Estimating Recharge to Heterogeneous Fractured-Rock and Karst Aquifer Systems in the Shenandoah Valley of Virginia and West Virginia

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Abstract

In recent years, the Northern Shenandoah Valley of Virginia and West Virginia has been experiencing rapid growth along the I-81 corridor and the eastern margin of the Valley. Increased development in rural areas is expected to continue as new residents commute to the Washington, D.C. metropolitan area. This growth has the potential to profoundly influence the region's land, water, and biological resources. Regional and local resource managers have major concerns over the region's ability to sustain future growth. Of particular concern is the sustainability and vulnerability of the region's water resources and the ability to provide a reliable long-term water supply. As of 2000, consumptive water use in the Shenandoah River Basin was estimated to be 33.4 million gallons per day, and is forecast to increase to over 40 million gallons per day by the year 2030. Water use is expected to increase by 30-percent in the main stem of the Shenandoah, while water use in the South Fork and North Fork are expected to increase by 16- and 25-percent, respectively. To address these concerns, the U.S. Geological Survey (USGS) Virginia, West Virginia and Leetown Science Centers are conducting cooperative investigations in the counties of Clarke, Frederick, and Warren in Virginia and the counties of Berkeley and Jefferson in West Virginia. These investigations focus on characterizing the carbonate and fractured-rock aquifer systems in these counties and providing relevant hydrogeologic information that can be used to guide the development and management of the ground-water resources. Since 2003, the Virginia and West Virginia Science Centers have also participated in a multidisciplinary regional assessment of the water resources of the Shenandoah Valley utilizing USGS Integrated Science Funding to develop and investigate methods to provide insight into the complex ground-water systems in the Valley.

A specific goal of our current studies is to improve our understanding of the recharge of ground water in the complexly folded and faulted fractured-rock and karst aquifer systems. Estimates of recharge to these fractured-rock and karst aquifer systems have been derived historically using graphical hydrograph separation techniques and, more recently, from linear regression techniques. These estimates are presented for the Valley as a whole, for different rock classes across the Valley, for individual watersheds within the Valley and, finally, for individual watersheds during both "average" and "drought" conditions. In spite of the fact that estimates of base flow and recharge from graphical separation techniques have been used for decades, substantial uncertainty is still associated with these estimates. While older, graphical methods for separating runoff from base flow are based on visual intuition, a newer chemical hydrograph-separation method is based on a physical process that can be measured in the field. An ongoing investigation using a chloride mass balance approach to calculate the components of the hydrologic budget for individual watersheds will verify and/or constrain recharge estimates obtained by graphical hydrograph-separation methods. The Shenandoah Valley was selected for more intense data collection where all current streamflow gaging stations are instrumented in addition to selected wells and springs. The objectives of this study are to (1) develop hydrologic budgets for the watersheds and counties of central and western Virginia, and (2) display this information as maps of Virginia by watershed and by county. The hydrologic budget components that will be shown in map view include rainfall, total evapotranspiration, riparian evapotranspiration, infiltration, recharge, runoff, and base flow.

Introduction

The Shenandoah Valley Region is located in the northwestern part of Virginia and the eastern Panhandle of West Virginia and extends from Augusta County, Virginia to Berkeley and Jefferson Counties, West Virginia **(fig. 1)**. Steadily increasing development of ground-water supplies in the Shenandoah Valley Region of Virginia and West Virginia has prompted concerns over the availability of the water resources to support both an increasing population and sustain a healthy aquatic ecosystem. Recent sustained drought has heightened the concern of local, state, and federal agencies, as well as private citizen groups and other water-use organizations, resulting in six county studies and regional instream-flow assessment in the Northern Shenandoah Valley as part of the WRD Cooperative Water Program, and establishment of the Great Valley Water-Resources Science Forum. Drought and development have impacted ground-water levels and flows in streams and rivers, affecting the availability of water for human needs, and possibly affecting the health of aquatic ecosystems.

The region contains complex hydrogeology, including karstic carbonate rocks, siliciclastic sedimentary rocks, and crystalline basement, all of which are highly folded and faulted **(table 1)**. The diverse lithologies result in both conduit (karst-based) and diffuse (fracture-based) ground-water flow. Ground water is a major contributor to flow in many streams and rivers and has a strong influence on river and wetland habitats for plants and animals. The interactions between ground water and surface water are difficult to observe and measure.

Table 1. Lithologic and hydrogeologic units of the Shenandoah Valley.

Lithologic unit	Hydrogeologic unit	
Devonian	Clastic rocks	
Mahantango Formation		
Needmore Formation		
Marcellus Formation		
Millboro Shale		
Silurian and Devonian		
Helderberg and Cayuga Groups		
Ridgeley Sandstone		
Silurian		
Massanutten Sandstone		
Ordovician		
Martinsburg and Oranda Formation		
Ordovician	Carbonate rocks	
Lincolnshire and New Market Limestone		
Edinburg Formation		
Beekmantown Group		
Cambrian and Ordovician		Western-toe carbonate rocks
Conococheague Formation		
Cambrian		
Elbrook Formation		
Waynesboro Formation		
Tomstown Formation		
Cambrian Chilhowee Group	Metamorphic rocks	
Antietam Formation		
Harpers Formation		
Weverton Formation		
Neoproterozoic		
Catoctin Formation		
Swift Run Formation		
Mesoproterozoic granitic gneiss		

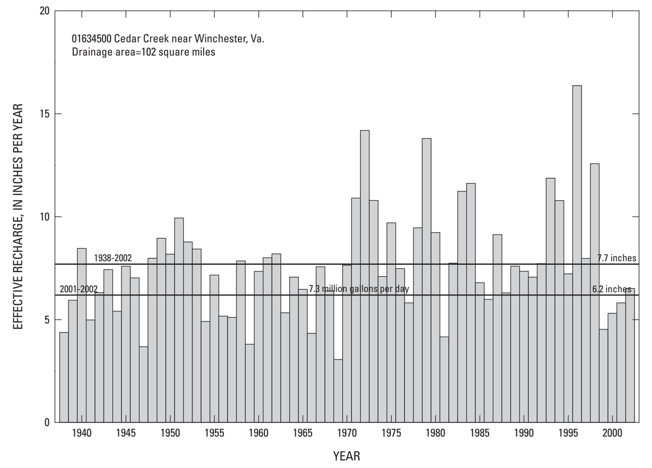

Figure 2. Average annual effective recharge for continuous discharge-measurement station 01634500, Cedar Creek near Winchester, Va., 1938-2002.

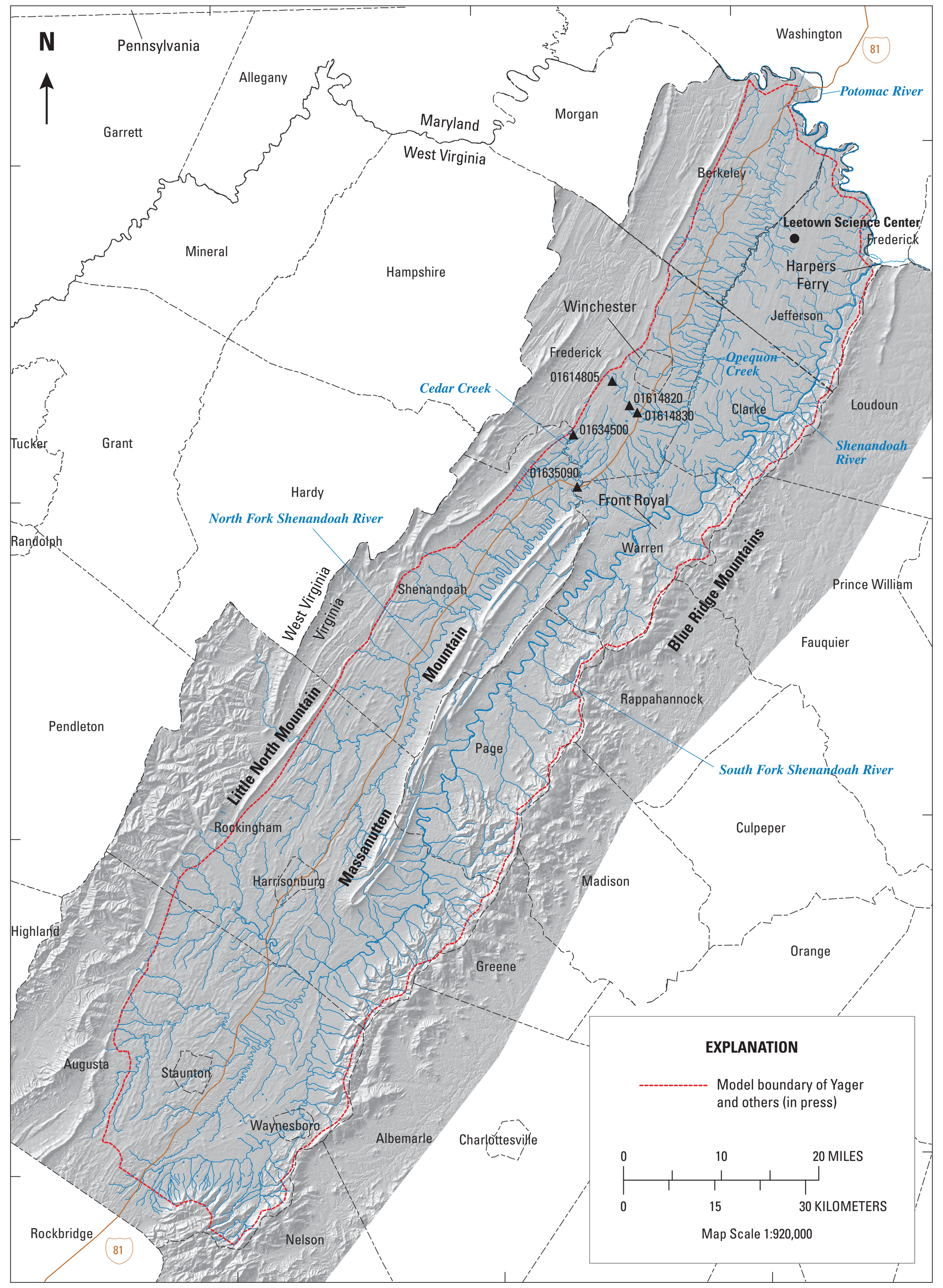

Figure 1. Generalized location map of the Shenandoah Valley of Virginia and West Virginia, showing geomorphic features and model boundary.

Recharge

Nelms and others (1997) used a streamflow-partitioning program (Rutledge, 1993) to analyze flow data from unregulated streams in Virginia to separate streamflow into its ground-water discharge (base flow) and surface-runoff components, and to estimate ground-water recharge. In using this method, one assumes 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 usually included in the ET component of 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 streamflow-measurement station 01634500, Cedar Creek near Winchester, Va., has been in operation since June 1937 **(fig. 1)**. The station is very close to the North Mountain fault zone that marks the western boundary of the Shenandoah Valley and the occurrence of carbonate bedrock. The entire drainage area above this station is underlain by siliciclastic bedrock. Harlow and others (2005) noted that the average annual effective recharge for this station for 1938-2002 was 7.7 in. **(fig. 2)**, with base-flow discharge comprising 60 percent of mean streamflow. The average annual effective recharge for 2001-02 (during drought conditions) 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.

Results from streamflow partitioning in Frederick County, Va. 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 2)**. 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 (Harlow and others, 2005).

An accurate assessment of ground-water recharge in the Leetown, West Virginia area was needed to develop a realistic ground-water flow model (Kozar and others, 2007). A streamflow-gaging station was installed on Hopewell Run **(fig. 3)** in April 2003 to provide data for model calibration and to estimate ground-water recharge. Streamflow data for a 30-month period was evaluated by hydrograph analysis to estimate recharge (Rutledge, 1998) and to provide base-flow discharge data. As a result of the analysis, an average value of 16.5 in/yr of recharge **(table 3)** were estimated for the Hopewell Run watershed for the period October 2003-September 2005. Precipitation records for the nearby Martinsburg airport (National Oceanic and Atmospheric Administration, 2006) indicated annual precipitation totals of 53.94, 46.41, and 30.38 in/yr for 2003, 2004, and 2005 respectively. Long-term mean annual precipitation (1891-2004) for the airport is 39.39 in. (National Oceanic and Atmospheric Administration, 2004). Mean annual precipitation for the 2-year period October 2003-September 2005 of 38.6 inches is within 1 in. of the long-term average. Therefore, the median annual recharge of 16.5 in/yr for the period September 2003 through October 2005 was used for development and calibration of the ground-water flow model and represents an average recharge rate for the Hopewell Run watershed.

Because streamflow data were available only for the Hopewell Run at Leetown gaging station for a 30-month period, recharge was also estimated for the Opequon Creek at Martinsburg. Streamflow data has been collected at this station since1947, and provide a measure of the variability of streamflow and ground-water recharge during average and drought periods. The long-term average recharge for the Opequon Creek watershed was estimated to be 9.8 in/yr (Kozar and Mathes, 2001). The recharge rate for the Hopewell Run watershed is higher as a result of the larger proportion of limestone bedrock which outcrops in the Hopewell Run basin. In contrast, the Opequon Creek watershed has substantial outcrops of the less permeable Martinsburg Formation. Meteorological records (Cornell University, 2006) indicate the most recent drought in the area occurred during the period from November 1998-January 2000. This was the fourth most severe drought on record dating back to 1895, and was the longest, lasting for approximately 16 months. An analysis of potential recharge for the Opequon Creek watershed, to which Hopewell Run drains, was conducted to estimate recharge for the Hopewell Run watershed for the 1999 drought was 5.69 in/yr. Extrapolating data from Opequon Creek to Hopewell Run results in a recharge rate of approximately 8.3 in/ yr for the Hopewell Run watershed during the 1999 drought.

Yager and others (in press) noted that ground-water withdrawals from wells and springs are equal to 2.4 percent of the measured base flow discharged from the Shenandoah Valley, suggesting that the aquifer system is near equilibrium and not greatly stressed at a regional scale. There are no major interbasin transfers of water from the valley and consumptive use of water resulting from irrigation is assumed to be negligible. Under these conditions, all of the recharge that enters the aquifer system discharges through base flow, and the recharge can be computed by dividing the estimated base flow by the area of the drainage basin. The mean recharge rate over the entire Shenandoah Valley is about 7.5 in/yr, but the recharge rate in local areas varies as it is controlled by the topography, precipitation and the underlying bedrock. A linear regression was conducted using the base flows presented by Nelms and others (1997) to determine the relative contributions of these factors. Recharge, expressed as base flow per basin area, was computed in the linear regression as a function of several variables. The following basin characteristics were included in the regression: (1) mean precipitation, (2) mean elevation, and (3) mean slope. The precipitation values were scaled from Nelms and others (1997, fig. 4), and the elevations and slopes were computed using digital elevation models (DEMs) with 30-m resolution. The proportions of the basin area underlain by four major rock classes were also included in the regression due to their differing influence on recharge to and discharge from underlying aquifers: (1) carbonate rock, (2) clastic rock, (3) metamorphic rock, and (4) western-toe carbonate rock **(fig. 4)**.
The proportions of the basin area underlain by the rock classes were the only significant variables found by regression, indicating that the variation in precipitation and topography is reflected by the rock class. Recharge (Rch, in cm/yr) can be computed with the following expression:

$$Rch = 13.9 + 10.8Carb + 9.07Meta + 25.6West, \quad \text{Eqn. 1}$$

where the independent variables are the proportions of the basin underlain by the following rock classes: carbonate (Carb), metamorphic (Meta), and western-toe carbonate (West). Only three of the four rock classes are included in this equation because the proportions of all rock classes in a basin must sum to 1.0, so the proportion of clastic rock is included implicitly. The correlation coefficient (r^2) between recharge values computed with eqn. 1 and from measured base flows was 0.785. The linear regression indicates that the recharge rate is lowest in areas underlain by clastic rocks (5.5 in/yr) and highest in areas underlain by the western-toe carbonates (15.6 in/yr).

In spite of the fact that estimates of base flow and recharge from graphical separation techniques (as used in Nelms and others, 1997) have been used for decades, substantial uncertainty is still associated with resulting estimates. This is because the method for separating runoff from base flow has as its basis visual intuition, rather than a physical process such as a mass balance (Hornberger et al., 1998). This uncertainty has been reinforced by results that have often been observed in chemical hydrograph separations that differ from results obtained by graphical separations. In order to verify and/or constrain the hydrologic budget components obtained by Nelms and others (1997), we propose to use a new method, based on the mass balance of chloride in the watersheds, to make independent estimates of the hydrologic budget components of the watersheds. We will compare the results from the chloride data to updated estimates of base flow by graphical separation methods, and compile water budgets for all of the watersheds and counties **(fig. 5)** in central and western Virginia.

Table 2. Streamflow partitioning and estimated recharge for discharge-measurement stations in the Cedar and Opequon Creek Basins, Frederick County, Va., (see Figure 1 for station locations).

[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	1938-02
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.

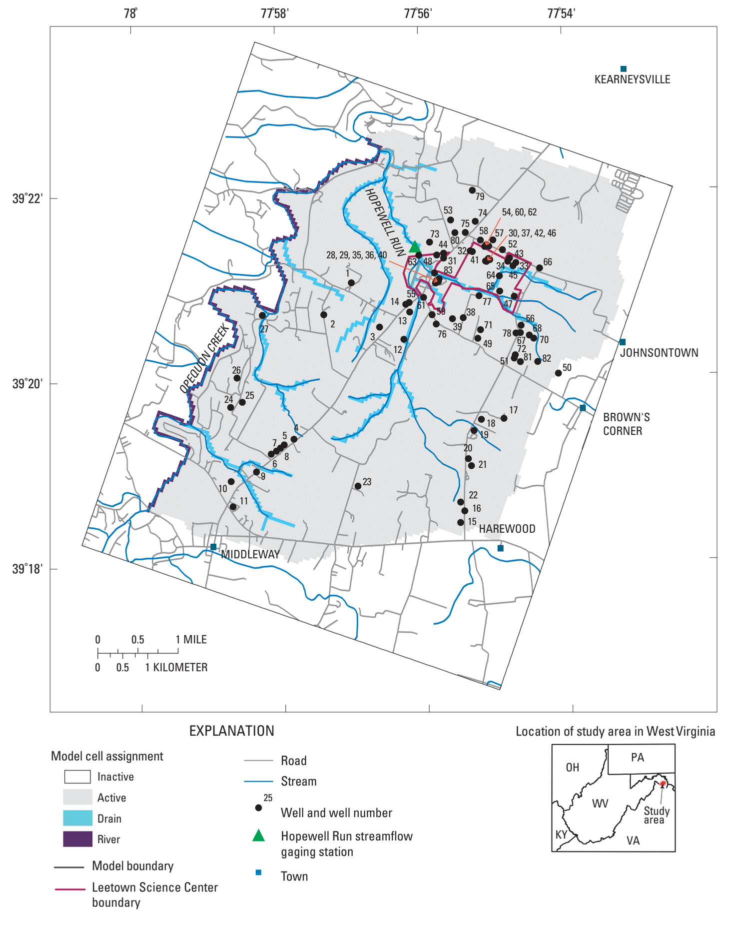

Figure 3. Location of study area and boundary conditions for the ground-water flow model of the Leetown area, West Virginia

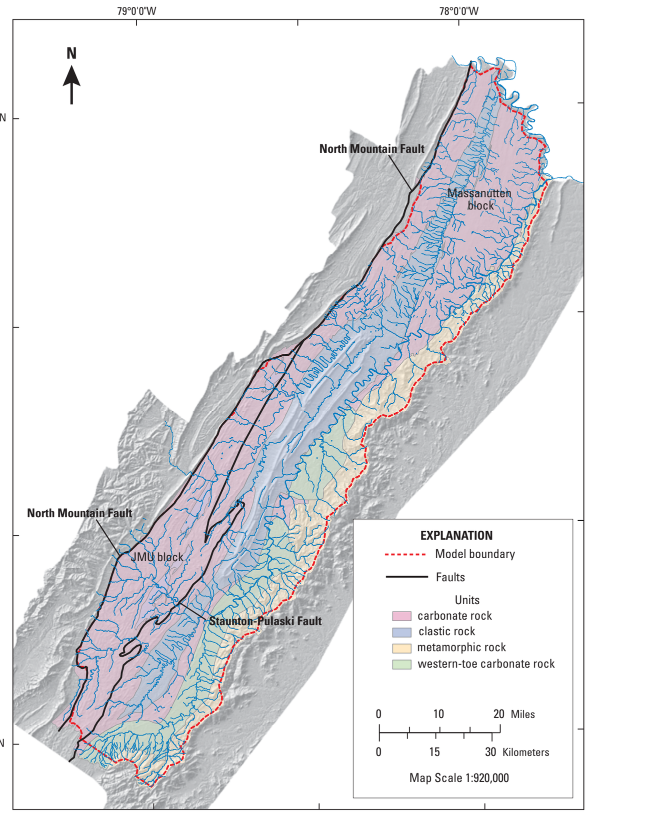

Figure 4. Generalized geologic map of the Shenandoah Valley showing model boundary, structural blocks, major faults, and hydrogeologic units.

Table 3. Quarterly estimates of ground-water recharge in inches for the Hopewell Run and Opequon Creek watersheds with statistical rank (highest to lowest) of annual totals.

[ind, indeterminate; water year, the period from October 1st through September 30th, designated by the calendar year in which it ends]

Water year	Oct-Dec	Jan-Mar	Apr-June	July-Sept	Annual total	Statistical Rank
Hopewell Run At Leetown, WV[2]						
2003	ind.	ind.	8.35	2.61	ind.	ind.
2004	6.46	5.21	6.01	3.54	21.22	1st
2005	3.48	5.76	1.65	0.97	11.86	2nd
Median	4.97	5.49	6.01	2.61	16.54	
Mean	4.97	5.49	5.34	2.37	16.54	
Opequon Creek near Martinsburg, WV[3]						
2003	3.75	6.33	5.68	2.86	18.62	2nd to 3rd
2004	4.77	3.93	4.42	2.92	16.04	3rd to 4th
2005	3.25	5.02	1.05	1.10	10.42	16th to 17th
Median	3.75	5.02	4.42	2.86	16.05	
Mean	3.92	5.09	3.72	2.29	15.02	

[2]Statistical analysis based on period from October 2003 to September 2005.
[3]Statistical analysis based on period from January 1948 to December 2004.

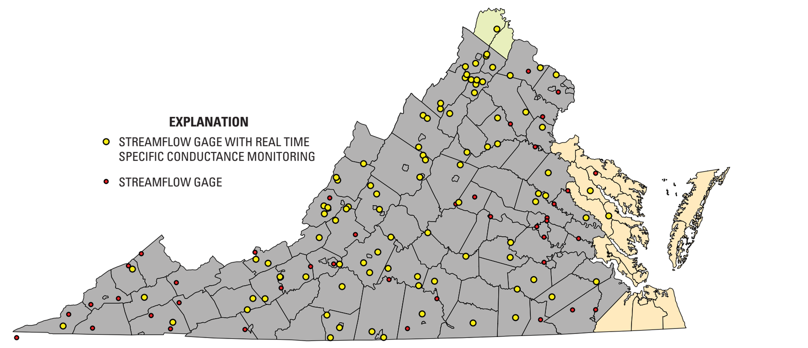

Figure 5. Location of streamflow gages, streamflow gages equipped with specific conductance probes, and counties in Virginia where hydrologic budgets will be estimated.

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