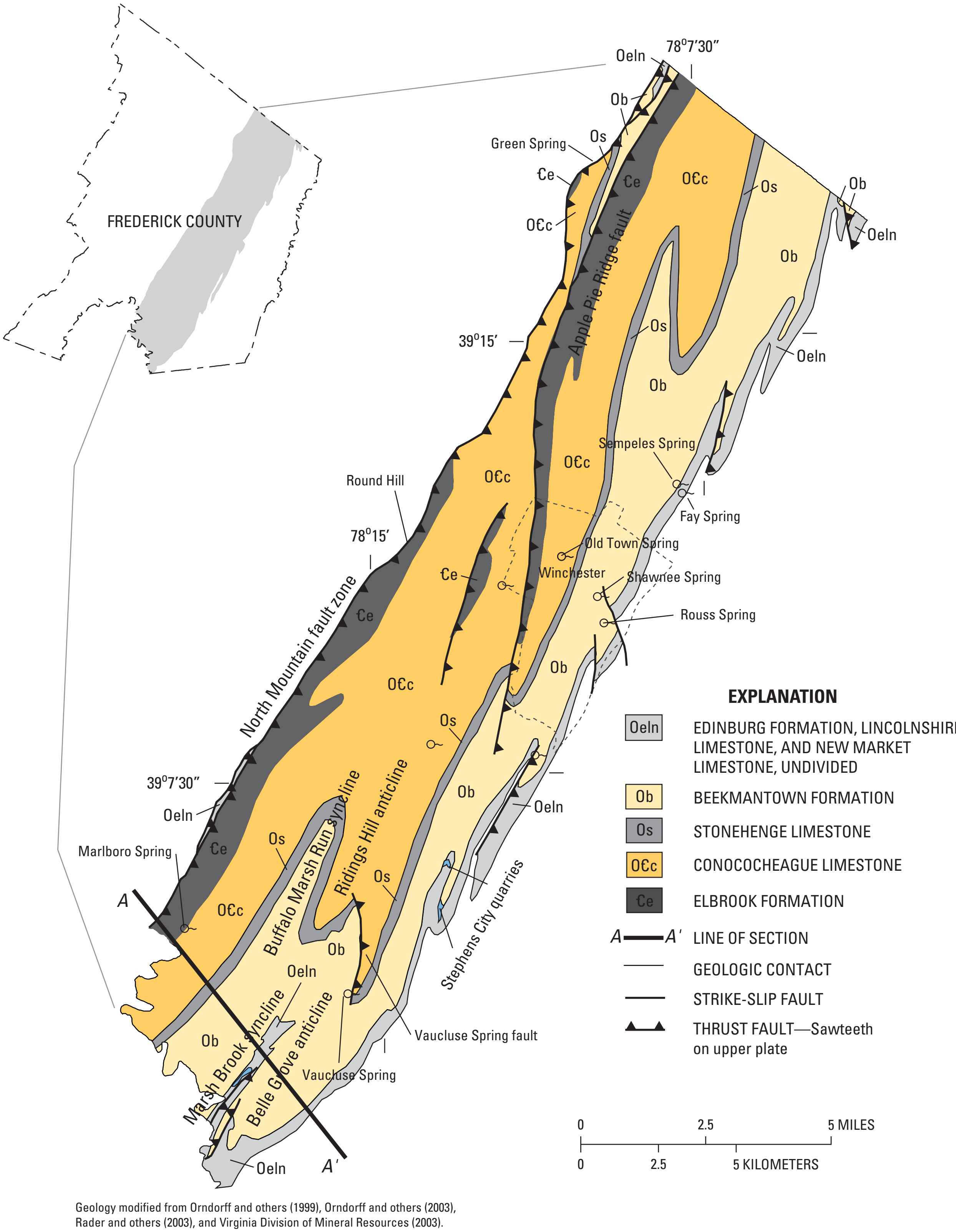

Figure 4. Geologic map of the carbonate valley in Frederick County, Va.

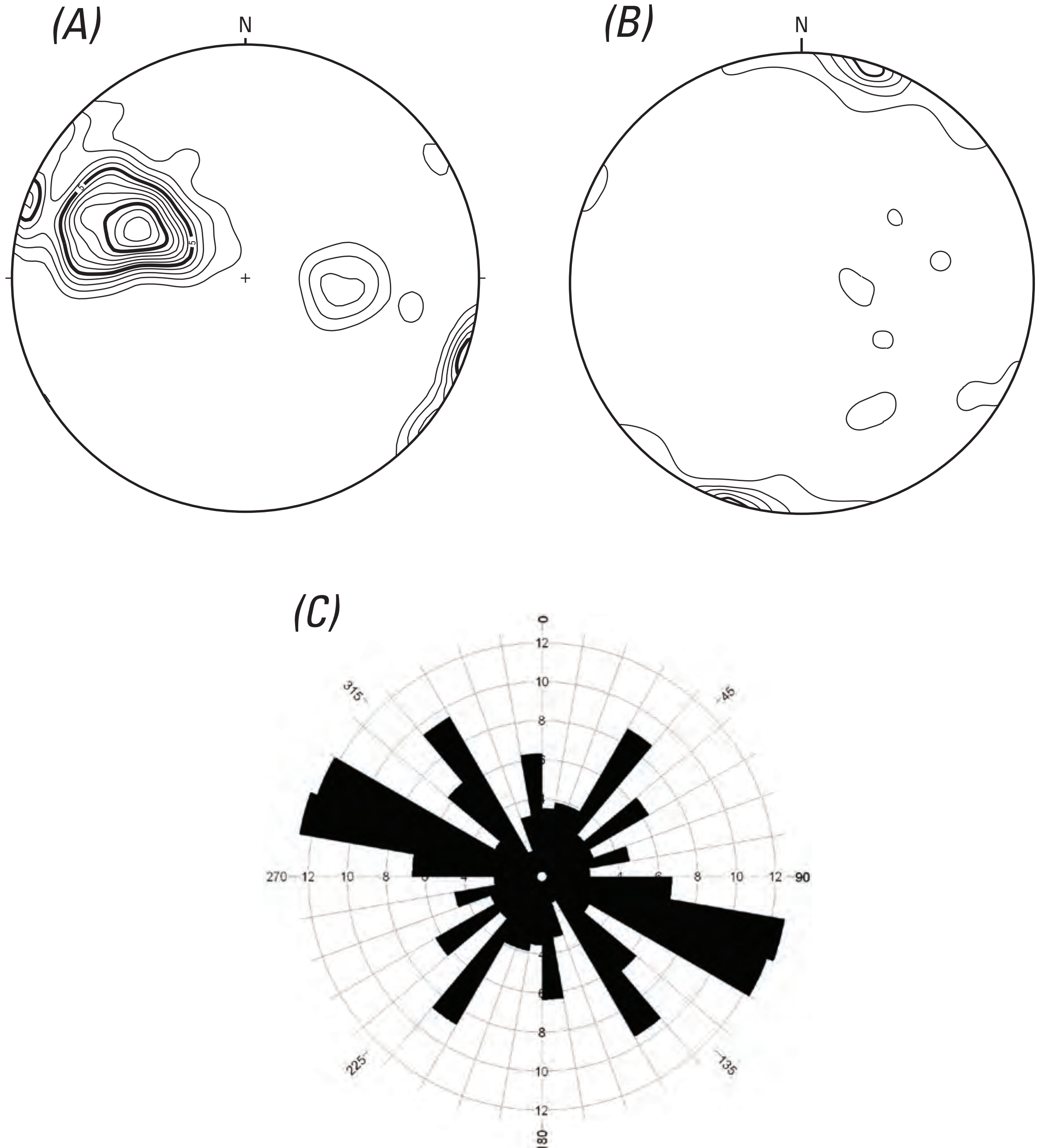

Figure 5. Diagrammatic representation of bedding planes and joints in the carbonate valley of Frederick County, Va., showing lower hemisphere equal area stereographic projection of poles to bedding, contour interval is 1 percent of 1 percent area, n=72 *(A)*; lower hemisphere equal area stereographic projection of poles to joints, contour interval is 2 percent of 1 percent area, n=286 *(B)*; and compass-rose diagram showing strike orientation of joints, circle interval is 2 percent of total, n=286 *(C)*.

major thrust fault zone known as the North Mountain fault zone (fig. 4). This fault zone extends from central Virginia to south-central Pennsylvania and is made up of many fault slices of rock units as old as Cambrian over rock units as young as Devonian. Evans (1989) suggests that displacement on the North Mountain fault zone is more than 35 mi. Physiographically, the fault zone is represented by Little North Mountain, a ridge held up by erosion-resistant Silurian and Devonian sandstone units that form the footwall of the fault zone. These ridges define the carbonate valley drainage basin. However, in some areas (at Green Spring and north of Round Hill), the North Mountain fault zone cuts out these resistant units, which results in surface drainage that flows west from the carbonate rocks and leaves the carbonate valley.

Various other thrust faults than described above have been mapped in the Cambrian and Ordovician carbonate rocks, but have much less displacement and traces of miles to tens of miles (fig. 4). The Apple Pie Ridge fault extends from south of Winchester into the panhandle of West Virginia where it merges with the North Mountain fault zone. The Vaucluse Spring fault trends NNE from Vaucluse Spring to west of the City of Winchester and may die out within the Ridings Hill anticline.

Various north-trending strike-slip faults have been mapped along the contact interval between Middle Ordovician limestone and the Martinsburg Formation. These cross-strike faults probably represent strain accommodation during tectonic shortening where north-trending faults represent conjugate shear during the Alleghanian orogeny, and northwest-trending faults represent extension in the least principal stress orientation (Orndorff, 1992).

Joints

In folded rocks of the carbonate valley, various types of joints result from tectonic forces of the Alleghanian orogeny (fig. 6). Dip joints develop perpendicular to fold axes and represent extension in the least principal stress direction. Oblique joints develop as conjugate sets representing shear. Strike joints develop parallel to fold axes along with tension joints that form along fold hinges.

Joints in rocks of Frederick County vary with rock type. The Cambrian and Ordovician carbonate rocks are brittle compared to the ductile Martinsburg Formation that contains a well-developed slaty cleavage. The carbonate rocks exhibit two sets of cross-strike joints that trend N. 70°–80° W. (dip joints) and N. 30° W. (oblique joints) and longitudinal joints that trend N. 30° E. (strike joints) (fig. 5). The Martinsburg Formation contains a cross-strike joint trend of about N. 45° W. Cleavage in the Martinsburg forms convergent fans and trends about N. 35° E. or parallels fold trends in the area (Epstein, 1993).

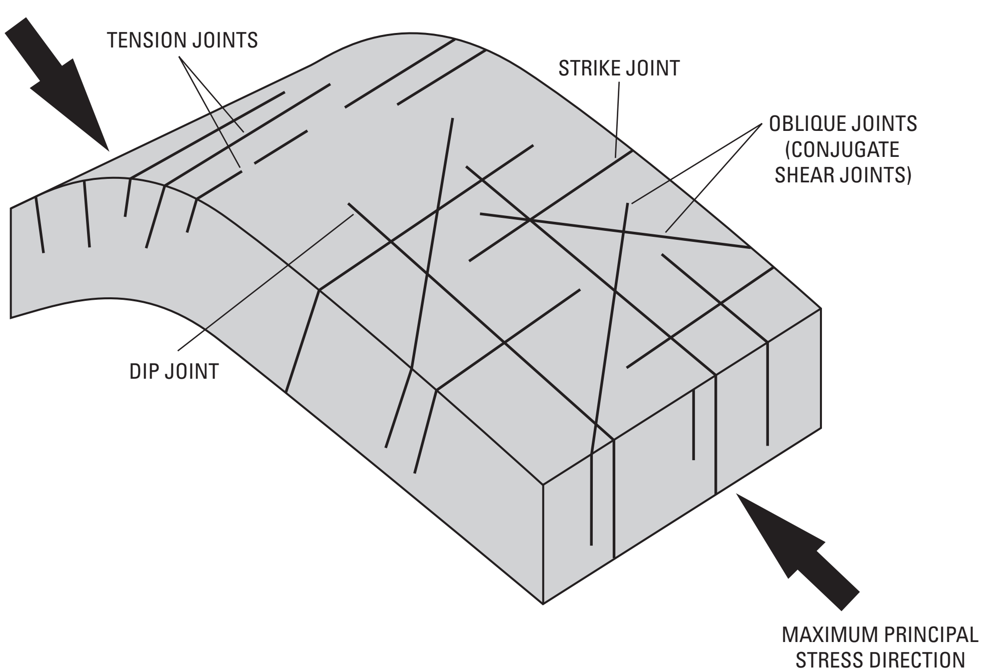

Figure 6. Graphic representation of joint types in folded rocks (modified from Earth Science Australia, 2004).

Karst Development

The soluble nature of carbonate rocks is important hydrologically because of the potential for the development of karst—a type of topography characterized by sinkholes, caves, and underground drainage. Karst forms from the dissolution of carbonate rocks by water. Precipitation, which is slightly acidic, becomes more acidic as it infiltrates through soil. The acidic water dissolves calcite—the principal mineral in limestone and an important mineral in dolostone. The acidic ground water flows through spaces and fractures in bedrock, gradually altering the small spaces and fractures into larger passages and networks of interconnected pathways. Ground-water flow within karst aquifers is commonly limited to these passages and networks, with little or no flow within the adjacent competent rock.

Hydrology

The study area is underlain by folded and fractured carbonate rocks that generally form unconfined, fractured-rock aquifers (carbonate aquifer system). These aquifers are recharged by precipitation across the study area and discharge locally to streams. Confined aquifers, however, may be present locally. Ground-water discharge provides part of the flow to streams during storm-water runoff periods and all of the base flow to streams, with a large part of this flow provided by spring discharge.

Relation of Geology to Ground-Water Flow

The flow of ground water is controlled primarily by effective porosity, recharge, and hydraulic head. The rocks that underlie the study area have no primary permeability (interconnected space around rock particles), and water that percolates through the unconsolidated regolith flows through zones of secondary permeability composed of fractures, joints, bedding, or possibly faults in the solid bedrock. The presence of carbonate rocks, combined with the slightly acidic characteristics of recharge water (precipitation), solutionally enlarge these pathways, forming what is sometimes referred to as tertiary permeability. Orndorff and Harlow (2002) suggest that linear features that develop along intersections of fractures such as bedding and joints may be important to solutional enlargement and ground-water flow. For instance, ground water would most likely flow along strike at the intersection of a bedding plane and a strike joint.

Ground water in the carbonate aquifer system is recharged by precipitation across the area and generally flows from recharge areas of high hydraulic head (Little North Mountain, Apple Pie Ridge) to discharge areas of low hydraulic head (valleys). Generally, the water table is a subdued reflection of the topography at land surface. However, ground-water-flow paths in this system are tortuous because of the geology. The secondary permeability of bedding planes, joints, and faults provide the pathways for ground-water movement from high hydraulic head to low hydraulic head. Dipping bedding planes are important pathways because they are more continuous than any other features. However, dip joints and oblique joints may allow water to flow across the strike of the structures. Many large springs in the carbonate valley are associated with faults, indicating that faults are important directional controls on the flow of ground water. Rouss, Shawnee, Vaucluse Springs, and possibly Sempeles and Fay Springs occur along or adjacent to faults (see fig. 4). Vaucluse Spring is a large spring that discharges from the Rockdale Run Formation and provides a major component of flow to Meadow Brook. Intense fracturing is observed in the Rockdale Run at the spring, which is adjacent to the Vaucluse Spring fault where rocks of the Conococheague Limestone are thrust over rocks of the Rockdale Run Formation (Orndorff and others, 1999) (fig.7).

Aquifer Properties

The capacities of aquifers to transmit and store water are their most important properties when considering water supply, and these properties are often determined by analysis of aquifer tests. Transmissivity is a measure of the capacity of an aquifer to transmit water, and is defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1979, p. 6). Transmissivity has units of length squared per time. Storativity is a measure of the capacity of an aquifer to store water; the property is termed specific yield in unconfined aquifers and storage coefficient in confined aquifers. Specific yield is defined as the ratio of the volume of water drained by gravity to the volume of aquifer material, and storage coefficient as the volume of water released from (or taken into) storage per unit surface area of an aquifer per unit change in head (Lohman, 1979, p. 6 and 8). The storage coefficient of unconfined aquifers is virtually equal to the specific yield, and both units are dimensionless (Heath, 1983, p. 29). The reliable yield of a well is an estimate of the capacity of a well to supply a given amount of water for an extended period of time with respect to specific effects of pumping, and is often based on specific capacity of a well (yield of a well per unit of drawdown).

Transmissivity and storage values for the carbonate rocks in the study area have been estimated by Trainer and Watkins (1975, p. 1), and, more recently, during aquifer tests conducted by Science Applications International Corporation (2000d, 2000e, 2004) (table 3). "Carbonate rock, in which fractures have been widened selectively by solution, especially near streams…" has an estimated average transmissivity of 500 ft^2/d and an average specific yield of 0.03–0.04 (Trainer and Watkins, 1975, p.1). SAIC (2000d) conducted a hydrogeologic evaluation of a site about 2.6 mi southwest of the Winchester city limit to develop a water supply. The study included hydrogeologic analyses, completion of a production well, test pumping and water-level monitoring, and water-quality analyses. On the basis of a 96-hour constant-rate pump test, the reli-

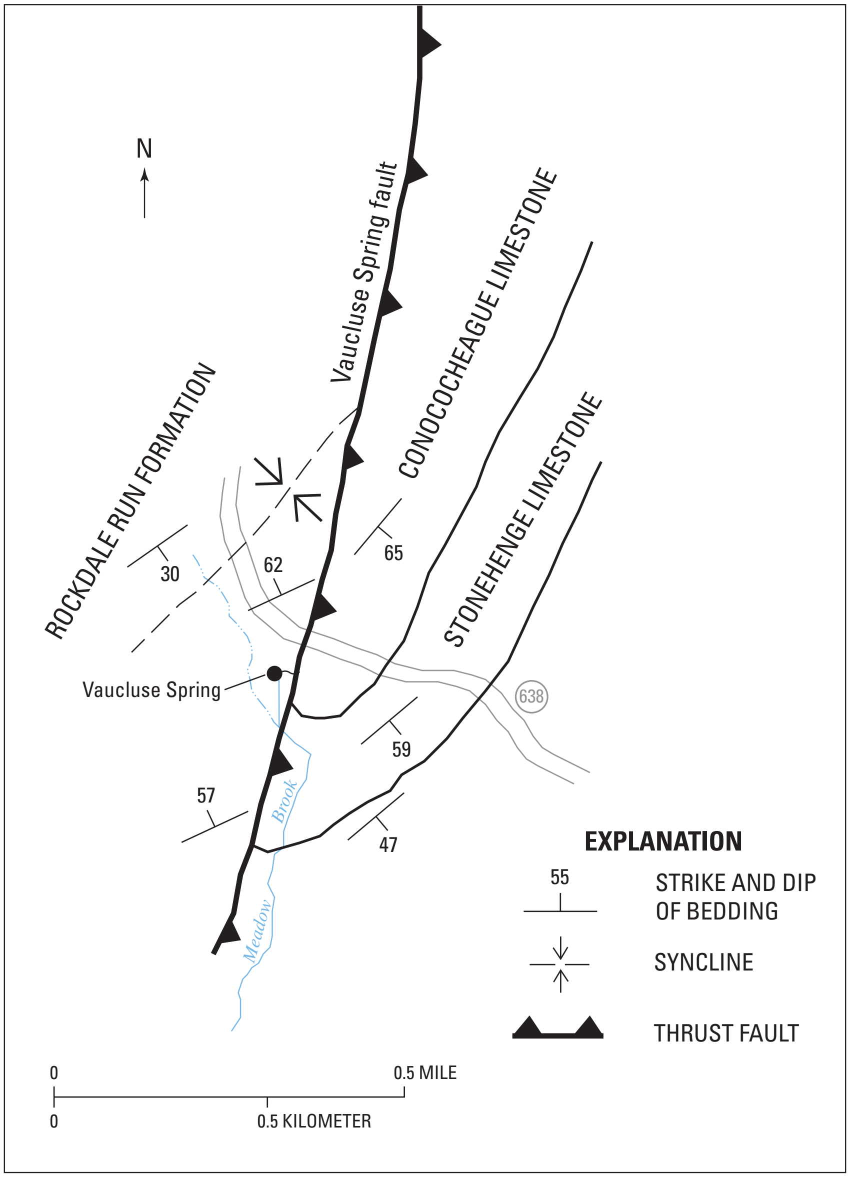

Figure 7. Schematic showing the geology around Vaucluse Spring, Frederick County, Va. (modified from Orndorff and others, 1999).

Table 3. Reported aquifer transmissivity and storage values for the carbonate aquifer system in and near Frederick County, Va.

[gal/min, gallons per minute; ft²/d, foot squared per day; nd, no data; SAIC, Science Applications International Corporation]

Well type	Length of test (hours)	Average pumping rate (gal/min)	Transmissivity (ft²/d)	Storage coefficient	Source of data
Both[1]	nd	nd	500	[3]0.03-0.04	Trainer and Watkins, 1975
Production	96	1,200	[2]6,080	nd	SAIC, 2000d
Observation	96	1,200	[2]18,000	0.029	SAIC, 2000d
Observation	96	1,200	[2]9,500	0.002	SAIC, 2000d
Production	96	660	[2]1,940	nd	SAIC, 2000e
Observation	96	660	[2]15,000	0.006	SAIC, 2000e
Production	51	350	[2]950	nd	SAIC, 2004
Observation	51	350	[2]1,100	0.00002	SAIC, 2004
Observation	51	350	[2]1,960	0.0006	SAIC, 2004
Observation	51	350	[2]1,840	0.0002	SAIC, 2004
Observation	51	350	[2]2,940	0.0006	SAIC, 2004
Observation	51	350	nd	0.02	SAIC, 2004

[1]From published multi-well aquifer tests in Maryland and published single-well aquifer tests in the Potomac River Basin.

[2]Values are from recovery water-level data after pump cutoff.

[3]Estimate of specific yield.

able yield was estimated to be 1,200 gal/min with an estimated long-term water-level drawdown of 104 ft and a corresponding specific capacity of 11.5 (gal/min)/ft. Transmissivity values of 1,350 and 6,080 ft²/d were calculated from the production well data. Transmissivity values ranging from 4,640 to 18,000 ft²/d were calculated from the observation well data and storativity values of 0.029 and 0.002 were calculated from pumping-induced drawdown in two observation wells.

SAIC (2000e) also conducted a hydrogeologic evaluation of a site about 6.2 mi northeast of the Winchester city limit to develop a water supply. This study included hydrogeologic analyses, completion of a production well, test pumping and water-level monitoring, and water-quality analyses. On the basis of a 96-hour constant-rate pump test, the reliable yield was estimated to be 750 gal/min with an estimated water-level drawdown of 527 ft and a corresponding specific capacity of 1.4 (gal/min)/ft. Transmissivity values of 1,260 and 1,940 ft²/d were calculated from the production well data. Transmissivity values of 15,000 and 20,800 ft²/d were calculated from the observation well data and a storativity value of 0.006 was calculated from pumping-induced drawdown in one observation well.

SAIC (2004) conducted a hydrogeologic evaluation of a site about 1.4 mi southeast of Vaucluse Spring to develop a water supply. The study included hydrogeologic analyses, completion of a production well, test pumping and water-level monitoring, and water-quality analyses. On the basis of a 96-hour constant-rate pump test, the reliable yield was estimated to be 350 gal/min with an estimated water-level drawdown of 66 ft and a corresponding specific capacity of 5.3 (gal/min)/ft. Transmissivity values of 950 and 1,070 ft²/d were calculated from the production well data. Transmissivity values ranging from 1,100 to 3,340 ft²/d were calculated from the observation well data and storativity values ranging from 0.00002 to 0.02 were calculated from pumping-induced drawdown in five observation wells.

Results from this limited aquifer testing of the carbonate aquifer system in and near Frederick County (table 3) produced 11 transmissivity values (10 of which were estimated from recovery water-level data after pump cutoff) that range from 500 to 18,000 ft²/d, with an average of about 5,400 ft²/d and a median of 1,960 ft²/d, and 9 storage estimates that range from a low of 0.00002 to a high of 0.04, with an average of about 0.01 and a median of 0.0006. Although limited in amount, these aquifer-test data illustrate the wide variability in aquifer properties of the carbonate aquifer system of the study area. Wide variability in aquifer properties is commonly observed in fractured-rock aquifer systems.

Spring Discharge

Springs are natural discharge points for water draining from the ground-water system and provide much of the base flow to streams in the area. In the past, many of the perennial springs served as public water supplies. Until recently, the City of Winchester obtained its water supply from a variety of springs that have included Old Town Spring, Rouss Spring, Shawnee Spring, and Fay Spring. Discharge was measured approximately 12 times at Marlboro, Vaucluse, Old Town, Shawnee, and Fay Springs between August 2001 and December 2002 (fig. 8) (White, Hayes, and others, 2003, p. 502 and 507; 2004, p. 538, 540–541). The mean discharge of 12 measurements at Marlboro Spring (station 01635005) was 2.6 ft^3/s with a minimum of 1.5 ft^3/s and a maximum of 6.5 ft^3/s. Marlboro Spring was the start of flow for Fawcett Run during this period, and concurrent discharge measurements downstream, at the mouth of Fawcett Run (station 01635008), indicate that it was contributing all the flow in the stream. The mean discharge of 12 measurements at Vaucluse Spring (station 01635070) was 1.8 ft^3/s with a minimum of 1.3 ft^3/s and a maximum of 3.2 ft^3/s. Vaucluse Spring was the start of flow for Meadow Brook during this period. The mean discharge of 11 measurements at Old Town Spring (station 01615515) was 0.5 ft^3/s with a minimum of 0.3 ft^3/s and a maximum of 0.8 ft^3/s. The mean discharge of 13 measurements at Shawnee Spring (station 01615518) was 1.1 ft^3/s with a minimum of 0.8 ft^3/s and a maximum of 1.4 ft^3/s. The mean discharge of 13 measurements at Fay Spring (station 01616075) was 1.5 ft^3/s with a minimum of 0.4 ft^3/s and a maximum of 2.5 ft^3/s.

Water Levels

In the absence of pumping stress, the primary factors contributing to seasonal water-level fluctuations are precipitation, ground-water evapotranspiration, and discharge to springs and streams. Water levels generally rise with precipitation and fall slowly during periods of little precipitation as a result of discharge from the aquifer system, particularly during the growing season. The amount of seasonal water-level fluctuation in the carbonate aquifer system varies across the study area 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) ground-water discharge to springs and streams. Generally, in a given ground-water basin, the larger the contributing area of recharge, the less seasonal water-level fluctuation; a topographic high (for example, a ground-water divide) will have a smaller contributing area of recharge and exhibit more fluctuation, whereas farther down (for example, midway between the recharge area and the discharge area) the flow system will have a larger contributing area of recharge and less fluctuation; the greater the amount of ET, the more fluctuation; and the greater the aquifer permeability, the less fluctuation.

The effects of changes in recharge and discharge during the extremely wet conditions of 1996 and early 1998, the drought of 1998–2002, and the recovery in 2003 are shown in the hydrograph of water levels from well 46W175 at the University of Virginia's Blandy Experimental Farm in neighboring Clarke County, Va. (fig. 9). The well is completed in the Conococheague Limestone of the carbonate aquifer system, and the period of record is from July 1987 to the current year (2005). Statistics are based on the period of record from water year 1988 to water year 2003. A water year is the 12-month period October 1 through September 30, and is designated by the calendar year in which it ends and which includes 9 of the 12 months. Many of the deepest daily water levels for the period of record were established during the drought in 2002. Some of the shallowest daily water levels for the period of record were established in late 1996 and early 1997 prior to the drought, and in 2003 after the drought.

Water levels were measured periodically by the USGS with a steel tape in 37 wells and continuously with water-level recorders in three wells between August 2001 and June 2003; additional water-level measurements were made by the FCSA in their observation wells during this time (fig. 8). The USGS data are published in White, Powell, and others (2003, pp. 119–156; 2004, pp. 117–155). Hydrographs of these data show the seasonal response of the carbonate aquifer system to recharge by precipitation and discharge from the aquifer system. Water-level fluctuations in the 37 wells measured periodically between March 2002 (a low-water period because of the prolonged drought) and March 2003 (a high-water period), ranged from 1.31 ft in well 45Y 8 to 76.78 ft in well 45Y 6. The median amount of fluctuation was 21.65 ft.

The relation among precipitation, the water levels observed in wells 44W 8, 45Y 5, and 46X108 in the carbonate valley of Frederick County, and the water level observed in well 46W175 at Blandy Experimental Farm in Clarke County, for 2001–02 are shown in figure 10. Precipitation during the summer (June through September) generally produces little increase in ground-water levels; ET is high and most of the infiltrated precipitation replenishes soil moisture and does not recharge the ground-water system. For example, the storm of August 12–13, 2001, produced 3.65 in. of precipitation; however, the water levels in wells 44W 8 and 46W175 did not respond and continued to decline. Wells 45Y 5 and 46X108, in the northern part of the carbonate valley of Frederick County, exhibited shallower depths to water prior to the storm, and did respond to the storm. The water level in well 45Y 5 rose 3.41 ft and gradually declined, whereas the water level in well 46X108 rose 17.08 ft and declined fairly rapidly back to pre-storm levels. Precipitation during the late fall and winter, after the soil-moisture deficit has been replenished, generally produces a larger increase in ground-water levels; however, little precipitation fell during late 2001 and early 2002 and water levels in all four wells generally declined and reached lows in March 2002. Precipitation in the spring of 2002 resulted in moderate increases in water levels through May and was generally followed by gradual declines over the summer. Precipitation during the late fall and winter of 2002 resulted in the end of the drought and increases in ground-water levels.

The approximate altitude and configuration of the water table was derived from water levels in open-hole bedrock wells (table 2) and the altitudes of flowing springs and streams in March 2002 (fig. 11). The well network is denser in the southern half of the study area and the authors spent considerable time walking stream reaches in this area. This situation was not the case in the northern half and is reflected

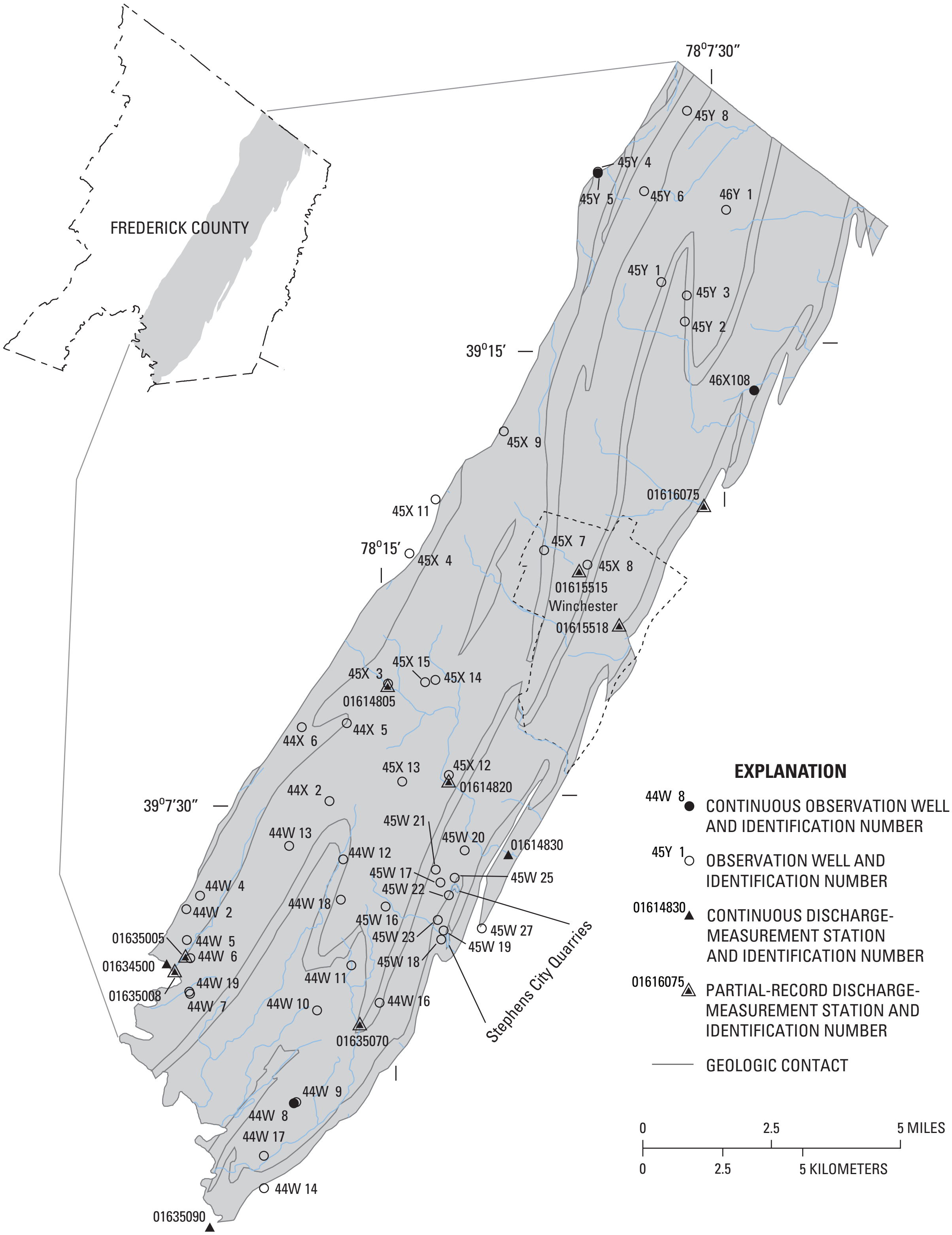

Figure 8. Locations of observation wells and discharge-measurement sites in the carbonate study area of Frederick County, Va.

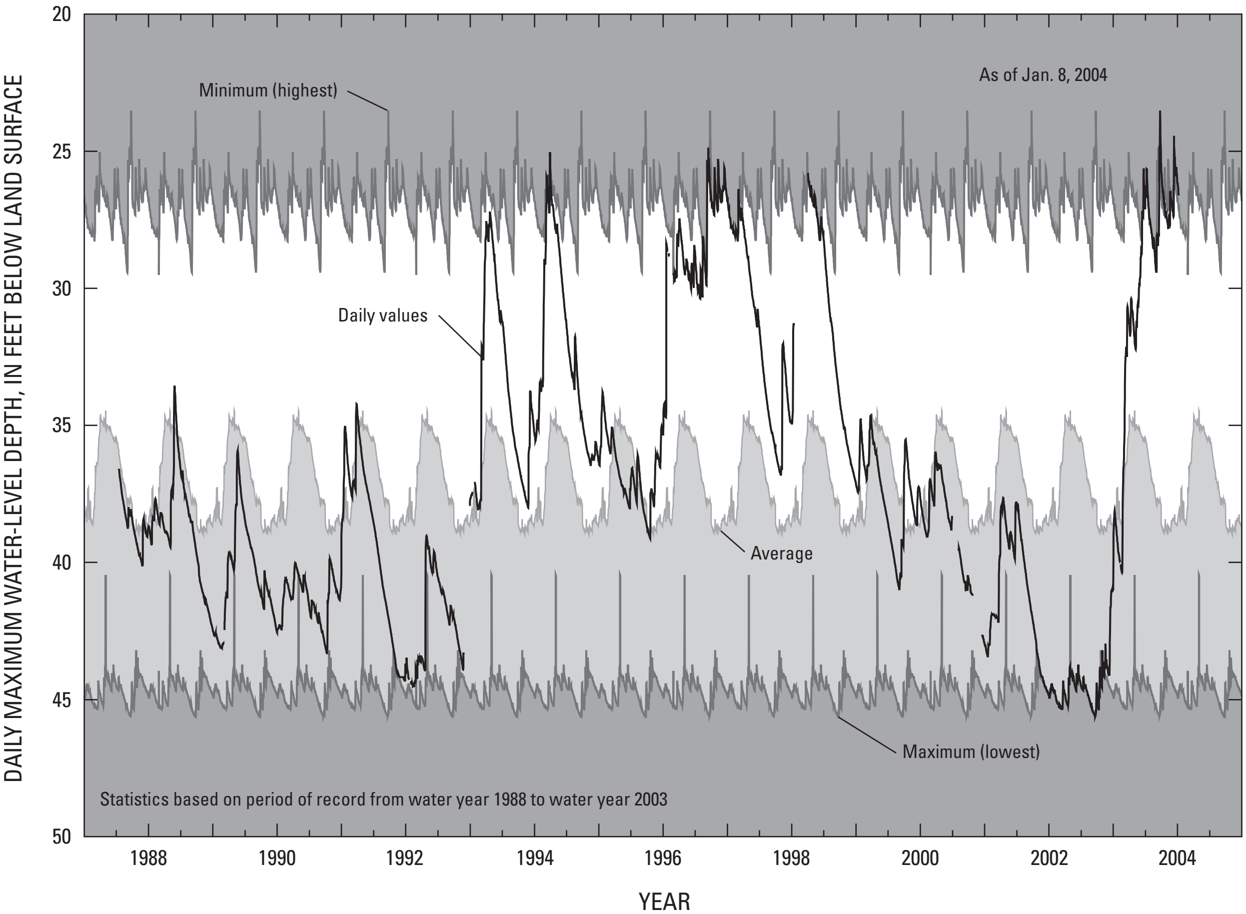

Figure 9. Hydrograph of daily maximum water-level depths compared to the minimum, average, and maximum depths for the period of record in well 46W175 at Blandy Experimental Farm, Clarke County, Va.

by the queried areas and contours. The northern half is currently (2005) being investigated as part of the ongoing USGS study of ground-water resources in the area. Streams are not depicted because long reaches of many "perennial" streams were dry in March 2002. Additionally, springs were the start of flow for many streams, and in some cases spring discharge accounted for all the flow in a stream. The "perennial" stream network in the study area is shown in figure 8, which does not reflect conditions in March 2002.

In isotropic aquifers the direction of ground-water flow is normal to the hydraulic gradient, whereas in anisotropic aquifers (such as the study area), the direction of ground-water flow is from higher to lower head, but is often at some angle from normal to the hydraulic gradient because the orientation of permeable zones in the aquifer system controls the direction of flow. The general direction of ground-water flow is from the hills in the west of the study area into and across the carbonate valley toward its eastern boundary. In the southern third of the study area, ground water flows toward the deeply intrenched Cedar Creek and toward the Stephens City quarries. A ground-water divide may be present north of Round Hill in the vicinity of the Apple Pie Ridge fault where the North Mountain fault zone cuts out the resistant Silurian and Devonian sandstone units and results in surface drainage from the carbonate rocks, which flows west and leaves the carbonate valley. However, additional, more detailed investigation is needed to document this divide.

Water levels decline in areas of ground-water withdrawal. The shape and magnitude of the decline depend on the characteristics of the aquifer and magnitude of the withdrawal. In isotropic and homogeneous aquifers, the decline is often termed a cone of depression because of its uniform conical shape. However, in anisotropic and heterogeneous aquifers, the water-level declines are often asymmetric as a result of the variation of permeability with direction. In general, under unconfined conditions, the change in head over distance is more in less permeable aquifers than in more permeable aquifers. At the upper end of the Stephens Run Basin, ground-water withdrawals from the Stephens City quarries cause a cone of depression (fig. 11). Burbey (2003, p. 11) noted that water-level declines associated with pumping largely occur in the immediate vicinity of the quarries, and are asymmetric, extending southward and slightly northward (along the strike of the geologic units). However, little water-level decline

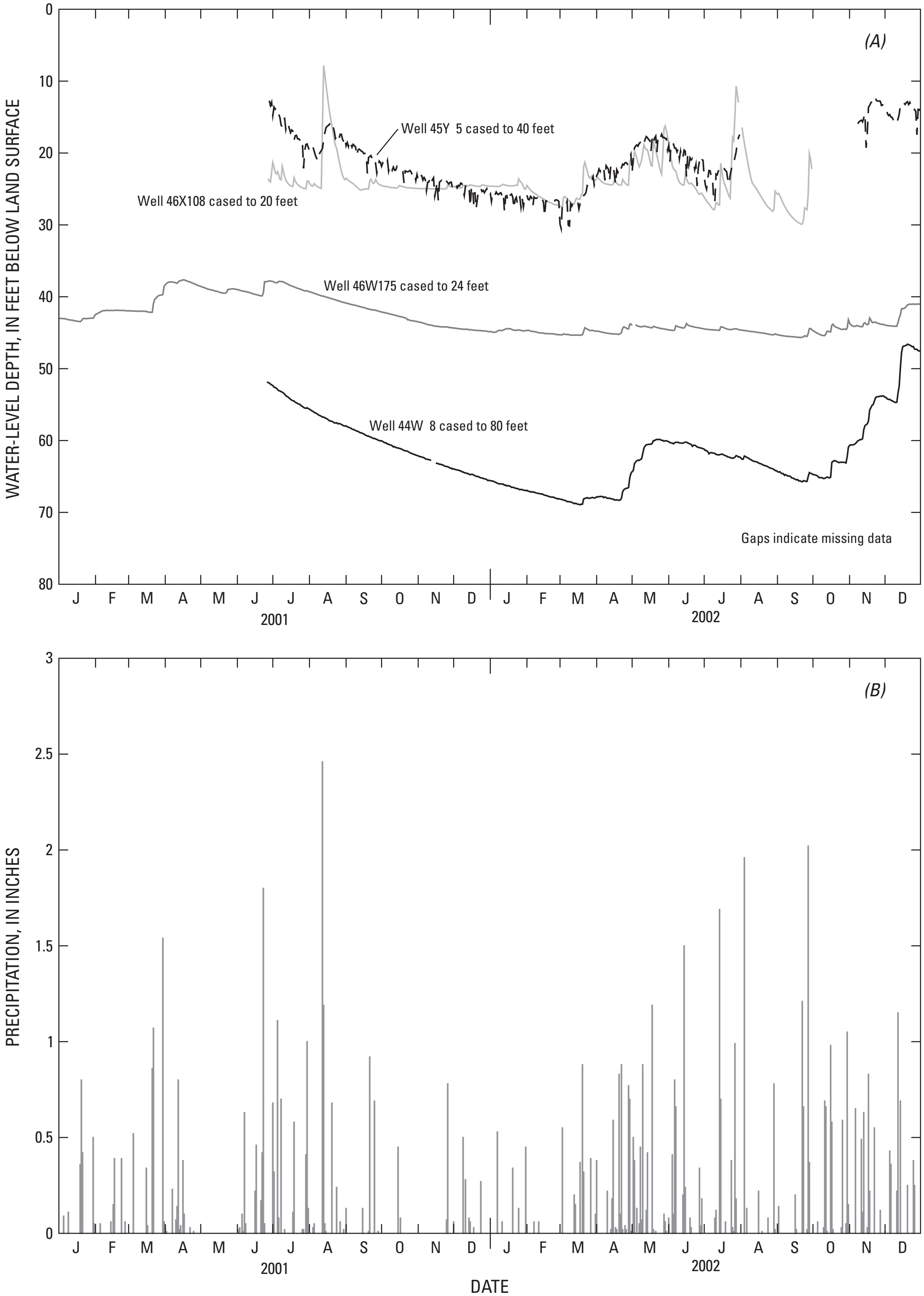

Figure 10. Hydrograph of water-level depths in wells 45Y 5, 46X108, 46W175, and 44W 8 *(A)*, and daily precipitation at National Weather Service climatological station 449186, located 7 miles southeast of Winchester, Va. *(B)*, 2001-02.

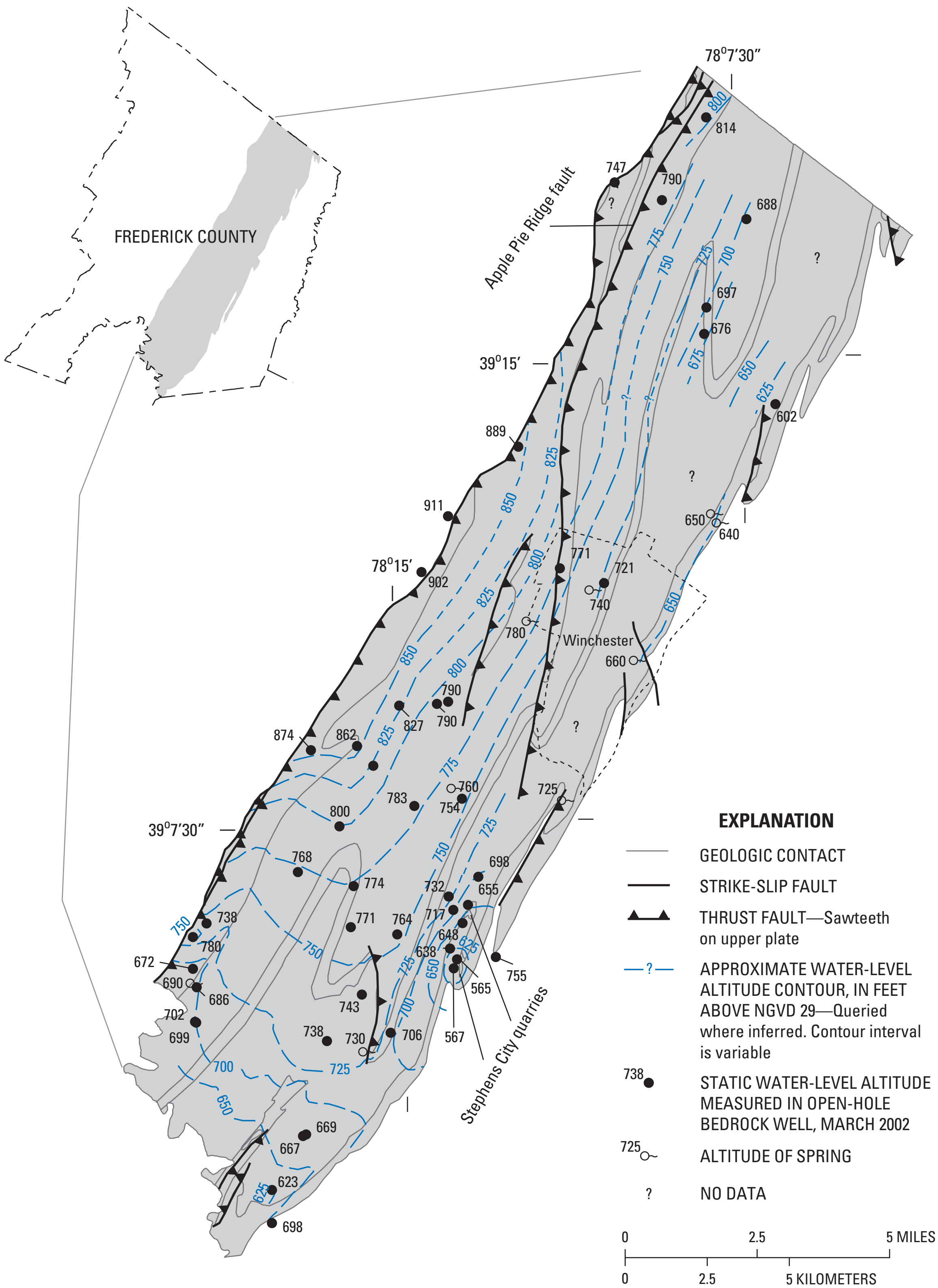

Figure 11. Approximate altitudes and configurations of the water table determined from water levels measured in open-hole bedrock wells and perennial spring altitudes, March 2002, Frederick County Va.

extends west of the quarries and may indicate a hydrologic boundary or decreased permeability in this direction. Such boundary and permeability controls likely result from effects of geologic structure in the area. Because of the steeply dipping rocks caused by folding and the thin thickness of some of the formations in the area, near-surface formations change over short distances (tens to hundreds of feet), likely affecting ground-water flow.

Ground-Water Availability

Rates of effective ground-water recharge were estimated on the basis of streamflow data from three gaging stations and a streamflow-partitioning program that separates streamflow into ground-water (base flow) and surface-runoff components (table 4). Additionally, average annual water budgets were prepared for two streams in the study area for 2001 and 2002, using streamflow and precipitation data and changes in ground-water storage from water-level data and estimates of specific yield of the carbonate aquifer system (table 5).

Recharge

Precipitation that infiltrates into the soil and percolates to the water table recharges the ground-water system. 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. Generally, recharge areas comprise topographic highs in an area, whereas topographic lows are commonly discharge areas. Because of climatic variability, the amount of recharge varies from year to year.

A streamflow-partitioning program (Rutledge, 1993) was used to analyze flow data from two unregulated streams in the study area to separate streamflow into its ground-water discharge (base flow) and surface-runoff components, and to estimate ground-water recharge (table 4). In using this method, it is assumed that the surface-water drainage basin and the recharge area are the same. The validity of this assumption, however, is uncertain. Base-flow discharge is commonly assumed to be equivalent to effective recharge; however, it is not the total recharge for a basin. Total recharge is always larger than effective recharge and includes riparian evapotranspiration (RET), which is the quantity of water evaporated or transpired by plants in the riparian zone adjacent to streams. Rutledge and Mesko (1996, p. B34) noted that RET generally ranges between 1 and 2 in/yr in the Appalachian Valley and Ridge from Alabama to New Jersey. RET is also a component of total ET and is included in the ET component of the water-budget estimates presented later in this report. Nelms and others (1997, p. 14) estimated a median effective recharge of 8.38 in/yr from 73 basins in the northern Valley and Ridge Province of Virginia.

Continuous discharge-measurement station 01634500, Cedar Creek near Winchester, Va., is at the southwestern corner of the study area and has been in operation since June 1937 (fig. 8). The station is close (approximately 2,200 ft) to the North Mountain fault zone that marks the western boundary of the study area and the occurrence of carbonate bedrock. The entire drainage area above this station is underlain by siliciclastic bedrock. The average annual effective recharge for this station for 1938–2002 was 7.7 in. (fig. 12), with base-flow discharge comprising 60 percent of mean streamflow. The average annual effective recharge for 2001–02 (during this investigation) was 6.2 in., with base-flow discharge again comprising 60 percent of mean streamflow. The 2001–02 average annual effective recharge is a decrease from the 1938–2002 average annual effective recharge by about 20 percent, which is equivalent to a decrease of approximately 7.3 Mgal/d over the 102-mi^2 drainage area.

Continuous discharge-measurement station 01635090, Cedar Creek above Highway 11 near Middletown, Va., is at the southeastern corner of the study area and was constructed in November 2000, as part of the current investigation (fig. 8). The station is close (approximately 400 ft) to the contact between the carbonate bedrock in the study area and the siliciclastic bedrock of the Martinsburg Formation. The average annual effective recharge for this station for 2001–02 was 5.8 in., with base-flow discharge comprising 64 percent of mean streamflow. Applying a factor of 1.2 (from upstream station 01634500) results in an average annual effective recharge value of 7.0 in. The annual computed recharge values are an average for the entire drainages above the discharge-measurement stations, 102 mi^2 for station 01634500 and 153 mi^2 for station 01635090. The recharge for the 51-mi^2 drainage area between the stations that is the part of the basin draining the carbonate aquifer system can be calculated by the following equation: $(153\ mi^2) \times (5.8\ in.) = (102\ mi^2) \times (6.2\ in.) + (51\ mi^2) \times (X\ in.)$; solving for X results in an average annual effective recharge of 5.0 in. for the carbonate part of the basin, with base-flow discharge comprising 77 percent of mean streamflow for 2001–02.

Continuous discharge-measurement station 01614830, Opequon Creek near Stephens City, Va., is on the eastern edge of the study area and was constructed in December 2000 (fig. 8). The station is also close to the contact between the carbonate bedrock in the study area and the siliciclastic bedrock of the Martinsburg Formation. The average annual effective recharge for this station for 2001–02 was 3.2 in., with base-flow discharge comprising 86 percent of mean streamflow.

Partial-record discharge measurements (sites where discrete discharge measurements were obtained over a period of time without continuous data being recorded) were also conducted upstream of the continuous station at two sites—station 01614820, Opequon Creek at old Route 628 near Opequon, Va., and station 01614805, Opequon Creek at Route 622 at Opequon, Va. (fig. 8). Graphical regression methods were used to relate logarithms of base-flow discharge measurements at

Table 4. Streamflow partitioning and estimated recharge for discharge-measurement stations in the Cedar and Opequon Creek Basins, Frederick County, Va.

[in., inches; mi^2, square miles; ft, feet; data presented were computed using the software package PART (Rutledge, 1993)]

Station name	Station number	Mean base flow [effective recharge] (in.)	Mean streamflow (in.)	Base flow as percent of streamflow	Gage datum elevation (ft)	Drainage area (mi^2)	Period of record
Cedar Creek near Winchester, Va.	01634500	7.7	12.9	60	647.09	102	1938–2002
Cedar Creek near Winchester, Va.	01634500	6.2	10.4	60	647.09	102	2001–02
Cedar Creek above Highway 11 near Middletown, Va.	01635090	5.8	9.1	64	525	153	2001–02
Cedar Creek above Highway 11 near Middletown, Va.	01635090	[1]5.0	[1]6.5	[1]77	525	[1]51	2001–02
Opequon Creek near Stephens City, Va.	01614830	3.2	3.7	86	705	15.2	2001–02
Opequon Creek at old Route 628 near Opequon, Va.	01614820	[2]3.5	[2]3.8	92	750	10.6	2001–02
Opequon Creek at Route 622 at Opequon, Va.	01614805	[2]3.8	[2]4.4	86	825	2.47	2001–02

[1]From carbonate part of drainage basin.

[2]Values determined by graphical regression methods relating logarithms of base-flow discharge measurements at these sites to concurrent daily mean discharge values at station 01614830.

Table 5. Annual water budgets for Cedar and Opequon Creek Basins, Frederick County, Va., 2001–02.

[in., inches; precipitation data from the National Weather Service station 449181 located at radio station WINC in Winchester, Va.]

Station	Station number (fig. 8)	Year	Inflow	Outflow		
			Precipitation (in.)	Streamflow (in.)	Change in ground-water storage (in.)	Evapotranspiration, other losses, and error (in.)
Cedar Creek above Highway 11 near Middletown, Va.	01635090	2001	33.1	9.0	-1.8	25.9
		2002	41.2	9.2	1.3	30.7
	Change 2001–02		8.1	.2	3.1	4.8
Opequon Creek near Stephens City, Va.	01614830	2001	33.1	3.7	-.4	29.8
		2002	41.2	3.7	0	37.5
	Change 2001–02		8.1	0	0.4	7.7

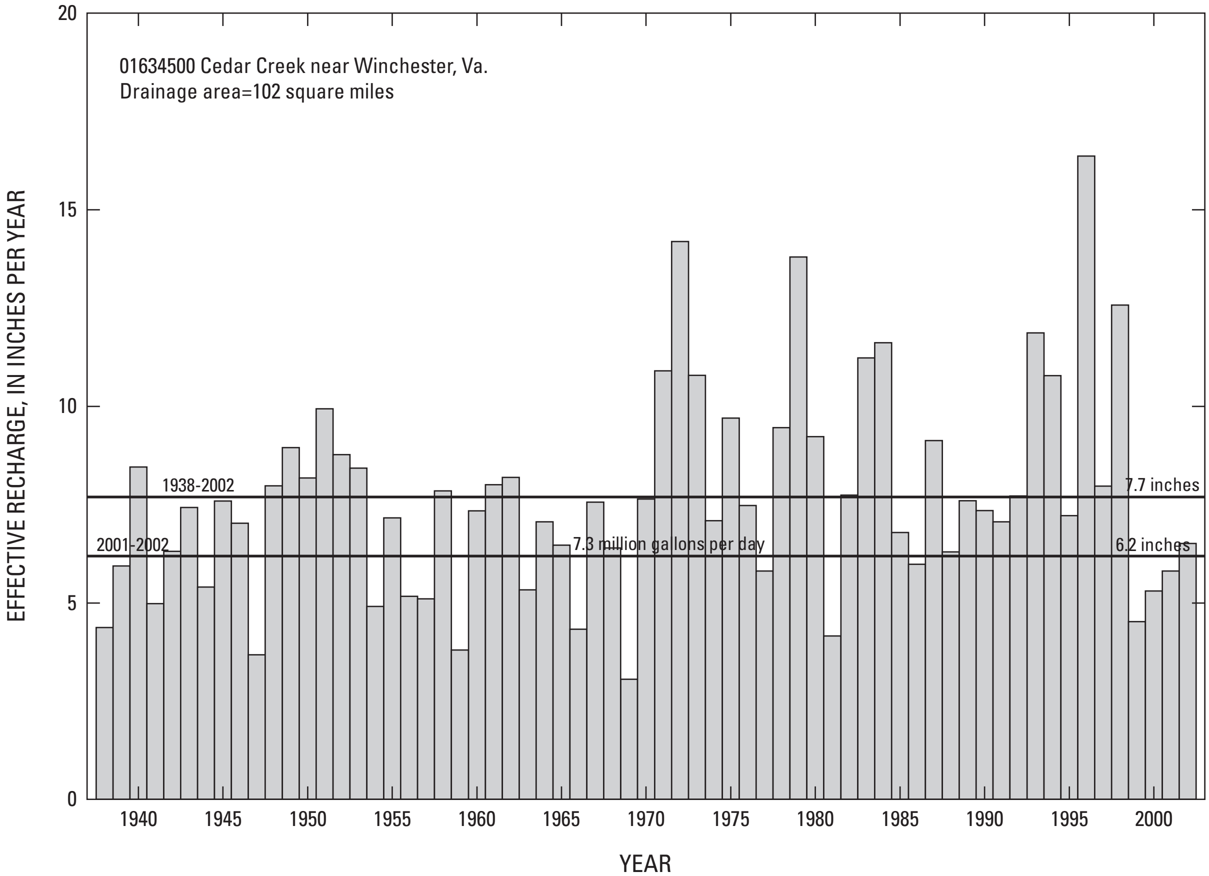

Figure 12. Average annual effective recharge for continuous discharge-measurement station 01634500, Cedar Creek near Winchester, Va., 1938-2002.

these sites to concurrent daily mean discharge at the continuous station 01614830. The measured discharges at the partial-record sites (upstream of the continuous site) were plotted on log-log paper against the concurrent daily mean discharge values at station 01614830. A curve was visually fitted to the data points and mean base-flow discharge was estimated by transferring the mean base-flow discharge from station 01614830 through the relation line to the partial-record station in the same manner as shown in figure 13. The mean base-flow discharges for the partial-record stations were divided by the respective drainage areas to obtain effective recharge values. Some discharge measurements were not used because either the partial-record station or the continuous-record station was affected by surface runoff. The average annual effective recharge values for partial-record stations 01614805 and 01614820 for 2001–02 were 3.8 and 3.5 in., respectively, with base-flow discharge comprising 86 and 92 percent of mean streamflow, respectively.

Results from streamflow partitioning for 2001–02, at the end of an extended drought period, yield mean streamflows that range from 3.7 to 10.4 in., mean base flows (effective recharge) that range from 3.2 to 6.2 in., and mean base flows as a percentage of mean streamflows that range from 60 to 92 percent (table 4). Drainage areas range from 2.47 to 153 mi^2, with the smaller drainages generally yielding lower mean streamflow, lower mean base flow, and base flow that comprised a higher percentage of mean streamflow. Results for the carbonate aquifer system yield mean streamflows that range from 3.7 to 6.5 in., effective recharge that ranges from 3.2 to 5.0 in., and mean base flows as a percentage of mean streamflows that range from 77 to 92 percent.

Water Budget

A water budget is an estimate of water entering and leaving a basin plus or minus storage changes for a given time period. Water enters a basin as precipitation and leaves as streamflow, ET, and diversions, such as surface-water withdrawals and ground-water pumpage. The only known interbasin transfer of water within the study area is from the Stephens Run Basin. In a basin where the ground-water and surface-water divides are not coincident, water may also enter or leave as underflow. Although there are currently no documented instances of underflow in the study area, underflow of 2.4 in/yr has been estimated for a basin underlain by carbonate rock in

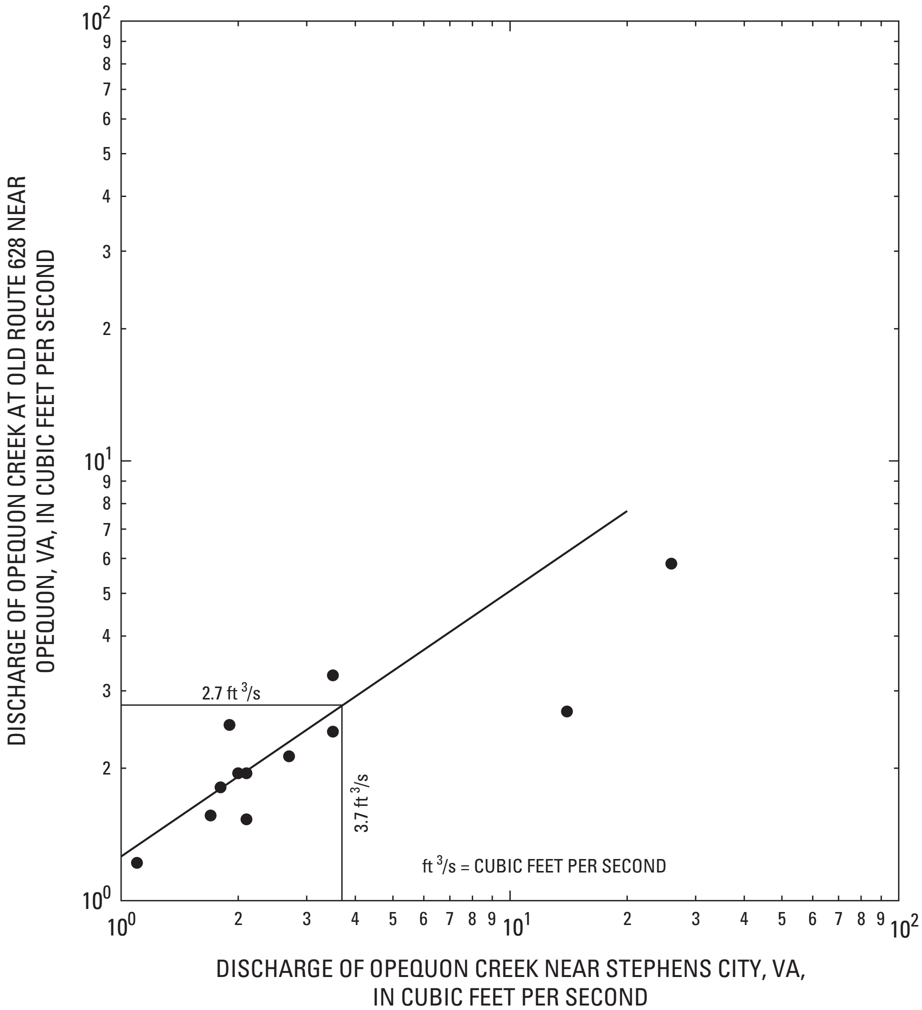

Figure 13. Relation of instantaneous discharge of Opequon Creek at old Route 628 near Opequon, Va., to concurrent daily mean discharge of Opequon Creek near Stephens City, Va.

Pennsylvania (Senior and others, 1997, p. 43). A simple water budget can be described by the following equation:

$$PR = ET + SF + \Delta S, \qquad (1)$$

where

PR is the mean precipitation, in inches per year,
ET is the mean evapotranspiration, in inches per year,
SF is the mean streamflow, in inches per year, and
ΔS is the change in ground-water storage, in inches per year.

All terms in the water-budget equation are known or can be estimated except ET; the equation is solved for ET. Deviations from the assumptions of the equation, such as underflow between basins, and errors in other terms, are, therefore, included in ET. Average annual water budgets for calendar years 2001 and 2002 were prepared for Cedar and Opequon Creek Basins in the study area (table 5).

Changes in storage are negligible given a sufficient period of data; however, considering the short period of operation of the two new continuous discharge-measurement stations, and the ongoing dry conditions when the investigation began, the changes in ground-water storage were estimated for each year. Water-level data from nine observation wells were averaged to calculate the change in ground-water storage in the Cedar Creek Basin, and water-level data from only one observation well was used to calculate the change in ground-water storage in the Opequon Creek Basin. Water levels measured in May 2001 (the first measurements during this study) and November 2001 were used for the 2001 annual budgets. These measurements do not cover an entire year, and, therefore, represent seasonal rather than annual changes in ground-water storage. Water-level measurements made in November 2001 and December 2002 were used for the 2002 annual budgets. These measurements cover slightly more than 1 year but are probably a good approximation of annual changes in storage. The average change in water level for each basin was multiplied by 0.01, the average value from table 3, and the estimated specific yield of the zone of water-level fluctuation, to calculate the annual change in ground-water storage.

Precipitation data from the National Weather Service station 449181, located at radio station WINC in Winchester, Va., were used for the water budgets. The station is the most proximal to the study area but is not located in either basin. Normal (1971–2000) annual precipitation at this station is 36.40 in. Annual precipitation for 2001 and 2002 was 33.1 and 41.2 in., respectively. Therefore, the water budgets for 2001 represent water budgets for below-normal precipitation and the water budgets for 2002 represent water budgets for above-normal precipitation. Precipitation measured at the station may not be representative of precipitation falling on the basins and may introduce error into the water budgets. Such errors in precipitation measurement are included in the ET term in equation 1.

Annual water budgets for Cedar and Opequon Creek Basins for 2001 and 2002, at the end of an extended drought period, show that the greatest outflow by far is ET, other losses, and error. The greatest change in outflow due to change in inflow (2001–02) is also ET, but not as much relatively. Changes in ground-water storage are a small part of the annual budgets. In the Cedar Creek Basin, the 3.1-in. change in ground-water storage (2001–02) is a large part of the 8.1-in. change in precipitation, whereas the 0.4-in. change in ground-water storage in the Opequon Basin is a small part of the 8.1-in. change in precipitation.

Summary

The 105-mi^2 study area includes approximately one-fourth of Frederick County, Va., and is underlain by carbonate bedrock. The area is undergoing increased urbanization as part of development around the City of Winchester and along U.S. Route 11 and Interstate 81. Ground water is a major source of supply in the area, and increased demands on the carbonate aquifer system are expected in the future. In order to quantify the amount of ground water available to meet these future demands, the U.S. Geological Survey, in cooperation with the County of Frederick, Va., began a long-term investigation of the hydrogeology and ground-water availability in the carbonate aquifer system of Frederick County in October 2000.

Most streams flow normal to geologic strike (from the northwest towards the southeast) across the study area. The entrenched channel of Cedar Creek marks the southern limit and drains the southern third of the study area. Its tributaries flow parallel to geologic strike (from the northeast towards the southwest).

All geologic units in the study area are considered to be aquifers. The geologic units are generally unconfined, fractured-rock aquifers that are recharged by precipitation and discharge locally to streams and springs and as evapotranspiration; however, confined ground water may be present locally. Ground-water discharge from springs comprises much of the base flow to streams in the area.

Joints in rocks of Frederick County vary with rock type. The Cambrian and Ordovician carbonate rocks are brittle compared to the ductile Martinsburg Formation that contains a well-developed slaty cleavage. The carbonate rocks exhibit two sets of cross-strike joints that trend N. 70º–80º W. (dip joints) and N. 30º W. (oblique joints) and longitudinal joints that trend N. 30º E. (strike joints).

The secondary permeability of bedding planes, joints, and faults provides the storage space and pathways for ground-water flow from high hydraulic head to low hydraulic head. Bedding planes are important pathways because they are more continuous than any other features. However, dip joints and oblique joints may allow ground water to flow across the strike of the structures. Many large springs in the carbonate valley are associated with faults, suggesting that faults may serve as important directional controls on ground-water flow.

Aquifer transmissivity and storage values have been estimated for the carbonate rocks in the study area. Reported aquifer transmissivities range from 500 to 18,000 ft^2/d, with an average of about 5,400 ft^2/d and a median of 1,960 ft^2/d. Reported storage values range from 0.00002 to 0.04, with an average of about 0.01 and a median of 0.0006.

The general direction of ground-water flow is from the hills in the west of the study area into and across the carbonate valley. In the southern third of the study area, ground water flows toward the deeply intrenched Cedar Creek. A ground-water divide may occur north of Round Hill in the vicinity of the Apple Pie Ridge fault where the North Mountain fault zone cuts out the resistant Silurian and Devonian sandstone units and results in surface drainage from the carbonate rocks that flows west and leaves the carbonate valley.

Effective ground-water recharge was estimated in both the Cedar and Opequon Creek Basins for 2001–02. Average estimated recharge was 5.8 and 6.2 in. above the two gages in the Cedar Creek Basin. Base flow accounted for between 60 and 64 percent of streamflow. For the part of the basin draining the carbonate aquifer system, the average estimated recharge was 5.0 in. Average estimated recharge ranged from 3.2 to 3.8 in. in the Opequon Creek Basin and accounted for between 86 and 92 percent of streamflow.

Water budgets for 2001, a year of below-normal precipitation (33.1 in.), and 2002, a year of above-normal precipitation (41.2 in.), were calculated for the Cedar and Opequon Creek Basins. Streamflow was 9.0 in. in 2001 and 9.2 in. in 2002 in Cedar Creek. Evapotranspiration was estimated to range from 25.9 to 30.7 in. Annual change in ground-water storage was a decrease of 1.8 in. in 2001 and an increase of 1.3 in. in 2002. Streamflow was 3.7 in. in 2001 and 2002 in Opequon Creek. Evapotranspiration was estimated to range from 29.8 to 37.5 in. Annual change in ground-water storage was a decrease of 0.4 in. in 2001 and no change in 2002.

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