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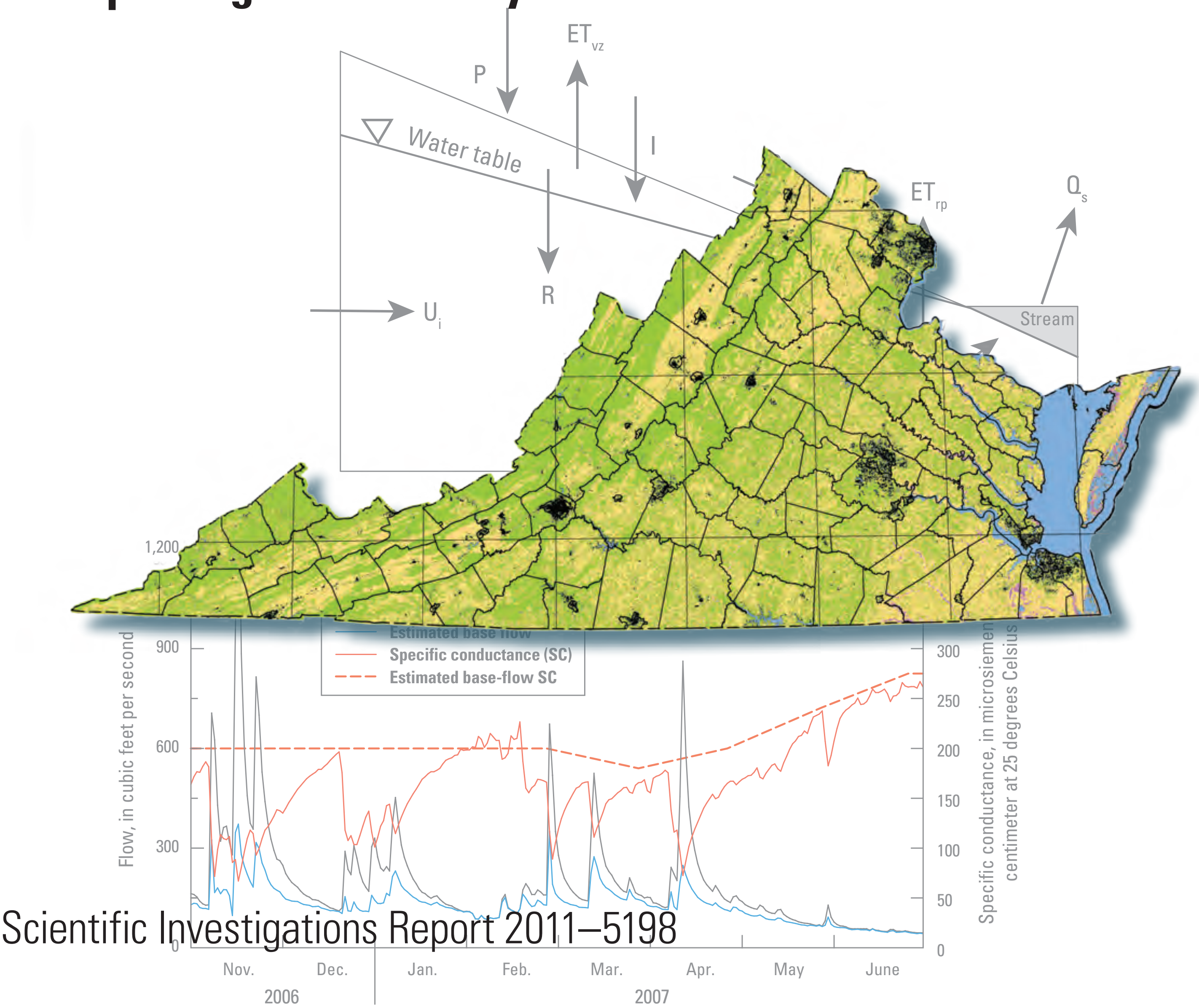
in cooperation with the Virginia Department of Environmental Quality

Quantifying Components of the Hydrologic Cycle in Virginia using Chemical Hydrograph Separation and Multiple Regression Analysis



Scientific Investigations Report 2011–5198

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

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By Ward E. Sanford, David L. Nelms, Jason P. Pope, and David L. Selnick

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
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	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F – 32) ÷ 1.8

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

°F = (°C x 1.8) + 32

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1983 (NGVD 83).

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

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

Cl	Chloride
ET	Evapotranspiration
>	greater than
µS/cm	microsiemens per centimeter
<	less than
NWIS	National Water Information Systems
RASA	Regional Aquifer System Analysis
SC	Specific conductance
USGS	U.S. Geological Survey

Quantifying Components of the Hydrologic Cycle in Virginia using Chemical Hydrograph Separation and Multiple Regression Analysis

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Abstract

This study by the U.S. Geological Survey, prepared in cooperation with the Virginia Department of Environmental Quality, quantifies the components of the hydrologic cycle across the Commonwealth of Virginia. Long-term, mean fluxes were calculated for precipitation, surface runoff, infiltration, total evapotranspiration (ET), riparian ET, recharge, base flow (or groundwater discharge) and net total outflow. Fluxes of these components were first estimated on a number of real-time-gaged watersheds across Virginia. Specific conductance was used to distinguish and separate surface runoff from base flow. Specific-conductance data were collected every 15 minutes at 75 real-time gages for approximately 18 months between March 2007 and August 2008. Precipitation was estimated for 1971–2000 using PRISM climate data. Precipitation and temperature from the PRISM data were used to develop a regression-based relation to estimate total ET. The proportion of watershed precipitation that becomes surface runoff was related to physiographic province and rock type in a runoff regression equation. Component flux estimates from the watersheds were transferred to flux estimates for counties and independent cities using the ET and runoff regression equations. Only 48 of the 75 watersheds yielded sufficient data, and data from these 48 were used in the final runoff regression equation. The base-flow proportion for the 48 watersheds averaged 72 percent using specific conductance, a value that was substantially higher than the 61 percent average calculated using a graphical-separation technique (the USGS program PART). Final results for the study are presented as component flux estimates for all counties and independent cities in Virginia.

Introduction

Water-resource managers within the Commonwealth of Virginia must allocate both groundwater and surface-water resources to multiple users based on estimates of short-term and long-term water availability. In response to the drought of 1999 to 2002, legislation (Senate Bill 1221) was passed in 2003 that required the development of a comprehensive, statewide, water-supply planning process. In 2005, localities were required to develop either local or regional water-supply plans in response to the Local and Regional Water Supply Planning Regulation (9 VAC 25-780). Although recent studies (McFarland and Bruce, 2006; Heywood and Pope, 2009; Sanford and others, 2009; and McFarland, 2010) have focused on the resources of the Virginia Coastal Plain, reliable information is frequently lacking on water availability west of the coastal plain, especially pertaining to long-term fluxes such as recharge to groundwater aquifers.

Flux estimates of components of the hydrologic cycle can be made by creating a water budget in which the various components must balance. Such a water balance approach is reasonably accurate when all of the terms in the budget can be calculated or estimated. This approach is appropriate for the scale of the entire Commonwealth, because most other methods used to estimate recharge are highly dependent on local measurements in both space and time (Healy and Scanlon, 2010). New tools, including national climate data sets with a resolution of less than one mile, and cost-effective specific-conductance data for base-flow separation, are now available to assess water availability across the entire Commonwealth of Virginia. Such an assessment will be valuable for water resource managers at the state, county, and local planning levels.

Purpose and Scope

The purpose of this report is to present the results of a study to quantify components of the hydrologic budget on a large number of watersheds across the entire Commonwealth of Virginia, and use the results to estimate hydrologic budget components for all of Virginia's counties and independent cities. These components include precipitation, surface runoff, infiltration, total evapotranspiration (ET), riparian ET, groundwater recharge, and base flow or groundwater discharge, and are calculated using long-term average values (1971–2000) from mean precipitation data, and base-flow separation data from 2007–2008. The latter were adjusted to long-term conditions based on historical streamflow data. Within watersheds or counties, actual values are expected to deviate, both temporally and locally, from mean values presented in this report. A few watersheds with historical specific conductance data from the neighboring states of Maryland and Delaware were included in the analysis to improve estimates of surface runoff and base flow for the Coastal Plain Province. A comparison was made between chemical and graphical hydrograph separation methods as they were used for estimating base-flow components of 52 watershed budgets. Two appendixes are included that present hydrograph and specific conductance data for 100 watersheds and plots of monthly mean flow versus the fraction of base flow for 84 watersheds.

Location and Setting of Study Area

The Commonwealth of Virginia is located in the east-central United States, bounded by the Potomac River and Maryland on the northeast, West Virginia on the north and west, Kentucky and Tennessee on the southwest, North Carolina on the south, and the Chesapeake Bay and Atlantic Ocean on the east (fig. 1). Virginia is positioned across five different physiographic provinces: the Coastal Plain Province in the far east, the Piedmont Province in the east, the Blue Ridge Province in the west, the Valley and Ridge Province in the far west, and the Appalachian Plateau in the extreme southwest. Politically, the Commonwealth is divided into 95 counties and an additional 39 independent cities (fig. 2). Land-surface elevations rise from sea level at the eastern coastline upward through the low-lying plains of the Coastal Plain Province and the rolling hills of the Piedmont Province, to the long, linear ridges of the mountains of the Blue Ridge and Valley and Ridge Provinces (fig. 3). The mountains of the Blue Ridge, Valley and Ridge Provinces, and Appalachian Plateau in Virginia frequently reach up to 2,000 to 3,000 feet (ft) above sea level, with local relief frequently exceeding 1,200 ft.

The climate of Virginia is diverse and varies from the warm, temperate, eastern coastal areas that have temperatures moderated by the Atlantic Ocean, to the cooler continental climate of the mountainous provinces in the north and west. Mean annual temperatures range from 60 degrees Fahrenheit (°F) in Virginia Beach in the southeast to 48°F in Highland County in the west (fig. 4). Rainfall patterns vary across Virginia and are affected by topography in the north and west, and by the presence of tropical moisture systems in the south and east. Annual precipitation is lowest in the northern valleys, where average values are less than 40 inches per year (in/yr) at many locations, and highest along the southwestern ridges where average values can exceed 50 in/yr (fig. 5). Temperature and rainfall are adequate to support a substantial agriculture industry, with crop and pasture lands evenly scattered between forests of mixed deciduous and evergreen trees across most of Virginia (fig. 6). In the mountainous western provinces, though, agriculture is restricted mostly to the valleys, with forests covering most of the ridges. The largest urban and suburban areas have developed around Fairfax County in the north, the Tidewater area of Norfolk and Hampton Roads in the southeast, the capital city of Richmond in the southeastern central region, and Roanoke in the west.

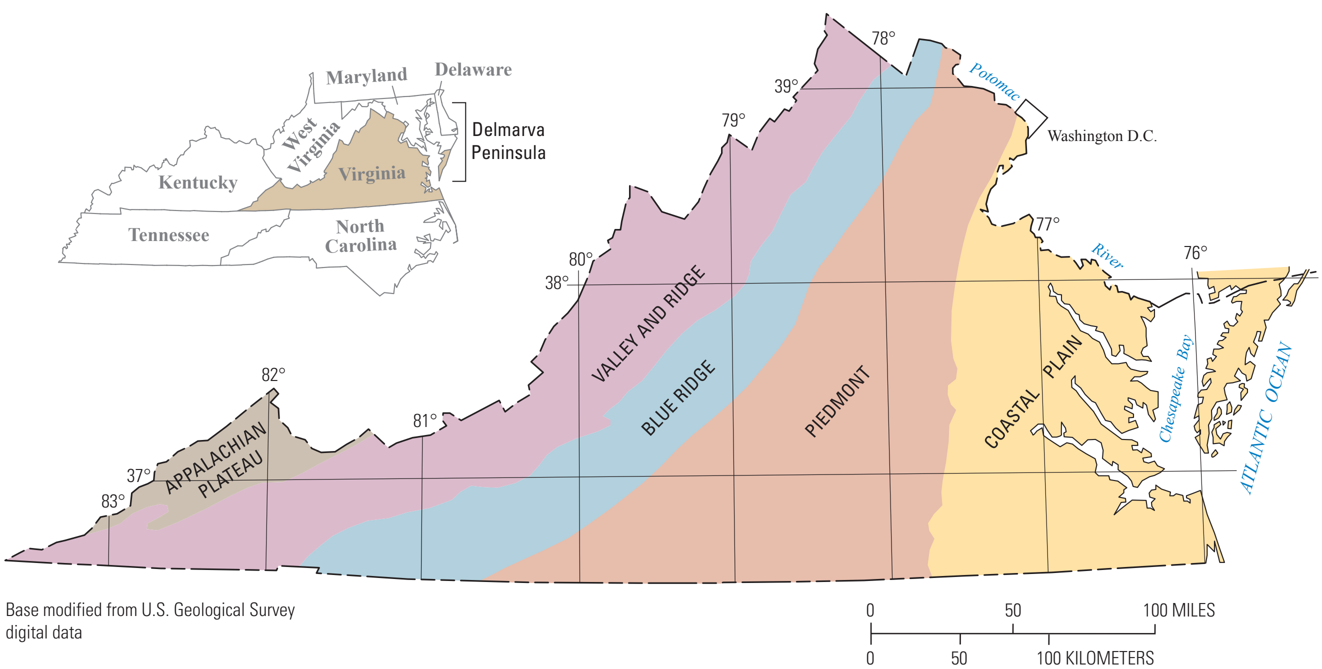


Figure 1. Physiographic provinces of Virginia. Modified from Fenneman and Johnson, 1946.

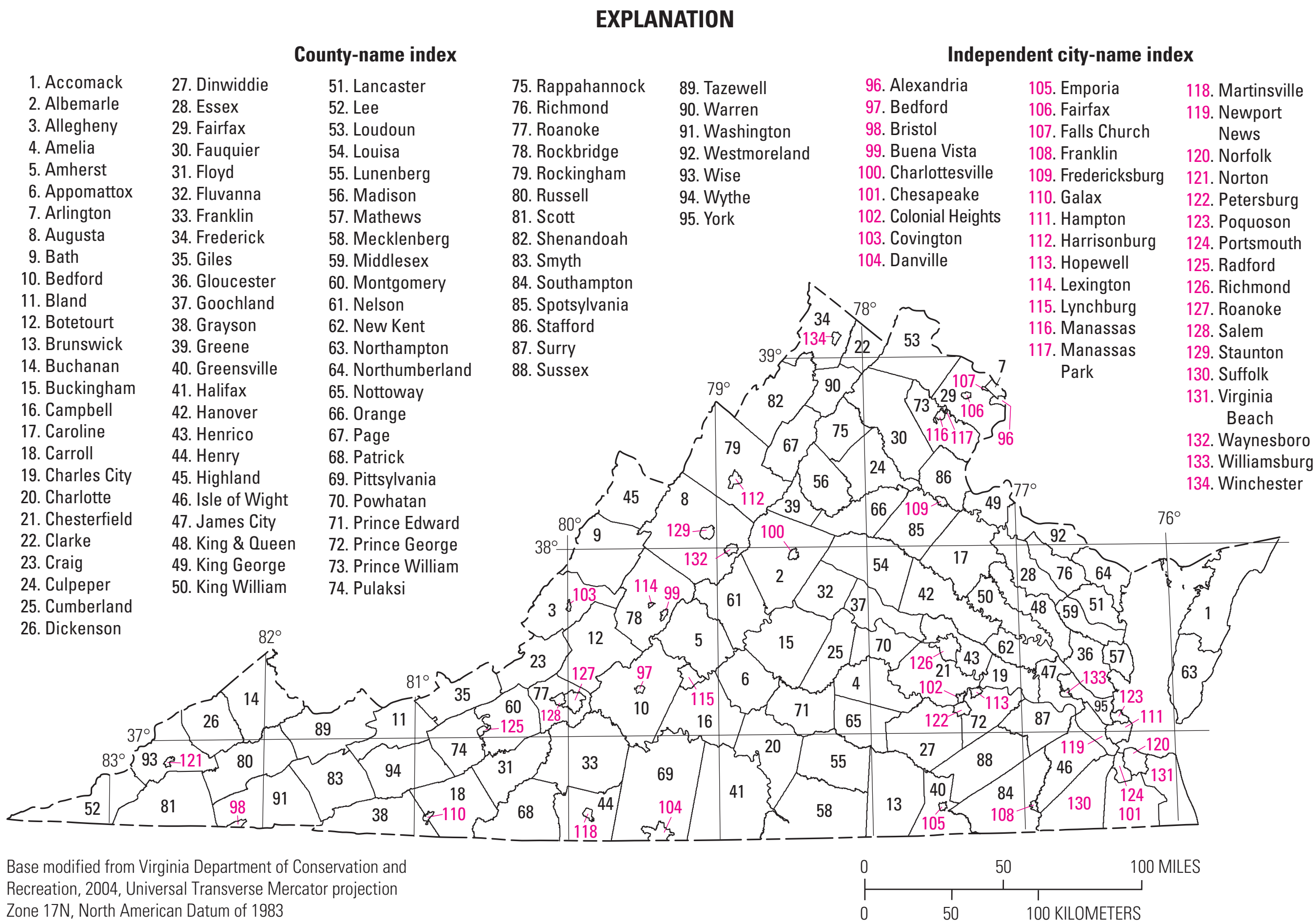


Figure 2. Names and locations of counties and independent cities in Virginia.

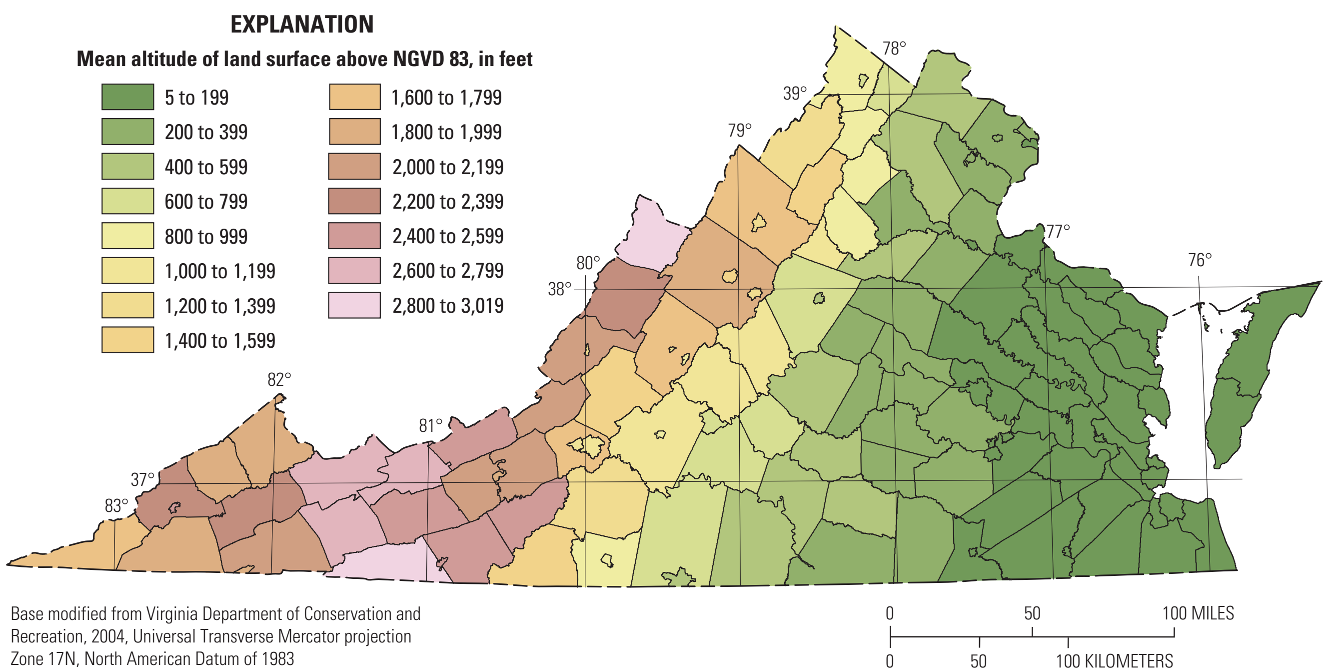


Figure 3. Mean altitude of land surface above National Geodetic Vertical Datum of 1983 for localites in Virginia. See figure 2 for locality names; data from U.S. Geological Survey 30-meter National Elevation Dataset, accessed July 2008 at *http://seamless.usgs.gov*.

Previous Investigations

Regional studies of water-resource characteristics of the Commonwealth of Virginia have previously been delineated by physiographic province. The water resources of the coal-mining areas in the Appalachian Plateau of Virginia have been studied in terms of hydrology (Hufschmidt and others, 1981), effects of mining (Larson and Powell, 1986), water quality (Rogers and Hufschmidt, 1980; Rogers and Powell, 1983), geochemistry (Powell and Larson, 1985), and hydraulic characteristics (Harlow and LeCain, 1993). The water-resource characteristics of the Valley and Ridge, Blue Ridge, and Piedmont Provinces have been studied as part of the USGS Regional Aquifer System Analysis (RASA) program. These studies in the western provinces included a summary of the hydrogeology (Swain and others, 2004), a study of groundwater quantity (Hollyday and Hileman, 1996), and a study of the shallow hydrologic characteristics through streamflow recession analysis (Rutledge and Mesko, 1996). In addition, Nelms and others (1997) determined base-flow characteristics for these provinces. Hayes (1991) defined low-flow characteristics of streams across the Commonwealth. In the Coastal Plain of Virginia, McFarland and Bruce (2006) described the hydrogeologic framework and McFarland (2010) the groundwater quality. Richardson (1994) focused on quantifying groundwater discharge in the Virginia Coastal Plain. Lorenz and Delin (2007) developed a regression approach for the State of Minnesota similar to the one used in this study, although the base-flow evaluation there was done using a physical hydrograph separation technique. Numerous techniques have been documented in the literature for estimating recharge (Scanlon and others, 2002; Risser and others, 2005; Healy and Scanlon, 2010), but most of these approaches are site- and time-specific field-based methods whose results are difficult to scale-up to long-term mean values for watersheds or counties.

Geologic Setting

The geology of Virginia is diverse with rocks and sediments that range in age from the early Proterozoic (>1 billion years old) to Holocene (<10,000 years old). The Coastal Plain is composed of unconsolidated sediments that pinch out at its western edge, but are up to several thousand feet thick at the Atlantic coastline. These sediments were deposited after being eroded from the Appalachian Mountains following the opening of the Atlantic Ocean during the Triassic and Jurassic Periods. The sediments vary in size from clay to gravel and were deposited in fluvial and marine environments as sea levels rose and fell (fig. 7). The hydrologic cycle on the Coastal Plain is impacted by the average grain size of surficial sediment, which can be classified as fine (silt and clay), medium (silt and sand), or coarse (sand and gravel). Average grain size is dependent on the stratigraphic unit exposed locally at the land surface (Ator and others, 2005).

The Piedmont Province is underlain by polydeformed rocks believed to be of late Proterozoic age that were metamor-phosed during the Paleozoic Era. Rock types vary, but the dominant varieties are gneiss, schist, granite, and slate (in the far south central region). During the Mesozoic Era, a number of rift basins opened up in the Atlantic Ocean, parallel

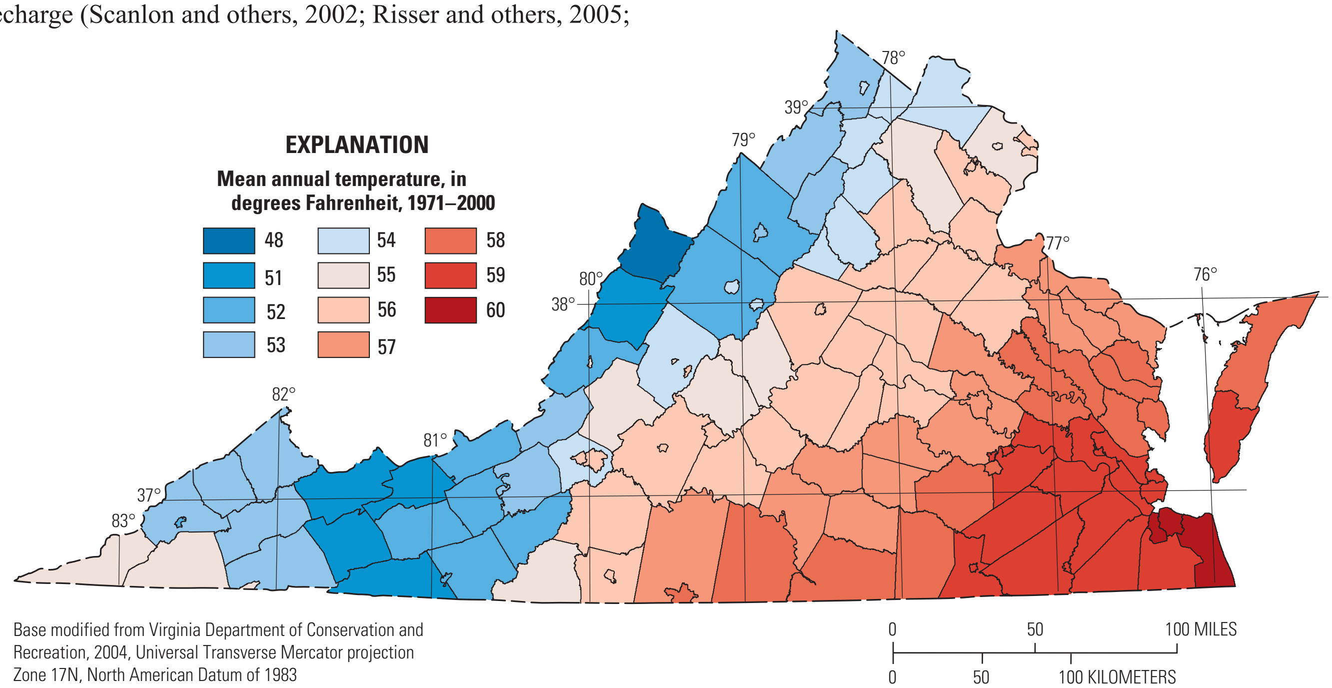


Figure 4. Mean annual temperature in Virginia by locality from 1971 to 2000. See figure 2 for locality names; compiled from data from PRISM Climate Group, Oregon State University, Daly and others (2008), accessed July 2008 at *http://www.prism.oregonstate.edu*.

to the Mid-Atlantic Ridge; they filled with siliciclastic and carbonate sediments which later were lithified. A few of these Mesozoic Rift Basins (fig. 7) are present in the Piedmont Province, the largest being the Culpeper Basin in Culpeper, Fauquier, Prince William, Fairfax, and Loudoun Counties.

The rocks of the Blue Ridge Province are the oldest in Virginia, and most formed during the Proterozoic Era (1.4–0.6 billion years ago). The rocks are predominantly basement granites and gneisses that have been exposed on the land surface by uplift and erosion. The province can be separated into two sections based on the origins of the topography (Hack, 1982). The section north of the Roanoke River (figs. 7 and 8) is characterized by a narrow range of high mountains underlain by Precambrian to Cambrian quartzite, phyllite, metabasalt, and granodiorite that form the northwest limb of

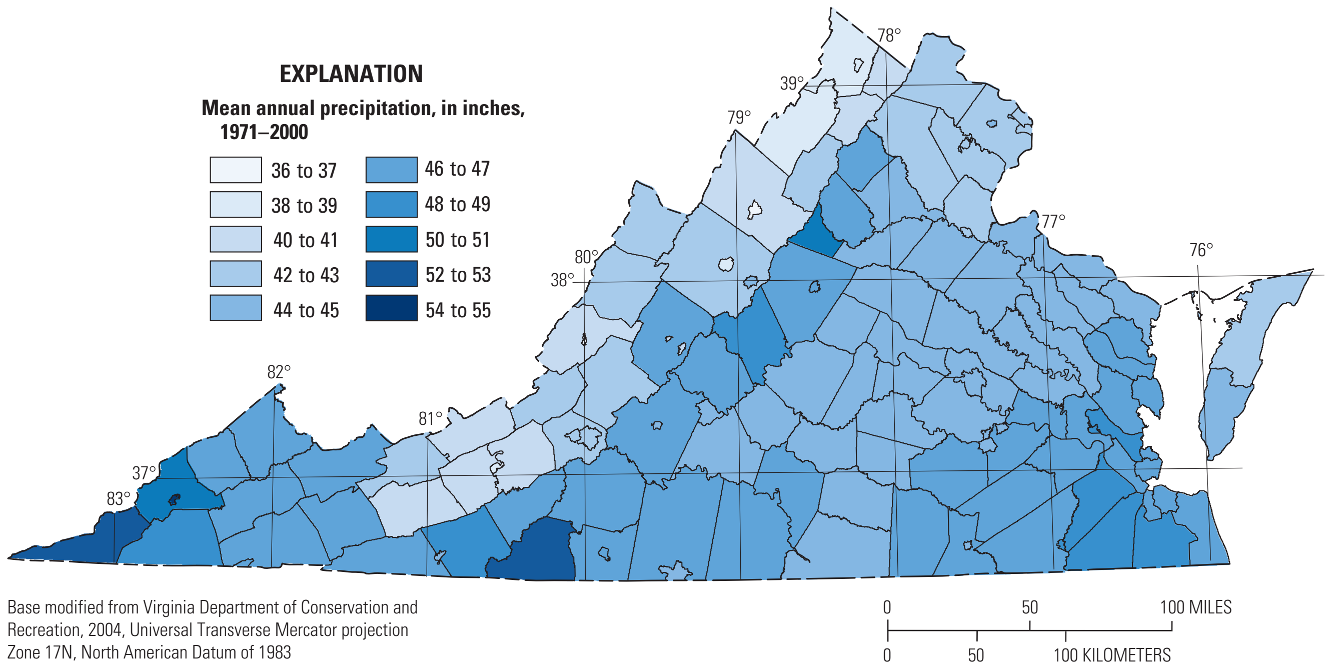


Figure 5. Mean annual precipitation in Virginia by locality from 1971 to 2000. See figure 2 for locality names; compiled from data from PRISM Climate Group, Oregon State University, Daly and others (2008), accessed July 2008 at *http://www.prism.oregonstate.edu*.

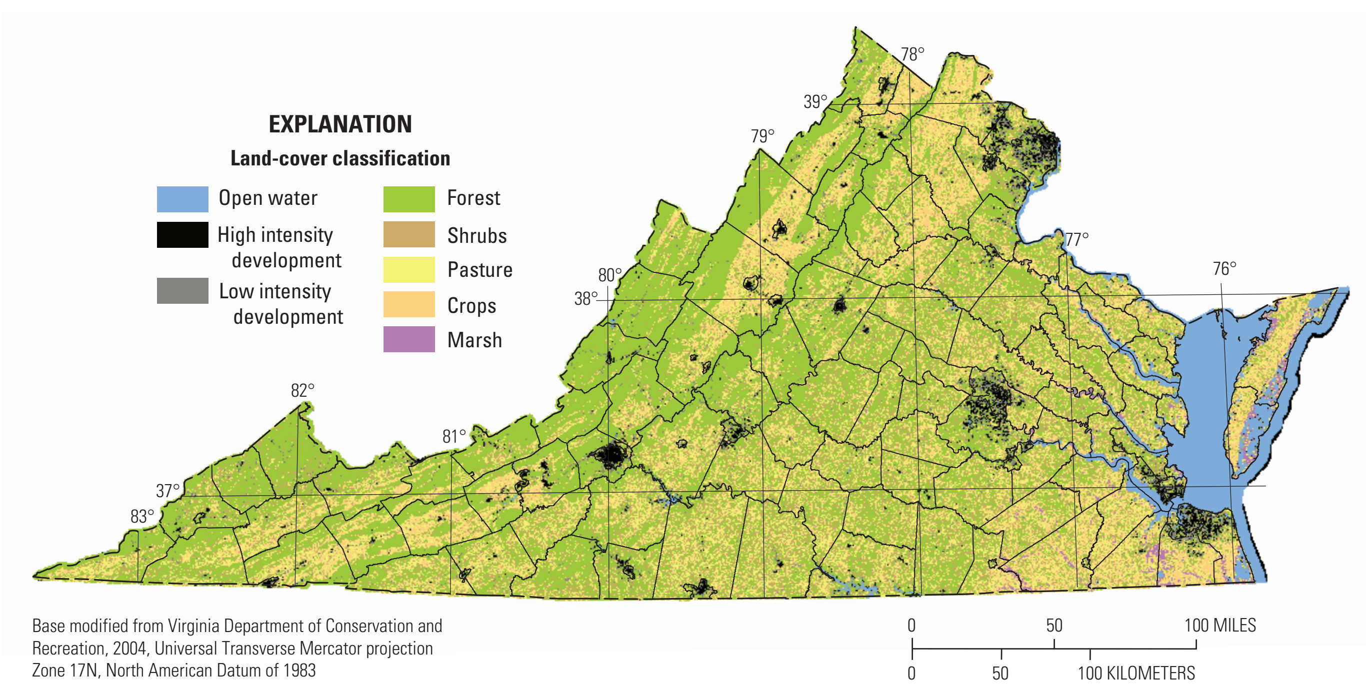
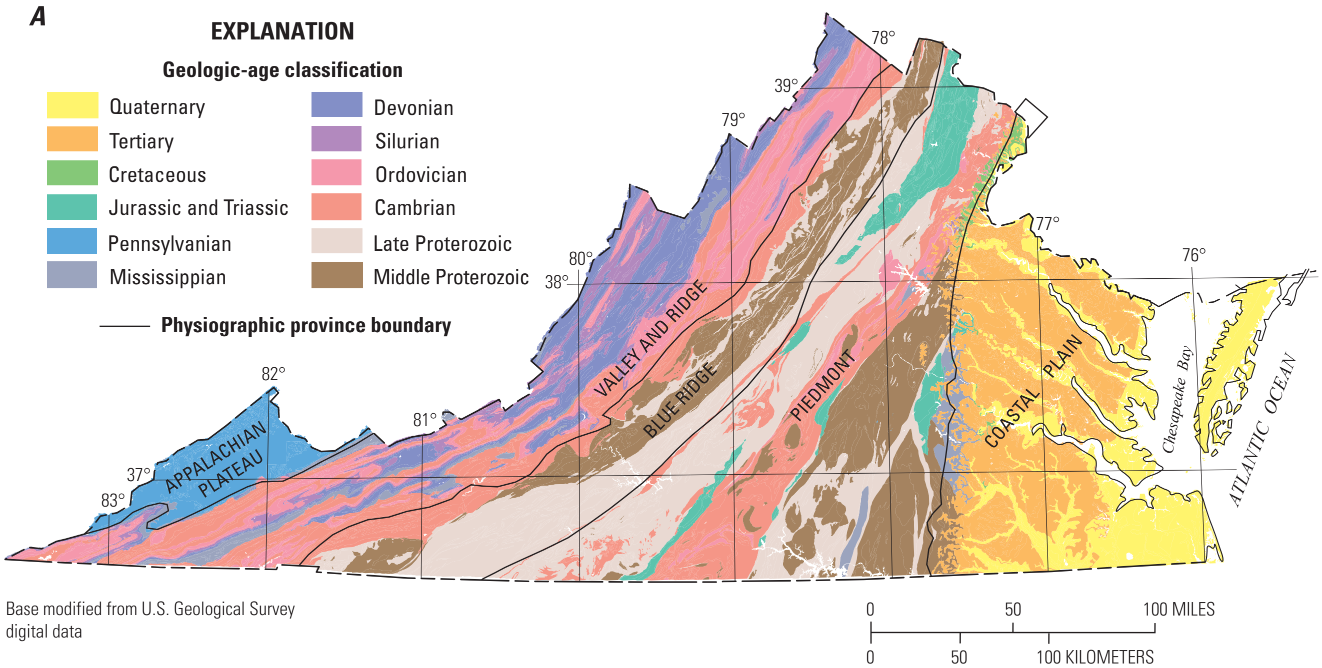


Figure 6. Land cover and localities of Virginia. See figure 2 for locality names; data from USGS National Land Cover Database 2001, accessed July 2008 at *http://cumulus.cr.usgs.gov/services.php#Land_Cover*.



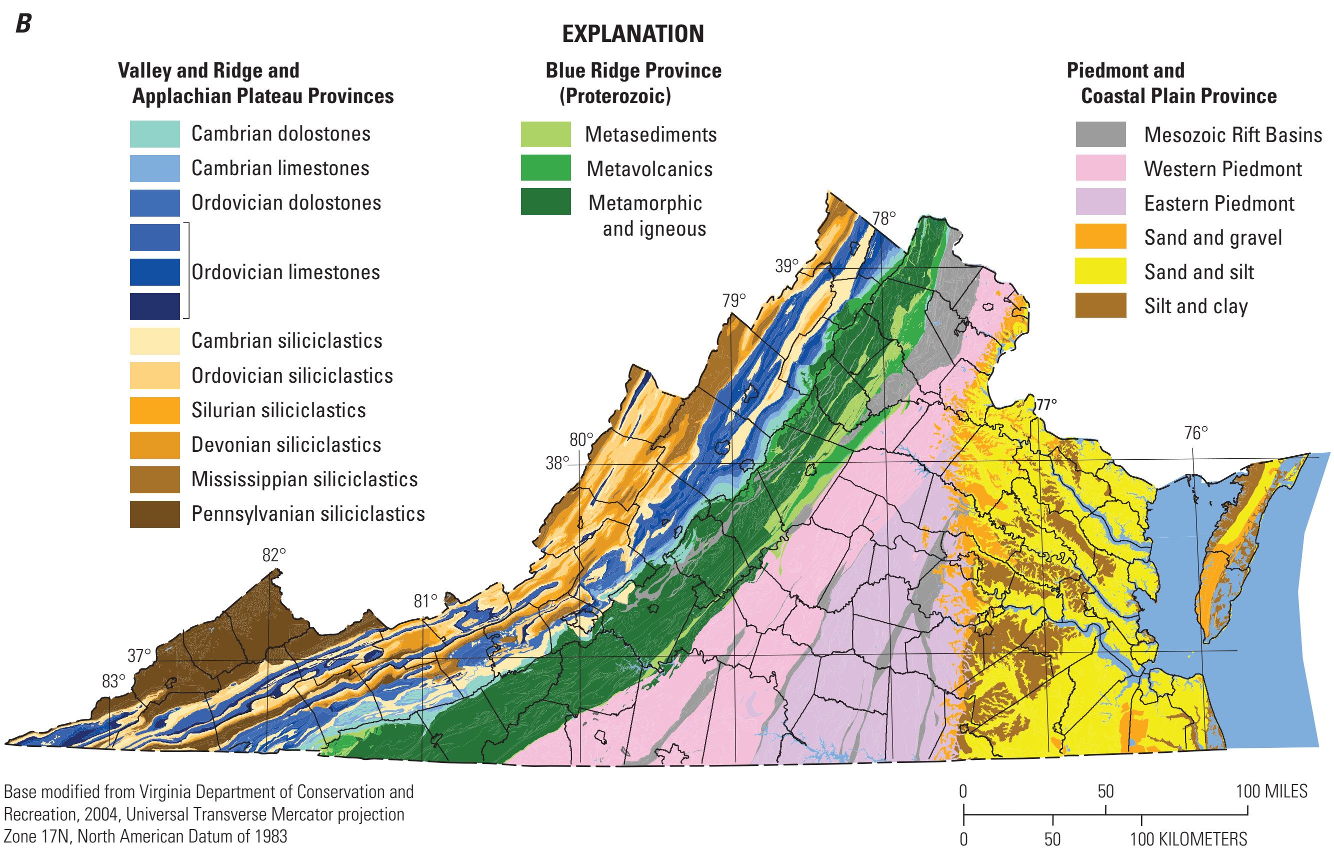


Figure 7. Maps showing (***A***) geologic age and physiographic provinces, and (***B***) geology and localities of Virginia. Modified from Virginia State Geologic Map, Virginia Department of Mines, Minerals, and Energy, 1993 and 2003, and Ator and others, 2005.

an anticlinorium (Nelms and others, 1997). The section south of the Roanoke River is much broader, with steep ridges separated by parallel valleys, high ridges, highlands, plateau, and escarpment. Precambrian gneiss, schist, amphibolite, volcanic and metasedimentary rocks, Cambrian quartzite, and faulted carbonate rocks and shale underlie this section of the Blue Ridge (Hack, 1982).

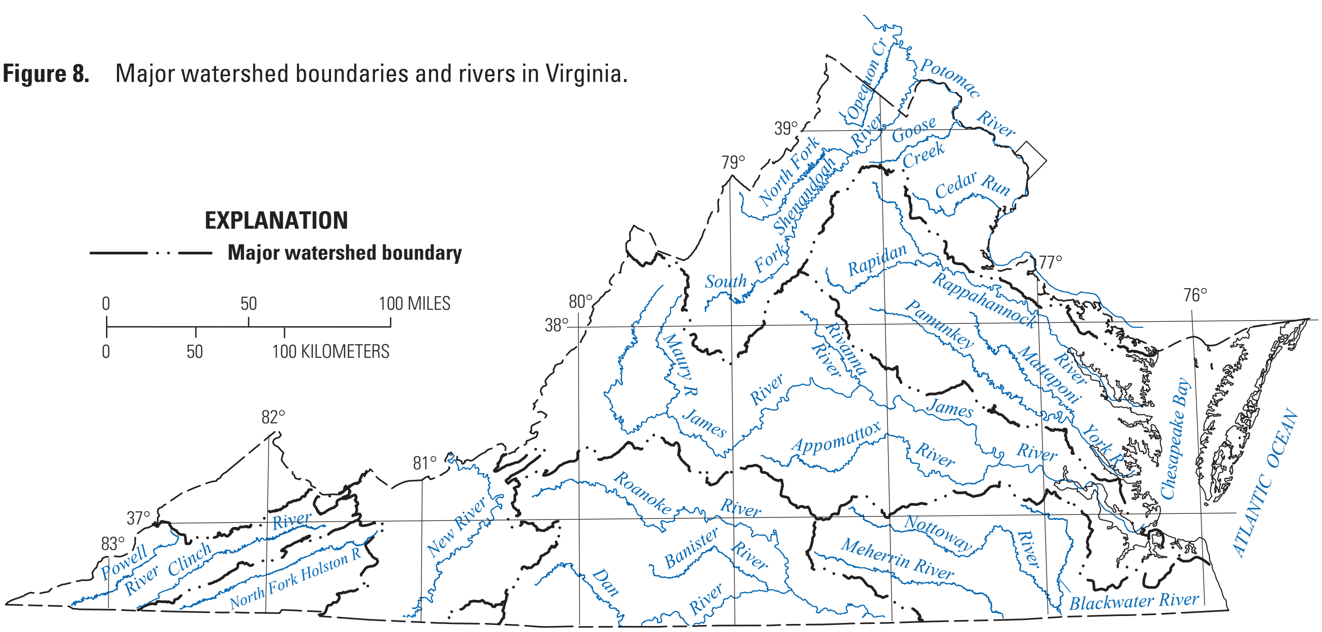
The Valley and Ridge Province is underlain by layered sedimentary rocks of the Paleozoic Era. The rocks were laid down horizontally as sediments, buried, and lithified, but were later folded and faulted, and finally eroded to their present state of exposure. The rocks vary in composition between carbonate and siliciclastic (fig. 7). Many of the oldest (from the Cambrian and Ordovician Periods) are carbonates and some of these have been dolomitized. The carbonate rocks tend to lie in the valleys of the province, whereas the more resistant sandstones are present along the ridges. Shales and siltstones occur both in the valleys and on the ridge slopes. Many of the carbonate regions have been karstified by percolating groundwater giving rise to many caves, springs, and sinkholes. The middle and late Paleozoic Era (Devonian though Mississippian) rocks in the province are almost entirely siliciclastic.

The Appalachian Plateau Province is characterized by a well-dissected, mountainous landscape with dendritic drainage formed on almost flat-lying to gently folded Paleozoic sedimentary rocks (Trapp and Horn, 1997). The rocks are predominantly siliciclastic in composition, with rock of Pennsylvanian age the most abundant at the land surface. Coal occurs in beds throughout the Pennsylvanian-aged rock.

Hydrologic Setting

Most of the rivers in the Commonwealth drain eastward to the Chesapeake Bay and Atlantic Ocean, but rivers in the southwestern section of Virginia drain toward the Ohio and Tennessee Rivers and the Gulf of Mexico (fig. 8). The New River and Appalachian Plateau watersheds drain north toward the Ohio River, and the Powell, Clinch, and Holston Rivers drain southwest toward the Tennessee River. In south-central Virginia the Dan and Banister Rivers join the Roanoke River, which reaches the Atlantic Ocean by flowing southeast through North Carolina. Likewise, in southeastern Virginia the Meherrin, Nottoway, and Blackwater Rivers do the same. Central Virginia is cut from west to east by the James River and its tributaries, and it is eventually joined by the Appomattox River before entering the James Estuary of the Chesapeake Bay. Northeast of the James River, the Pamunkey and Mattaponi Rivers and their tributaries enter the tidal York River and estuary of the Chesapeake Bay. North of these rivers, the Rapidan River joins the Rappahannock River, carrying flow from the Blue Ridge Mountains to the Chesapeake Bay. The remainder of Northern Virginia drains into the Potomac River, with a number of small streams running through the suburban regions of Prince William, Fairfax, and Loudoun Counties. The upper Potomac River Basin includes the watershed of the Shenandoah River, which drains the northern Valley and Ridge Province of Virginia. The Shenandoah is a broad, shallow, meandering river that is divided into two main stems, the North and South Forks; these reach their confluence near the town of Front Royal. The Eastern Shore of Virginia, east of the Chesapeake Bay, includes Accomac and Northampton Counties, and has very few streams of any substantial size; but the peninsula is drained in roughly equal proportions into the Chesapeake Bay and Atlantic Ocean.

Figure 8. Major watershed boundaries and rivers in Virginia.



Base modified from U.S. Geological Survey digital data
Hydrologic features from National Hydrography Dataset, accessed July 2008 at *http://nhd.usgs.gov*

Methods

The approach taken in this study was based on the principle of mass conservation, both of water and solute, within a watershed. Mass conservation equations were developed for components of the hydrologic budget, including precipitation, surface runoff, ET, infiltration, recharge, riparian ET, and base flow. The components were estimated from (1) external data sources, (2) data collected from watersheds across Virginia, or (3) solving the mass-balance equations when all other components were estimated (table 1). Data were analyzed from 108 gaged watersheds across Virginia (table 2; fig. 9), and two multiple-parameter regression equations were developed that allowed the results to be applied across the Commonwealth of Virginia, including in areas where no data were collected. Long-term mean precipitation and streamflow data for individual watersheds were used to estimate evapotranspiration rates. The first regression equation was developed for evapotranspiration as a function of climatic variables. Specific conductance and chloride analyses were used to estimate surface runoff and base-flow components for 48 watersheds. The second regression equation was developed for surface runoff as a percent of precipitation, as a function of the two landscape parameters, bedrock type and physiographic province. Finally, all of the hydrologic budget components were estimated for the entire Commonwealth of Virginia on a locality (county and independent city) basis, using existing precipitation data, the regression equations developed for evapotranspiration and surface runoff, and the mass-balance equations.

Table 1. Methods used in this study for estimating individual components of the hydrologic budgets and numbered according to the order in which they were calculated.

[PRISM climate data, Daly and others (2008); eq., equation; ET, evapotranspiration; FM, fraction of marsh area]

Budget component	Estimates for watersheds	Estimates for localities
Precipitation	1. PRISM climate data (1971–2000)	10. PRISM climate data (1971–2000)
Total streamflow	2. USGS NWIS database (1971–2000)	Not applicable as locality and watershed boundaries do not coincide, but represented rather as net total outflow (see below)
Evapotranspiration (total)	3. Precipitation minus streamflow (eq. 3). Regression equation developed for application to localities	11. Estimated from a regression equation (eq. 15) relating total evaporation estimates from watersheds to climatic characteristics, with an additional adjustment for percent impermeable surface
Base flow	4. Estimated from chemical hydrograph using equation 11, assuming two different values of runoff concentration. Values were then adjusted for 1971–2000 conditions using a regression equation relating monthly base flow to streamflow	Not applicable as locality and watershed boundaries do not coincide, but represented rather as net groundwater discharge (see below)
Surface runoff	5. Streamflow minus base flow (eq. 7)	12. Estimated from a regression equation (table 12) relating surface runoff as a percentage of precipitation from watersheds to rock type and physiography, with an additional adjustment for percent impermeable surface
Evapotranspiration (riparian)	6. Estimated from chemical hydrograph using (eq. 14)	13. Estimated from (eq. 18) relating riparian ET to the estimated fraction of marsh area (FM), which was estimated from (eq. 17) relating FM to the air temperature and topographic slope
Evapotranspiration (vadose)	7. ET (total) minus ET (riparian) (eq. 3)	14. ET (total) minus ET (riparian) (eq. 3)
Infiltration	8. Precipitation minus surface runoff (assumes negligible ET from precipitation ponded on surface)	15. Precipitation minus surface runoff (assumes negligible ET from precipitation ponded on surface)
Recharge	9. Infiltration minus ET (vadose) (eq. 5)	16. Infiltration minus ET(vadose) (eq. 5)
Net total outflow	Not calculated. Equivalent to total streamflow (see above)	17. Precipitation minus ET(total) (eq. 3)
Net groundwater discharge	Not calculated. Equivalent to base flow (see above)	18. Net total outflow minus surface runoff (eq. 7)

Table 2. Watersheds included in this study with characteristics and data that were collected and used.

[See figure 9 for map locations; ET, evapotranspiration; Del., Delaware; Va., Virginia; W. Va., West Virginia; Md., Maryland; SC, specific conductance; CP, Coastal Plain; VR, Valley and Ridge; BR, Blue Ridge; PM, Piedmont; AP, Appalachian Plateau; unk, unknown; —, not available; X, yes; Hwy., highway; Rt., route; SF, South Fork; NF, North Fork; MF, Middle Fork; NE, northeast; NW, northwest; STP, sewage treatment plant]

Map number	USGS station number	USGS station name	Physiographic Province	Area in square miles	Flow used to estimate ET	SC probe installed for this study	Samples collected for chloride analysis	SC data used for base-flow estimate
1	01487000	Nanticoke River near Bridgeville, Del.	CP	75	—	—	—	X
2	01613900	Hogue Creek near Hayfield, Va.	VR	16	X	—	X	X
3	01614830	Opequon Creek near Stephens City, Va.	VR	15	—	—	X	—
4	01615000	Opequon Creek near Berryville, Va.	VR	58	X	—	X	X
5	01616075	Fay Spring near Winchester, Va.	VR	unk	—	X	X	—
6	01616100	Dry Marsh Run near Berryville, Va.	VR	11	—	—	X	—
7	01616500	Opequon Creek at Martinsburg, W. Va.	VR	273	X	X	X	—
8	01622000	North River near Burketown, Va.	VR	376	X	X	X	X
9	01625000	Middle River near Grottoes, Va.	VR	373	X	X	X	X
10	01626000	South River near Waynesboro, Va.	BR	127	X	X	X	X
11	01627500	South River at Harriston, Va.	BR	212	X	X	X	X
12	01629500	SF Shenandoah River near Luray, Va.	VR	1,377	—	X	X	X
13	01630700	Gooney Run near Glen Echo, Va.	BR	21	—	—	X	—
14	01631000	SF Shenandoah River at Front Royal, Va.	VR	1,634	X	—	X	X
15	01632000	NF Shenandoah River at Cootes Store, Va.	VR	210	X	X	X	X
16	01632082	Linville Creek at Broadway, Va.	VR	46	—	—	X	X
17	01632900	Smith Creek near New Market, Va.	VR	94	X	—	X	X
18	01633000	NF Shenandoah River at Mount Jackson, Va.	VR	508	X	X	X	X
19	01634000	NF Shenandoah River near Strasburg, Va.	VR	770	X	—	X	X
20	01634500	Cedar Creek near Winchester, Va.	VR	102	X	—	X	X
21	01635090	Cedar Creek above Hwy. 11 near Middletown, Va.	VR	153	—	X	X	X
22	01635500	Passage Creek near Buckton, Va.	VR	87	X	—	X	X
23	01636242	Crooked Run below Hwy. 30 at Riverton, Va.	VR	47	—	—	X	—
24	0163626650	Manassas Run at Rt. 645 near Front Royal, Va.	BR	11	—	—	X	—
25	01636316	Spout Run at Rt. 621 near Millwood, Va.	VR	21	—	—	X	X
26	01643700	Goose Creek near Middleburg, Va.	BR	122	X	X	X	X
27	01644280	Broad Run near Leesburg, Va.	PM	76	—	X	X	—
28	01646000	Difficult Run near Great Falls, Va.	PM	58	X	X	X	X
29	01649500	NE Branch Anacostia River at Riverdale, Md.	CP	73	—	—	—	X
30	01651000	NW Branch Anacostia River near Hyattsville, Md.	PM	49	—	—	—	X
31	01656000	Cedar Run near Catlett, Va.	PM	93	X	X	X	X
32	01658000	Mattawoman Creek near Pomonkey, Md.	CP	55	—	—	—	X
33	01660400	Aquia Creek near Garrisonville, Va.	PM	35	X	X	X	X
34	01663500	Hazel River at Rixeyville, Va.	BR	287	—	X	X	—
35	01664000	Rappahannock River at Remington, Va.	BR	619	X	—	—	—

Table 2. Watersheds included in this study with characteristics and data that were collected and used.—Continued

[See figure 9 for map locations; ET, evapotranspiration; Del., Delaware; Va., Virginia; W. Va., West Virginia; Md., Maryland; SC, specific conductance; CP, Coastal Plain; VR, Valley and Ridge; BR, Blue Ridge; PM, Piedmont; AP, Appalachian Plateau; unk, unknown; —, not available; X, yes; Hwy., highway; Rt., route; SF, South Fork; NF, North Fork; MF, Middle Fork; NE, northeast; NW, northwest; STP, sewage treatment plant]

Map number	USGS station number	USGS station name	Physiographic Province	Area in square miles	Flow used to estimate ET	SC probe installed for this study	Samples collected for chloride analysis	SC data used for base-flow estimate
36	01665500	Rapidan River near Ruckersville, Va.	BR	115	X	X	X	X
37	01666500	Robinson River near Locust Dale, Va.	BR	179	X	X	X	X
38	01667500	Rapidan River near Culpeper, Va.	BR	468	X	X	X	X
39	01669000	Piscataway Creek near Tappahannock, Va.	CP	28	—	X	X	—
40	01669520	Dragon Swamp at Mascot, Va.	CP	108	—	X	X	X
41	01671020	North Anna River at Hart Corner near Doswell, Va.	PM	463	—	X	X	—
42	01671100	Little River near Doswell, Va.	PM	107	—	X	X	—
43	01672500	South Anna River near Ashland, Va.	PM	395	X	X	X	X
44	01673000	Pamunkey River near Hanover, Va.	PM	1,078	X	—	—	—
45	01673638	Cohoke Mill Creek near Lestor Manor, Va.	CP	9	—	X	X	—
46	01674000	Mattaponi River near Bowling Green, Va.	PM	257	—	X	X	—
47	01674500	Mattaponi River near Beulahville, Va.	CP	602	X	—	—	—
48	02011400	Jackson River near Bacova, Va.	VR	158	—	X	X	X
49	02011500	Back Creek near Mountain Grove, Va.	VR	134	—	X	X	—
50	02013000	Dunlap Creek near Covington, Va.	VR	162	X	X	X	X
51	02013100	Jackson River below Dunlap Creek at Covington, Va.	VR	614	—	X	X	—
52	02014000	Potts Creek near Covington, Va.	VR	153	X	X	X	X
53	02015700	Bullpasture River at Williamsville, Va.	VR	110	—	X	X	X
54	02016000	Cowpasture River near Clifton Forge, Va.	VR	461	X	X	X	—
55	02016500	James River at Lick Run, Va.	VR	1,373	—	X	X	X
56	02017500	Johns Creek at New Castle, Va.	VR	105	X	X	X	X
57	02018000	Craig Creek at Parr, Va.	VR	329	X	X	X	X
58	02020500	Calfpasture River above Mill Creek at Goshen, Va.	VR	141	X	X	X	X
59	02021500	Maury River at Rockbridge Baths, Va.	VR	329	X	X	X	X
60	02024000	Maury River near Buena Vista, Va.	VR	647	X	X	X	X
61	02025500	James River at Holcomb Rock, Va.	VR	3,259	—	X	X	—
62	02026000	James River at Bent Creek, Va.	VR	3,683	—	X	X	—
63	02030000	Hardware River below Briery Run near Scottsville, Va.	BR	116	—	X	X	—
64	02032640	NF Rivanna River near Earlysville, Va.	BR	108	—	X	X	X
65	02039500	Appomattox River at Farmville, Va.	PM	303	—	X	X	—
66	02040000	Appomattox River at Mattoax, Va.	PM	725	X	X	X	X
67	02041000	Deep Creek near Mannboro, Va.	PM	158	X	X	X	X
68	02042500	Chickahominy River near Providence Forge, Va.	CP	251	X	—	—	—
69	02044500	Nottoway River near Rawlings, Va.	PM	317	X	X	X	X
70	02045500	Nottoway River near Stony Creek, Va.	PM	579	—	X	X	—

Table 2. Watersheds included in this study with characteristics and data that were collected and used.—Continued

[See figure 9 for map locations; ET, evapotranspiration; Del., Delaware; Va., Virginia; W. Va., West Virginia; Md., Maryland; SC, specific conductance; CP, Coastal Plain; VR, Valley and Ridge; BR, Blue Ridge; PM, Piedmont; AP, Appalachian Plateau; unk, unknown; —, not available; X, yes; Hwy., highway; Rt., route; SF, South Fork; NF, North Fork; MF, Middle Fork; NE, northeast; NW, northwest; STP, sewage treatment plant]

Map number	USGS station number	USGS station name	Physiographic Province	Area in square miles	Flow used to estimate ET	SC probe installed for this study	Samples collected for chloride analysis	SC data used for base-flow estimate
71	02046000	Stony Creek near Dinwiddie, Va.	PM	112	—	X	X	—
72	02047500	Blackwater River near Dendron, Va.	CP	290	X	X	X	X
73	02049500	Blackwater River near Franklin, Va.	CP	613	X	—	—	—
74	02051500	Meherrin River near Lawrenceville, Va.	PM	552	X	X	X	X
75	02052000	Meherrin River at Emporia, Va.	PM	744	X	—	—	—
76	02053800	SF Roanoke River near Shawsville, Va.	BR	109	X	X	X	—
77	02054500	Roanoke River at Lafayette, Va.	VR	254	X	—	—	—
78	02055000	Roanoke River at Roanoke, Va.	VR	384	X	—	—	—
79	02056000	Roanoke River at Niagara, Va.	VR	509	X	X	X	—
80	02056900	Blackwater River near Rocky Mount, Va.	BR	115	—	X	X	—
81	02059485	Goose Creek at Rt. 747 near Bunker Hill, Va.	BR	125	—	—	X	—
82	02059500	Goose Creek near Huddleston, Va.	BR	188	X	X	—	X
83	02061000	Big Otter River near Bedford, Va.	BR	114	—	—	X	—
84	02061500	Big Otter River near Evington, Va.	BR	315	X	X	X	X
85	02062500	Roanoke (Staunton) River at Brookneal, Va.	BR	2,415	—	X	X	—
86	02064000	Falling River near Naruna, Va.	PM	173	—	X	X	—
87	02065500	Cub Creek at Phenix, Va.	PM	98	X	X	X	—
88	02070000	North Mayo River near Spencer, Va.	PM	108	—	X	X	—
89	02072000	Smith River near Philpott, Va.	BR	216	—	X	X	—
90	02073000	Smith River at Martinsville, Va.	PM	380	—	X	X	—
91	02074500	Sandy River near Danville, Va.	PM	112	—	X	X	—
92	02075045	Dan River at STP near Danville, Va.	BR	2,105	—	X	X	—
93	02077000	Banister River at Halifax, Va.	PM	547	X	X	X	—
94	02079640	Allen Creek near Boydton, Va.	PM	54	X	X	X	—
95	03165500	New River at Ivanhoe, Va.	BR	1,340	—	X	X	—
96	03167000	Reed Creek at Grahams Forge, Va.	VR	258	X	X	X	X
97	03168000	New River at Allisonia, Va.	BR	2,202	—	X	X	—
98	03170000	Little River at Graysontown, Va.	BR	309	X	—	—	—
99	03171000	New River at Radford, Va.	BR	2,748	—	X	X	—
100	03173000	Walker Creek at Bane, Va.	VR	299	X	X	X	—
101	03175500	Wolf Creek near Narrows, Va.	VR	223	—	X	X	—
102	03207800	Levisa Fork at Big Rock, Va.	AP	297	X	—	—	—
103	03208500	Russell Fork at Haysi, Va.	AP	286	X	X	X	—
104	03473000	SF Holston River near Damascus, Va.	BR	303	X	—	—	—
105	03475000	MF Holston River near Meadowview, Va.	VR	206	X	X	X	—
106	03488000	NF Holston River near Saltville, Va.	VR	221	X	—	—	—
107	03524000	Clinch River at Cleveland, Va.	VR	533	X	X	X	X
108	03531500	Powell River near Jonesville, VA	VR	319	X	X	X	X

EXPLANATION

Watershed abbreviated name/location index—See table 2 for additional descriptions; W. Va., West Virginia; Md., Maryland; R., River; Ck., Creek; SF, South Fork; NF, North Fork; MF, Middle Fork

1. Nanticoke R., Delaware
2. Hogue Creek
3. Opequon Creek near Stephens City
4. Opequon Ck., Berryville
5. Faye Spring
6. Dry Marsh Run
7. Opequon Ck., W. Va.
8. North River
9. Middle River
10. South R., Waynesboro
11. South R., Harriston
12. SF Shenandoah R., Luray
13. Gooney Run
14. SF Shenandoah River at Front Royal
15. NF Shenandoah River at Cootes Store
16. Linville Creek
17. Smith Creek
18. NF Shenandoah River at Mount Jackson
19. NF Shenandoah River near Strasburg
20. Cedar Ck., Winchester
21. Cedar Ck., Highway 11
22. Passage Creek
23. Crooked Creek
24. Manassas Run
25. Spout Run
26. Goose Ck., Middleburg
27. Broad Run
28. Difficult Run
29. NE Anacostia R., Md.
30. NW Anacostia R., Md.
31. Cedar Run
32. Mattawoman Ck., Md.
33. Aquia Creek
34. Hazel River
35. Rappahannock River
36. Rapidan R., Ruckersville
37. Robinson River
38. Rapidan R., Culpeper
39. Piscataway Creek
40. Dragon Swamp
41. North Anna River
42. Little River
43. South Anna River
44. Pamunkey River
45. Cohoke Mill Creek
46. Mattaponi River near Bowling Green
47. Mattaponi R., Beulah
48. Jackson River, Bacova
49. Back Creek
50. Dunlap Creek
51. Jackson R., Covington
52. Potts Creek
53. Bullpasture River
54. Cowpasture River
55. James River, Lick Run
56. Johns Creek
57. Craig Creek
58. Calfpasture River
59. Maury River, Rockbridge
60. Maury River, Buena Vista
61. James River, Holcomb
62. James River, Bent Creek
63. Hardware River
64. NF Rivanna River
65. Appomattox R., Farmville
66. Appomattox R., Mattoax
67. Deep Creek, Mannboro
68. Chickahominy River
69. Nottoway River, Rawlings
70. Nottoway R., Stony Creek
71. Stony Creek, Dinwiddie
72. Blackwater R., Dendron
73. Blackwater R., Franklin
74. Meherrin R., Lawrenceville
75. Meherrin R., Emporia
76. SF Roanoke River
77. Roanoke R., Lafayette
78. Roanoke R., Roanoke
79. Roanoke R., Niagara
80. Blackwater River near Rocky Mount
81. Goose Ck., Bunker Hill
82. Goose Ck., Huddleston
83. Big Otter R., Bedford
84. Big Otter R., Evington
85. Roanoke R., Brookneal
86. Falling River, Naruna
87. Cub Creek, Phenix
88. North Mayo R., Spencer
89. Smith River, Philpott
90. Smith R., Martinsville
91. Sandy River, Danville
92. Dan RIver, Danville
93. Banister River, Halifax
94. Allen Creek, Boydton
95. New River, Ivanhoe
96. Reed Creek, Grahams Forge
97. New River, Allisonia
98. Little R., Graysontown
99. New River, Radford
100. Walker Creek, Bane
101. Wolf Creek, Narrows
102. Levisa Fork, Big Rock
103. Russell Fork, Haysi
104. SF Holston R., Damascus
105. MF Holston R., Meadowview
106. NF Holston River, Saltville
107. Clinch River, Cleveland
108. Powell River, Jonesville

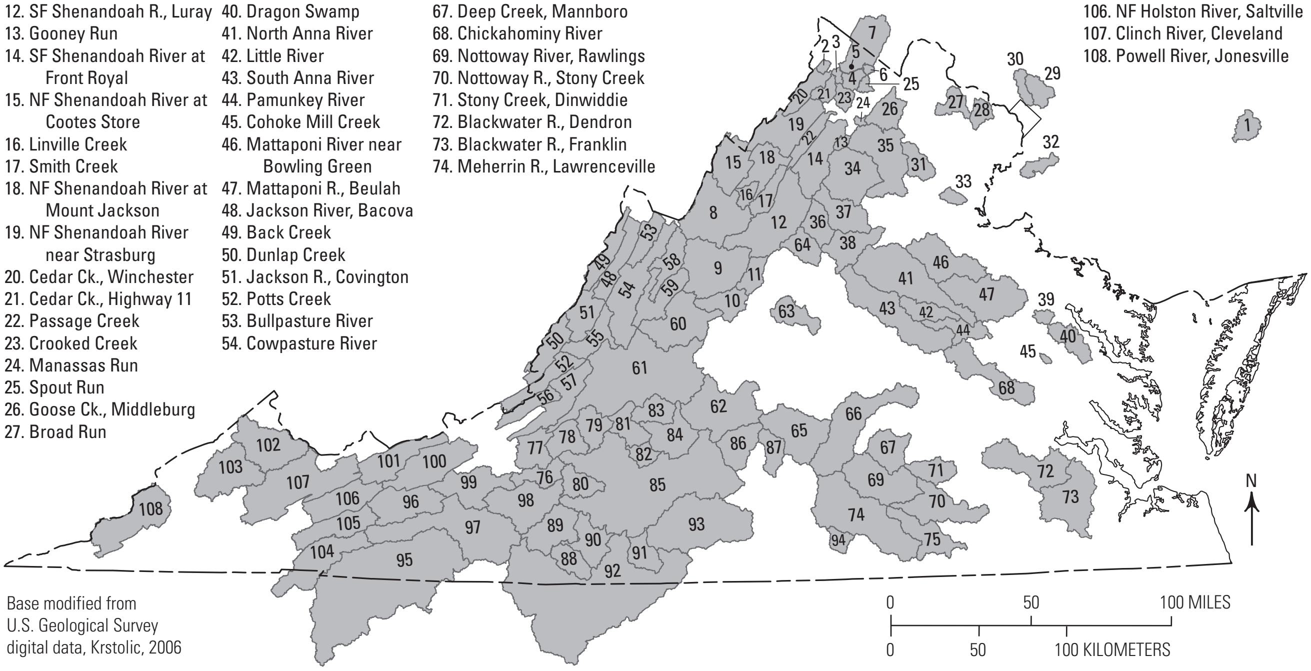


Figure 9. Names and locations of watersheds of Virginia, West Virginia, Delaware, and Maryland with real-time data used in this study. See table 2 for a list of watershed characteristics and data.

Budget Components of the Hydrologic Cycle

Individual watersheds can be envisioned as having both a water and solute budget. Each of these budgets has different terms that represent flow into or out of the watershed (fig. 10). Based on the principle of mass conservation and the assumption of long-term steady state conditions, a number of equations can be written that represent the balance of mass moving into and/or out of the watershed. A total water balance across the watershed can be written as:

$$P - Q_s/A + U_i/A = ET_{vz} + ET_{rp} + U_o/A \qquad (1)$$

where

P is the average rate of precipitation $[L/t]$,

Q_s is the average rate of streamflow out of the watershed $[L^3/t]$,

A is the area of the watershed $[L^2]$,

ET_{vz} is the average rate of evapotranspiration from the soil or vadose zone, if distributed across the entire area of the watershed $[L/t]$,

ET_{rp} is the average rate of evapotranspiration directly from groundwater near the stream in the riparian zone, if distributed across the entire area of the watershed $[L/t]$,

U_i is the average rate of groundwater underflow into the watershed $[L^3/t]$,

U_o is the average rate of groundwater underflow out of the watershed $[L^3/t]$,

L is the dimension of length, and

t is the dimension of time.

EXPLANATION

Components of budget

C_{gd}	Concentration of solute in groundwater discharge
C_{gw}	Concentration of solute in groundwater
C_i	Concentration of solute in incoming underflow
C_o	Concentration of solute in outgoing underflow
C_p	Concentration of solute in precipitation
C_r	Concentration of solute in surface runoff
C_s	Concentration of solute in stream
ET_{rp}	Evapotranspiration from groundwater
ET_{vz}	Evapotranspiration from vadose zone
I	Infiltration
P	Precipitation
Q_{gd}	Groundwater discharge
Q_r	Surface runoff
Q_s	Streamflow
R	Recharge
U_i	Underflow coming into watershed
U_o	Underflow going out of watershed

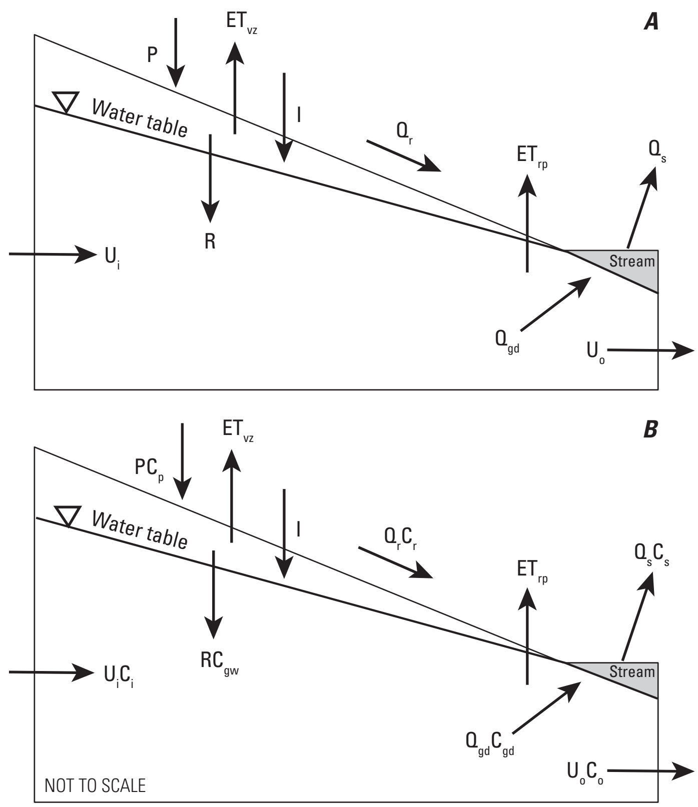


Figure 10. An idealized watershed with components of the ***(A)*** water and ***(B)*** conservative-solute budgets.

A similar equation can be written for the concentration of a conservative solute:

$$PC_p - Q_sC_s/A + U_iC_i/A = ET_{vz}C_{vz} + ET_{rp}C_{rp} + U_oC_o/A \quad (2)$$

where

- Cp is the average concentration of the solute in precipitation $[M/L^3]$,
- Cs is the average concentration of the solute in the stream at the outflow point $[M/L^3]$,
- Ci is the average concentration of the solute in the groundwater flowing into the watershed $[M^3/t]$,
- Cvz is the average concentration of the solute in the water evapotranspiring from the vadose zone $[M/L^3]$,
- Crp is the average concentration of the solute in the water evapotranspiring from the riparian zone $[M/L^3]$,
- Co is the average concentration of the solute in the groundwater flowing out of the watershed $[M/L^3]$, and
- $[M]$ is the dimension of mass.

Because C_{vz} and C_{rp} are virtually zero, and the value $(U_i - U_o)$ is assumed to be negligible, equations 1 and 2 reduce to:

$$P - Q_s/A = ET_{vz} + ET_{rp} = ET \quad (3)$$

where

- ET is the total evapotranspiration, $[L/t]$,

and

$$PC_pA = Q_sC_s. \quad (4)$$

At this point, equation 4 assumes there is no source of solute from the land surface or subsurface mineral dissolution, but these sources are accounted for later when estimating C_r, the average concentration of the solute in the surface runoff. Other portions of the hydrologic budget can also be incorporated into mass-balance equations, including those that represent water and solute budgets for the vadose zone:

$$R = I - ET_{vz} \quad (5)$$

where

- R is the annual average rate of recharge to the water table $[L/t]$, and
- I is the average rate of infiltration at the land surface, equal to $P - Q_r$ $[L/t]$, where Qr is the surface runoff,

and

$$R\ C_{gw} = I\ C_p \quad (6)$$

where

C_{gw} is the average concentration of the solute in the groundwater [M/L^3].

Equation 5 assumes that evaporation from ponded surface water is negligible, and that data were not collected from watersheds with substantial impounded surface water bodies. Equation 6 is often used in arid environments to estimate recharge based on the amount of precipitation and the ratio of the chloride in precipitation to that in groundwater, with the assumption that Qr at the site location is zero (Wood and Sanford, 1995). Additional equations can be written for the stream water balance:

$$Q_s = Q_{gd} + Q_r, \quad (7)$$

where

Q_{gd} is the average annual groundwater discharge, or base flow, to the stream network [L^3/t];

the water balance relating base flow and groundwater recharge:

$$Q_{gd}/A = R - ET_{rp} \quad (8)$$

the stream solute balance:

$$Q_s C_s = Q_{gd} C_{gd} + Q_r C_r \quad (9)$$

where

Cgd is the concentration of the solute in the groundwater discharge to the stream [M/L3];

and by applying a solute balance to equation 8, a solute relation between groundwater and base flow:

$$RC_{gw}A = Q_{gd}C_{gd}. \quad (10)$$

Q_{gd}/A is often referred to as the effective recharge and R as the total recharge (Risser and others, 2005, p. 6). In this study, the term “recharge” is used to mean total recharge.

Some of these budget components can be estimated from existing data, but some would be very difficult to estimate with available data; still other components could be calculated based on the known values and the above equations if all of the other values were known. In this study, available data was used to estimate precipitation, P, and average streamflow, Q_s. Evapotranspiration was then estimated using mass-balance equation 3. By combining the stream balance equations 7 and 9, another equation can be obtained:

$$Q_r = Q_s\ (C_{gd} - C_s) / (C_{gd} - C_r) \quad (11)$$

that represents the fraction of streamflow that is from surface runoff as a ratio of the concentrations in the stream and groundwater discharge, otherwise known as a chemical hydrograph separation. This equation can apply to the average concentrations over a long time period, or continuous concentrations measured over a short period of time. An 18-month time period between March 1997 and August 1998 was used during this study to estimate the fraction of surface runoff in watersheds. The average groundwater discharge component of streamflow was then calculated using water balance equation 7. To do this, the concentrations of C_s, C_{gd}, and C_r were estimated. The first two could be estimated from chemical hydrographs, but the latter had to be estimated independently. The value of C_p might help in estimating C_r, but obtaining precipitation samples in sufficient quantities over a wide expanse such as Virginia is difficult, and the assumption would have to be made that the solute in the stream originated only from precipitation—not a very good assumption in most localities. Instead, bounds were placed on C_r by envisioning two different end-member processes by which solutes in the streams might have originated. In one process, it is assumed that the solute constituent behaves conservatively in the subsurface, but is present in either rainwater or in soluble mineral form (fertilizer, road salt, and so forth.) on the land surface. Then mass-balance equation 4 can be rewritten as:

$$C_r = Q_s C_s / PA. \quad (12)$$

This assumption then leads to a second assumption—that the solute concentrations of the surface runoff and infiltration are equal. Based on this assumption, the only reason the solute in the stream is more concentrated than that in the precipitation is because evapotranspiration in the watershed removed water but not solute molecules in the soil zone. The other end-member process that can explain solute concentrations in streams is the opposite—that virtually all of the solute in the stream was derived from subsurface mineral reactions, and that C_r is that of pure rainwater. In most watersheds, the conditions are likely to lie somewhere between these two end-member processes, but in this study calculations were made assuming both end members, and then also estimated the fraction of the stream solute that originates from the subsurface. In many watersheds, the calculations of C_r and Q_r based on the two end-member assumptions were not substantially different.

The final hydrologic budget component to estimate is recharge (R) to the water table. To estimate recharge, another component had to be estimated—either Cgw so that either equation 6 or 10 could be used to calculate recharge, or ET_{rp} so that either equation 5 or 8 could be used for the calculation. It is difficult to estimate C_{gw} because not enough wells with water-quality data are usually available to obtain a good statistical average. ET_{rp} is not easy to estimate, but the value is relatively small compared to the other components, so a substantial error in the ET_{rp} estimate is not likely to translate into a substantial error in the recharge estimate.

Riparian Evapotranspiration Estimation

Estimates of ET_{rp} were obtained by using the seasonal difference between the values of C_{gd}. Most watersheds show a substantial difference in C_{gd}, with values being highest in late summer and early fall and lowest in late winter and early spring. This can be attributed to the presence of riparian *ET* during the summer and its absence during the winter. If the riparian zone has a chance to flush out over a number of months, then in late winter, $C_{gdw} = C_{gw}$. If this is the case then equations 8 and 10 can be rewritten as:

$$ET_{rps} = (Q_{gd}/A)\ ((C_{gds}/C_{gdw}) - 1) \qquad (13)$$

where

- ET_{rps} is the riparian *ET* rate during the summer [*L/t*],
- C_{gds} is the average concentration of the groundwater discharge during late summer [*M/t*], and
- C_{gdw} is the average concentration of the groundwater discharge during late winter [*M/t*].

It was assumed that the summer riparian *ET* rate occurs for about one third of the year, with a small to negligible rate operating the remainder of the year. The equation for the watershed mean-annual riparian *ET* calculation therefore became:

$$ET_{rp} = (Q_{gd}/A)\ ((C_{gds}/C_{gdw}) - 1) / 3. \qquad (14)$$

One can observe from equations 13 and 14 that if there is no seasonal fluctuation in the concentration of discharging groundwater ($C_{gdw} = C_{gds}$), the riparian evapotranspiration would equal zero. Our estimates of riparian *ET* using equation 14 yielded values similar to those estimated by Rutledge and Mesko (1996) and Nelms and Moberg (2010b) in the Mid-Atlantic region (see later section on riparian *ET*), and were small compared to the magnitude of recharge and groundwater discharge. Using these values of ET_{rp}, equation 3 was used to compute values for ET_{vz}. Equation 5 was then used to calculate recharge for the watersheds by reducing infiltration by the amount of vadose-zone evapotranspiration. According to the water balance, equation 8 could also be used to calculate recharge by adding the riparian *ET* to the base flow, and the resulting value would be the same.

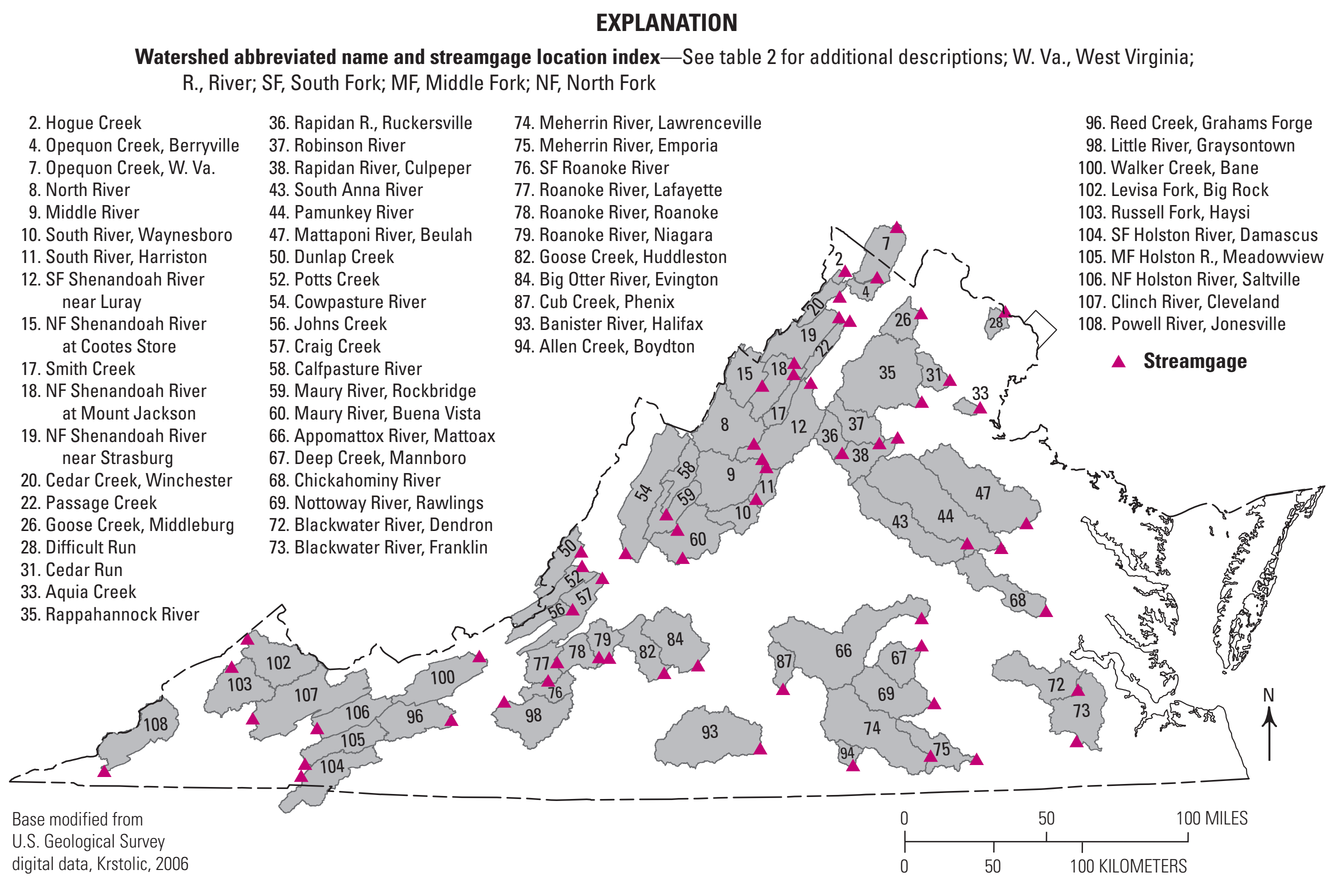


Figure 11. Names and locations of real-time streamgages within associated watersheds in Virginia and West Virginia selected to estimate evapotranspiration in this study.

Total Evapotranspiration Estimation

Total evapotranspiration for the watersheds of interest was estimated by subtracting streamflow from total precipitation using equation 3 (Daniel, 1976). A total of 60 watersheds were selected (table 3; fig. 11) that met the criteria of complete flow record availability between 1971 and 2000. These dates were chosen because precipitation data were available from the PRISM climate database (Daly and others, 2008) as mean rates for that time interval for the entire Commonwealth of Virginia. Average flow rates from that time period were obtained from the USGS National Water Information System (NWIS) database. The assumption was made that for a long period of record, such as 30 years, three components of flux out of each watershed were negligible compared to the total flow of water: (1) water-use withdrawals, (2) the net underflow through the basin, and (3) change in storage of water within the watershed. All three components are believed to be small in Virginia for nearly all of the watersheds of interest. The magnitude of water-use withdrawals are discussed toward the end of this report, and found to be relatively small. Net underflow was suspected to be substantial in only a few localized karst regions of the Valley and Ridge province; those watersheds were excluded. Watersheds with substantial surface-water impoundments were not used.

Once the total evapotranspiration for each watershed was estimated, the values were related to the precipitation and temperature data from the PRISM climate database (table 3). A multiple-regression equation was created that related the mean total evapotranspiration rate of each watershed to the precipitation rate (fig. 12), the mean maximum daily temperature (fig. 13), and the mean daily minimum temperature (fig. 14). All PRISM climate data averaged for the 1971–2000 data period were available as a raster grid for the entire Commonwealth on an 800-meter spacing. A geographical information system was used to average the climatic data for each watershed. Evapotranspiration is known to be a function of climatic variables and, in this situation, the calculated evapotranspiration data correlated well with a multiple-regression equation of the form:

$$ET = aP + bT_{max} + c\,T_{min} + d \qquad (15)$$

where

T_{max} and T_{min} are the mean daily maximum and minimum temperatures, respectively, and

a, b, c, and d are coefficients estimated by the regression.

The regression had an R^2 value of 0.844 and a slope of 0.84. Land cover data were also considered as a potential variable in the regression (table 3), but it did not substantially improve the regression and therefore was not included in the final equation (table 4). For the remainder of Virginia, equation 15 was used to estimate total evapotranspiration by locality, along with a correction for percent impervious surface.

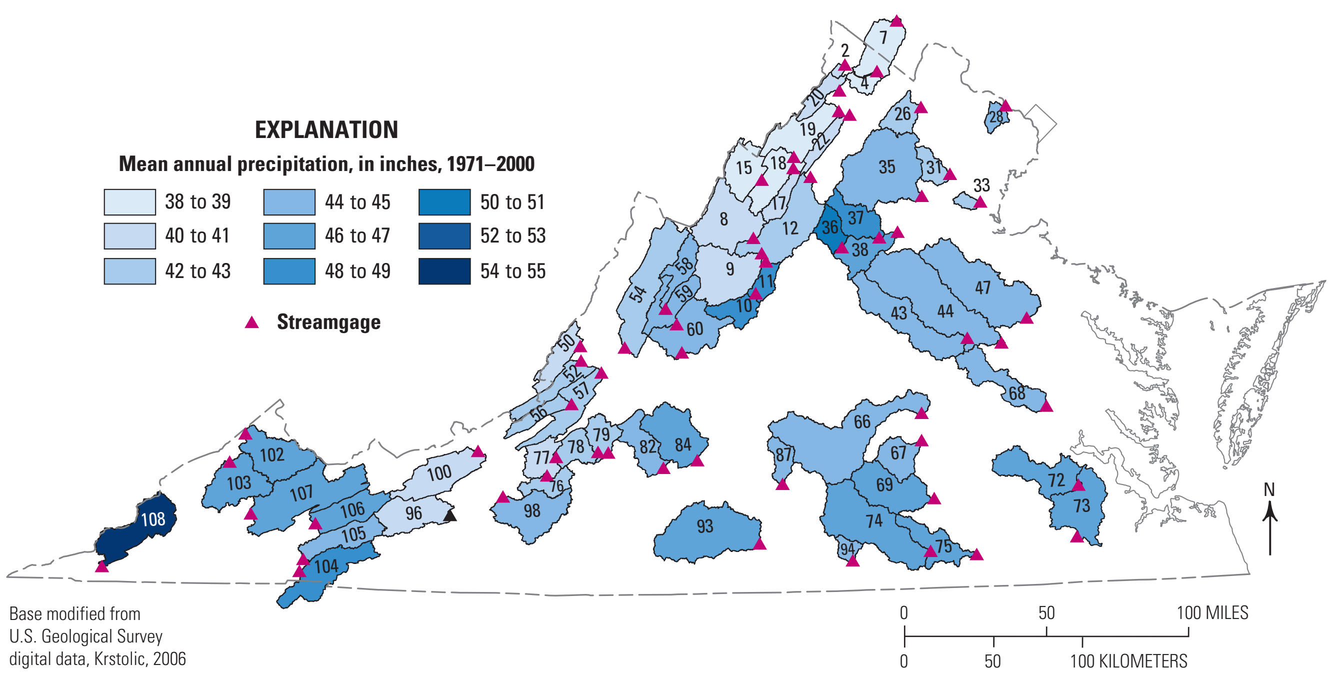


Figure 12. Mean annual precipitation in selected watersheds in Virginia from 1971 to 2000. (See figure 9 for watershed number list; compiled from data from PRISM Climate Group, Oregon State University, Daly and others (2008), accessed July 2008 at *http://www.prism.oregonstate.edu*.)

Chemical Hydrograph Separation

The components of streamflow—surface runoff and base flow—are represented in the hydrologic budget in equations 7 and 11. The term base flow is used to represent groundwater discharge. Numerous studies have measured the concentrations of various solutes and isotopes during storm events to separate the hydrograph components of surface runoff and groundwater discharge since the 1970s (Sklash and Farvolden, 1979; Hooper and Shoemaker, 1986). This classical chemical hydrograph separation approach requires collecting and analyzing individual water samples frequently, and so is labor intensive and costly for long periods of time. This high cost precluded using this approach because of the large scale of this study. As an alternative, specific conductance (SC), which has been demonstrated to be effective for chemical hydrograph separation (Stewart and others, 2007), was chosen as a proxy for total solute concentration in the stream. Even with the costs of the instrumentation and its maintenance, this latter approach proved to be very cost effective because data could be collected multiple times per hour (usually every 15 minutes) continuously for 18 months.

Instrumentation was done on 75 streams (and 1 spring) across Virginia at real-time streamgaging sites (fig. 15) for SC. Data were transferred to spreadsheets where both streamflow and SC could be plotted together (fig. 16). The SC of the base-flow component was estimated by visual inspection of the SC data. A value for the base SC was estimated at the beginning of each month and the daily values were then interpolated between these values. Drops in the SC measurements during high-flow peaks were assumed to be from sudden inflows of surface runoff or subsurface storm flow, and conversely, time periods long after high-flow peaks were assumed to contain little surface runoff component (fig. 16). On occasion, high-frequency variability was observed in SC during low-flow periods that was attributed to causes other than rainfall (for example, during February 2007, fig, 16). The base SC was often estimated to fall in the average range of this SC, and given that the percentage of flow occurring during these periods was low, the base-flow calculations were relatively insensitive to the base-SC estimate during those times. From this knowledge, the continuous SC of the base-flow component could be estimated and plotted. The surface-runoff (Q_r) and base-flow (Q_{gd}) components were then calculated for each time interval using equations 7 and 11 for two end-members, depending on the assumed value of C_r. A SC value of 15 microsiemens per centimeter (µS/cm) was used for one end-member and a value calculated using equation 12 was used for the other end-member. The former value was used to represent the SC of average rainwater (Hem, 1970). Data collection began in March 2007 and continued for 18 months, through August 2008.

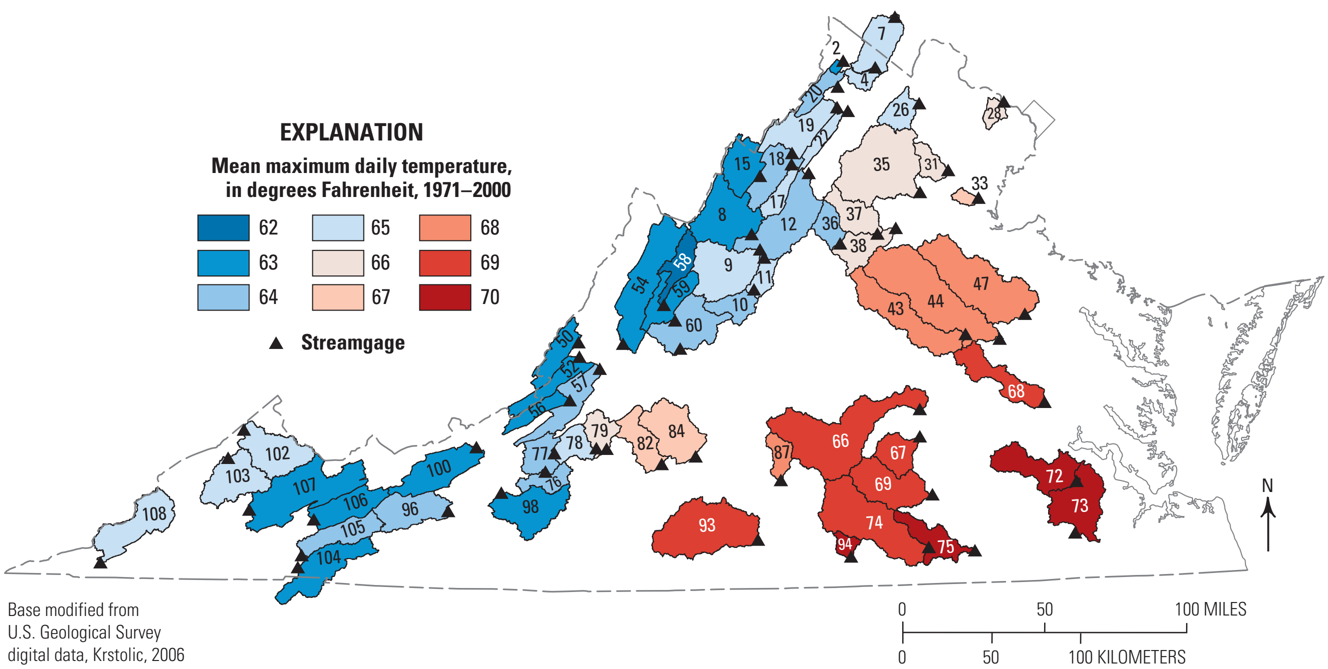


Figure 13. Mean maximum daily air temperature in selected watersheds in Virginia from 1971 to 2000. (See figure 9 for watershed number list; compiled from data from PRISM Climate Group, Oregon State University, Daly and others (2008), accessed July 2008 at *http://www.prism.oregonstate.edu*.)

Table 3. Watershed climate and landscape characteristics used to evaluate evapotranspiration in this study.

[See figure 9 for watershed locations, SF, South Fork; NF, North Fork; MF, Middle Fork]

Map number	USGS station number	Watershed name	Area, in square miles	Flow, in cubic feet per second (1971–2000)	Mean annual precipitation, in inches (1971–2000)	Mean daily temperature, in degrees Fahrenheit (1971–2000)		Land use, in percent		
						Maximum	Minimum	Forest	Agriculture	Marsh
2	01613900	Hogue Creek	16	17.3	39.9	63.4	41.6	76.4	22.9	0.00
4	01615000	Opequon Creek	58	54.1	39.0	64.6	42.6	29.8	59.3	0.24
7	01616500	Opequon Creek	273	281.5	39.4	64.7	42.6	28.8	59.6	0.22
8	01622000	North River	376	425.7	40.0	62.7	39.4	60.1	34.5	0.00
9	01625000	Middle River	373	362.4	40.4	64.9	41.3	37.7	56.8	0.00
10	01626000	South River	127	169.3	48.2	64.3	41.1	63.1	32.5	0.00
11	01627500	South River	212	288.6	47.6	64.7	41.4	59.9	33.1	0.00
12	01631000	SF Shenandoah River	1,634	1,790.0	42.1	64.4	40.8	54.7	39.6	0.79
15	01632000	NF Shenandoah River	210	221.4	39.4	62.8	39.2	89.8	9.5	0.00
17	01632900	Smith Creek	94	82.6	39.6	65.3	40.9	45.7	50.7	0.00
18	01633000	NF Shenandoah River	508	457.3	38.7	64.3	40.2	59.1	38.9	0.38
19	01634000	NF Shenandoah River	770	682.8	38.7	64.5	40.3	58.1	39.1	0.42
20	01634500	Cedar Creek	102	115.8	40.3	63.8	40.3	87.7	12.2	0.00
22	01635500	Passage Creek	87	79.7	41.4	64.5	40.7	87.0	12.6	0.02
26	01643700	Goose Creek	122	140.1	42.3	64.9	42.8	46.4	52.6	0.06
28	01646000	Difficult Run	58	71.0	43.7	65.7	44.1	37.5	41.7	1.39
31	01656000	Cedar Run	93	100.3	43.3	65.8	43.6	35.4	59.2	0.58
33	01660400	Aquia Creek	35	35.9	43.3	66.8	44.8	72.0	21.5	1.23
35	01664000	Rappahannock River	619	769.0	44.7	65.8	42.7	59.2	39.6	0.29
36	01665500	Rapidan River	115	166.5	50.2	64.3	41.6	70.7	28.6	0.00
37	01666500	Robinson River	179	256.5	49.0	66.0	42.9	60.0	38.6	0.33
38	01667500	Rapidan River	468	619.9	46.7	66.0	43.0	56.5	41.8	0.38
43	01672500	South Anna River	395	411.7	44.2	67.9	44.0	64.4	31.4	1.54
44	01673000	Pamunkey River	1,078	1,115.4	44.1	67.9	44.1	62.9	30.5	1.88
47	01674500	Mattaponi River	602	622.0	43.8	67.7	44.7	68.6	23.3	3.60
50	02013000	Dunlap Creek	162	190.9	41.4	63.0	39.8	92.0	6.1	0.01
52	02014000	Potts Creek	153	192.6	43.1	62.7	40.6	91.0	7.8	0.01
54	02016000	Cowpasture River	461	589.6	41.8	62.8	39.1	87.7	11.6	0.00
56	02017500	Johns Creek	105	144.4	43.1	63.3	40.8	92.2	7.2	0.00
57	02018000	Craig Creek	329	427.6	43.0	64.1	41.8	90.2	9.1	0.00

Table 3. Watershed climate and landscape characteristics used to evaluate evapotranspiration in this study.—Continued

[See figure 9 for watershed locations, SF, South Fork; NF, North Fork; MF, Middle Fork]

Map number	USGS station number	Watershed name	Area, in square miles	Flow, in cubic feet per second	Mean annual precipitation, in inches	Mean daily temperature, in degrees Fahrenheit		Land use, in percent		
				1971–2000		Maximum	Minimum	Forest	Agriculture	Marsh
58	02020500	Calfpasture River	141	189.9	44.8	61.8	38.5	89.5	10.2	0.00
59	02021500	Maury River	329	436.4	45.4	62.8	39.3	87.7	11.5	0.00
60	02024000	Maury River	647	744.9	45.2	63.8	40.3	73.2	25.0	0.00
66	02040000	Appomattox River	725	810.1	45.1	68.6	44.5	65.7	28.4	4.05
67	02041000	Deep Creek	158	165.1	45.3	69.0	44.8	62.0	30.4	5.54
68	02042500	Chickahominy River	251	276.1	44.4	68.6	45.9	46.4	29.8	8.79
69	02044500	Nottoway River	317	334.2	45.6	68.9	44.9	66.1	27.6	4.05
72	02047500	Blackwater River	290	340.4	46.2	69.9	47.2	58.3	28.6	9.07
73	02049500	Blackwater River	613	671.1	46.2	70.0	47.3	51.7	32.7	12.42
74	02051500	Meherrin River	552	553.3	45.5	69.4	45.7	68.7	27.7	2.05
75	02052000	Meherrin River	744	775.7	45.6	69.5	45.8	68.1	27.8	2.21
76	02053800	SF Roanoke River	109	122.3	42.7	63.7	42.0	81.0	17.2	0.12
77	02054500	Roanoke River	254	256.5	41.4	64.4	42.2	77.9	18.1	0.05
78	02055000	Roanoke River	384	385.2	41.6	65.0	42.8	70.9	17.3	0.03
79	02056000	Roanoke River	509	561.8	42.1	65.5	43.1	64.1	20.3	0.03
82	02059500	Goose Creek	188	202.5	45.3	67.4	44.3	62.1	35.9	0.00
84	02061500	Big Otter River	315	364.0	45.8	67.3	44.4	56.5	39.3	0.00
87	02065500	Cub Creek	98	113.6	45.3	67.9	44.3	63.1	32.9	3.12
93	02077000	Banister River	547	543.3	45.6	68.8	45.2	56.5	40.5	1.51
94	02079640	Allen Creek	54	50.3	45.2	69.8	46.0	71.5	26.3	1.39
96	03167000	Reed Creek	258	285.4	40.2	63.5	40.3	50.8	46.2	0.06
98	03170000	Little River	309	373.7	45.2	63.5	41.0	59.0	40.5	0.15
100	03173000	Walker Creek	299	321.1	40.8	62.9	40.4	75.9	23.6	0.10
102	03207800	Levisa Fork	297	373.5	46.6	64.8	41.5	84.9	11.9	0.00
103	03208500	Russell Fork	286	346.4	47.4	64.7	41.2	81.4	16.0	0.00
104	03473000	SF Holston River	303	482.8	49.0	62.5	39.8	72.6	27.0	0.05
105	03475000	MF Holston River	206	254.2	45.3	64.0	39.9	53.0	43.9	0.08
106	03488000	NF Holston River	221	295.0	46.3	63.1	39.9	70.0	29.7	0.11
107	03524000	Clinch River	533	693.6	45.8	63.4	40.9	57.9	37.9	0.01
108	03531500	Powell River	319	537.0	54.4	64.8	42.1	71.9	21.0	0.00

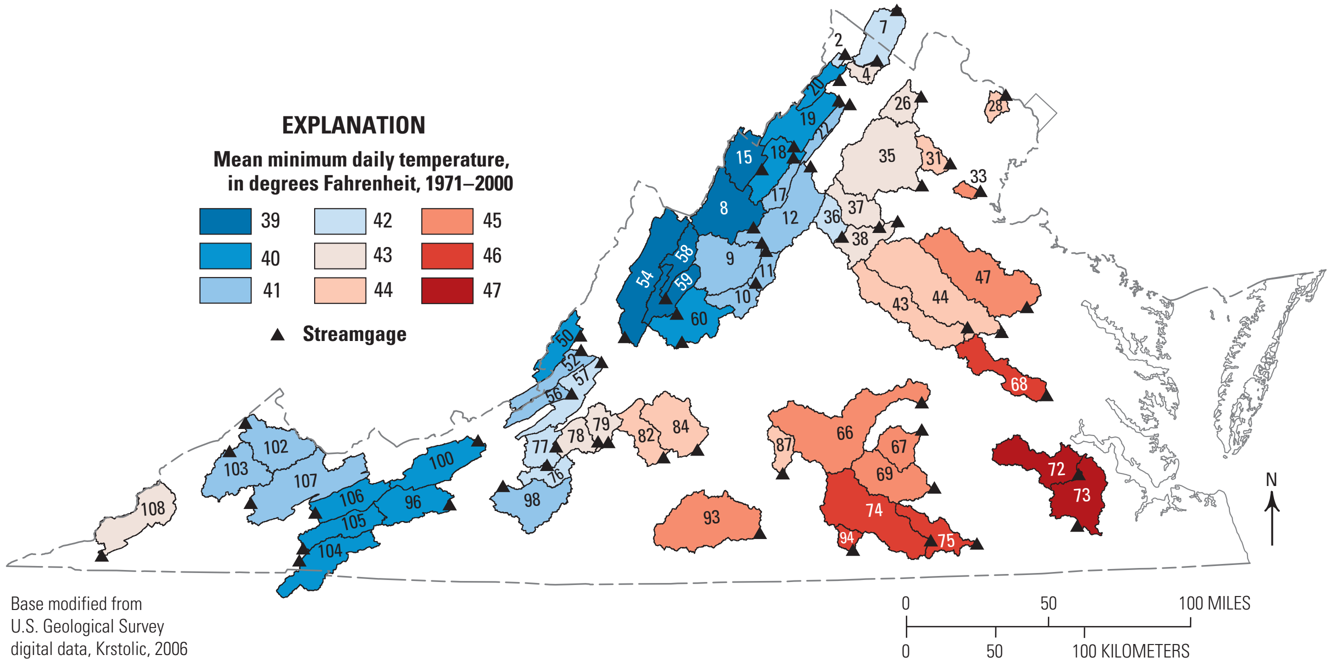


Figure 14. Mean minimum daily air temperature in selected watersheds in Virginia and West Virginia from 1971 to 2000. See figure 9 for watershed number list; compiled from data from PRISM Climate Group, Oregon State University, Daly and others (2008), accessed July 2008 at *http://www.prism.oregonstate.edu*.

During 2007–2008, water samples were also collected at approximately six-week intervals (during normal gage maintenance visits) from 90 streamgaging stations and analyzed for SC and anion concentrations of chloride, sulfate, and nitrate (table 5). Chloride (Cl) tends to be the most conservative ion in the subsurface for most regions (Hem, 1970) and was therefore used as an indicator of the component of the dissolved salts that originated at the land surface. By using the Cl/SC ratio, the fraction of salts that were dissolved at the land surface, versus that dissolved by subsurface mineral dissolution could be estimated. A ratio of zero indicated zero salts from the land surface. To obtain the ratio that would likely represent zero salts from mineral dissolution, a situation was chosen in which land-surface salts would completely dominate the stream chemistry signal. Road salt runoff after a heavy winter road salting event was chosen to determine this ratio. The Difficult Run watershed in Fairfax County, Virginia, was sampled at 24 locations in January 2009, following a small rain event that followed a period of heavy road salting (table 6). A plot of chloride concentration versus SC for the Difficult Run samples and all of the other watershed samples (fig. 17) reveals that a Cl/SC ratio of about 0.33 was observed for all of the samples with a SC of greater than 1,000 µS/cm (heavy road salt content). This ratio is characteristic of a stream that has 100 percent surface salts and virtually no mineral dissolution component. An examination of the rest of

Table 4. Regression equations for evapotranspiration as a function of climate and land-surface characteristics in this study.

[—, not applicable; bold text indicates equation and parameters used in evaluating equation 15]

Number of parameters	Regression equation[a]	Best fit value of parameter					Sum of squared errors	Standard error of regression
		a	b	c	d	e		
1	E=aP	0.643	—	—	—	—	164.9	2.58
2	E=aP+bT	0.293	0.287	—	—	—	93.4	1.48
3	E=aP+bT+d	0.370	0.590	—	–19.741	—	58.4	0.94
4	**E=aP+bTx+cTn+d**	**0.370**	**0.957**	**–0.383**	**–34.277**	**—**	**44.4**	**0.73**
5	E=aP+bTx+cTn+d+eF	0.374	0.961	–0.400	–33.757	–0.396	44.2	0.74
5	E=aP+bTx+cTn+d+eA	0.375	0.955	–0.395	–34.168	0.715	43.9	0.73
5	E=aP+bTx+cTn+d+eS	0.342	1.007	–0.328	–39.178	0.029	43.0	0.72

[a]E, evapotranspiration in inches; P, precipitation in inches; T, mean temperature; Tx, mean maximum daily temperature; Tn, mean minimum daily temperature; F, percent forest; A, percent agriculture; S, slope as topographic grade.

the average yearly data indicated that two streams with heavy winter salting, Difficult Run and Broad Run, also have relatively large surface-salt composition on average. Conversely, many streams had a ratio below 0.03, indicating a low average surface-salt composition.

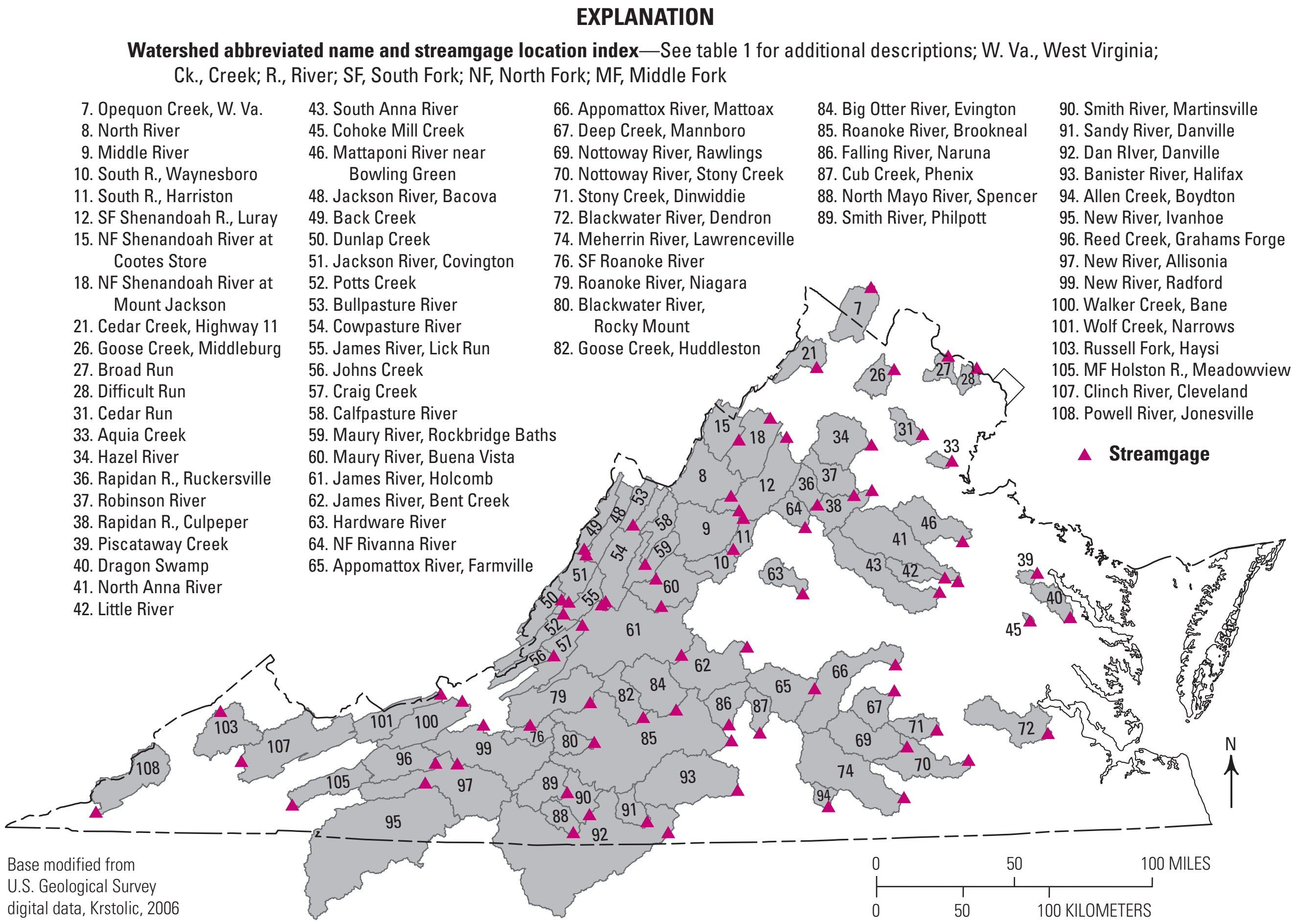


Figure 15. Names and locations of watersheds in Virginia and West Virginia where real-time specific conductance probes were installed at the streamgages for this study.

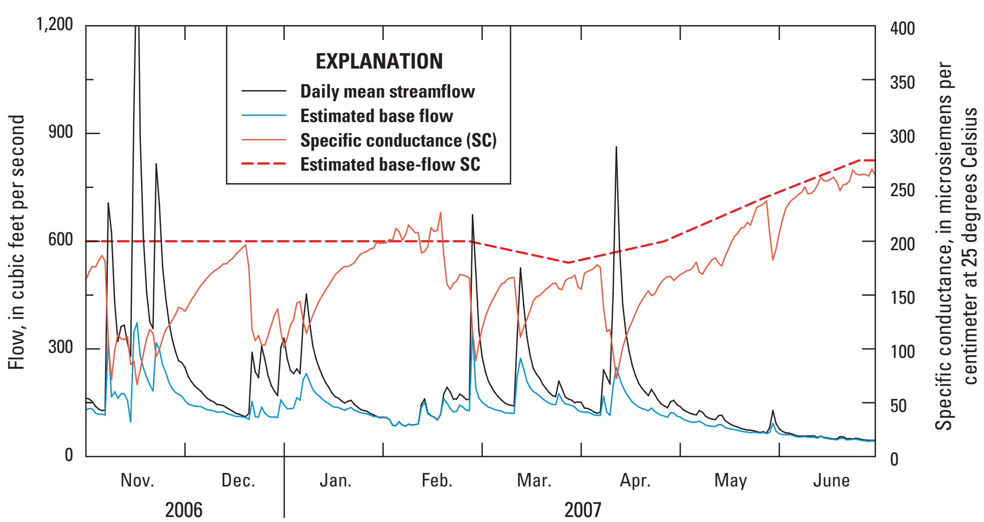


Figure 16. Daily mean streamflow, specific conductance, estimated base flow, and estimated base-flow specific conductance for gage 01626000 South River near Waynesboro, Virginia, for November 2006 through June 2007.

Table 5. Specific conductance, and chloride, sulfate, and nitrate concentrations for streams in this study.

[See figure 9 for map locations of watersheds; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; N, nitrogen; Stdev, standard deviation; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest; Mt. Mount; R., River; Ck., Creek]

Map number	USGS station number	Stream name	Specific conductance, in µS/cm at 25 °C			Chloride, in milligrams per liter			Sulfate, in milligrams per liter			Nitrate as N, in milligrams per liter		
			Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev
2	01613900	Hogue Creek Hayfield	6	205	55	8	5.8	1.6	8	13.4	3.5	7	0.2	0.11
3	01614830	Opequon Creek Stephens City	14	606	65	14	18.8	2.2	14	22.1	2.7	7	2.2	0.27
4	01615000	Opequon Creek Berryville	10	687	164	10	56.1	23.8	10	57.8	13.3	6	3.9	1.76
5	01616075	Fay Spring Winchester	6	711	22	6	30.9	4.1	6	35.9	2.2	5	2.3	0.10
6	01616100	Dry Marsh Run Berryville	23	637	19	23	13.9	1.4	23	17.4	0.7	7	1.6	0.22
7	01616500	Opequon Creek Martinsburg	25	613	125	29	41.6	15.1	29	38.5	5.7	22	2.1	0.24
8	01622000	North River Burketown	10	332	157	10	23.3	16.3	10	13.4	3.9	8	2.0	0.71
9	01625000	Middle River Grottoes	12	404	43	12	12.4	0.9	12	13.2	2.1	9	1.3	0.24
10	01626000	South River Waynesboro	11	223	47	11	4.7	0.6	11	10.7	3.1	9	0.8	0.24
11	01627500	South River Harriston	14	256	56	14	10.4	3.6	14	9.7	1.9	11	1.4	0.31
12	01629500	SF Shenandoah River Luray	13	303	88	13	14.2	5.0	13	13.2	2.4	10	1.3	0.16
13	01630700	Gooney Run Glen Echo	12	79	23	13	2.3	0.8	13	4.1	1.0	7	0.1	0.04
14	01631000	SF Shenandoah R. Front Royal	15	306	44	15	12.5	3.0	15	12.5	1.1	10	0.8	0.36
15	01632000	NF Shenandoah River Cootes	9	114	25	8	3.5	0.9	8	10.0	0.9	6	0.5	0.60
16	01632082	Linville Creek Broadway	10	523	66	11	18.4	4.7	11	24.6	10.9	9	2.6	0.77
17	01632900	Smith Creek New Market	10	450	69	10	15.2	2.4	10	16.5	1.8	9	1.9	0.24
18	01633000	NF Shenandoah R. Mt. Jackson	12	368	96	12	13.1	4.7	12	17.0	2.6	9	2.0	0.29
19	01634000	NF Shenandoah R. Strasburg	11	324	86	11	11.6	4.1	11	17.6	3.5	7	1.1	0.51
20	01634500	Cedar Creek Winchester	10	169	65	12	3.5	1.3	12	11.6	2.0	10	0.2	0.05
21	01635090	Cedar Creek Middletown	12	323	75	13	8.3	2.0	13	20.4	3.7	8	0.9	0.21
22	01635500	Passage Creek Bucktown	7	124	55	9	3.0	1.1	9	9.3	2.5	8	0.1	0.11
23	01636242	Crooked Run Riverton	12	514	73	13	22.4	5.3	13	47.5	7.7	6	0.9	0.19
24	0163626650	Manassas Run Front Royal	12	195	51	12	17.2	7.7	12	10.7	2.0	6	0.3	0.11

Table 5. Specific conductance, and chloride, sulfate, and nitrate concentrations for streams in this study.—Continued

[See figure 9 for map locations of watersheds; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; N, nitrogen; Stdev, standard deviation; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest; Mt. Mount; R., River; Ck., Creek]

Map number	USGS station number	Stream name	Specific conductance, in µS/cm at 25 °C			Chloride, in milligrams per liter			Sulfate, in milligrams per liter			Nitrate as N, in milligrams per liter		
			Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev
25	01636316	Spout Run Millwood	18	555	46	18	12.9	1.0	18	13.8	1.1	8	2.2	0.23
26	01643700	Goose Creek Middleburg	9	168	35	13	18.9	6.2	13	13.0	4.2	8	0.4	0.18
27	01644280	Broad Run Leesburg	12	588	291	13	87.2	310	12	27.0	7.8	8	0.7	0.40
28	01646000	Difficult Run Great Falls	13	231	57	14	41.5	15.5	14	6.2	0.6	10	0.9	0.43
31	01656000	Cedar Run Catlett	13	202	63	15	18.8	13.1	15	14.8	6.7	10	0.5	0.30
33	01660400	Aquia Creek Garrisonville	8	155	28	8	7.1	2.7	8	16.0	4.1	7	0.4	0.10
34	01663500	Hazel River Rixeyville	6	196	231	8	5.2	1.5	8	3.8	0.9	5	0.2	0.08
36	01665500	Rapidan River Ruckersville	9	57	7	13	4.1	1.3	13	3.4	0.5	9	0.5	0.11
37	01666500	Robinson River Locust Dale	10	64	11	13	5.7	1.3	13	3.3	0.5	9	0.6	0.22
38	01667500	Rapidan River Culpeper	31	74	11	33	5.5	1.5	33	4.6	0.9	20	0.6	0.28
39	01669000	Piscataway Creek Tappahanock	12	70	10	12	7.7	1.4	12	7.4	3.1	8	0.6	0.45
40	01669520	Dragon Swamp Mascot	11	73	27	11	6.3	1.7	11	3.6	2.7	7	0.1	0.04
41	01671020	North Anna River Doswell	22	73	19	23	5.9	1.9	23	7.1	1.7	16	0.2	0.10
42	01671100	Little River Doswell	13	140	139	13	4.6	2.1	13	35.9	55.7	9	0.2	0.17
43	01672500	South Anna River Ashland	7	96	19	7	5.3	0.6	7	4.7	1.3	4	0.2	0.11
45	01673638	Cohoke Mill Ck. Lestor Manor	7	110	16	7	5.8	0.9	7	3.7	2.8	6	0.2	0.21
46	01674000	Mattaponi River Bowling Green	12	68	24	12	6.4	1.3	12	7.2	4.6	8	0.2	0.06
48	02011400	Jackson River Bacova	10	183	26	10	2.8	1.4	10	10.9	2.1	8	0.3	0.25
49	02011500	Back Ck. Mountain Grove	9	126	16	9	2.7	0.8	9	10.8	1.5	8	0.3	0.20
50	02013000	Dunlap Creek Covington	10	307	121	10	7.4	2.2	10	56.3	29.7	8	0.2	0.07
51	02013100	Jackson River Covington	5	523	240	5	26.9	14.1	5	125.6	76.0	3	0.5	0.13
52	02014000	Potts Creek Covington	10	143	55	10	2.6	0.6	10	9.1	1.6	8	0.3	0.16
53	02015700	Bullpasture River Williamsville	9	150	20	10	2.0	0.8	10	7.8	1.8	7	0.3	0.20

Table 5. Specific conductance, and chloride, sulfate, and nitrate concentrations for streams in this study.—Continued

[See figure 9 for map locations of watersheds; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; N, nitrogen; Stdev, standard deviation; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest; Mt. Mount; R., River; Ck., Creek]

Map number	USGS station number	Stream name	Specific conductance, in µS/cm at 25 °C			Chloride, in milligrams per liter			Sulfate, in milligrams per liter			Nitrate as N, in milligrams per liter		
			Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev
54	02016000	Cowpasture R. Clifton Forge	8	155	26	8	2.6	1.0	8	9.8	2.3	7	0.2	0.08
55	02016500	James River Lick Run	9	505	190	10	26.8	12.8	10	112.6	47.8	8	0.3	0.10
56	02017500	Johns Creek New Castle	11	86	48	12	1.8	0.4	12	5.3	0.4	9	0.2	0.17
57	02018000	Craig Creek at Parr	10	109	42	10	2.0	0.4	10	6.4	0.7	8	0.1	0.07
58	02020500	Calfpasture River Goshen	11	74	31	11	1.7	0.3	11	7.0	0.7	7	0.2	0.14
59	02021500	Maury R. Rockbridge Baths	8	127	39	8	2.7	1.5	8	7.2	1.1	5	0.1	0.06
60	02024000	Maury River, Buena Vista	8	253	52	10	5.0	0.7	10	9.1	0.8	7	0.4	0.21
61	02025500	James R. Holcomb Rock	7	308	133	8	13.3	7.6	8	44.4	27.1	4	0.2	0.08
62	02026000	James River Bent Creek	9	296	123	9	12.1	7.6	9	39.5	23.4	5	0.3	0.14
63	02030000	Hardware River Scottsville	10	60	10	12	4.3	0.7	12	2.6	0.7	8	0.3	0.09
64	02032640	NF Rivanna R. Earlysville	8	58	7	10	4.0	0.6	10	3.0	1.2	7	0.2	0.17
65	02039500	Appomattox R. Farmville	12	89	8	13	4.0	0.5	13	4.6	1.5	8	0.2	0.10
66	02040000	Appomattox R. Mattoax	10	99	18	11	5.5	1.4	11	5.5	1.6	8	0.3	0.12
67	02041000	Deep Creek Mannboro	12	105	24	13	6.1	1.4	13	5.8	4.7	8	0.4	0.22
69	02044500	Nottoway River Rawlings	12	93	23	12	5.6	1.9	12	5.2	2.1	8	0.3	0.10
70	2045500	Nottoway River Stony Creek	11	181	32	11	8.4	1.5	11	17.7	2.7	8	0.5	0.04
71	02046000	Stony Creek Dinwiddie	12	78	34	13	4.2	0.9	13	3.8	2.5	7	0.2	0.04
72	02047500	Blackwater R. Dendron	11	103	50	11	8.2	1.8	11	11.3	16.3	7	0.3	0.16
74	02051500	Meherrin R. Lawrenceville	5	84	4	5	4.8	0.5	5	4.0	1.7	3	0.2	0.08
76	02053800	SF Roanoke R. Shawsville	10	260	75	11	5.0	1.6	11	11.6	2.9	8	0.5	0.38
79	02056000	Roanoke River Niagara	9	471	74	9	30.2	9.8	9	31.8	6.3	7	3.0	1.35
80	02056900	Blackwater River Rocky Mount	5	81	6	5	4.5	0.9	5	4.8	0.5	2	0.6	0.09
81	02059485	Goose Creek Bunker Hill	10	163	87	10	4.6	0.6	10	18.3	17.5	8	0.4	0.24

Table 5. Specific conductance, and chloride, sulfate, and nitrate concentrations for streams in this study.—Continued

[See figure 9 for map locations of watersheds; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; N, nitrogen; Stdev, standard deviation; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest; Mt. Mount; R., River; Ck., Creek]

Map number	USGS station number	Stream name	Specific conductance, in µS/cm at 25 °C			Chloride, in milligrams per liter			Sulfate, in milligrams per liter			Nitrate as N, in milligrams per liter		
			Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev	Count	Mean	Stdev
82	02059500	Goose Creek Huddleston	13	165	47	13	4.0	0.3	13	20.2	7.4	9	0.2	0.06
83	02061000	Big Otter River Bedford	10	71	35	10	3.9	1.0	10	2.5	0.6	8	0.3	0.12
84	02061500	Big Otter River Evington	12	97	25	13	7.0	1.6	13	3.8	0.4	9	0.5	0.10
85	02062500	Roanoke River Brookneal	3	142	190	3	7.3	8.3	3	8.8	43.6	1	0.2	0.38
86	02064000	Falling River Naruna	13	72	10	14	3.6	0.5	14	3.3	1.0	9	0.3	0.26
87	02065500	Cub Creek Phenix.	7	73	6	8	2.9	0.3	8	3.1	0.9	4	0.5	0.37
88	02070000	North Mayo R. Spencer	10	58	8	10	2.2	0.3	10	2.1	0.3	8	0.4	0.26
89	02072000	Smith River Philpott	5	60	5	5	3.0	0.5	5	4.1	0.0	3	0.3	0.22
90	02073000	Smith River Martinsville	10	68	8	10	3.5	0.5	10	4.4	0.4	7	0.2	0.01
91	02074500	Sandy River Danville	12	65	9	12	2.8	0.2	12	2.2	0.9	8	0.2	0.13
92	02075045	Dan River Danville	5	126	20	5	14.4	2.7	5	6.3	0.6	2	0.7	0.21
93	02077000	Banister River Halifax	6	77	13	6	4.0	0.2	6	4.0	1.9	4	0.2	0.12
94	02079640	Allen Creek Boydton	14	116	49	15	8.7	9.2	15	4.3	2.6	11	0.5	0.34
95	03165500	New River Ivanhoe	9	70	9	9	6.6	1.6	9	3.6	0.5	8	0.6	0.23
96	03167000	Reed Creek Gra-hams Forge	10	370	51	10	18.2	3.7	10	16.9	3.3	8	0.9	0.20
97	03168000	New River Allisonia	9	126	12	9	7.3	1.9	9	5.2	1.4	8	0.5	0.23
99	03171000	New River Radford	9	130	14	9	6.8	0.4	9	7.0	1.1	8	0.6	0.23
100	03173000	Walker Creek Bane	10	242	74	10	6.4	2.1	10	7.6	3.0	8	0.4	0.07
101	03175500	Wolf Creek Narrows	10	225	53	10	8.4	3.7	10	9.6	4.9	8	0.7	0.33
103	03208500	Russell Fork Haysi	9	688	314	11	25.5	17.9	11	137.5	41.1	10	0.3	0.23
105	03475000	MF Holston R. Meadowview	8	366	72	9	13.9	3.5	9	17.1	5.9	8	1.4	0.49
107	03524000	Clinch River Cleveland	7	328	73	9	12.8	3.8	9	24.9	5.1	8	0.8	0.43
108	03531500	Powell River Jonesville	8	579	165	9	9.1	2.7	9	152.1	33.9	8	0.6	0.14

Table 6. Specific conductance (SC) and anion concentrations in Difficult Run watershed, January 29, 2009.

[µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; Cl, chloride; SF, South Fork; W&OD, Washington and Old Dominion]

Sample number	Location of sample	Time sampled	SC, in µS/cm at 25 °C	Chloride	Sulfate	Nitrate as nitrogen	Cl/SC ratio
				Milligrams per liter			
1	SF Colvin Run at Wiehle Avenue	7:55	5,150	1,640	23.9	1.6	0.32
2	Colvin Run at Carpers Farm Way	8:25	380	94	6.52	1.2	0.25
3	Difficult Run at Route 7	8:35	3,030	937	13.2	1.6	0.31
4	Piney Run and Walker Road	8:45	480	121	6.3	2.9	0.25
5	Captain Hickory Run at Captain Hickory Drive	9:00	420	102	5.99	3.3	0.24
6	Difficult Run at Georgetown Pike	9:30	2,640	845	12.6	1.8	0.32
7	Rocky Run at Towlston Road	9:45	4,380	1,460	15.8	1.7	0.33
8	Rocky Run at Lewinsville Road	10:00	5,600	1,910	22.6	0.9	0.34
9	Courthouse Spring Branch at Laurel Hill Road	10:15	4,090	1,400	19.7	1.4	0.34
10	Wolftrap Creek at Bois Avenue	10:30	3,200	1,080	20.7	1.2	0.34
11	Wolftrap Creek at Beulah Road	10:45	3,480	1,200	18.4	1.4	0.34
12	Difficult Run at W&OD Trail	11:15	2,760	921	14.9	1.6	0.33
13	Piney Branch at W&OD Trail	11:30	4,920	1,760	21.1	1.8	0.36
14	Angelica Branch at Cedar Pond Drive	11:50	690	212	10.2	2.5	0.31
15	The Glade at Twin Branches Road	12:40	670	212	4.54	0.6	0.32
16	Snakeden Branch at Twin Branches Road	12:50	120	28	3.59	0.2	0.23
17	Little Difficult Run at Birdfoot Lane	13:05	230	60	4.33	2.5	0.26
18	Little Difficult Run at Stuart Mill Road	13:15	1,080	336	7.39	2.5	0.31
19	SF Little Difficult Run at Marshall Lake Drive	13:35	450	130	4.83	2.6	0.29
20	Difficult Run at Vale Road	14:00	2,990	1,040	16.9	1.5	0.35
21	Rocky Branch at Hunters Mill Drive	14:10	890	276	9.98	1.9	0.31
22	Rocky Branch at Samage Drive	14:20	1,360	439	13.8	2.0	0.32
23	Difficult Run at Fox Lake Gage	14:45	2,930	1,070	16.8	1.2	0.37
24	Difficult Run at Valley Road	15:15	4,350	1,590	21.1	0.6	0.37

The mean specific conductance of the streams measured in Virginia (fig. 18) is a reflection, in large part, of the solubility of minerals in the soils and rocks through which the groundwater passes (Briel, 1997). Watersheds in the Valley and Ridge Province had the highest mean SC values, especially the watersheds that were underlain by carbonate rocks, which frequently had mean SC values in excess of 300 µS/cm (fig. 19; table 6). Conversely, watersheds in the Blue Ridge and Coastal Plain Provinces frequently had mean SC values less than 100 µS/cm because of the relative abundance of quartz sand and lack of soluble minerals in the soils and rocks. Many of the watersheds that had groundwater-discharge SC values consistently well below 100 µS/cm were too difficult to interpret; this is because the precipitation event did not create a signal that was substantially different than the random noise in the SC signal that was present during the measurement period. A second major reason why some watershed SC values could not be interpreted was because some streams had a substantial volume of water impounded upstream in a reservoir. These reservoirs controlled the flow in the downstream reaches and at the gage such that the natural response of the flow and SC to the precipitation events was muted. Watersheds with low SC or impounded water were not used for base-flow calculations, even though some of these watersheds were initially instrumented. Out of the 75 streams instrumented, only data from 48 were used for base-flow calculations, but historical SC and flow data from an additional 4 streams on the coastal plain of Maryland and Delaware were also used (table 7).

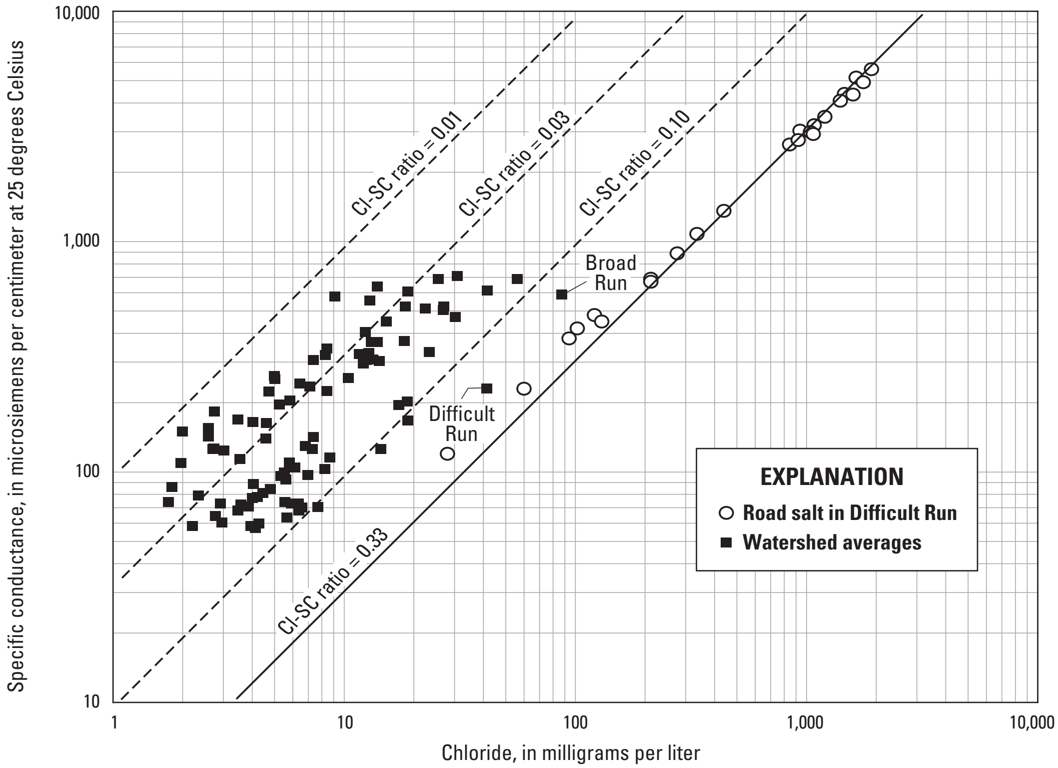


Figure 17. Relation between dissolved chloride and specific conductance in stream waters of Virginia. See tables 6 and 7 for data values.

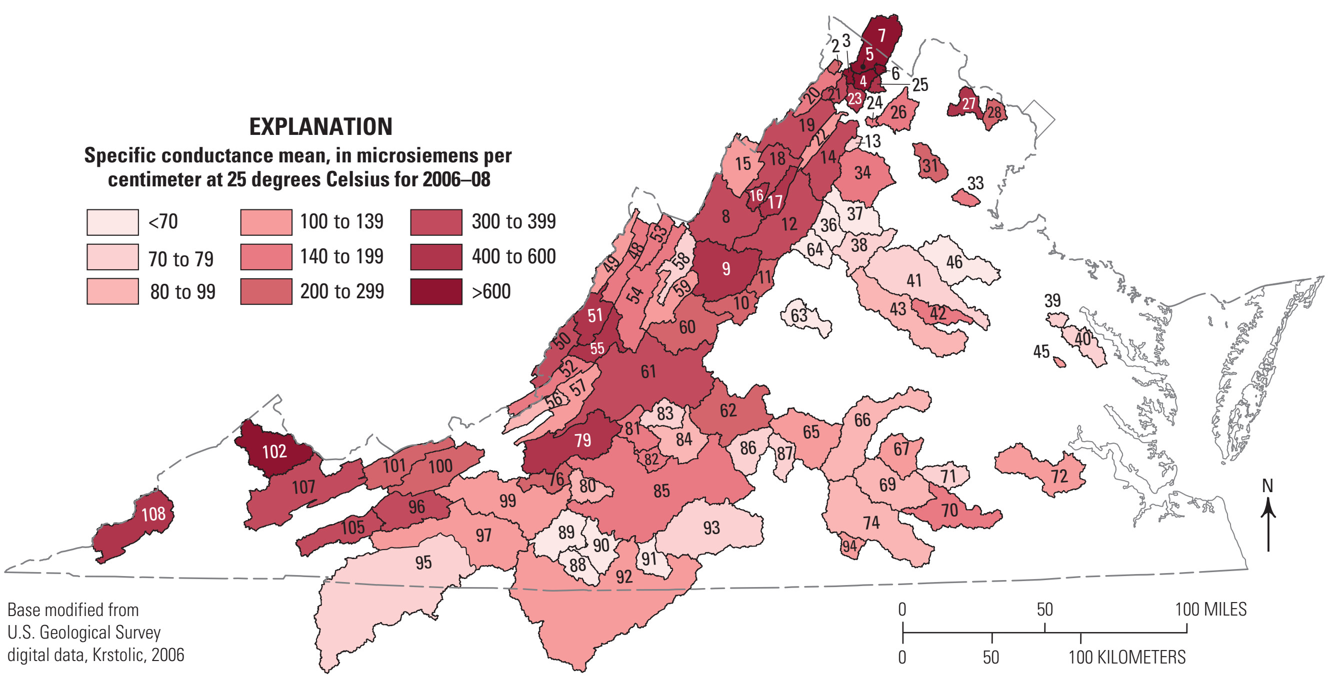


Figure 18. Mean specific conductance of water at selected streamgages in Virginia and West Virginia during 2006–2008. See figure 9 for watershed number list; table 5 for data.

Table 7. Real-time gages in Virginia with specific conductance (SC) data used to estimate base flow for watersheds in this study.

[See figure 9 for map locations; µS/cm, microsiemens per centimeter at 25 degrees Celsius; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest]

Map number	USGS station number	Watershed name	Area, in square miles	Mean precipitation, in inches	Mean flow, in cubic feet per second		SC of mean base flow, in µS/cm			Mean annual stream SC, in µS/cm at 25°C	Calculated surface runoff SC, in µS/cm at 25°C
					Period of record	2006–2008	Summer	Winter	Annual		
1	01487000	Nanticoke River	75	45.0	93.3	92.4	160	140	136	128	48
2	01613900	Hogue Creek	16	39.9	15.6	15.8	275	175	182	127	42
4	01615000	Opequon Creek	58	39.0	47.2	46.6	850	625	680	510	144
8	01622000	North River	376	40.0	387.8	370.1	500	300	335	222	78
9	01625000	Middle River	373	40.4	321.8	328.1	450	400	415	356	103
10	01626000	South River	127	48.2	150.8	147.2	275	200	207	149	50
11	01627500	South River	212	47.6	260.8	253.7	300	225	251	170	60
12	01629500	SF Shenandoah River	1,377	42.0	1,425.1	1,420.0	400	300	304	249	84
14	01631000	SF Shenandoah River	1,634	42.1	1,598.3	1,597.8	375	300	314	255	80
15	01632000	NF Shenandoah River	210	39.6	76.8	75.5	500	400	457	397	112
16	01632082	Linville Creek	46	39.4	198.2	197.2	175	100	89	66	21
17	01632900	Smith Creek	94	38.7	407.1	410.2	500	350	379	264	74
18	01633000	NF Shenandoah River	508	38.7	608.8	613.4	450	350	367	265	74
19	01634000	NF Shenandoah River	770	40.3	99.2	101.2	250	150	159	118	39
20	01634500	Cedar Creek	102	39.8	148.9	147.9	450	325	335	206	68
21	01635090	Cedar Creek	153	41.4	73.0	72.3	200	120	126	93	26
22	01635500	Passage Creek	87	39.1	24.8	24.6	575	500	587	547	220
25	01636316	Spout Run	21	36.8	39.2	39.9	600	520	571	540	171
26	01643700	Goose Creek	122	42.3	135.6	132.3	250	125	152	125	45
28	01646000	Difficult Run	58	43.7	62.4	62.2	240	200	227	142	48
29	01649500	NE Branch Anacostia River	73	45.0	87.6	88.6	300	275	286	209	76
30	01651000	NW Branch Anacostia River	49	45.0	49.8	50.8	350	350	353	187	57
31	01656000	Cedar Run	93	43.3	90.4	91.2	200	180	196	134	41
32	01658000	Mattawoman Creek	55	45.0	57.3	56.4	140	140	153	127	40
33	01660400	Aquia Creek	35	43.3	35.3	35.2	180	100	91	69	22
36	01665500	Rapidan River	115	50.2	155.3	154.0	75	55	59	51	19
37	01666500	Robinson River	179	46.1	226.3	220.7	85	65	65	57	21
38	01667500	Rapidan River	468	46.7	543.9	550.0	95	75	73	67	23
40	01669520	Dragon Swamp	108	45.1	126.6	124.4	125	70	75	62	22
43	01672500	South Anna River	395	44.2	369.8	372.6	80	80	77	55	16

Table 7. Real-time gages in Virginia with specific conductance (SC) data used to estimate base flow for watersheds in this study.—Continued

[See figure 9 for map locations; µS/cm, microsiemens per centimeter at 25 degrees Celsius; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest]

Map number	USGS station number	Watershed name	Area, in square miles	Mean precipitation, in inches	Mean flow, in cubic feet per second		SC of mean base flow, in µS/cm			Mean annual stream SC, in µS/cm at 25°C	Calculated surface runoff SC, in µS/cm at 25°C
					Period of record	2006–2008	Summer	Winter	Annual		
48	02011400	Jackson River	158	42.7	170.1	168.2	225	175	185	152	52
49	02011500	Back Creek	134	43.6	180.7	175.4	150	110	119	104	44
50	02013000	Dunlap Creek	162	41.4	169.6	170.6	450	250	263	161	55
52	02014000	Potts Creek	153	43.1	179.5	174.5	210	125	135	95	35
53	02015700	Bullpasture River	110	41.7	153.7	150.1	185	150	158	126	57
55	02016500	James River	1,373	42.1	1,697.8	1,702.4	700	400	445	308	123
56	02017500	Johns Creek	105	43.1	129.6	130.9	160	60	54	37	14
57	02018000	Craig Creek	329	43.0	389.6	389.1	180	100	97	65	24
58	02020500	Calfpasture River	141	44.8	169.2	164.7	150	60	72	52	19
59	02021500	Maury River	329	45.4	387.3	397.7	180	100	105	74	26
60	02024000	Maury River	647	45.2	684.6	692.6	310	240	228	164	52
64	02032640	NF Rivanna River	108	49.3	134.0	135.5	68	53	55	50	17
66	02040000	Appomattox River	725	45.1	708.6	729.1	125	90	101	80	24
67	02041000	Deep Creek	158	45.3	149.4	146.9	150	115	116	85	24
69	02044500	Nottoway River	317	45.6	308.1	310.4	110	85	81	66	19
72	02047500	Blackwater River	290	46.2	316.2	319.8	150	100	105	75	24
74	02051500	Meherrin River	552	45.5	504.7	497.4	110	70	78	60	16
82	02059500	Goose Creek	188	45.3	180.3	183.1	250	140	135	106	30
84	02061500	Big Otter River	315	45.8	334.8	327.0	140	90	87	75	24
96	03167000	Reed Creek	258	40.2	267.4	270.6	400	350	355	263	92
107	03524000	Clinch River	533	45.8	708.3	697.4	425	350	334	296	117
108	03531500	Powell River	319	54.4	538.1	537.8	750	575	557	379	160

[a]Assuming all dissolved solids originate at the land surface.

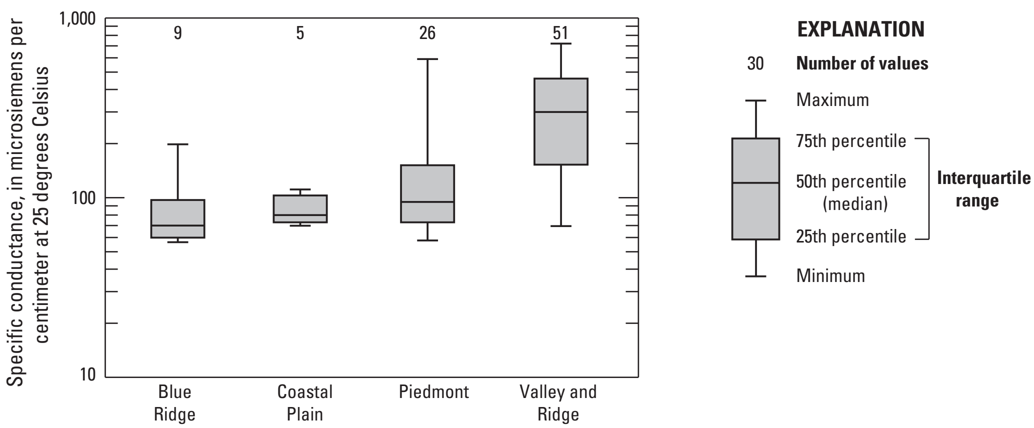


Figure 19. Mean specific conductance of streams by physiographic province. See table 6 for data.

Graphical Hydrograph Separation

The fraction of streamflow that is from groundwater discharge can also be estimated from the classical graphical hydrograph separation techniques that separate base flow from a streamflow hydrograph (Risser and others, 2005). A graphical technique was included in this study only as a comparison to the chemical hydrograph separation; the results were not used as budget component estimates. The graphical technique is based solely on an intuitive assumption that increases in flows during and following precipitation events are dominated by precipitation water from that event, rather than being based on actual mass-balance calculations (Hornberger and others, 1998, p. 202). Historically, comparisons of chemical versus graphical techniques at individual stream locations for individual runoff events suggest that the graphical techniques frequently underestimate the size of the base-flow component (Wels and others, 1991; Rice and Hornberger, 1998; Halford and Mayer, 2000). This is because the chemical tracer signature suggests a higher component of pre-event water in the hydrograph peak than is accounted for by the automated graphical algorithms. For the watersheds in this study, the USGS automated program, PART (Rutledge, 1993), was used to calculate the base-flow or groundwater-discharge component of streamflow. The major assumptions of PART are that base flow is equivalent to groundwater discharge and that effective recharge is approximately equal to groundwater discharge (Risser and others, 2005). It has been noted by the developer of the automated routines, such as PART, that care must be used selecting an appropriate stream and in applying the program (Rutledge, 1993, 2005). This study provided a good opportunity to compare the two techniques over a much larger number of streams and flow events than has been previously conducted. In order to make an appropriate comparison for each watershed, PART was used on the hydrographs for the same time periods that the chemical hydrograph technique was applied. Results of this comparison are given in the Graphical Hydrograph Separation section of the Estimates of Hydrologic Budget Components section that follows.

Regression Analysis

In order to fulfill the objective of this study to estimate the hydrologic budget components for all regions of Virginia the results from the watersheds analysis needed to be transferred to other regions. This was quantitatively conducted by developing regression equations. The first equation expressed the fraction of the precipitation that results in surface runoff as

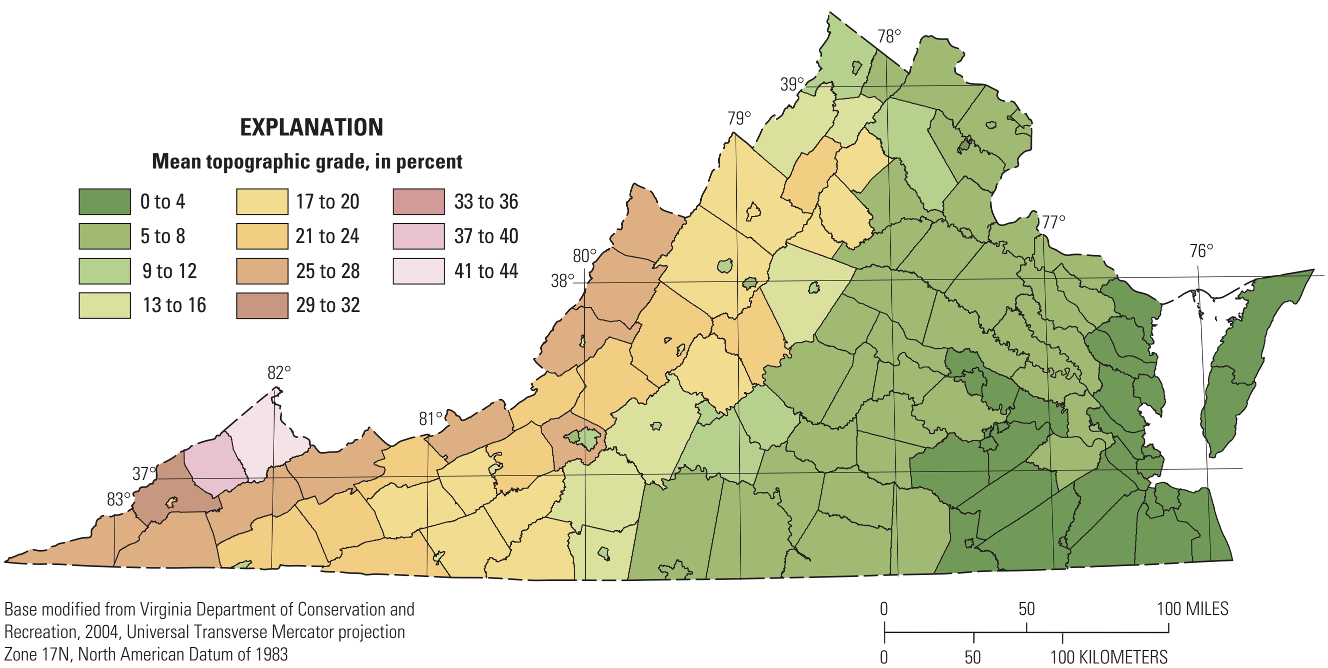


Figure 20. Median topographic slope of the land surface in Virginia by locality as topographic grade. See figure 2 for locality names; data compiled from U.S. Geological Survey 30-meter National Elevation Dataset, accessed July 2008 at *http://seamless.usgs.gov*.

a function of landscape characteristics of the watersheds. The same landscape characteristics of Virginia localities (counties and independent cities) could then be put into the regression equation to obtain the surface-runoff-fraction component for each locality. Precipitation and temperatures for each locality were obtained from the PRISM climate database, and the evapotranspiration was obtained using that data in the ET regression equation developed from the watershed data. Surface runoff and ET were also adjusted for impervious surface (see below). Riparian ET for the localities was estimated with a regression equation of percent marsh in the landscape based on temperature and topographic slope. With these estimates of surface-runoff-fraction and total and riparian ET for each locality, recharge and net-groundwater-discharge components were calculated by mass balance (table 1).

A variety of different landscape characteristics were evaluated for correlation with the watershed estimates of surface runoff, including the physiographic province (fig. 1), land cover (fig. 6), rock type (fig. 7), median topographic slope (fig. 20), mean soil permeability (fig. 21), and percent impervious surface (which correlates to the developed land cover, (fig. 22). After examination of each of these factors in the regression equation it was concluded that physiographic province, rock type (table 8), and percent impervious surface were capable of explaining much of the variability in the runoff between watersheds, and that topographic slope, soil permeability, and land cover were only capable of improving the fit by a very small insignificant amounts. There was also substantial amount of cross-correlation between these factors, for example between rock type and soil permeability and between land cover and topographic slope. Only a few watersheds had substantial percentages of impervious surface, which was not enough to determine the contribution to runoff implicitly in the regression. However, previous investigations (Lull and Sopper, 1969) into the role of impervious surface on runoff have indicated an average of 29 percent increase in runoff for areas with 50 percent impervious surface. This ratio of surface runoff to impervious surface was applied to the regression estimate of surface runoff, and did improve the fit in the few watersheds that had substantial impervious surface cover. The same study that indicated the increase in surface runoff indicated a 38 percent decrease in ET for areas with 50 percent impervious surface. This percent of ET decline was also applied to the regression estimate of for the localities as a function of the climatic variables. These two effects of impervious surface were negligible in most of the counties, but substantial in the independent cities that had relatively high percentages of impervious surface.

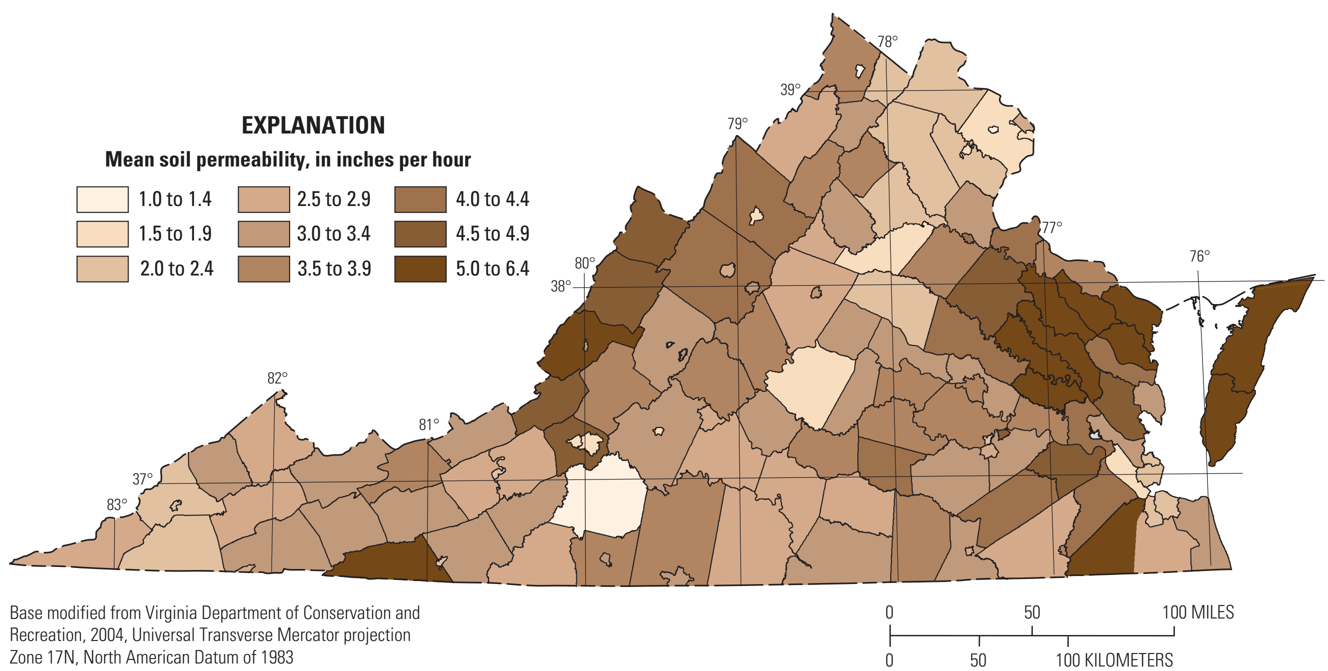


Figure 21. Mean soil permeability of the counties and independent cities of Virginia. See figure 2 for locality names; data from Natural Resources Conservation Service, U.S. Department of Agriculture, Soil Survey Geographic (SSURGO) Database for Virginia, accessed July 2009 at *http://soildatamart.nrcs.usda.gov*.

Table 8. Percentages of rock types underlying the watersheds in this study used to generate the runoff-regression-equation parameters.

[See figure 9 for map locations; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest]

Map number	USGS station number	Watershed located in Blue Ridge Province	Type 1 Meta-volcanics	Type 2 Meta-sediments	Type 3 Plutonic	Type 4 Mesozoic Basins	Type 5	Type 6	Type 7	Type 8
26	01643700	Goose Creek	16.6	0.4	83.0	0.0	0.0	0.0	0.0	0.0
31	01656000	Cedar Run	39.4	0.0	0.0	60.6	0.0	0.0	0.0	0.0
36	01665500	Rapidan River	14.2	3.9	81.9	0.0	0.0	0.0	0.0	0.0
37	01666500	Robinson River	13.0	28.5	53.8	4.6	0.0	0.0	0.0	0.0
38	01667500	Rapidan River	22.1	24.4	43.8	9.7	0.0	0.0	0.0	0.0
64	02032640	NF Rivanna River	16.6	3.6	79.2	0.7	0.0	0.0	0.0	0.0
82	02059500	Goose Creek	0.8	18.5	64.8	15.9	0.0	0.0	0.0	0.0
84	02061500	Big Otter River	6.8	34.1	59.0	0.0	0.0	0.0	0.0	0.0

Map number	USGS station number	Watershed located in Coastal Plain Province	Type 1 Fine grained	Type 2 Mixed grained	Type 3 Coarse grained	Type 4 Northern Piedmont	Type 5	Type 6	Type 7	Type 8
1	01487000	Nanticoke River	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0
29	01649500	NE Branch Anacostia River	0.0	0.0	78.6	21.3	0.0	0.0	0.0	0.0
32	01658000	Mattawoman Creek	0.0	30.0	70.0	0.0	0.0	0.0	0.0	0.0
40	01669520	Dragon Swamp	37.3	62.7	0.0	0.0	0.0	0.0	0.0	0.0
72	02047500	Blackwater River	80.7	18.6	0.0	0.0	0.0	0.0	0.0	0.0

Map number	USGS station number	Watershed located in Piedmont Province	Type 1 North-western	Type 2 South-eastern	Type 3 Mesozoic Basins	Type 4 Coarse-grained sediment	Type 5	Type 6	Type 7	Type 8
28	01646000	Difficult Run	96.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0
30	01651000	NW Branch Anacostia River	83.8	0.0	0.0	16.2	0.0	0.0	0.0	0.0
33	01660400	Aquia Creek	99.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
43	01672500	South Anna River	55.6	37.9	6.5	0.0	0.0	0.0	0.0	0.0
66	02040000	Appomattox River	39.3	58.3	2.4	0.0	0.0	0.0	0.0	0.0
67	02041000	Deep Creek	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
69	02044500	Nottoway River	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
74	02051500	Meherrin River	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 8. Percentages of rock types underlying the watersheds in this study used to generate the runoff-regression-equation parameters.—Continued

[See figure 9 for map locations; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest]

Map number	USGS station number	Watershed located in Valley and Ridge Province	Cambrian dolomites	Cambrian-Ordovician limestones	Ordovician dolomites	Ordovician siliciclastics	Silurian siliciclastics and limestones	Devonian siliciclastics	Mississippian siliciclastics	Appalachian Plateau siciliclastics
2	01613900	Hogue Creek	0.0	0.0	0.0	0.0	44.3	44.7	11.0	0.0
4	01615000	Opequon Creek	0.0	27.0	14.7	57.3	1.1	0.0	0.0	0.0
8	01622000	North River	0.0	26.3	15.2	4.5	0.4	2.6	51.1	0.0
9	01625000	Middle River	0.0	41.5	23.0	22.6	1.4	2.8	8.8	0.0
10	01626000	South River	59.4	27.6	3.8	0.0	0.0	0.2	0.0	0.0
11	01627500	South River	59.3	30.8	2.3	0.0	0.0	0.1	0.0	0.0
12	01629500	SF Shenandoah River	17.7	29.5	14.8	13.7	1.8	1.7	16.4	0.0
14	01631000	SF Shenandoah River	16.7	27.0	14.6	14.7	1.6	1.4	13.8	0.0
15	01632000	NF Shenandoah River	0.0	0.5	0.0	0.9	10.0	26.6	62.0	0.0
16	01632082	Linville Creek	0.0	43.7	28.4	28.0	0.0	0.0	0.0	0.0
17	01632900	Smith Creek	0.0	31.3	29.8	31.9	7.1	0.0	0.0	0.0
18	01633000	NF Shenandoah River	0.0	23.1	20.5	12.1	5.8	11.5	27.1	0.0
19	01634000	NF Shenandoah River	0.0	23.2	21.1	16.5	9.0	11.0	19.2	0.0
20	01634500	Cedar Creek	0.0	0.7	0.0	12.3	40.3	32.1	14.7	0.0
21	01635090	Cedar Creek	0.0	15.4	12.8	10.6	27.4	23.3	10.5	0.0
22	01635500	Passage Creek	0.0	0.0	0.0	9.1	55.5	35.4	0.0	0.0
25	01636316	Spout Run	3.0	33.6	59.6	0.0	3.8	0.0	0.0	0.0
48	02011400	Jackson River	0.0	7.8	0.9	16.1	55.2	19.9	0.0	0.1
50	02013000	Dunlap Creek	0.0	2.5	0.0	4.6	14.3	29.9	47.8	0.8
52	02014000	Potts Creek	0.0	5.0	0.1	13.1	41.7	40.1	0.0	0.0
53	02015700	Bullpasture River	0.0	0.0	0.0	2.6	68.0	29.4	0.0	0.0
55	02016500	James River	0.0	2.9	0.3	7.1	35.3	39.3	15.0	0.1
56	02017500	Johns Creek	0.0	0.0	0.0	1.4	39.9	58.7	0.0	0.0
57	02018000	Craig Creek	0.0	2.8	0.0	2.7	35.5	53.5	5.5	0.0
58	02020500	Calfpasture River	0.0	0.0	0.0	0.0	10.6	38.2	51.2	0.0
59	02021500	Maury River	0.0	0.2	0.0	1.2	29.3	42.2	27.0	0.0
60	02024000	Maury River	8.4	19.5	12.0	6.1	15.4	21.7	13.7	0.0
96	03167000	Reed Creek	11.9	33.6	2.4	3.2	4.8	28.5	7.4	8.2
107	03524000	Clinch River	0.0	39.3	0.0	15.1	3.4	13.6	0.9	27.7
108	03531500	Powell River	0.0	8.9	4.3	7.1	8.3	0.0	5.8	65.6

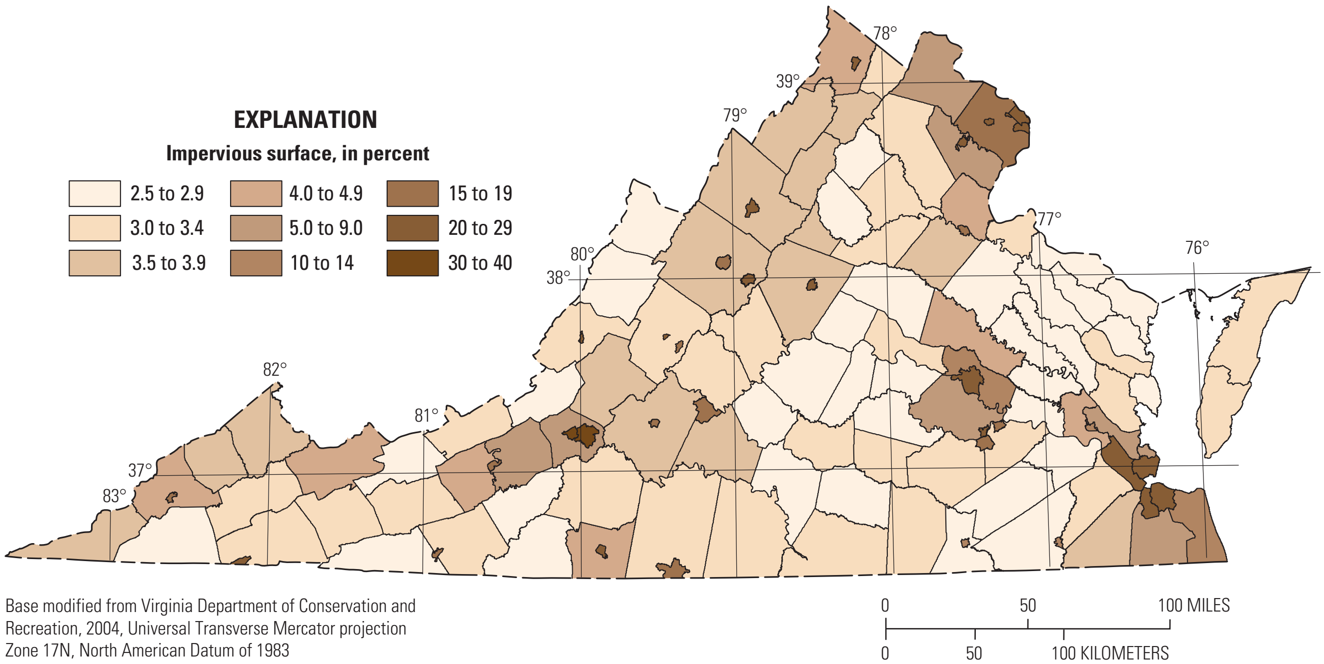


Figure 22. Percent developed land cover in the counties and independent cities of Virginia by locality. See figure 2 for locality names; data compiled from U.S. Geological Survey National Land-Cover Database 2001, accessed August 2007 at *http://landcover.usgs.gov/natllandcover.php*.

Estimates of Hydrologic Budget Components

Components of the hydrologic budgets were first calculated for the watersheds based on streamflow, climatic data, and chemical hydrograph separations in the watersheds (table 1). These results were used to create regression equations that described total ET and the mean annual surface runoff as a function of rock type and physiographic province. The components of the hydrologic budgets for all the localities (counties and independent cities) were then calculated based on the climatic data for the localities, the regression equations for ET and surface runoff, and the water balance equations. Estimates of runoff and recharge may be particularly useful for water managers.

Results from Watersheds

The hydrologic budget components were estimated for a number of watersheds across Virginia as an average annual rate in inches per year during the period 1971–2000. The precipitation was estimated by using the PRISM data directly without any additional interpretation. Mean annual precipitation rates for the watersheds used for the ET and chemical hydrograph separation calculations (table 9) range from less than 40 in/yr in the watersheds in the Shenandoah Valley to more than 50 in/yr in some high-elevation watersheds in the Blue Ridge, Valley and Ridge, and Appalachian Plateau Provinces.

Total Evapotranspiration

Total evapotranspiration was calculated for the watersheds using the water (mass) balance approach described earlier in the methods section of this report, in which the mean annual streamflow from 1971–2000 is subtracted from the mean annual precipitation of the same period multiplied by the watershed area (table 9). Results indicate that mean annual total ET rates in the watersheds evaluated in Virginia range from 24 in/yr in some of the higher elevation watersheds in western Virginia to 32 in/yr in some of the wetter and warmer watersheds in southwestern and southern Virginia (fig. 23). This range of values is very similar to that of potential ET estimated across Virginia at weather stations by the University of Virginia Climatology Center (*http://climate.virginia.edu/va_pet_prec_diff.htm*). Expressed as a percentage of precipitation, the ET rates for the watersheds range from less than 60 percent in some of the higher elevation watersheds in western and southwestern Virginia to more than 70 percent in some of the warmer watersheds in southern Virginia (fig. 24). When the ET rates for these watersheds were related to the mean annual precipitation and minimum and maximum daily temperature for the same watersheds, a regression (eq. 15) was developed that contained four parameters. Different forms of the regression equation were fit to the data but a standard error of regression analysis indicated that four parameters were optimal for estimating the ET (table 4; fig. 25). A plot of the ET calculated using the water balance versus that estimated by the regression (eq. 15; fig. 26) indicates a relatively good fit (R2=0.8435, slope=0.844) and that ET in Virginia is controlled predominantly by variations in climate.

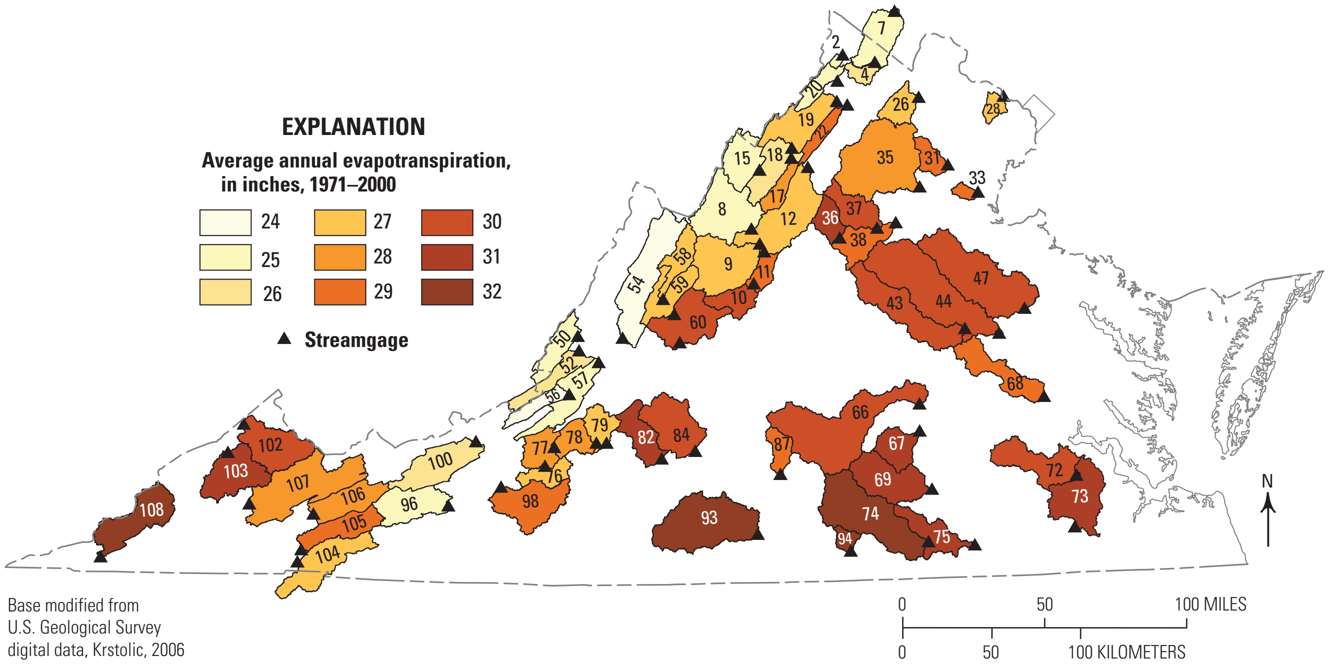


Figure 23. Evapotranspiration from 1971 to 2000 calculated by mass balance for watersheds of Virginia and West Virginia in this study. Numbers on watersheds are indexed to the watershed names in table 2 and figure 9.

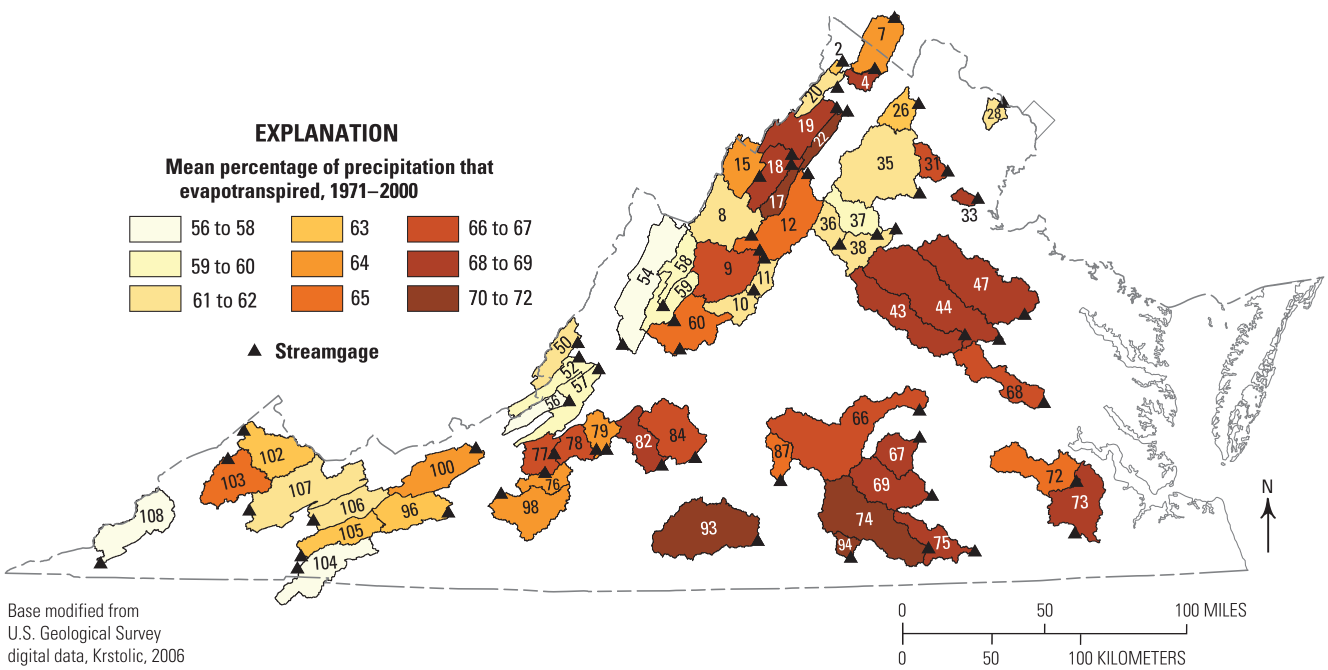


Figure 24. Mean percentage of precipitation that evapotranspired from 1971 to 2000 in watersheds of Virginia and West Virginia in this study. Numbers on watersheds are indexed to the watershed names in table 2 and figure 9.

Table 9. Watershed calculated and estimated total evapotranspiration in this study.

[See figure 9 for map locations; USGS, U.S. Geological Survey; SF, South Fork; NF, North Fork; MF, Middle Fork]

Map number	USGS station number	Watershed name	Area, in square miles	Mean annual amount, in inches, 1971–2000		Evapotranspiration				
				Streamflow	Precipitation	Total (precipitation minus flow), in inches	As percent of precipitation	From regression, in inches	From regression, in percent	Error in percent of precipitation
2	01613900	Hogue Creek	16	14.8	39.9	25.1	63.0	25.2	63.1	0.2
4	01615000	Opequon Creek	58	12.6	39.0	26.4	67.6	25.6	65.7	–3.0
7	01616500	Opequon Creek	273	14.0	39.4	25.4	64.5	25.9	65.6	1.8
8	01622000	North River	376	15.4	40.0	24.6	61.6	25.4	63.5	3.0
9	01625000	Middle River	373	13.2	40.4	27.2	67.3	26.9	66.6	–1.1
10	01626000	South River	127	18.1	48.2	30.1	62.4	29.3	60.8	–2.7
11	01627500	South River	212	18.5	47.6	29.1	61.2	29.3	61.6	0.8
12	01631000	SF Shenandoah River	1,634	14.9	42.1	27.2	64.7	27.2	64.7	0.1
15	01632000	NF Shenandoah River	210	14.3	39.4	25.1	63.7	25.3	64.3	1.0
17	01632900	Smith Creek	94	12.0	39.6	27.6	69.7	27.1	68.6	–1.7
18	01633000	NF Shenandoah River	508	12.2	38.7	26.5	68.4	26.1	67.5	–1.3
19	01634000	NF Shenandoah River	770	12.0	38.7	26.7	68.9	26.3	67.9	–1.4
20	01634500	Cedar Creek	102	15.4	40.3	24.9	61.7	26.2	65.0	5.2
22	01635500	Passage Creek	87	12.5	41.4	28.9	69.8	27.1	65.5	–6.3
26	01643700	Goose Creek	122	15.6	42.3	26.7	63.1	27.0	63.9	1.2
28	01646000	Difficult Run	58	16.7	43.7	27.0	61.8	27.8	63.7	2.9
31	01656000	Cedar Run	93	14.6	43.3	28.7	66.3	28.0	64.6	–2.7
33	01660400	Aquia Creek	35	13.9	43.3	29.4	67.8	28.5	65.7	–3.2
35	01664000	Rappahannock River	619	16.9	44.7	27.8	62.2	28.8	64.5	3.5
36	01665500	Rapidan River	115	19.7	50.2	30.5	60.8	29.8	59.4	–2.3
37	01666500	Robinson River	179	19.5	49.0	29.5	60.3	30.5	62.3	3.3
38	01667500	Rapidan River	468	18.0	46.7	28.7	61.5	29.6	63.5	3.2
43	01672500	South Anna River	395	14.2	44.2	30.0	68.0	30.1	68.2	0.3
44	01673000	Pamunkey River	1,078	14.1	44.1	30.0	68.1	30.1	68.2	0.1
47	01674500	Mattaponi River	602	14.0	43.8	29.8	68.0	29.5	67.5	–0.7
50	02013000	Dunlap Creek	162	16.0	41.4	25.4	61.3	26.0	62.9	2.5
52	02014000	Potts Creek	153	17.1	43.1	26.0	60.3	26.1	60.5	0.3
54	02016000	Cowpasture River	461	17.4	41.8	24.4	58.4	26.3	62.8	7.2
56	02017500	Johns Creek	105	18.7	43.1	24.4	56.7	26.6	61.6	8.4
57	02018000	Craig Creek	329	17.7	43.0	25.3	58.9	26.9	62.6	6.0

Table 9. Watershed calculated and estimated total evapotranspiration in this study.—Continued

[See figure 9 for map locations; USGS, U.S. Geological Survey; SF, South Fork; NF, North Fork; MF, Middle Fork]

Map number	USGS station number	Watershed name	Area, in square miles	Mean annual amount, in inches, 1971–2000		Evapotranspiration				
				Streamflow	Precipitation	Total (precipitation minus flow), in inches	As percent of precipitation	From regression, in inches	From regression, in percent	Error in percent of precipitation
58	02020500	Calfpasture River	141	18.3	44.8	26.5	59.2	26.6	59.5	0.5
59	02021500	Maury River	329	18.0	45.4	27.4	60.3	27.5	60.6	0.5
60	02024000	Maury River	647	15.6	45.2	29.6	65.4	28.0	62.0	–5.4
66	02040000	Appomattox River	725	15.2	45.1	29.9	66.3	31.0	68.6	3.4
67	02041000	Deep Creek	158	14.2	45.3	31.1	68.7	31.3	69.1	0.6
68	02042500	Chickahominy River	251	14.9	44.4	29.5	66.3	30.2	67.9	2.3
69	02044500	Nottoway River	317	14.3	45.6	31.3	68.6	31.3	68.6	–0.0
72	02047500	Blackwater River	290	15.9	46.2	30.3	65.5	31.6	68.3	4.3
73	02049500	Blackwater River	613	14.9	46.2	31.3	67.8	31.6	68.5	1.0
74	02051500	Meherrin River	552	13.6	45.5	31.9	70.1	31.4	69.0	–1.5
75	02052000	Meherrin River	744	14.2	45.6	31.4	68.9	31.5	69.2	0.35
76	02053800	SF Roanoke River	109	15.2	42.7	27.5	64.3	26.3	61.7	–4.16
77	02054500	Roanoke River	254	13.7	41.4	27.7	66.9	26.4	63.8	–4.62
78	02055000	Roanoke River	384	13.6	41.6	28.0	67.2	26.9	64.6	–4.04
79	02056000	Roanoke River	509	15.0	42.1	27.1	64.4	27.4	65.1	1.14
82	02059500	Goose Creek	188	14.6	45.3	30.7	67.7	30.0	66.1	–2.34
84	02061500	Big Otter River	315	15.7	45.8	30.1	65.7	30.0	65.5	–0.31
87	02065500	Cub Creek	98	15.8	45.3	29.5	65.1	30.5	67.2	3.20
93	02077000	Banister River	547	13.5	45.6	32.1	70.4	31.0	68.0	–3.46
94	02079640	Allen Creek	54	12.8	45.2	32.4	71.7	31.6	69.8	–2.70
96	03167000	Reed Creek	258	15.0	40.2	25.2	62.6	25.9	64.4	2.75
98	03170000	Little River	309	16.4	45.2	28.8	63.7	27.4	60.7	–4.78
100	03173000	Walker Creek	299	14.6	40.8	26.2	64.2	25.5	62.6	–2.63
102	03207800	Levisa Fork	297	17.1	46.6	29.5	63.3	29.1	62.3	–1.59
103	03208500	Russell Fork	286	16.5	47.4	30.9	65.3	29.4	62.0	–5.13
104	03473000	SF Holston River	303	21.6	49.0	27.4	55.8	28.4	58.0	3.81
105	03475000	MF Holston River	206	16.8	45.3	28.5	63.0	28.4	62.7	–0.51
106	03488000	NF Holston River	221	18.1	46.3	28.2	60.8	27.9	60.2	–1.07
107	03524000	Clinch River	533	17.7	45.8	28.1	61.4	27.6	60.3	–1.81
108	03531500	Powell River	319	22.9	54.4	31.5	58.0	31.7	58.2	0.46

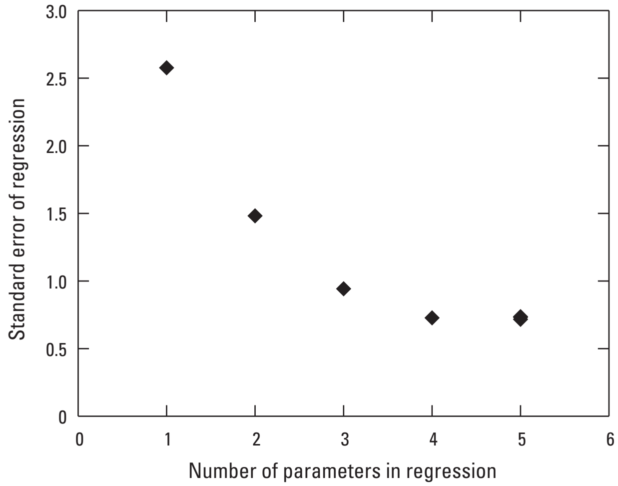


Figure 25. Standard error of regression as a function of the number of parameters in the evapotranspiration regression equation.

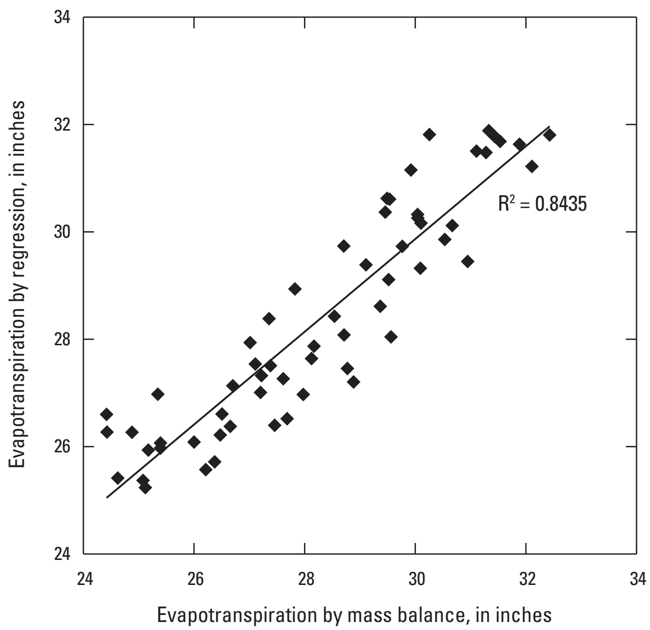


Figure 26. Comparison of evapotranspiration calculated by mass balance versus that estimated through the regression equation.

Chemical Hydrograph Separation

Hydrographs and records of specific conductance during the same period were obtained and plotted for 100 watersheds across the region (Appendix 1-1). In addition to the 75 watersheds instrumented with real time specific-conductance probes during this study, 25 watersheds that had historical specific conductance records were also examined. Three of these watersheds were from Maryland, one was from Delaware, and one was instrumented in Opequon Creek at Martinsburg, West Virginia. The watersheds in Maryland and Delaware were added as additional information for the Coastal Plain Province, as there were only two watershed records from the Virginia Coastal Plain that proved to be useful for chemical hydrograph separation.

Base Flow

Base flow in 52 watersheds (fig. 27) was estimated using the chemical hydrograph separation method described in the methods section of this report. Specific conductance was measured at the watersheds for a period of approximately 18 months between March 2007 and August 2008. One challenge in estimating a long-term mean base flow for a watershed is the assumption that this 18-month period represents average long-term flow conditions for the watershed. Upon examination of stream-flow records, it was determined that a substantial number of the watersheds had flow conditions during the 18-month period of record that did not adequately represent long-term mean conditions. These watersheds were in a period of drought (mostly in southern Virginia) during that time, yielding higher than usual base-flow fractions and lower than usual surface-runoff fractions. To overcome this problem, base-flow estimates were adjusted to be consistent with long-term mean flow conditions. To accomplish this the monthly flow for each watershed was plotted versus its base-flow calculation (fig. 28; app. 2). Log-linear curves of the form:

$$BF = a \ln(Q) + b\,Q + c \qquad (16)$$

were then fit to these data yielding the parameters *a, b,* and *c* (table 10), where *BF* equals the base-flow fraction and *Q* equals the monthly mean streamflow in cubic feet per second.

The long-term past monthly flows (*Q*) for each watershed were compiled and ranked by flow magnitude and input into equation 16 to obtain a flow-weighted, long-term, adjusted mean base flow. A long-term-adjustment ratio was then calculated by dividing the long-term adjusted mean base flow by the observed mean base flow. These long-term adjustment ratios were multiplied by estimates of the base flow that assumed the origin of the specific conductance was either from surface salts or subsurface mineral dissolution (as described earlier in the methods section of this report) to yield the values listed in table 11, columns 1 and 2. An average base flow (table 11, column 3) was then calculated from the two end-members based on a weighting term that is a function of the SC/Cl ratio (also described earlier in the methods section).

Results of the base-flow analyses demonstrated a substantial difference in base-flow indices across Virginia (fig. 29). The base-flow index is the percentage of the mean annual streamflow that is base flow over the entire period of record, which in this study includes the long-term adjustments. The Valley and Ridge carbonate rocks consistently yield base-flow indices of over 90, whereas the Valley and Ridge siliciclastic rocks consistently yield values between 60 and 70 percent. The Piedmont watersheds also yield values typically between 60 and 70 percent, and the Blue Ridge watersheds yield values typically between 80 and 85 percent. This primary finding led to the development of the regression equation for surface runoff as a percent of precipitation that was predominantly a function of the physiographic province and rock type (described earlier in the methods section of this report).

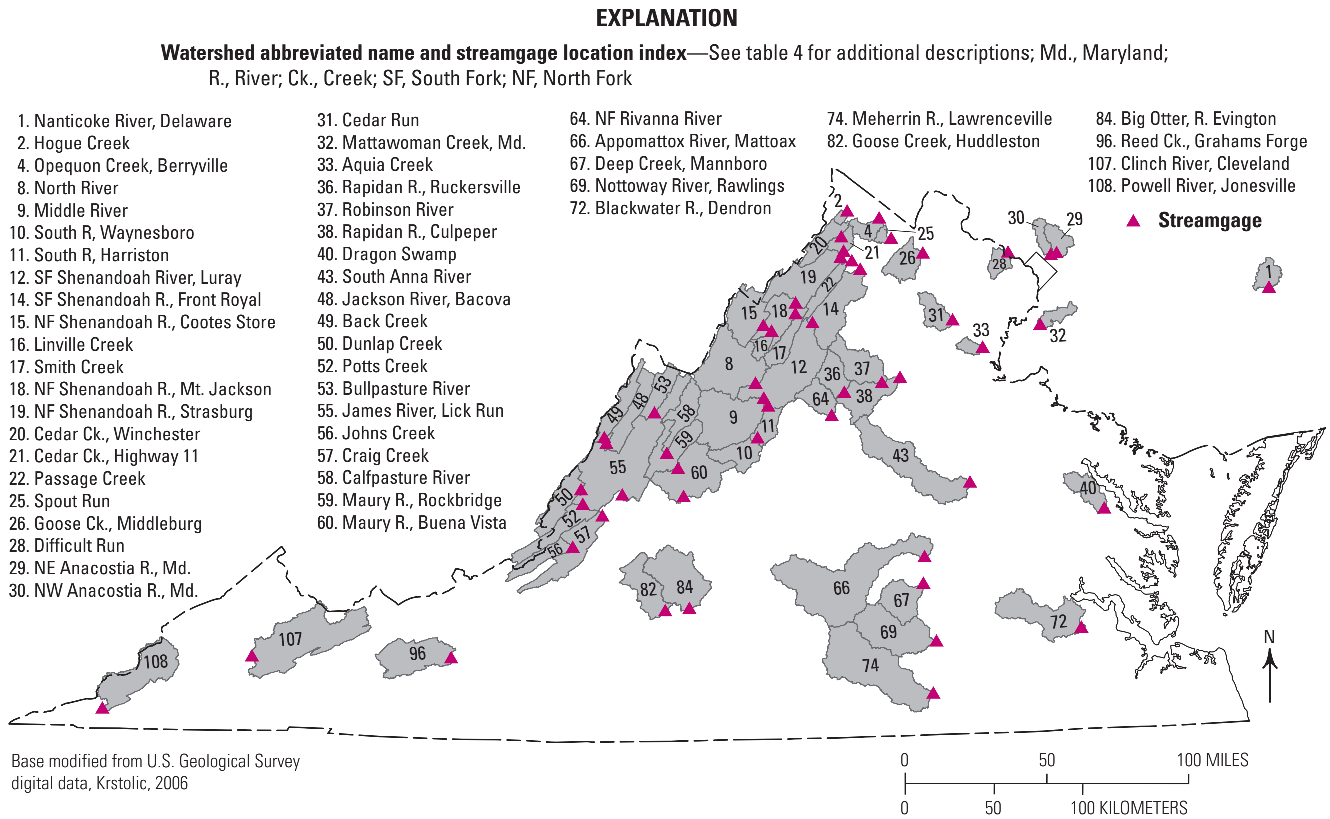


Figure 27. Names and locations of real-time streamgages and watersheds in Virginia, Maryland, and Delaware selected to estimate base flow by chemical hydrograph separation. Numbers on watersheds are indexed to the watershed names in table 2.

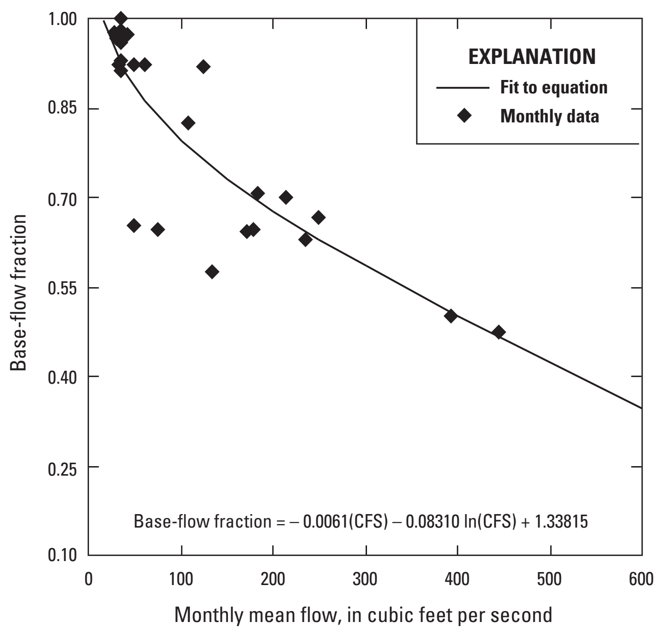


Figure 28. Monthly mean streamflow versus fraction base flow at the real-time streamgage 01626000 South River near Waynesboro, Virginia, between 2007 and 2008.

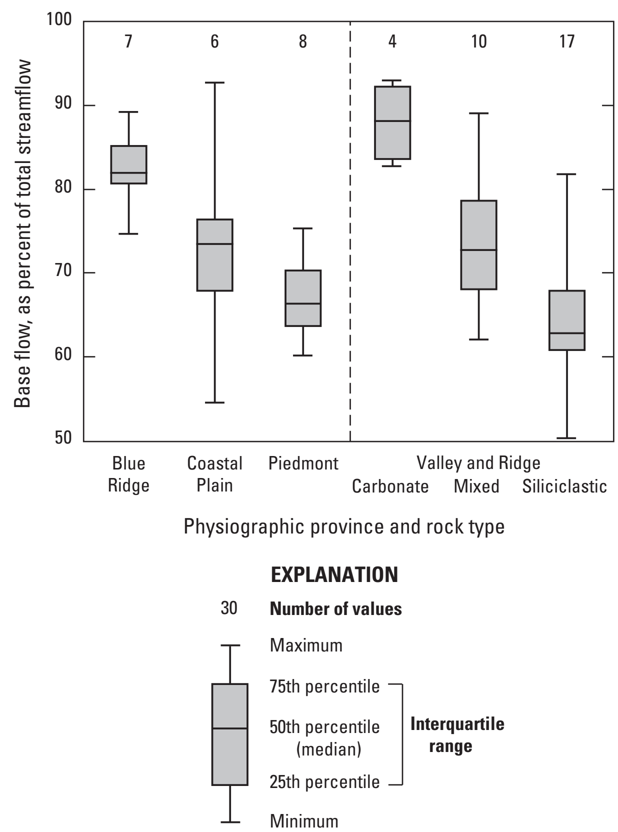


Figure 29. Estimates of base flow in streams of Virginia by physiographic province and bedrock type between 2006 and 2008.

Table 10. Watershed parameters (*a*, *b*, and *c*) for equation 16 relating base flow to monthly streamflow.

[See figure 9 for map watershed locations; Del., Delaware; Va., Virginia; W. Va., West Virginia; Md., Maryland; SF, South Fork; NF, North Fork; MF, Middle Fork; NE, northeast; NW, northwest; STP, sewage treatment plant]

Map number	USGS station number	Watershed name and location	Log constant (*a*)	Linear constant (*b*)	Intercept (*c*)
1	01487000	Nanticoke River near Bridgeville, Del.	–0.01225	–0.00021	1.01435
2	01613900	Hogue Creek near Hayfield, Va.	–0.04470	–0.00280	0.92050
3	01614830	Opequon Creek near Stephens City, Va.	–0.02485	–0.00455	1.00640
4	01615000	Opequon Creek near Berryville, Va.	–0.05295	–0.00115	1.04960
6	01616100	Dry Marsh Run near Berryville, Va.	–0.07190	–0.00425	1.17595
7	01616500	Opequon Creek at Martinsburg, W. Va.	–0.02695	–0.00009	1.03880
8	01622000	North River near Burketown, Va.	–0.07425	–0.00023	1.22680
9	01625000	Middle River near Grottoes, Va.	–0.03980	–0.00015	1.14500
10	01626000	South River near Waynesboro, Va.	–0.08310	–0.00061	1.23810
11	01627500	South River at Harriston, Va.	–0.09260	–0.00039	1.33185
12	01629500	SF Shenandoah River near Luray, Va.	–0.05855	–0.00004	1.28195
13	01630700	Gooney Run near Glen Echo, Va.	–0.02675	–0.00130	0.97125
14	01631000	SF Shenandoah River at Front Royal, Va.	–0.07155	–0.00006	1.42190
15	01632000	NF Shenandoah River at Cootes Store, Va.	–0.03575	–0.00023	1.00275
16	01632082	Linville Creek at Broadway, Va.	–0.00800	–0.00023	0.98235
17	01632900	Smith Creek near New Market, Va.	–0.04025	–0.00065	1.10595
18	01633000	NF Shenandoah River at Mount Jackson, Va.	–0.06005	–0.00017	1.16890
19	01634000	NF Shenandoah River near Strasburg, Va.	–0.06685	–0.00012	1.29560
20	01634500	Cedar Creek near Winchester, Va.	–0.06035	–0.00081	1.10665
21	01635090	Cedar Creek above Hwy 11 near Middletown, Va.	–0.07685	–0.00062	1.18480
22	01635500	Passage Creek near Buckton, Va.	–0.04710	–0.00087	1.02715
23	01636242	Crooked Run below Hwy 30 at Riverton, Va.	–0.06000	–0.00225	0.99525
24	0163626650	Manassas Run at Rt 645 near Front Royal, Va.	–0.01245	–0.00575	0.93015
25	01636316	Spout Run at Rt 621 near Millwood, Va.	–0.02130	–0.00165	1.03390
26	01643700	Goose Creek near Middleburg, Va.	–0.01430	–0.00025	0.96595
27	01644280	Broad Run near Leesburg, Va.	–0.06785	–0.00048	1.03520
28	01646000	Difficult Run near Great Falls, Va.	–0.05745	–0.00125	0.98715
29	01649500	NE Branch Anacostia River at Riverdale, Md.	–0.07610	–0.00093	1.21515
30	01651000	NW Branch Anacostia River near Hyattsville, Md.	–0.10325	–0.00168	1.11691
31	01656000	Cedar Run near Catlett, Va.	–0.02730	–0.00047	0.94985
32	01658000	Mattawoman Creek near Pomonkey, Md.	–0.03805	–0.00072	0.95150
33	01660400	Aquia Creek near Garrisonville, Va.	–0.02845	–0.00135	0.89500
36	01665500	Rapidan River near Ruckersville, Va.	–0.02695	–0.00031	1.03315
37	01666500	Robinson River near Locust Dale, Va.	–0.02450	–0.00026	1.02970
38	01667500	Rapidan River near Culpeper, Va.	–0.00825	–0.00010	0.99510
40	01669520	Dragon Swamp at Mascot, Va.	–0.02400	–0.00039	0.96505
42	01671100	Little River near Doswell, Va.	–0.02745	–0.00068	0.83600
43	01672500	South Anna River near Ashland, Va.	–0.04800	–0.00019	1.03555
44	01673000	Pamunkey River near Hanover, Va.	–0.04190	–0.00003	0.98040
48	02011400	Jackson River near Bacova, Va.	–0.03830	–0.00029	1.11605

Table 10. Watershed parameters (*a*, *b*, and *c*) for equation 16 relating base flow to monthly streamflow.—Continued

[See figure 9 for map watershed locations; Del., Delaware; Va., Virginia; W. Va., West Virginia; Md., Maryland; SF, South Fork; NF, North Fork; MF, Middle Fork; NE, northeast; NW, northwest; STP, sewage treatment plant]

Map number	USGS station number	Watershed name and location	Log constant (*a*)	Linear constant (*b*)	Intercept (*c*)
49	02011500	Back Creek near Mountain Grove, Va.	–0.01660	–0.00012	1.01745
50	02013000	Dunlap Creek near Covington, Va.	–0.07430	–0.00064	1.14615
52	02014000	Potts Creek near Covington, Va.	–0.06585	–0.00050	1.14750
53	02015700	Bullpasture River at Williamsville, Va.	–0.06255	–0.00041	1.22575
55	02016500	James River at Lick Run, Va.	–0.11455	–0.00007	1.64460
56	02017500	Johns Creek at New Castle, Va.	–0.06980	–0.00078	1.02580
57	02018000	Craig Creek at Parr, Va.	–0.07125	–0.00027	1.18600
58	02020500	Calfpasture River above Mill Creek at Goshen, Va.	–0.04095	–0.00028	0.95240
59	02021500	Maury River at Rockbridge Baths, Va.	–0.04870	–0.00018	1.08760
60	02024000	Maury River near Buena Vista, Va.	–0.05595	–0.00011	1.20535
61	02025500	James River at Holcomb Rock, Va.	–0.06890	–0.00002	1.39270
62	02026000	James River at Bent Creek, Va.	–0.05825	–0.00002	1.28910
63	02030000	Hardware River BL Briery Run near Scottsville, Va.	–0.02695	–0.00040	0.98560
64	02032640	NF Rivanna River near Earlysville, Va.	–0.01110	–0.00017	0.95700
65	02039500	Appomattox River at Farmville, Va.	–0.02665	–0.00018	1.02455
66	02040000	Appomattox River at Mattoax, Va.	–0.03180	–0.00009	1.01070
67	02041000	Deep Creek near Mannboro, Va.	–0.03515	–0.00070	1.02330
69	02044500	Nottoway River near Rawlings, Va.	–0.03085	–0.00018	1.03775
72	02047500	Blackwater River near Dendron, Va.	–0.02480	–0.00027	0.98370
74	02051500	Meherrin River near Lawrenceville, Va.	–0.04060	–0.00015	1.03495
75	02052000	Meherrin River at Emporia, Va.	–0.05940	–0.00006	1.20060
76	02053800	SF Roanoke River near Shawsville, Va.	–0.02015	–0.00035	0.95805
79	02056000	Roanoke River at Niagara, Va.	–0.06630	–0.00020	1.25210
82	02059500	Goose Creek near Huddleston, Va.	–0.03420	–0.00040	1.03645
84	02061500	Big Otter River near Evington, Va.	–0.00545	–0.00004	0.89555
92	02075045	Dan River at STP near Danville, Va.	–0.07645	–0.00004	1.35720
93	02077000	Banister River at Halifax, Va.	–0.05690	–0.00021	1.20220
94	02079640	Allen Creek near Boydton, Va.	–0.04660	–0.00330	0.96520
96	03167000	Reed Creek at Grahams Forge, Va.	–0.08710	–0.00052	1.37115
100	03173000	Walker Creek at Bane, Va.	–0.03675	–0.00016	0.97895
101	03175500	Wolf Creek near Narrows, Va.	–0.06675	–0.00038	1.22185
103	03208500	Russell Fork at Haysi, Va.	–0.05830	–0.00033	1.12420
105	03475000	MF Holston River near Meadowview, Va.	–0.07175	–0.00060	1.27845
107	03524000	Clinch River at Cleveland, Va.	–0.02315	–0.00006	1.08035
108	03531500	Powell River near Jonesville, Va.	–0.06385	–0.00019	1.23320

Table 11. Hydrologic budget component estimates for watersheds in this study.

[See figure 9 for watershed locations; base flows calculated using chemical hydrograph separation have been adjusted to long-term flow conditions; PART, U.S. Geological Survey graphical-separation technique program; SF, South Fork; NF, North Fork]

Map number	USGS station number	Watershed name	Base flow, in percent				Runoff		Infiltration in inches	Riparian evapotrans-piration, in inches	Mean annual recharge, in inches
			With surface salts	With sub-surface salts	Estimated	Using PART	As percent of total flow	Calculated annual, in inches			
1	01487000	Nanticoke River	91.1	93.0	92.6	85.0	7.4	1.2	43.8	0.7	16.0
2	01613900	Hogue Creek	62.3	68.4	67.9	55.7	32.1	4.3	35.6	1.5	10.6
4	01615000	Opequon Creek	68.0	72.4	71.3	48.9	28.7	3.2	35.8	0.9	8.8
8	01622000	North River	56.3	63.8	62.2	66.7	37.8	5.3	34.7	1.7	10.5
9	01625000	Middle River	79.3	83.4	83.0	69.7	17.0	2.0	38.4	0.4	10.1
10	01626000	South River	57.4	62.0	61.7	73.8	38.3	6.2	42.0	1.3	11.2
11	01627500	South River	56.0	62.7	61.9	72.4	38.1	6.4	41.2	1.1	11.4
12	01629500	SF Shenandoah River	73.9	79.5	78.7	66.7	21.3	3.0	39.0	1.2	12.3
14	01631000	SF Shenandoah River	73.9	78.9	78.3	66.0	21.7	2.9	39.2	0.8	11.2
15	01632000	NF Shenandoah River	70.8	70.1	70.2	46.7	29.8	3.8	35.6	2.1	11.1
16	01632082	Linville Creek	90.9	93.1	92.9	71.8	7.1	0.8	36.0	0.6	11.4
17	01632900	Smith Creek	79.7	83.3	82.9	72.7	17.1	1.9	37.7	0.8	10.0
18	01633000	NF Shenandoah River	62.4	67.8	67.2	59.8	32.8	3.6	35.1	1.0	8.3
19	01634000	NF Shenandoah River	68.7	74.7	74.0	64.0	26.0	2.8	35.9	0.7	8.6
20	01634500	Cedar Creek	66.3	65.8	65.8	59.7	34.2	4.5	35.8	1.9	10.6
21	01635090	Cedar Creek	53.6	61.2	60.6	64.5	39.4	5.2	34.6	0.9	8.8
22	01635500	Passage Creek	66.7	68.0	67.9	58.0	32.1	3.7	37.7	1.7	9.5
25	01636316	Spout Run	89.3	93.0	92.7	88.1	7.3	1.1	38.0	0.7	15.3
26	01643700	Goose Creek	77.8	82.5	80.9	67.1	19.1	2.9	39.4	3.8	16.0
28	01646000	Difficult Run	56.4	63.4	60.3	58.5	39.7	5.8	37.9	0.5	9.4
29	01649500	NE Anacostia River	65.8	73.8	70.6	46.9	29.4	4.8	40.2	0.3	11.9
30	01651000	NW Anacostia River	50.0	57.6	54.6	43.7	45.4	6.2	38.8	0.0	7.5
31	01656000	Cedar Run	66.4	73.1	71.2	39.7	28.8	3.8	39.5	0.3	9.7
32	01658000	Mattawoman Creek	76.1	77.5	76.5	39.2	23.5	3.3	41.7	0.0	10.9
33	01660400	Aquia Creek	68.5	70.2	70.0	51.8	30.0	4.1	39.2	2.5	12.1
36	01665500	Rapidan River	80.0	82.2	81.7	72.3	18.3	3.4	46.8	1.8	16.8
37	01666500	Robinson River	80.1	80.7	80.5	64.6	19.5	3.3	42.8	1.4	15.3
38	01667500	Rapidan River	89.0	89.1	89.1	74.0	10.9	1.7	45.0	1.2	15.3
40	01669520	Dragon Swamp	74.2	76.5	75.9	39.2	24.1	3.8	41.3	3.1	15.1
43	01672500	South Anna River	61.5	61.5	61.5	51.8	38.5	4.9	39.3	0.0	7.8

Table 11. Hydrologic budget component estimates for watersheds in this study.—Continued

[See figure 9 for watershed locations; base flows calculated using chemical hydrograph separation have been adjusted to long-term flow conditions; PART, U.S. Geological Survey graphical-separation technique program; SF, South Fork; NF, North Fork]

Map number	USGS station number	Watershed name	Base flow, in percent				Runoff		Infiltration in inches	Riparian evapotrans-piration, in inches	Mean annual recharge, in inches
			With surface salts	With sub-surface salts	Estimated	Using PART	As percent of total flow	Calculated annual, in inches			
48	02011400	Jackson River	77.2	82.0	81.8	66.9	18.2	2.7	40.0	1.1	13.1
49	02011500	Back Creek	84.3	89.4	89.0	54.5	11.0	2.0	41.6	1.8	18.1
50	02013000	Dunlap Creek	46.4	53.1	52.6	54.5	47.4	6.7	34.7	1.9	9.4
52	02014000	Potts Creek	57.0	62.9	62.6	65.6	37.4	6.0	37.1	2.2	12.1
53	02015700	Bullpasture River	70.5	79.3	78.9	66.1	21.1	4.0	37.7	1.0	16.0
55	02016500	James River	60.0	62.7	62.3	57.6	37.7	6.3	35.8	2.4	12.9
56	02017500	Johns Creek	54.0	50.2	50.4	66.6	49.6	8.3	34.8	5.3	13.8
57	02018000	Craig Creek	54.1	56.9	56.8	62.2	43.2	7.0	36.0	2.4	11.5
58	02020500	Calfpasture River	59.1	60.9	60.8	50.6	39.2	6.4	38.4	5.1	15.0
59	02021500	Maury River	63.1	67.1	66.8	54.2	33.2	5.3	40.1	2.6	13.3
60	02024000	Maury River	64.7	70.9	70.5	62.3	29.5	4.2	41.0	0.9	11.0
64	02032640	NF Rivanna River	86.3	86.8	86.7	58.1	13.3	2.2	47.1	1.4	16.0
66	02040000	Appomattox River	66.2	68.2	67.9	52.1	32.1	4.3	40.8	1.3	10.3
67	02041000	Deep Creek	61.8	65.7	65.0	51.8	35.0	4.5	40.8	0.9	9.2
69	02044500	Nottoway River	74.3	75.4	75.2	56.5	24.8	3.3	42.3	1.0	10.9
72	02047500	Blackwater River	65.1	67.6	67.0	72.4	33.0	4.9	41.3	1.6	11.5
74	02051500	Meherrin River	64.7	64.3	64.4	48.0	35.6	4.4	41.1	1.7	9.7
82	02059500	Goose Creek	71.1	75.1	74.8	65.0	25.2	3.3	42.0	2.5	12.2
84	02061500	Big Otter River	81.6	84.3	83.7	66.3	16.3	2.4	43.4	2.2	14.3
96	03167000	Reed Creek	59.9	66.8	65.8	70.2	34.2	4.8	35.4	0.4	9.7
107	03524000	Clinch River	82.0	87.6	86.9	59.2	13.1	2.4	43.4	1.1	16.8
108	03531500	Powell River	52.1	62.5	62.0	54.8	38.0	8.7	45.7	1.3	15.5

The range of base-flow indices in the individual watersheds (fig. 30) ranged from under 60 percent in some of the siliciclastic rocks of western Virginia to more than 90 percent in some of the carbonate watersheds of the Shenandoah Valley. The sandy coastal plain watershed in Delaware also yielded a value over 90 percent.

Surface Runoff

The long-term mean surface runoff component of the hydrologic budget of each watershed was calculated by subtracting the long-term base-flow component (base flow) from the total streamflow. The surface runoff values for the different watersheds across Virginia range from 2 in/yr or less in the Valley and Ridge Province carbonate rocks and the Blue Ridge Province to 8 or more in/yr in some of the siliciclastic rocks of the Valley and Ridge Province (fig. 31). The regression equation described in the methods section was used to estimate the surface runoff as a percentage of the precipitation depending on the physiographic province and rock type or region within that province (table 12). In order for the regression to reflect only natural surfaces, an adjustment was made to calculate a "natural runoff" whereby the percent impervious surface was subtracted from the percent runoff (table 13). When the regression was later applied to the localities, the effect of impervious surfaces was reintroduced as described earlier in the methods section. Results from the surface runoff calculations were plotted against those values obtained by the regression (fig. 32), and the plot illustrates that some of the Valley and Ridge Province watersheds had the highest errors in the regression predictions. The estimated percent of precipitation attributed to end up as surface runoff varied between approximately 4 and 16 percent.

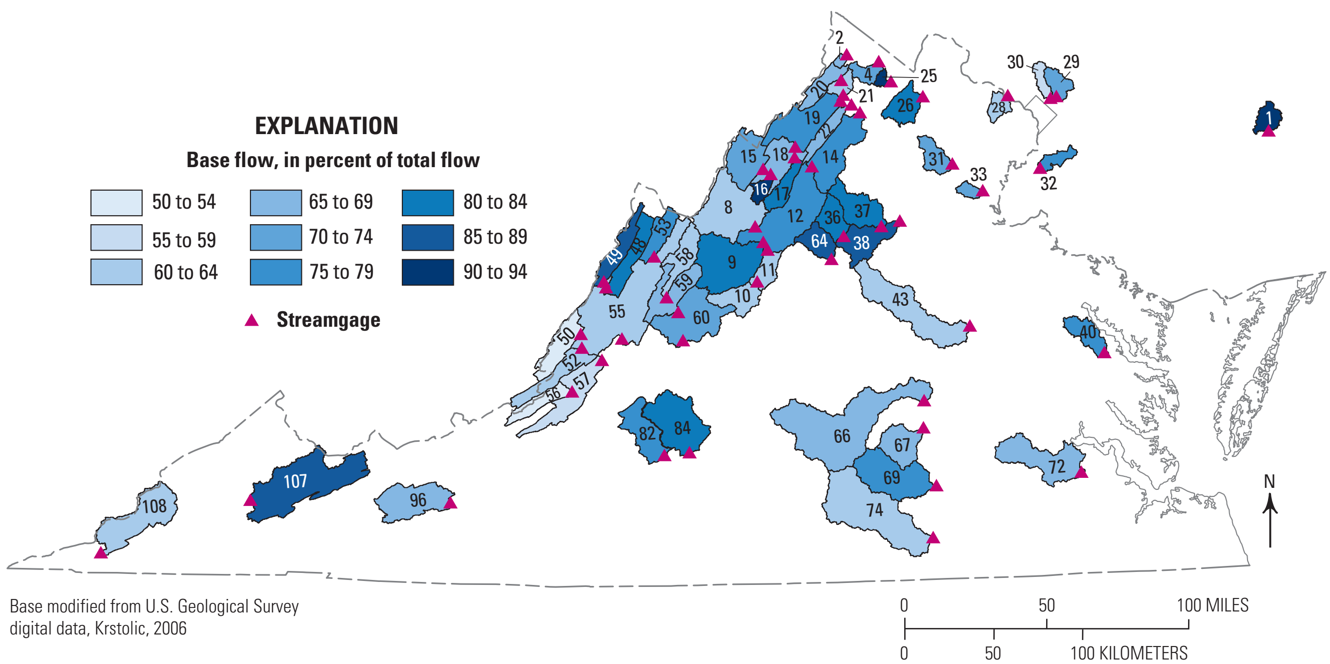


Figure 30. Estimates of mean base flow as percent of total mean streamflow for selected watersheds in Virginia, Maryland, and Delaware. See figure 27 for watershed number list.

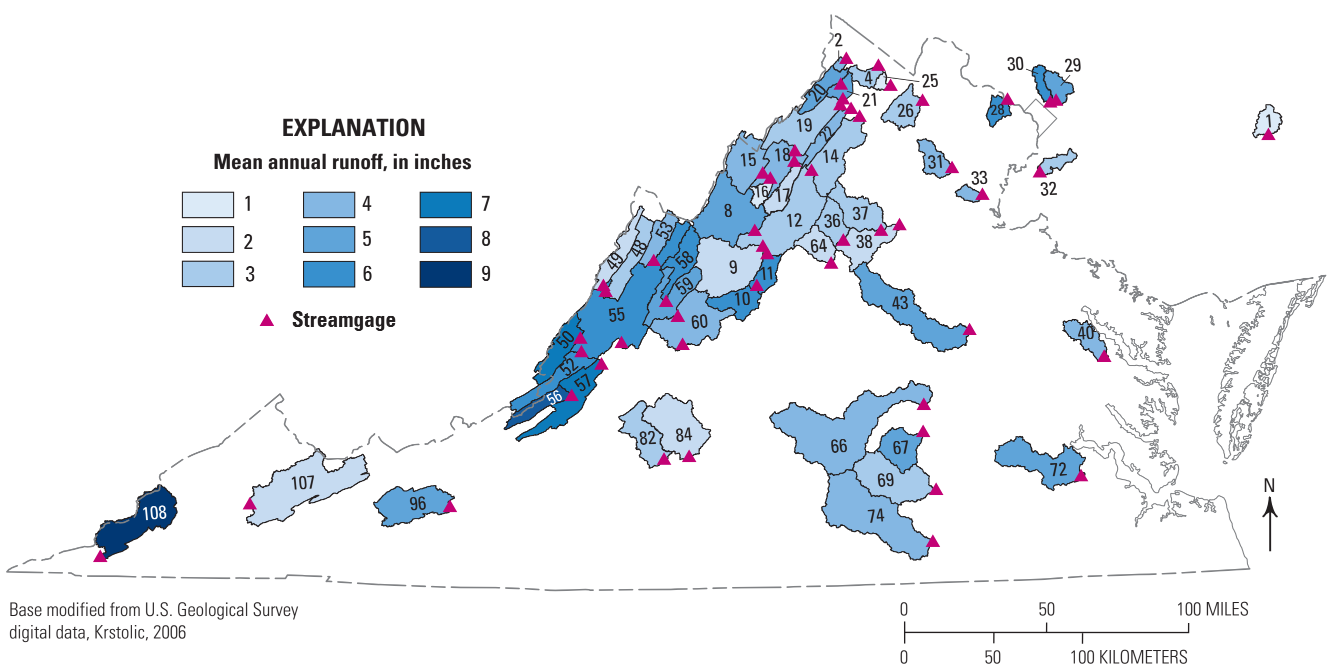


Figure 31. Estimates of mean annual surface runoff for selected watersheds in Virginia, Maryland, and Delaware.

Table 12. Runoff regression equations and their parameter values for this study.

[—, not applicable]

Physiographic Province	Regression equation with linear constants and rock-type variables[a]	Regression parameter values representing percent runoff from each corresponding rock type							
		a	b	c	d	e	f	g	h
Blue Ridge	R = aMV + bMS + cPL + dMB	1.0[b]	2.8	7.1	13.1	—	—	—	—
Coastal Plain	R = aFG + bMG + c CG	11.0	7.5	4.1	—	—	—	—	—
Piedmont	R = aNW + bSE + cMB + dCG	10.5	8.9	13.1	4.1	—	—	—	—
Valley and Ridge	R = aCD + bCOL + cOD + dOS + eSSL + fDS + gMS + hAP	19.6	1.0[b]	4.6	8.1	2.8	24.4	11.2	17.8

[a] MV, fraction metavolcanics; MS, fraction metasediments; PL, fraction plutonic; MB, fraction Mesozoic Basin; FG, fraction fine-grained sediment; MG, fraction mixed-grained sediment; CG, coarse-grained sediment; NW, fraction northwestern zone; SE, fraction southeastern zone, CD, fraction Cambrian dolostones; COL, fraction Cambrian-Ordovician limestones; OD, fraction Ordovician Dolostones; OS, fraction Ordovician siliciclastics; SSL, fraction Silurian siliciclastics and limestones; DS, fraction Devonian siliciclastics; MS, fraction Mississippian siliciclastics; AP, fraction Appalachian Plateau siliciclastics; R, percent of precipitation that runs off; see table 10 for the fractions of these rock types in the watersheds.

[b] Values of 1.0 were assigned when the regression attempted to fit a value below zero.

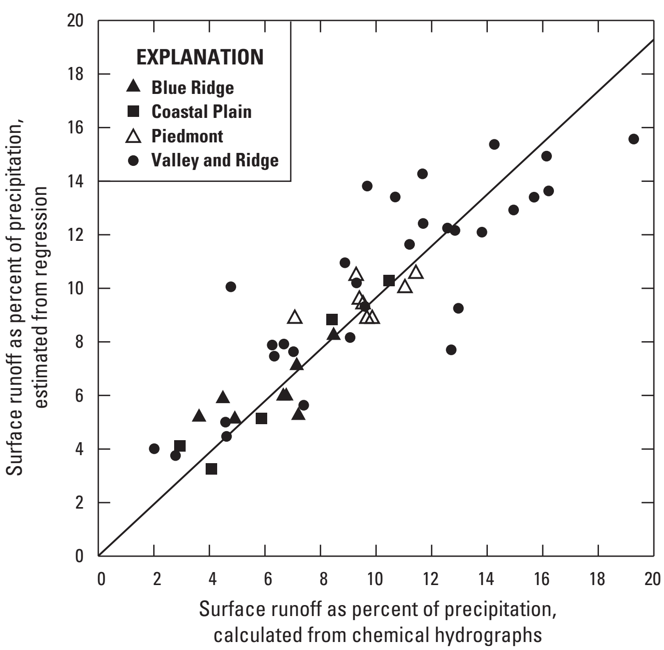


Figure 32. Comparison of calculated surface runoff versus that estimated by the regression.

Graphical Hydrograph Separation

Historically, graphical hydrograph separation has been a standard technique for estimating a base-flow component of a stream hydrograph. As discussed in the methods section, the graphical hydrograph separation was not the method of choice in this study because the chemical hydrograph technique, which uses specific conductance, yields more information in the hydrographs and therefore potentially more meaningful separation estimates. A graphical technique was, however, applied to all of the watersheds in this study to compare the two methods. The USGS separation code, PART, was applied to each watershed for the same time period for which the chemical method was applied. Results of the comparison (fig. 33) reveal that the chemical method consistently (but not always) produces a value for the base flow that is greater than that produced by the graphical method. The graphical method yielded an average base flow of 61 percent of the mean annual streamflow, whereas the chemical method yielded an average of 72 percent. In addition, in 80 percent of the watersheds the chemical method yielded a higher base flow than the graphical method. When the chemical base flow was higher, it had an average of 77 percent of mean annual streamflow versus 62 percent from the graphical method, and when the chemical base flow was lower, it had an average of 61 percent versus 66 percent from the graphical method. All but one of the watersheds where the graphical method yielded a value higher than the chemical method were in the Valley and Ridge Province. In the Coastal Plain, Blue Ridge, Piedmont, and Valley and Ridge Provinces, the chemical method yielded base flows that averaged 20, 17, 15, and 8 percentage points above the graphical method, respectively.

Riparian Evapotranspiration

Riparian Evapotranspiration, *ETrp*, was calculated for each of the watersheds in which the chemical hydrograph method was employed, using the seasonal difference in specific conductance (eq. 14). The values calculated for ET_{rp} ranged from less than 0.5 in/yr to more than 4 in/yr (fig. 34). Estimates of ET_{rp} from an earlier investigation based on a combination of graphical hydrograph separation methods (Rutledge and Mesko, 1996) also yielded a similar distribution of values of ET_{rp} for watersheds in Virginia (fig. 35).

Table 13. Land-surface characteristics considered in the runoff regression and estimated mean runoff values for watersheds in this study.

[CP, Coastal Plain; VR, Valley and Ridge; BR, Blue Ridge; PM, Piedmont; nd, no data; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest]

Map number	USGS station number	Watershed name	Physiographic Province	Topographic grade, in percent	Soil permeability, in inches per hour	Percent impervious surface	Percent agriculture	Percent forest	Estimated surface runoff as percent of total streamflow (ESR)	Natural surface runoff (ESR less percent impervious surface)	Natural surface runoff as percent of precipitation	Regressed natural runoff as percent of precipitation	Regression error
1	01487000	Nanticoke River	CP	1.5	nd	0.1	nd	nd	7.4	7.4	2.9	4.1	–1.2
2	01613900	Hogue Creek	VR	16.1	3.6	0.0	22.9	76.4	32.1	32.1	10.7	13.4	–2.7
3	01615000	Opequon Creek	VR	6.9	2.3	2.5	59.3	29.7	28.7	26.2	7.4	5.6	1.8
8	01622000	North River	VR	19.5	5.2	1.5	34.5	60.1	37.8	36.3	12.7	7.7	5.0
9	01625000	Middle River	VR	12.5	3.3	1.2	56.8	37.7	17.0	15.8	4.6	5.0	–0.4
10	01626000	South River	VR	15.6	5.2	0.7	32.5	63.2	38.3	37.6	12.6	12.2	0.3
11	01627500	South River	VR	15.5	4.9	1.5	33.1	60.0	38.1	36.6	12.8	12.2	0.7
12	01629500	SF Shenandoah River	VR	16.4	4.2	1.4	41.4	53.3	21.3	19.9	6.7	7.9	–1.2
14	01631000	SF Shenandoah River	VR	16.9	4.1	1.6	39.6	55.3	21.7	20.1	6.3	7.5	–1.1
15	01632000	NF Shenandoah River	VR	27.8	4.9	0.0	9.5	90.1	29.8	29.8	9.7	13.8	–4.1
16	01632082	Linville Creek	VR	10.1	1.7	0.7	nd	nd	7.1	6.4	2.0	4.0	–2.0
17	01632900	Smith Creek	VR	13.1	2.8	0.7	50.7	45.9	17.1	16.4	4.6	4.5	0.1
18	01633000	NF Shenandoah River	VR	18.1	3.3	0.6	38.9	59.0	32.8	32.2	9.1	8.2	0.9
19	01634000	NF Shenandoah River	VR	16.9	3.6	0.7	39.1	58.2	26.0	25.3	7.0	7.6	–0.6
20	01634500	Cedar Creek	VR	19.0	3.6	0.0	12.2	87.6	34.2	34.2	11.2	11.6	–0.4
21	01635090	Cedar Creek	VR	15.5	3.2	0.1	28.5	70.4	39.4	39.3	13.0	9.3	3.7
22	01635500	Passage Creek	VR	21.2	3.3	0.0	12.6	87.0	32.1	32.1	8.9	11.0	–2.1
25	01636316	Spout Run	VR	4.2	1.4	0.4	nd	nd	7.3	6.9	2.8	3.8	–1.0
26	01643700	Goose Creek	BR	12.1	2.9	0.1	52.6	46.3	19.1	19.0	6.8	6.1	0.7
28	01646000	Difficult Run	PM	7.2	1.1	5.6	41.7	37.5	39.7	34.1	11.4	10.6	0.8
29	01649500	NE Branch Anacostia River	CP	5.0	nd	18.7	nd	nd	29.4	10.7	4.1	3.3	0.8
30	01651000	NW Branch Anacostia River	PM	5.0	nd	15.8	nd	nd	45.4	29.6	9.5	9.5	0.1
31	01656000	Cedar Run	CP	6.0	2.3	0.9	59.2	35.5	28.8	27.9	8.5	8.3	0.2
32	01658000	Mattawoman Creek	CP	nd	nd	6.1	nd	nd	23.5	17.4	5.9	5.1	0.7
33	01660400	Aquia Creek	PM	6.2	2.4	0.6	21.5	71.9	30.0	29.4	9.3	10.5	–1.3

Table 13. Land-surface characteristics considered in the runoff regression and estimated mean runoff values for watersheds in this study.—Continued

[CP, Coastal Plain; VR, Valley and Ridge; BR, Blue Ridge; PM, Piedmont; nd, no data; SF, South Fork; NF, North Fork; NE, northeast; NW, northwest]

Map number	USGS station number	Watershed name	Physiographic Province	Topographic grade, in percent	Soil permeability, in inches per hour	Percent impervious surface	Percent agriculture	Percent forest	Estimated surface runoff as percent of total streamflow (ESR)	Natural surface runoff (ESR less percent impervious surface)	Natural surface runoff as percent of precipitation	Regressed natural runoff as percent of precipitation	Regression error
36	01665500	Rapidan River	BR	23.0	3.2	0.1	28.6	70.7	18.3	18.2	6.7	6.1	0.6
37	01666500	Robinson River	BR	15.4	3.3	0.2	38.6	60.0	19.5	19.3	7.2	5.3	1.9
38	01667500	Rapidan River	BR	14.7	2.8	0.2	41.8	56.5	10.9	10.7	3.6	5.3	–1.6
40	01669520	Dragon Swamp	CP	2.8	4.3	0.0	23.6	65.5	24.1	24.1	8.4	8.8	–0.4
43	01672500	South Anna River	PM	6.0	2.3	0.1	31.4	64.4	38.5	38.4	11.0	10.1	1.0
48	02011400	Jackson River	VR	24.2	4.6	0.0	19.2	80.6	18.2	18.2	6.3	7.9	–1.6
50	02013000	Dunlap Creek	VR	27.9	5.0	0.2	6.1	92.8	47.4	47.2	16.2	13.6	2.6
52	02014000	Potts Creek	VR	24.6	4.9	0.0	7.8	91.7	37.4	37.4	13.8	12.1	1.7
53	02015700	Bullpasture River	VR	21.7	5.3	0.0	nd	nd	21.1	21.1	9.6	9.3	0.3
55	02016500	James River	VR	26.4	4.9	0.3	10.5	87.8	37.7	37.4	15.0	12.9	2.0
56	02017500	Johns Creek	VR	23.4	4.6	0.0	7.2	92.2	49.6	49.6	19.3	15.6	3.7
57	02018000	Craig Creek	VR	25.4	4.7	0.1	9.1	90.2	43.2	43.1	16.1	14.9	1.2
58	02020500	Calfpasture River	VR	27.4	4.9	0.0	10.2	89.5	39.2	39.2	14.3	15.4	–1.1
59	02021500	Maury River	VR	23.6	4.6	0.1	11.5	87.7	33.2	33.1	11.7	14.3	–2.6
60	02024000	Maury River	VR	22.4	4.0	0.3	25.0	73.2	29.5	29.2	9.3	10.2	–0.9
64	02032640	NF Rivanna River	BR	18.6	3.1	0.2	30.4	67.9	13.3	13.1	4.5	6.0	–1.5
66	02040000	Appomattox River	PM	7.6	3.4	0.2	28.4	65.7	32.1	31.9	9.4	9.7	–0.3
67	02041000	Deep Creek	PM	6.6	3.7	0.2	30.4	62.0	35.0	34.8	9.9	8.9	0.9
69	02044500	Nottoway River	PM	6.4	3.8	0.4	27.6	66.1	24.8	24.4	7.1	8.9	–1.9
72	02047500	Blackwater River	CP	3.6	3.9	0.4	28.6	58.3	33.0	32.7	10.5	10.3	0.2
74	02051500	Meherrin River	PM	5.9	2.8	0.2	27.7	68.7	35.6	35.4	9.7	8.9	0.7
82	02059500	Goose Creek	BR	16.6	3.5	0.4	35.9	62.1	25.2	24.8	7.1	7.2	–0.0
84	02061500	Big Otter River	BR	14.4	3.3	0.7	39.3	56.5	16.3	15.6	4.9	5.2	–0.3
96	03167000	Reed Creek	VR	16.9	3.3	0.8	46.2	50.8	34.2	33.4	11.7	12.4	–0.7
107	03524000	Clinch River	VR	26.7	2.7	1.0	37.9	57.9	13.1	12.1	4.8	10.1	–5.3
108	03531500	Powell River	VR	31.3	2.3	0.8	21.0	72.0	38.0	37.3	15.7	13.4	2.3

Groundwater Recharge

The mean recharge rate for a watershed can be calculated by subtracting the mean rate of vadose zone ET from the mean rate of infiltration (eq. 4). In our situation we have calculated a total ET and a riparian ET and the vadose zone ET is the latter subtracted from the former. Also, the infiltration is the surface runoff subtracted from the precipitation, and given that we have calculated both of these, the infiltration, and thus also the recharge, can be calculated. As this analysis produces a closed hydrologic budget, the recharge can also be calculated by adding the groundwater discharge and the riparian ET with identical results. The calculated recharge rates for the various watersheds ranged between 8 and 18 in/yr (fig. 36).

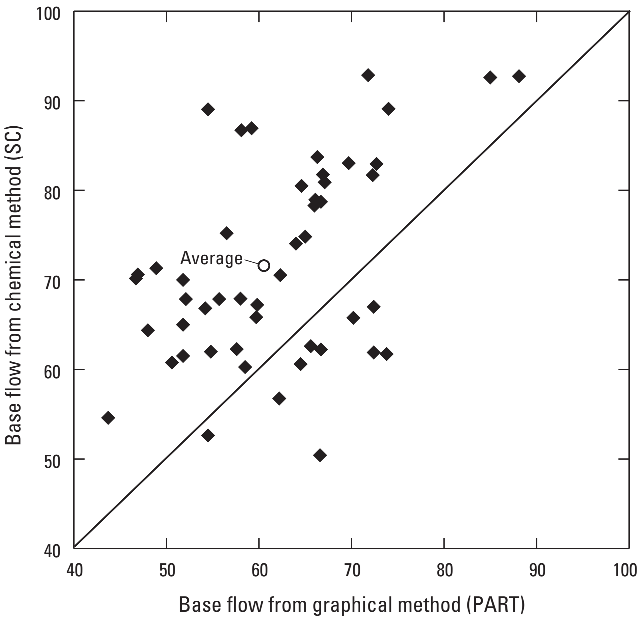


Figure 33. Comparison of mean base flow estimated using graphical (PART) versus chemical (specific conductance, SC) hydrograph separation techniques.

Estimates for Localities

The purpose of this study was to be able to make quantitative estimates of the components of the hydrologic budgets for the entire Commonwealth of Virginia. Because the direct measurements were made on individual watersheds, and the watersheds do not cover the entire region, the regression equations were used to make estimates for all the counties and independent cities. In order to apply the ET regressions to the localities, certain climatic and land cover (marsh) variables were first needed for each locality (table 14). The climatic variables needed included the mean annual temperature (fig. 4), the mean annual precipitation (fig. 5), the mean daily maximum temperature (fig. 37), the mean daily minimum temperature (fig. 38), and the mean difference in daily temperature (fig. 39). In addition, the percentage of physiographic province and rock types in each county were required (table 15) in order to apply the regression used to calculate the percent of precipitation that becomes surface runoff. Resulting hydrologic budget components for the localities include precipitation, total ET, riparian ET, surface runoff, infiltration, recharge, net groundwater outflow, and net total outflow (table 16).

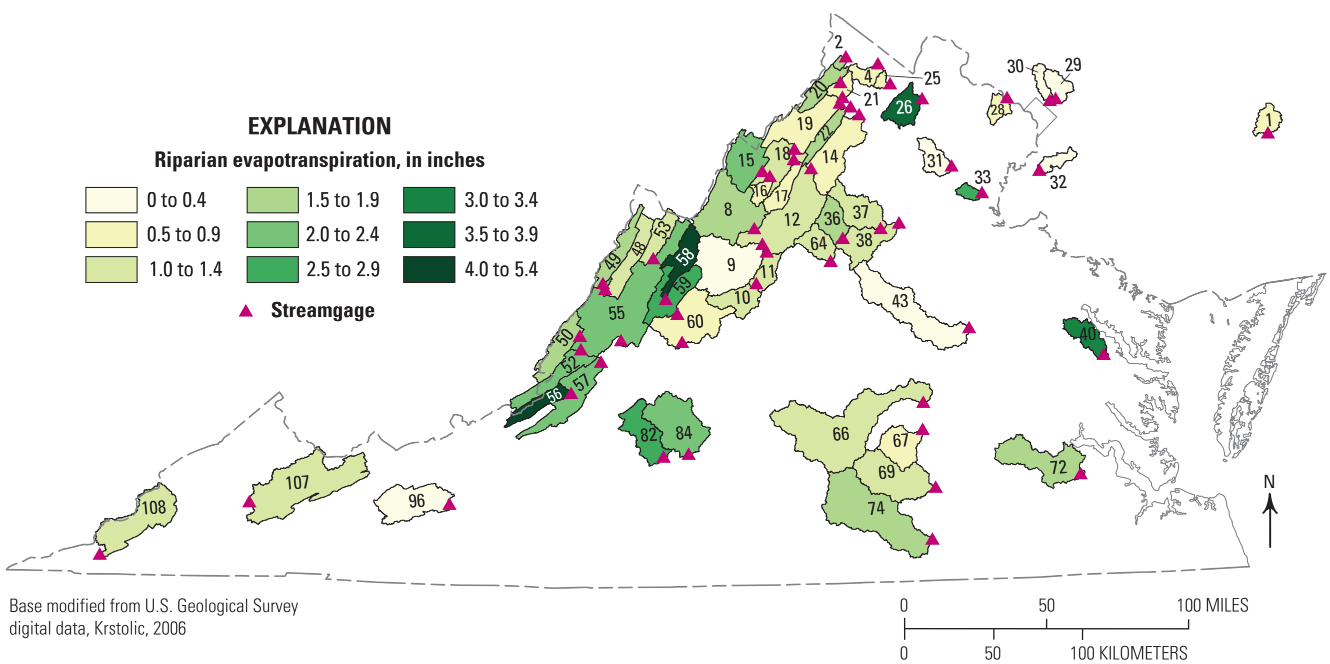


Figure 34. Estimates of mean annual riparian evapotranspiration from seasonal specific conductance for selected watersheds in Virginia, Maryland, and Delaware. See figure 27 for watershed number list.

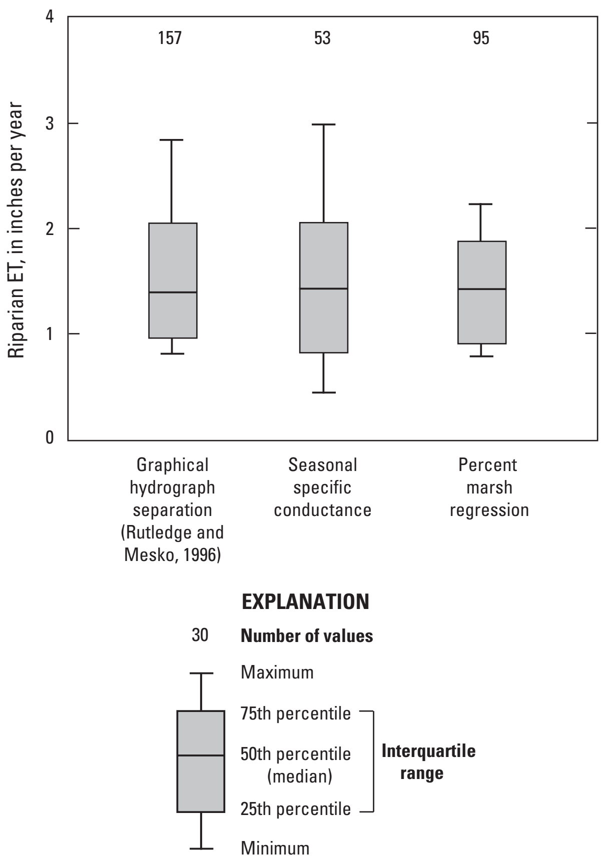


Figure 35. Comparisons of different methods for estimating mean annual riparian evapotranspiration (*ETrp*).

Total Evapotranspiration

The total ET for the localities of Virginia was estimated by the climate regression (eq. 15) and the values thus reflect the local climatic conditions of each locality. The lowest values are 25 in/yr or less in some of the far western and northern counties (fig. 40); these include Highland and Frederick Counties in the extreme north and west and Fairfax County in the northeast. The latter is relatively low because of the relatively high amount of impervious surface in the County. Many of the independent cities also have estimated total evapotranspiration of 25 in/yr or lower because of the relatively high amounts of impervious surface (fig. 22). The highest evapotranspiration values are greater than 30 in/yr and occur typically in the warmest counties in the southern region of Virginia. Lee and Patrick Counties, in southwestern Virginia, also have relatively high ET rates because of their high mean annual precipitation rates. Another useful way to express ET is by its relation to P, or as the ratio of ET to P. This is the fraction of precipitation that is evaporated or transpired. For independent cities, this estimate is typically less than 55 percent (fig. 41) and between 55 and 60 percent in southwestern Virginia. The value for Fairfax County is also in the latter range because of the relatively high amount of impervious surface, and the Atlantic coastal counties of Accomac, Northampton, and Virginia Beach are also in this range because of the effect of higher humidity near the ocean. The areas with the highest ratios of ET/P (above 66 percent) are the warmest counties in southern and south-central Virginia. Shenandoah County in the north is also in this upper range because of the relatively low mean annual precipitation rate.

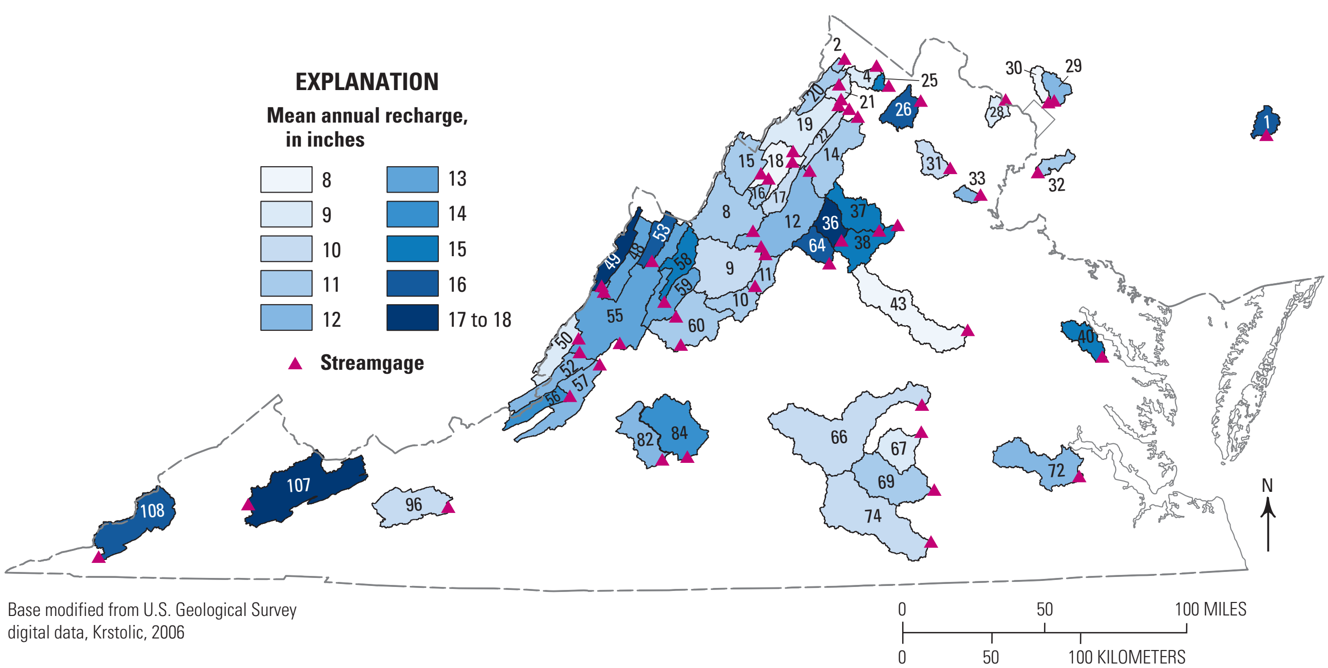


Figure 36. Estimates of mean annual total recharge for selected watersheds in Virginia, Maryland, and Delaware. See figure 27 for watershed number list.

Table 14. Climatic and landscape characteristics of localities in Virginia.

[See figure 2 for map number locations]

Map number	Locality name	FIPS number (county or independent city)	Area, in square miles	Precipitation, in inches per year	Average daily temperature, in degrees Fahrenheit		Mean soil permeability, in inches per hour	Average topographic grade, in percent	Land use, in percent			
					Maximum	Minimum			Forest	Agriculture	Marsh	Impervious surface
1	Accomack County	1	463.5	43.0	66.2	49.0	5.58	0.6	26.5	25.1	23.7	3.0
2	Albemarle County	3	726.3	46.8	66.9	44.1	2.90	14.2	72.9	23.1	0.4	3.6
3	Alleghany County	5	448.3	41.4	64.0	40.9	5.10	25.7	91.9	5.5	0.1	3.4
4	Amelia County	7	358.4	44.9	69.0	44.7	3.62	6.4	70.5	22.9	2.7	2.7
5	Amherst County	9	478.9	47.2	66.9	43.7	3.80	19.7	82.6	13.8	0.1	3.4
6	Appomattox County	11	336.1	45.2	67.6	44.3	3.13	9.3	73.3	20.2	1.1	2.9
7	Arlington County	13	26.1	42.7	66.4	45.6	2.74	6.6	21.6	11.6	0.1	32.0
8	Augusta County	15	972.9	43.2	63.8	40.4	4.28	17.5	59.9	37.6	0.3	3.7
9	Bath County	17	535.0	42.3	62.7	39.2	4.78	26.4	90.7	7.5	0.2	2.7
10	Bedford County	19	769.2	45.6	67.4	44.4	3.38	16.1	67.8	28.4	0.1	3.6
11	Bland County	21	358.2	41.7	62.6	40.1	3.53	23.5	79.8	19.3	0.1	2.8
12	Botetourt County	23	545.7	43.4	66.3	43.1	3.78	22.6	78.1	18.5	0.1	3.5
13	Brunswick County	25	570.3	46.0	69.9	46.0	3.47	5.4	69.9	19.5	4.3	3.1
14	Buchanan County	27	498.7	46.7	65.1	41.4	2.81	44.4	96.4	1.5	0.0	3.5
15	Buckingham County	29	584.0	45.1	68.1	44.3	1.75	7.7	81.2	12.5	1.7	2.7
16	Campbell County	31	506.0	44.7	67.8	44.7	2.59	8.7	68.7	24.8	0.4	3.5
17	Caroline County	33	537.0	44.0	67.8	45.1	4.51	5.9	68.3	17.3	7.7	2.8
18	Carroll County	35	477.4	47.9	63.7	40.8	3.35	18.9	63.9	34.4	0.1	3.0
19	Charles City County	36	182.9	45.6	69.6	47.8	3.49	3.8	58.8	17.8	11.4	2.6
20	Charlotte County	37	477.8	45.6	68.8	45.0	2.54	6.8	68.7	22.4	5.5	2.8
21	Chesterfield County	41	434.2	44.6	69.1	45.8	3.90	4.8	71.8	10.3	1.6	6.3
22	Clarke County	43	178.4	39.6	65.0	42.6	2.38	8.0	40.6	57.5	0.4	3.2
23	Craig County	45	328.8	43.5	63.8	41.6	4.67	24.4	87.2	12.2	0.1	2.8
24	Culpepper County	47	383.1	44.2	67.3	43.8	2.11	6.6	52.6	43.6	0.3	3.2
25	Cumberland County	49	300.8	44.9	68.8	44.1	3.24	6.3	72.9	18.1	5.4	2.7
26	Dickenson County	51	332.9	47.2	64.6	40.9	3.20	38.3	93.4	3.2	0.0	3.6
27	Dinwiddie County	53	508.0	45.6	69.7	45.7	3.02	4.0	72.3	20.2	2.1	3.0
28	Essex County	57	265.7	44.4	68.1	46.5	5.38	5.3	53.3	26.3	7.2	2.8
29	Fairfax County	59	402.3	43.2	66.3	44.7	1.51	6.4	47.8	11.0	2.0	14.7
30	Fauquier County	61	653.1	43.2	65.8	43.3	2.38	8.7	51.5	44.7	0.1	3.1
31	Floyd County	63	381.4	47.2	63.2	40.9	3.40	18.5	66.3	32.9	0.2	2.7
32	Fluvanna County	65	290.5	43.7	68.0	44.1	3.03	7.4	76.3	16.4	1.6	2.8
33	Franklin County	67	711.4	46.0	67.2	44.3	1.40	15.7	71.7	23.9	0.1	3.0
34	Frederick County	69	414.8	39.3	64.1	41.9	3.49	11.6	62.3	34.6	0.1	4.2
35	Giles County	71	359.9	41.2	62.5	40.6	3.08	25.2	82.3	14.7	0.0	3.2

Table 14. Climatic and landscape characteristics of localities in Virginia.—Continued

[See figure 2 for map number locations]

Map number	Locality name	FIPS number (county or independent city)	Area, in square miles	Precipitation, in inches per year	Average daily temperature, in degrees Fahrenheit		Mean soil permeability, in inches per hour	Average topographic grade, in percent	Land use, in percent			
					Maximum	Minimum			Forest	Agriculture	Marsh	Impervious surface
36	Gloucester County	73	219.0	46.8	68.8	48.1	4.81	3.1	54.0	16.1	9.8	3.1
37	Goochland County	75	287.6	43.6	68.3	44.2	3.28	6.9	70.2	21.6	3.3	3.0
38	Grayson County	77	445.7	46.0	62.0	39.5	5.01	20.8	70.5	27.9	0.1	2.8
39	Greene County	79	156.8	49.6	65.3	42.4	2.84	18.8	72.1	25.2	0.2	3.5
40	Greensville County	81	297.3	45.8	70.4	46.8	3.21	2.8	48.3	27.1	19.0	2.9
41	Halifax County	83	829.8	45.6	69.5	45.8	2.59	6.7	67.1	23.4	4.7	3.0
42	Hanover County	85	474.5	44.1	68.3	45.2	4.04	5.1	57.3	29.3	5.8	3.8
43	Henrico County	87	240.7	44.4	68.8	46.1	3.13	3.1	40.6	20.6	7.1	10.5
44	Henry County	89	383.7	47.3	68.3	44.5	3.61	12.8	75.5	16.2	0.3	4.0
45	Highland County	91	415.5	43.2	59.6	36.5	4.51	26.2	79.8	19.7	0.1	2.6
46	Isle Of Wight County	93	322.2	47.6	69.7	48.4	4.20	2.0	37.2	33.4	13.4	3.0
47	James City County	95	143.3	47.3	69.5	47.9	4.14	6.1	52.9	12.7	9.4	4.7
48	King and Queen County	97	314.5	45.0	68.8	46.4	4.97	5.2	67.3	19.9	7.8	2.6
49	King George County	99	178.5	43.9	67.6	46.1	4.16	6.2	62.1	23.1	6.5	3.2
50	King William County	101	273.0	44.6	69.0	46.3	5.51	6.0	57.7	24.9	10.5	2.7
51	Lancaster County	103	135.5	46.0	67.9	47.2	5.64	3.9	46.7	18.5	2.4	2.9
52	Lee County	105	437.1	52.1	66.6	42.8	2.64	25.5	78.2	20.6	0.1	3.5
53	Loudoun County	107	522.1	42.5	65.5	43.0	2.29	7.4	39.7	53.6	1.1	5.8
54	Louisa County	109	511.4	44.2	67.9	43.9	2.00	6.0	72.0	18.7	3.2	2.8
55	Lunenburg County	111	432.8	45.4	69.1	45.4	2.62	5.9	71.6	21.2	3.3	2.8
56	Madison County	113	322.1	47.0	65.7	42.6	3.16	17.2	65.2	32.9	0.3	2.9
57	Mathews County	115	85.3	46.7	68.1	48.7	3.24	1.6	39.7	15.4	20.1	2.8
58	Mecklenburg County	117	679.6	45.0	69.8	46.1	3.15	5.5	56.8	27.0	4.3	3.1
59	Middlesex County	119	132.9	45.9	68.4	47.7	4.13	3.8	42.8	21.2	4.0	3.0
60	Montgomery County	121	388.6	40.1	64.4	41.7	2.48	22.0	67.5	27.8	0.0	5.7
61	Nelson County	125	474.2	49.1	66.7	43.7	3.70	21.4	83.8	13.6	0.2	3.0
62	New Kent County	127	207.2	45.4	69.2	47.1	5.08	7.6	64.3	13.4	12.1	2.8
63	Northampton County	131	217.5	44.7	67.3	50.1	5.10	0.8	15.6	23.6	19.5	3.1
64	Northumberland County	133	194.7	45.2	67.7	47.0	5.25	3.9	53.5	27.8	2.8	2.8
65	Nottoway County	135	316.6	45.5	68.9	44.7	4.00	6.9	69.3	21.4	3.2	3.4
66	Orange County	137	343.7	44.6	67.2	43.9	1.72	7.4	61.5	34.3	0.7	3.0
67	Page County	139	313.3	43.3	65.0	40.8	3.83	20.7	69.0	26.8	0.2	3.6
68	Patrick County	141	486.0	52.2	66.4	43.8	2.49	20.4	79.5	18.6	0.1	2.7
69	Pittsylvania County	143	977.9	45.6	68.7	45.2	3.72	7.3	66.5	28.2	0.7	3.2
70	Powhatan County	145	264.5	43.7	68.5	44.3	3.48	6.6	72.1	19.2	4.5	2.7

Table 14. Climatic and landscape characteristics of localities in Virginia.—Continued

[See figure 2 for map number locations]

Map number	Locality name	FIPS number (county or independent city)	Area, in square miles	Precipitation, in inches per year	Average daily temperature, in degrees Fahrenheit		Mean soil permeability, in inches per hour	Average topographic grade, in percent	Land use, in percent			
					Maximum	Minimum			Forest	Agriculture	Marsh	Impervious surface
71	Prince Edward County	147	354.0	45.3	68.7	44.6	3.54	7.6	72.7	19.6	4.6	3.0
72	Prince George County	149	269.2	45.6	70.1	47.5	3.22	3.4	66.7	20.9	2.0	3.3
73	Prince William County	153	343.0	43.0	66.7	44.6	2.26	6.7	57.7	23.3	0.9	7.6
74	Pulaski County	155	329.9	39.6	64.0	41.0	2.67	18.2	59.1	34.4	0.0	4.1
75	Rappahannock County	157	267.1	46.1	65.4	42.1	3.85	18.1	68.5	30.1	0.1	2.7
76	Richmond County	159	192.4	44.4	67.9	46.8	6.40	4.5	49.9	27.6	7.3	2.8
77	Roanoke County	161	251.6	43.3	65.4	43.5	4.65	25.0	78.0	13.8	0.1	6.8
78	Rockbridge County	163	600.0	45.5	65.4	41.9	3.36	22.3	71.3	26.5	0.1	3.3
79	Rockingham County	165	853.7	40.2	64.0	40.2	4.25	18.7	60.5	36.5	0.1	3.7
80	Russell County	167	476.6	46.2	64.4	41.4	2.52	26.8	75.1	22.4	0.1	3.4
81	Scott County	169	538.5	49.4	66.5	43.2	2.45	26.7	87.4	11.7	0.1	2.9
82	Shenandoah County	171	511.4	39.2	64.9	40.5	2.80	15.4	62.0	34.2	0.1	3.5
83	Smyth County	173	452.0	47.0	63.2	39.8	2.96	23.1	73.7	23.6	0.1	3.1
84	Southampton County	175	601.7	47.1	71.0	47.3	4.97	2.0	39.6	37.7	19.1	2.7
85	Spotsylvania County	177	412.0	43.6	67.6	44.1	3.73	6.0	70.3	19.9	1.4	3.7
86	Stafford County	179	275.6	43.0	67.1	45.0	3.36	7.7	67.2	17.0	2.7	4.4
87	Surry County	181	281.7	46.8	69.7	47.8	4.95	4.7	54.0	22.2	11.0	2.6
88	Sussex County	183	494.1	46.4	70.4	46.7	3.97	2.8	62.8	20.5	12.4	2.8
89	Tazewell County	185	519.2	46.0	62.4	40.4	3.26	26.7	72.1	25.4	0.1	4.2
90	Warren County	187	218.2	41.2	65.0	42.4	3.42	16.1	67.4	25.8	0.2	4.1
91	Washington County	191	567.2	46.8	65.4	41.3	3.03	22.1	70.6	26.4	0.1	3.1
92	Westmoreland County	193	233.6	44.3	67.8	46.7	3.50	5.0	49.1	31.1	6.3	2.9
93	Wise County	195	403.5	51.3	64.0	41.8	2.11	30.6	86.8	3.9	0.2	4.2
94	Wythe County	197	464.4	40.3	63.6	40.4	3.32	17.5	53.7	43.6	0.1	3.4
95	York County	199	108.6	47.6	69.1	48.3	3.24	3.4	54.4	8.4	5.6	6.3
96	Alexandria	510	15.4	41.8	66.6	46.0	1.56	5.3	16.0	5.7	1.0	39.9
97	Bedford	515	6.8	45.0	67.9	45.0	1.82	9.0	41.7	29.6	0.0	19.6
98	Bristol	520	11.5	46.3	66.9	42.8	2.89	10.4	36.1	8.5	0.3	22.5
99	Buena Vista	530	6.5	41.4	68.7	42.8	3.37	13.3	55.4	15.7	0.1	15.9
100	Charlottesville	540	10.5	46.5	67.4	45.3	3.01	8.8	37.3	4.4	0.3	30.7
101	Chesapeake	550	349.1	47.6	69.8	48.8	2.94	0.3	7.4	30.4	44.8	6.3
102	Colonial Heights	570	7.7	44.9	70.0	47.5	2.10	3.2	22.0	7.6	10.6	20.5
103	Covington	580	4.4	37.0	67.5	41.8	2.59	12.7	37.1	11.8	0.2	31.0
104	Danville	590	43.9	45.3	70.0	46.4	3.21	7.4	41.8	11.5	0.7	16.7
105	Emporia	595	6.7	45.1	70.4	46.7	2.79	2.8	30.4	19.7	13.2	13.5

Table 14. Climatic and landscape characteristics of localities in Virginia.—Continued

[See figure 2 for map number locations]

Map number	Locality name	FIPS number (county or independent city)	Area, in square miles	Precipitation, in inches per year	Average daily temperature, in degrees Fahrenheit		Mean soil permeability, in inches per hour	Average topographic grade, in percent	Land use, in percent			
					Maximum	Minimum			Forest	Agriculture	Marsh	Impervious surface
106	Fairfax	600	6.4	44.2	66.0	44.6	1.12	5.7	31.0	6.8	0.2	27.0
107	Falls Church	610	2.0	43.9	66.1	45.1	1.61	4.3	28.9	2.4	0.4	25.5
108	Franklin	620	7.7	47.8	71.1	47.7	3.80	1.7	26.6	25.5	15.4	10.7
109	Fredericksburg	630	10.6	42.7	67.4	44.7	4.14	7.1	36.5	21.5	1.9	18.7
110	Galax	640	8.1	44.3	63.8	40.1	2.44	14.5	32.6	27.4	0.2	14.9
111	Hampton	650	52.0	47.2	68.4	49.7	2.32	1.0	17.0	12.4	8.1	21.8
112	Harrisonburg	660	17.5	36.4	65.4	41.3	1.90	7.0	19.5	33.6	0.1	29.8
113	Hopewell	670	10.4	44.9	70.5	48.0	3.80	3.7	27.6	6.5	0.9	19.9
114	Lexington	678	2.5	41.1	67.5	43.1	2.33	10.2	25.0	22.7	0.0	26.8
115	Lynchburg	680	49.4	44.4	67.9	44.8	2.62	11.2	52.8	11.9	0.2	19.0
116	Manassas	683	10.1	43.1	67.4	44.6	1.56	3.4	13.3	18.7	0.1	30.4
117	Manassas Park	685	1.8	43.1	67.3	44.6	1.57	5.9	26.4	6.7	0.1	28.9
118	Martinsville	690	10.9	46.1	68.5	44.2	3.06	11.7	36.7	3.1	0.2	21.0
119	Newport News	700	69.0	47.3	68.9	49.4	1.81	1.5	19.5	5.2	4.9	21.2
120	Norfolk	710	54.9	46.8	68.5	50.6	2.06	0.9	5.6	7.3	2.2	33.6
121	Norton	720	7.6	55.3	63.1	41.5	2.00	23.3	81.4	1.1	0.1	16.2
122	Petersburg	730	23.1	45.0	69.8	47.1	2.55	3.3	42.9	15.7	0.4	14.9
123	Poquoson	735	16.3	47.2	68.2	49.6	2.36	0.6	18.4	6.0	39.2	7.0
124	Portsmouth	740	32.7	47.2	68.8	50.2	2.01	0.8	7.2	5.5	5.0	26.1
125	Radford	750	10.1	38.1	64.8	41.6	2.15	13.0	48.4	15.6	0.2	17.1
126	Richmond	760	62.0	44.4	68.8	46.1	3.51	3.9	18.3	4.6	1.2	25.9
127	Roanoke	770	42.4	42.7	67.6	45.0	1.78	9.4	27.3	13.5	0.0	34.2
128	Salem	775	14.4	41.6	67.6	44.6	1.79	8.5	31.5	15.9	0.0	34.2
129	Staunton	790	19.3	38.6	65.5	42.3	2.60	11.1	29.4	40.4	0.1	17.1
130	Suffolk	800	411.8	48.3	69.9	48.3	4.99	1.3	26.0	31.2	29.3	3.7
131	Virginia Beach	810	258.0	46.1	68.6	50.9	3.25	0.6	11.8	22.4	21.6	11.9
132	Waynesboro	820	14.0	44.0	65.9	42.6	3.03	6.1	25.5	34.4	0.5	23.2
133	Williamsburg	830	9.0	48.2	69.8	47.6	4.46	6.3	59.9	9.5	4.1	12.2
134	Winchester	840	9.3	38.8	64.3	42.9	1.00	6.7	19.8	28.4	0.1	32.1

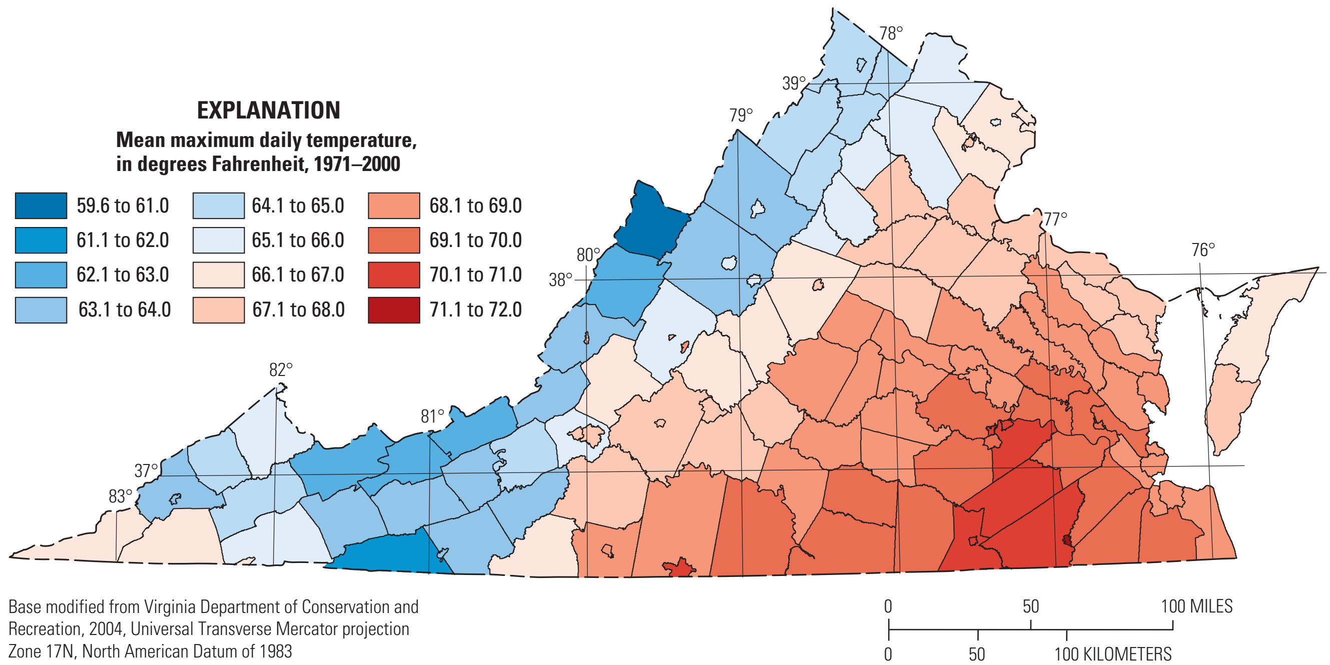


Figure 37. Mean maximum daily temperature in Virginia by locality from 1971 to 2000. See figure 2 for locality names; data compiled from PRISM Climate Group, Oregon State University, Daly and others 2008, accessed July 2008 at *http://www.prism.oregonstate.edu*.

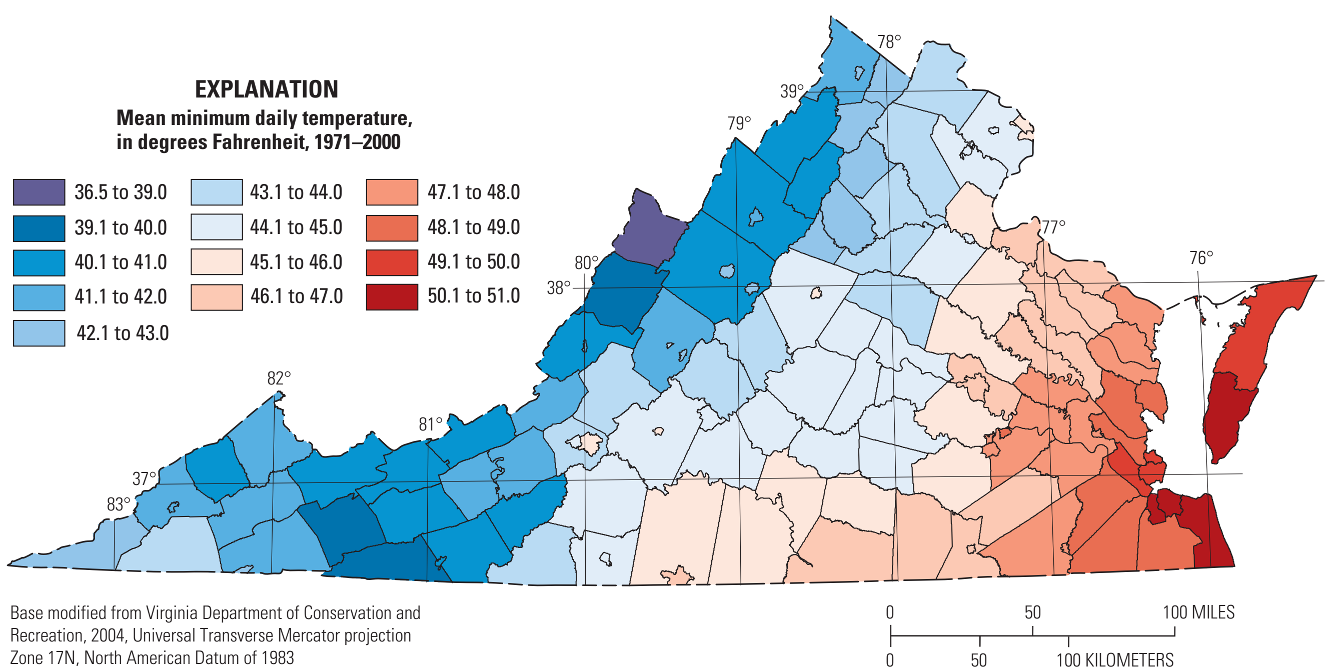


Figure 38. Mean minimum daily temperature in Virginia by locality from 1971 to 2000. See figure 2 for locality names; data compiled from PRISM Climate Group, Oregon State University, Daly and others 2008, accessed July 2008 at *http://www.prism.oregonstate.edu*.

Table 15. Percentages of areas of Virginia localities underlain by different physiographic provinces and rock types.

[See figure 2 for map number locations]

Map number	Locality name	Percent area in Blue Ridge			Percent area in Coastal Plain			Percent area in Piedmont		
		Meta-volcanics	Meta-sediments	Plutonic	Fine-grained sediments	Mixed-grained sediments	Coarse-grained sediments	North-western	South-eastern	Mesozoic Basins
1	Accomack County	0.0	0.0	0.0	49.1	30.5	20.4	0.0	0.0	0.0
2	Albemarle County	33.7	14.7	41.5	0.0	0.0	0.0	5.0	0.0	4.2
4	Amelia County	0.0	0.0	0.0	0.0	0.0	0.0	0.1	96.7	3.2
5	Amherst County	4.0	23.7	65.6	0.0	0.0	0.0	0.0	0.0	0.0
6	Appomattox County	0.3	7.3	0.0	0.0	0.0	0.0	92.3	0.0	0.1
7	Arlington County	0.0	0.0	0.0	1.2	11.7	50.6	36.4	0.0	0.0
8	Augusta County	1.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
10	Bedford County	7.2	27.9	59.5	0.0	0.0	0.0	0.1	0.0	0.0
12	Botetourt County	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0	0.0
13	Brunswick County	0.0	0.0	0.0	0.0	0.0	0.8	0.0	99.2	0.0
15	Buckingham County	3.7	1.4	0.0	0.0	0.0	0.0	91.3	0.0	3.5
16	Campbell County	3.4	24.3	0.0	0.0	0.0	0.0	65.7	0.0	6.6
17	Caroline County	0.0	0.0	0.0	0.4	60.7	33.5	0.0	5.2	0.3
18	Carroll County	0.3	91.2	1.1	0.0	0.0	0.0	0.0	0.0	0.0
19	Charles City County	0.0	0.0	0.0	27.2	72.8	0.0	0.0	0.0	0.0
20	Charlotte County	0.0	0.0	0.0	0.0	0.0	0.0	50.9	47.5	1.6
21	Chesterfield County	0.0	0.0	0.0	5.5	9.1	26.1	0.0	35.0	24.3
22	Clarke County	8.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	Culpepper County	12.1	22.9	15.1	0.0	0.0	0.0	12.3	0.0	37.7
25	Cumberland County	0.0	0.0	0.0	0.0	0.0	0.0	27.2	60.7	12.1
27	Dinwiddie County	0.0	0.0	0.0	16.4	4.0	8.4	0.0	70.5	0.7
28	Essex County	0.0	0.0	0.0	19.1	79.0	1.9	0.0	0.0	0.0
29	Fairfax County	0.0	0.0	0.0	1.5	7.0	14.6	58.9	0.0	17.9
30	Fauquier County	23.3	7.6	30.3	0.0	0.0	0.0	9.7	0.0	28.0
31	Floyd County	0.2	76.9	21.0	0.0	0.0	0.0	0.0	0.0	0.0
32	Fluvanna County	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
33	Franklin County	4.1	61.4	20.2	0.0	0.0	0.0	14.3	0.0	0.0
36	Gloucester County	0.0	0.0	0.0	26.1	73.9	0.0	0.0	0.0	0.0
37	Goochland County	0.0	0.0	0.0	0.0	0.0	3.1	30.7	59.6	6.6
38	Grayson County	1.1	37.4	54.3	0.0	0.0	0.0	0.0	0.0	0.0
39	Greene County	18.7	9.4	71.5	0.0	0.0	0.0	0.0	0.0	0.0
40	Greensville County	0.0	0.0	0.0	23.6	28.2	17.3	0.0	30.9	0.0
41	Halifax County	0.0	0.0	0.0	0.0	0.0	0.0	78.9	19.3	1.8
42	Hanover County	0.0	0.0	0.0	4.2	21.0	31.5	0.0	39.4	3.9
43	Henrico County	0.0	0.0	0.0	32.9	26.5	17.8	0.0	20.2	2.6
44	Henry County	0.6	0.8	0.0	0.0	0.0	0.0	98.3	0.0	0.3
46	Isle Of Wight County	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
47	James City County	0.0	0.0	0.0	42.3	57.7	0.0	0.0	0.0	0.0
48	King and Queen County	0.0	0.0	0.0	28.9	71.1	0.0	0.0	0.0	0.0
49	King George County	0.0	0.0	0.0	6.0	84.1	9.9	0.0	0.0	0.0

Table 15. Percentages of areas of Virginia localities underlain by different physiographic provinces and rock types.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Percent area in Blue Ridge			Percent area in Coastal Plain			Percent area in Piedmont		
		Meta-volcanics	Meta-sediments	Plutonic	Fine-grained sediments	Mixed-grained sediments	Coarse-grained sediments	North-western	South-eastern	Mesozoic Basins
50	King William County	0.0	0.0	0.0	13.8	82.6	3.6	0.0	0.0	0.0
51	Lancaster County	0.0	0.0	0.0	0.1	99.7	0.2	0.0	0.0	0.0
53	Loudoun County	15.4	5.8	36.7	0.0	0.0	0.0	0.1	0.0	38.3
54	Louisa County	0.2	0.0	0.0	0.0	0.0	0.0	78.0	21.7	0.0
55	Lunenburg County	0.0	0.0	0.0	0.0	0.0	0.0	2.4	97.6	0.0
56	Madison County	12.9	26.1	58.6	0.0	0.0	0.0	0.0	0.0	2.3
57	Mathews County	0.0	0.0	0.0	4.8	94.5	0.8	0.0	0.0	0.0
58	Mecklenburg County	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
59	Middlesex County	0.0	0.0	0.0	0.0	99.9	0.1	0.0	0.0	0.0
60	Montgomery County	0.0	0.3	4.5	0.0	0.0	0.0	0.0	0.0	0.0
61	Nelson County	15.9	20.1	62.1	0.0	0.0	0.0	0.2	0.0	0.7
62	New Kent County	0.0	0.0	0.0	47.0	50.5	2.4	0.0	0.0	0.0
63	Northampton County	0.0	0.0	0.0	22.2	0.0	77.8	0.0	0.0	0.0
64	Northumberland County	0.0	0.0	0.0	1.3	98.5	0.2	0.0	0.0	0.0
65	Nottoway County	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
66	Orange County	26.9	6.4	0.0	0.0	0.0	0.0	59.2	0.0	7.5
67	Page County	14.5	0.0	10.9	0.0	0.0	0.0	0.0	0.0	0.0
68	Patrick County	2.3	57.1	0.0	0.0	0.0	0.0	40.7	0.0	0.0
69	Pittsylvania County	0.9	4.2	0.0	0.0	0.0	0.0	80.0	0.0	14.9
70	Powhatan County	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.9	9.1
71	Prince Edward County	0.0	0.0	0.0	0.0	0.0	0.0	42.5	56.0	1.5
72	Prince George County	0.0	0.0	0.0	62.1	37.0	1.0	0.0	0.0	0.0
73	Prince William County	0.2	0.0	0.0	0.0	3.5	10.7	32.7	0.0	51.9
75	Rappahannock County	7.3	5.6	87.1	0.0	0.0	0.0	0.0	0.0	0.0
76	Richmond County	0.0	0.0	0.0	20.5	77.4	2.1	0.0	0.0	0.0
77	Roanoke County	0.0	0.0	30.4	0.0	0.0	0.0	0.0	0.0	0.0
78	Rockbridge County	0.0	0.0	5.7	0.0	0.0	0.0	0.0	0.0	0.0
79	Rockingham County	2.4	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
83	Smyth County	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
84	Southampton County	0.0	0.0	0.0	14.9	83.3	1.7	0.0	0.0	0.0
85	Spotsylvania County	0.0	0.0	0.0	0.1	7.2	17.8	58.0	16.9	0.0
86	Stafford County	0.1	0.0	0.0	0.5	30.8	21.0	47.1	0.5	0.0
87	Surry County	0.0	0.0	0.0	45.0	54.6	0.4	0.0	0.0	0.0
88	Sussex County	0.0	0.0	0.0	57.1	39.1	2.3	0.0	1.4	0.0
90	Warren County	20.0	0.1	17.1	0.0	0.0	0.0	0.0	0.0	0.0
91	Washington County	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
92	Westmoreland County	0.0	0.0	0.0	14.8	78.6	6.6	0.0	0.0	0.0
95	York County	0.0	0.0	0.0	6.1	93.9	0.0	0.0	0.0	0.0
96	Alexandria	0.0	0.0	0.0	3.8	28.6	65.3	2.3	0.0	0.0
97	Bedford	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 15. Percentages of areas of Virginia localities underlain by different physiographic provinces and rock types.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Percent area in Blue Ridge			Percent area in Coastal Plain			Percent area in Piedmont		
		Meta-volcanics	Meta-sediments	Plutonic	Fine-grained sediments	Mixed-grained sediments	Coarse-grained sediments	North-western	South-eastern	Mesozoic Basins
100	Charlottesville	38.7	61.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101	Chesapeake	0.0	0.0	0.0	30.5	69.5	0.0	0.0	0.0	0.0
102	Colonial Heights	0.0	0.0	0.0	0.0	74.8	17.3	0.0	7.9	0.0
104	Danville	0.0	0.0	0.0	0.0	0.0	0.0	97.8	0.0	2.2
105	Emporia	0.0	0.0	0.0	67.1	28.6	0.0	0.0	4.4	0.0
106	Fairfax	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
107	Falls Church	0.0	0.0	0.0	0.0	0.0	5.7	94.3	0.0	0.0
108	Franklin	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
109	Fredericksburg	0.0	0.0	0.0	0.0	37.7	43.6	7.8	10.9	0.0
110	Galax	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
111	Hampton	0.0	0.0	0.0	1.0	96.2	2.9	0.0	0.0	0.0
113	Hopewell	0.0	0.0	0.0	0.0	85.5	14.5	0.0	0.0	0.0
115	Lynchburg	7.2	81.3	11.5	0.0	0.0	0.0	0.0	0.0	0.0
116	Manassas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
117	Manassas Park	0.0	0.0	0.0	0.0	0.0	0.0	11.4	0.0	88.6
118	Martinsville	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
119	Newport News	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
120	Norfolk	0.0	0.0	0.0	0.0	95.4	4.6	0.0	0.0	0.0
122	Petersburg	0.0	0.0	0.0	67.9	26.3	3.0	0.0	2.9	0.0
123	Poquoson	0.0	0.0	0.0	42.9	57.1	0.0	0.0	0.0	0.0
124	Portsmouth	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
126	Richmond	0.0	0.0	0.0	17.7	19.1	41.1	0.0	22.1	0.0
127	Roanoke	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0
130	Suffolk	0.0	0.0	0.0	14.4	84.9	0.7	0.0	0.0	0.0
131	Virginia Beach	0.0	0.0	0.0	20.7	73.3	6.0	0.0	0.0	0.0
133	Williamsburg	0.0	0.0	0.0	1.2	98.8	0.0	0.0	0.0	0.0

Table 15. Percentages of areas of Virginia localities underlain by different physiographic provinces and rock types.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Percent area in Valley and Ridge							
		Cambrian dolomites	Cambrian-Ordovician limestones	Ordovician dolomite	Ordovician siliciclastics	Silurian siliciclastics and limestones	Devonian siliciclastics	Mississippian siliciclastics	Appalachian Plateau siliciclastics
3	Alleghany County	0.0	2.8	0.3	7.7	26.7	45.4	16.8	0.2
5	Amherst County	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Augusta County	14.5	29.0	11.5	10.2	3.3	9.1	20.6	0.0
9	Bath County	0.0	1.3	0.2	4.7	40.3	40.1	13.4	0.0
10	Bedford County	2.1	0.1	0.0	0.0	0.0	3.1	0.0	0.0
11	Bland County	0.0	20.5	0.0	7.3	18.1	43.5	5.6	5.0
12	Botetourt County	10.0	27.7	2.4	9.2	14.8	25.0	4.2	0.0
14	Buchanan County	0.0	0.0	0.0	0.0	0.2	0.0	0.0	99.8
18	Carroll County	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	Clarke County	29.3	32.3	26.4	2.2	1.0	0.0	0.0	0.0
23	Craig County	0.0	11.5	0.0	7.1	32.3	46.1	3.0	0.0
26	Dickenson County	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
30	Fauquier County	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	Floyd County	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	Frederick County	0.0	15.0	8.6	21.8	12.2	21.1	21.3	0.0
35	Giles County	0.0	35.9	0.0	18.5	31.0	11.1	0.1	3.4
38	Grayson County	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
45	Highland County	0.0	7.7	0.9	9.1	38.3	25.0	19.1	0.0
52	Lee County	0.0	35.0	11.9	11.8	13.0	2.2	5.0	21.0
53	Loudoun County	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	Montgomery County	8.0	26.5	0.0	2.4	16.5	31.7	8.6	1.6
61	Nelson County	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
67	Page County	20.3	14.8	14.4	17.7	6.6	0.8	0.0	0.0
73	Prince William County	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
74	Pulaski County	17.1	35.1	0.0	1.3	4.9	25.5	13.5	2.4
77	Roanoke County	9.9	12.3	1.7	3.0	8.7	20.9	13.1	0.0
78	Rockbridge County	15.6	31.4	15.5	12.9	10.6	8.1	0.2	0.0
79	Rockingham County	9.3	21.8	17.2	10.8	3.8	6.8	27.2	0.0
80	Russell County	0.0	39.2	0.0	8.9	4.3	24.4	1.5	21.7
81	Scott County	0.0	30.8	1.7	2.5	6.0	29.4	2.4	27.1
82	Shenandoah County	0.0	20.3	17.8	20.5	21.0	14.9	5.5	0.0
83	Smyth County	28.3	25.6	1.9	4.2	6.1	22.5	2.5	5.9
89	Tazewell County	0.0	28.8	0.0	14.6	7.2	10.8	1.0	37.6
90	Warren County	10.5	11.0	7.8	33.0	0.6	0.0	0.0	0.0
91	Washington County	6.5	35.5	11.0	11.1	6.7	8.8	1.0	17.6
93	Wise County	0.0	0.0	0.0	0.5	2.7	0.3	3.3	93.1
94	Wythe County	31.5	20.3	1.3	2.4	3.2	31.3	5.2	4.6
98	Bristol	0.0	53.0	40.0	7.0	0.0	0.0	0.0	0.0
99	Buena Vista	91.4	8.6	0.0	0.0	0.0	0.0	0.0	0.0
103	Covington	0.0	0.0	0.0	0.0	16.2	83.8	0.0	0.0

Table 15. Percentages of areas of Virginia localities underlain by different physiographic provinces and rock types.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Percent area in Valley and Ridge							
		Cambrian dolomites	Cambrian-Ordovician limestones	Ordovician dolomite	Ordovician siliciclastics	Silurian siliciclastics and limestones	Devonian siliciclastics	Mississippian siliciclastics	Appalachian Plateau siliciclastics
112	Harrisonburg	0.0	43.4	43.0	13.6	0.0	0.0	0.0	0.0
114	Lexington	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
121	Norton	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
125	Radford	0.0	62.5	0.0	3.1	7.6	26.8	0.0	0.0
127	Roanoke	8.2	20.9	0.9	0.0	0.0	68.4	0.0	0.0
128	Salem	0.0	40.9	0.0	6.0	0.0	53.0	0.0	0.0
129	Staunton	0.0	44.0	43.0	13.0	0.0	0.0	0.0	0.0
132	Waynesboro	43.6	56.4	0.0	0.0	0.0	0.0	0.0	0.0
134	Winchester	0.0	50.3	42.3	7.4	0.0	0.0	0.0	0.0

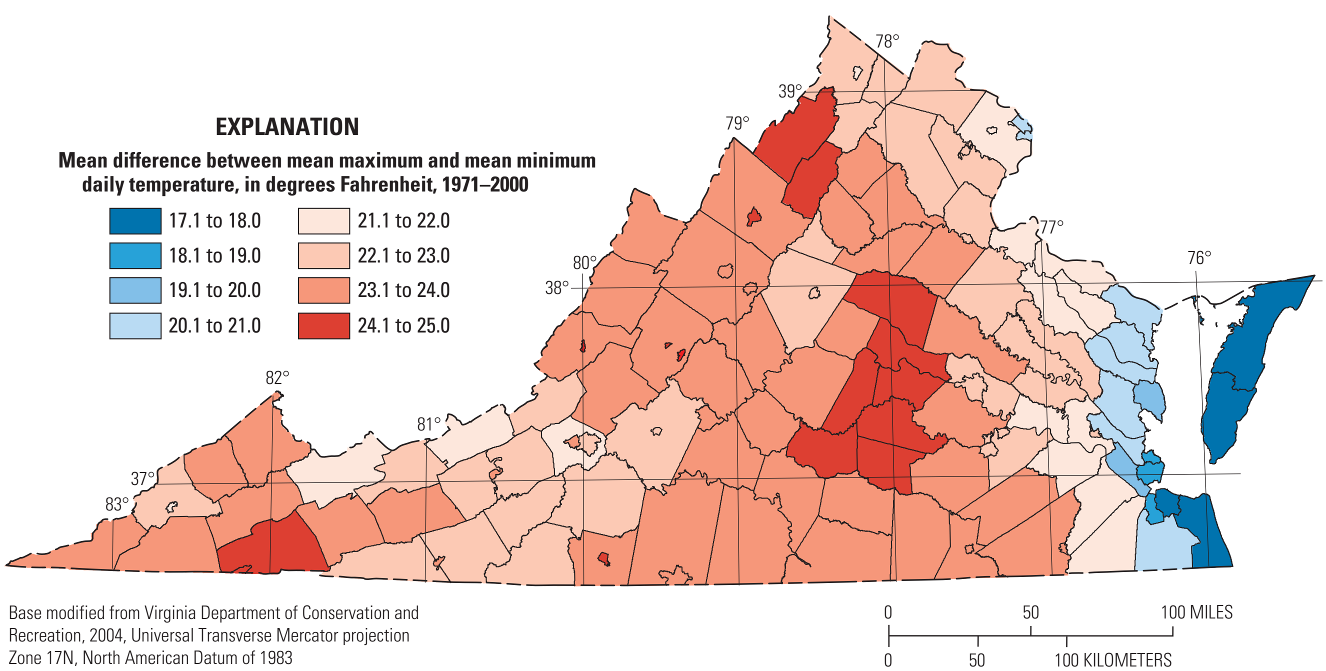


Figure 39. Mean difference between mean maximum and minimum daily temperature in Virginia by locality from 1971 to 2000. See figure 2 for locality names; data compiled from PRISM Climate Group, Oregon State University, Daly and others 2008, accessed July 2008 at *http://www.prism.oregonstate.edu*.

Table 16. Hydrologic budget components estimated for localities in Virginia for this study.

[See figure 2 for map number locations]

Map number	Locality name	Precipitation, in inches	Evapotranspiration: Total, in inches	Evapotranspiration: Total, as percent of precipitation	Evapotranspiration: Estimated riparian, in inches	Runoff: As percent of precipitation	Runoff: In inches	Infiltration, in inches	Recharge, in inches	Net groundwater outflow, in inches	Net total outflow, in inches	Net groundwater outflow, as percent
1	Accomack County	43.0	25.6	59.6	1.9	10.3	4.4	38.6	14.9	13.0	17.4	74.6
2	Albemarle County	46.8	29.3	62.7	1.2	7.0	3.3	43.5	15.4	14.2	17.5	81.2
3	Alleghany County	41.4	25.9	62.6	0.7	16.4	6.8	34.6	9.4	8.7	15.4	56.2
4	Amelia County	44.9	30.6	68.2	1.7	10.6	4.8	40.1	11.2	9.5	14.3	66.6
5	Amherst County	47.2	29.7	62.9	1.1	8.6	4.1	43.1	14.5	13.4	17.5	76.7
6	Appomattox County	45.2	29.5	65.2	1.4	11.6	5.2	40.0	11.9	10.5	15.8	66.7
7	Arlington County	42.7	20.9	48.9	1.0	25.5	10.9	31.8	11.9	10.9	21.8	50.2
8	Augusta County	43.2	26.6	61.5	0.9	11.3	4.9	38.4	12.6	11.8	16.7	70.8
9	Bath County	42.3	25.8	61.0	0.7	14.4	6.1	36.2	11.1	10.4	16.5	63.1
10	Bedford County	45.6	29.2	64.2	1.2	8.3	3.8	41.8	13.7	12.5	16.3	76.7
11	Bland County	41.7	25.2	60.3	0.7	15.1	6.3	35.4	11.0	10.3	16.5	62.1
12	Botetourt County	43.4	27.9	64.3	0.9	12.6	5.5	37.9	10.9	10.0	15.5	64.7
13	Brunswick County	46.0	31.3	68.0	2.0	10.6	4.9	41.1	11.9	9.8	14.7	66.8
14	Buchanan County	46.7	28.6	61.4	0.6	19.8	9.2	37.4	9.4	8.8	18.0	48.8
15	Buckingham County	45.1	30.0	66.5	1.5	11.7	5.3	39.8	11.4	9.8	15.1	65.0
16	Campbell County	44.7	29.3	65.5	1.5	10.5	4.7	40.0	12.2	10.7	15.4	69.5
17	Caroline County	44.0	28.9	65.8	1.6	8.1	3.6	40.4	13.1	11.5	15.1	76.4
18	Carroll County	47.9	28.1	58.7	0.9	5.8	2.8	45.1	17.9	17.0	19.8	85.9
19	Charles City County	45.6	30.3	66.4	2.2	10.0	4.5	41.1	13.0	10.8	15.3	70.3
20	Charlotte County	45.6	30.6	67.0	1.7	11.4	5.2	40.4	11.6	9.8	15.0	65.5
21	Chesterfield County	44.6	29.3	65.8	1.8	12.3	5.5	39.1	11.6	9.8	15.3	64.1
22	Clarke County	39.6	25.6	64.7	1.1	9.4	3.7	35.9	11.4	10.3	14.0	73.4
23	Craig County	43.5	26.3	60.6	0.8	14.8	6.4	37.0	11.5	10.7	17.1	62.5
24	Culpepper County	44.2	29.0	65.6	1.5	9.9	4.4	39.8	12.3	10.8	15.2	71.2
25	Cumberland County	44.9	30.7	68.2	1.7	11.4	5.1	39.8	10.8	9.1	14.3	64.0
26	Dickenson County	47.2	28.6	60.5	0.7	19.9	9.4	37.8	9.9	9.2	18.6	49.6
27	Dinwiddie County	45.6	31.0	68.0	2.1	10.6	4.8	40.8	11.8	9.8	14.6	66.9
28	Essex County	44.4	28.8	65.0	1.8	9.7	4.3	40.0	13.0	11.2	15.5	72.2
29	Fairfax County	43.2	24.9	57.7	1.2	18.4	7.9	35.3	11.6	10.4	18.3	56.6
30	Fauquier County	43.2	27.4	63.5	1.2	9.3	4.0	39.2	13.0	11.7	15.7	74.5
31	Floyd County	47.2	27.4	58.1	0.9	5.6	2.6	44.6	18.0	17.1	19.8	86.6
32	Fluvanna County	43.7	29.5	67.4	1.5	12.1	5.3	38.4	10.5	9.0	14.3	62.8
33	Franklin County	46.0	29.4	63.8	1.2	6.4	3.0	43.1	14.9	13.7	16.6	82.3
34	Frederick County	39.3	24.7	62.9	0.9	12.7	5.0	34.3	10.5	9.6	14.6	65.9
35	Giles County	41.2	24.6	59.8	0.7	7.9	3.3	37.9	14.0	13.3	16.6	80.3

Table 16. Hydrologic budget components estimated for localities in Virginia for this study.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Precipitation, in inches	Evapotranspiration: Total, in inches	Evapotranspiration: Total, as percent of precipitation	Evapotranspiration: Estimated riparian, in inches	Runoff: As percent of precipitation	Runoff: In inches	Infiltration, in inches	Recharge, in inches	Net groundwater outflow, in inches	Net total outflow, in inches	Net groundwater outflow, as percent
36	Gloucester County	46.8	29.7	63.5	2.2	10.2	4.8	42.0	14.5	12.3	17.1	72.1
37	Goochland County	43.6	29.7	68.0	1.6	11.2	4.9	38.7	10.7	9.1	14.0	64.9
38	Grayson County	46.0	26.4	57.3	0.8	7.9	3.6	42.4	16.7	16.0	19.6	81.4
39	Greene County	49.6	29.5	59.4	1.0	7.6	3.8	45.9	17.4	16.4	20.1	81.2
40	Greensville County	45.8	31.4	68.7	2.4	9.8	4.5	41.3	12.2	9.8	14.3	68.5
41	Halifax County	45.6	30.8	67.6	1.8	12.0	5.5	40.1	11.2	9.3	14.8	63.1
42	Hanover County	44.1	29.2	66.4	1.7	9.5	4.2	39.9	12.3	10.6	14.8	71.6
43	Henrico County	44.4	27.9	62.8	1.8	14.6	6.5	37.9	11.9	10.0	16.5	60.8
44	Henry County	47.3	30.6	64.7	1.4	12.7	6.0	41.3	12.0	10.7	16.7	63.9
45	Highland County	43.2	24.3	56.3	0.6	11.6	5.0	38.2	14.4	13.9	18.9	73.4
46	Isle Of Wight County	47.6	30.8	64.7	2.6	9.3	4.4	43.2	15.0	12.4	16.8	73.8
47	James City County	47.3	30.2	63.9	2.0	11.7	5.5	41.8	13.6	11.5	17.1	67.6
48	King and Queen County	45.0	29.9	66.4	1.9	10.0	4.5	40.5	12.5	10.6	15.1	70.1
49	King George County	43.9	28.3	64.5	1.6	9.2	4.0	39.8	13.1	11.5	15.6	74.0
50	King William County	44.6	29.9	66.9	1.8	9.5	4.2	40.4	12.4	10.5	14.8	71.4
51	Lancaster County	46.0	29.0	63.1	1.9	9.2	4.2	41.8	14.7	12.8	17.0	75.1
52	Lee County	52.1	31.5	60.4	1.0	9.1	4.7	47.4	16.9	15.9	20.6	77.1
53	Loudoun County	42.5	26.4	62.1	1.2	12.1	5.1	37.4	12.2	11.0	16.1	68.2
54	Louisa County	44.2	29.6	67.0	1.6	11.7	5.2	39.0	11.0	9.4	14.6	64.4
55	Lunenburg County	45.4	30.6	67.4	1.8	10.5	4.8	40.6	11.8	10.0	14.8	67.7
56	Madison County	47.0	29.0	61.6	1.0	7.0	3.3	43.7	15.8	14.7	18.0	81.7
57	Mathews County	46.7	28.9	61.9	2.3	9.3	4.3	42.3	15.8	13.5	17.8	75.7
58	Mecklenburg County	45.0	30.8	68.4	2.0	10.7	4.8	40.2	11.4	9.4	14.2	66.2
59	Middlesex County	45.9	29.2	63.6	2.0	9.2	4.2	41.6	14.5	12.5	16.7	74.6
60	Montgomery County	40.1	25.1	62.6	0.8	15.1	6.1	34.0	9.7	8.9	15.0	59.6
61	Nelson County	49.1	30.3	61.7	1.0	7.2	3.5	45.6	16.3	15.3	18.8	81.2
62	New Kent County	45.4	30.1	66.3	1.8	10.7	4.8	40.5	12.3	10.5	15.3	68.3
63	Northampton County	44.7	26.8	60.0	2.3	7.4	3.3	41.4	16.8	14.5	17.9	81.4
64	Northumberland County	45.2	28.6	63.2	1.8	9.2	4.1	41.1	14.4	12.5	16.7	75.1
65	Nottoway County	45.5	30.6	67.2	1.7	10.8	4.9	40.5	11.7	10.0	14.9	67.0
66	Orange County	44.6	29.1	65.1	1.4	9.4	4.2	40.4	12.8	11.4	15.6	73.0
67	Page County	43.3	27.5	63.6	0.9	9.6	4.2	39.1	12.5	11.6	15.7	73.6
68	Patrick County	52.2	31.1	59.6	1.1	7.5	3.9	48.3	18.3	17.2	21.1	81.5
69	Pittsylvania County	45.6	30.3	66.4	1.7	12.3	5.6	39.9	11.4	9.7	15.3	63.3
70	Powhatan County	43.7	29.8	68.2	1.6	10.9	4.7	39.0	10.7	9.1	13.9	65.8

Table 16. Hydrologic budget components estimated for localities in Virginia for this study.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Precipitation, in inches	Evapotranspiration			Runoff		Infiltration, in inches	Recharge, in inches	Net groundwater outflow, in inches	Net total outflow, in inches	Net groundwater outflow, as percent
			Total, in inches	Total, as percent of precipitation	Estimated riparian, in inches	As percent of precipitation	In inches					
71	Prince Edward County	45.3	30.4	67.2	1.6	11.4	5.2	40.1	11.3	9.7	14.9	65.3
72	Prince George County	45.6	30.7	67.3	2.3	11.5	5.3	40.3	12.0	9.7	14.9	64.8
73	Prince William County	43.0	26.8	62.2	1.3	15.5	6.7	36.4	10.9	9.6	16.3	59.0
74	Pulaski County	39.6	25.1	63.4	0.8	14.5	5.7	33.8	9.6	8.8	14.5	60.4
75	Rappahannock County	46.1	28.6	62.1	1.0	8.0	3.7	42.4	14.8	13.8	17.5	78.9
76	Richmond County	44.4	28.6	64.5	1.8	9.8	4.3	40.0	13.2	11.4	15.7	72.5
77	Roanoke County	43.3	26.3	60.7	0.8	15.3	6.6	36.7	11.2	10.4	17.0	61.0
78	Rockbridge County	45.5	28.4	62.3	0.9	9.7	4.4	41.1	13.6	12.7	17.2	74.2
79	Rockingham County	40.2	25.7	63.8	0.8	10.7	4.3	35.9	11.0	10.2	14.5	70.3
80	Russell County	46.2	27.9	60.3	0.8	13.2	6.1	40.1	13.0	12.2	18.3	66.8
81	Scott County	49.4	30.4	61.6	0.9	14.7	7.3	42.2	12.6	11.7	19.0	61.7
82	Shenandoah County	39.2	26.1	66.5	0.9	9.5	3.7	35.4	10.3	9.4	13.1	71.5
83	Smyth County	47.0	27.6	58.8	0.8	15.1	7.1	39.9	13.0	12.3	19.3	63.3
84	Southampton County	47.1	32.3	68.6	2.8	9.5	4.5	42.6	13.1	10.3	14.8	69.7
85	Spotsylvania County	43.6	28.8	66.2	1.5	11.0	4.8	38.8	11.5	9.9	14.7	67.5
86	Stafford County	43.0	27.7	64.3	1.4	10.8	4.6	38.4	12.1	10.7	15.4	69.9
87	Surry County	46.8	30.8	65.9	2.2	10.6	5.0	41.9	13.2	11.0	16.0	69.0
88	Sussex County	46.4	31.7	68.4	2.4	11.0	5.1	41.3	12.0	9.5	14.7	65.0
89	Tazewell County	46.0	26.1	56.7	0.7	13.5	6.2	39.8	14.4	13.7	19.9	68.7
90	Warren County	41.2	26.1	63.3	0.9	9.0	3.7	37.5	12.4	11.4	15.1	75.5
91	Washington County	46.8	29.1	62.1	0.9	10.5	4.9	41.9	13.8	12.9	17.8	72.4
92	Westmoreland County	44.3	28.4	64.2	1.7	9.5	4.2	40.1	13.4	11.7	15.8	73.6
93	Wise County	51.3	29.0	56.5	0.8	19.6	10.0	41.2	13.0	12.3	22.3	55.0
94	Wythe County	40.3	25.3	62.8	0.8	17.7	7.1	33.1	8.6	7.8	15.0	52.2
95	York County	47.6	29.5	61.9	2.2	11.4	5.4	42.2	14.9	12.7	18.1	70.2
96	Alexandria	41.8	19.1	45.6	0.9	28.6	12.0	29.8	11.7	10.8	22.8	47.4
97	Bedford	45.0	25.7	57.0	1.2	18.5	8.3	36.7	12.3	11.1	19.4	57.1
98	Bristol	46.3	25.3	54.6	1.0	16.0	7.4	38.9	14.7	13.6	21.0	64.9
99	Buena Vista	41.4	26.7	64.5	1.1	27.2	11.3	30.1	4.5	3.4	14.7	23.2
100	Charlottesville	46.5	23.1	49.6	1.1	19.9	9.3	37.3	15.2	14.2	23.4	60.5
101	Chesapeake	47.6	29.9	62.8	2.8	12.2	5.8	41.8	14.7	11.9	17.7	67.1
102	Colonial Heights	44.9	26.3	58.6	1.9	18.9	8.5	36.4	12.0	10.1	18.6	54.4
103	Covington	37.0	21.4	57.9	0.8	38.9	14.4	22.6	2.0	1.2	15.6	7.8
104	Danville	45.3	27.7	61.2	1.6	20.2	9.2	36.2	10.1	8.4	17.6	47.9
105	Emporia	45.1	28.6	63.4	2.1	17.7	8.0	37.1	10.6	8.5	16.5	51.5

Table 16. Hydrologic budget components estimated for localities in Virginia for this study.—Continued

[See figure 2 for map number locations]

Map number	Locality name	Precipitation, in inches	Evapotranspiration			Runoff		Infiltration, in inches	Recharge, in inches	Net groundwater outflow, in inches	Net total outflow, in inches	Net groundwater outflow, as percent
			Total, in inches	Total, as percent of precipitation	Estimated riparian, in inches	As percent of precipitation	In inches					
106	Fairfax	44.2	22.4	50.6	1.1	26.1	11.5	32.6	11.3	10.3	21.8	47.1
107	Falls Church	43.9	22.5	51.4	1.1	24.9	10.9	32.9	11.5	10.4	21.3	48.7
108	Franklin	47.8	30.5	63.8	2.7	13.7	6.6	41.2	13.4	10.8	17.3	62.1
109	Fredericksburg	42.7	24.8	58.2	1.2	17.2	7.4	35.3	11.7	10.5	17.9	58.8
110	Galax	44.3	24.6	55.6	0.8	11.5	5.1	39.2	15.4	14.6	19.7	74.2
111	Hampton	47.2	24.7	52.4	2.1	20.1	9.5	37.7	15.1	13.0	22.4	57.8
112	Harrisonburg	36.4	20.1	55.2	0.8	20.8	7.6	28.8	9.5	8.7	16.3	53.5
113	Hopewell	44.9	26.7	59.4	2.0	18.6	8.3	36.6	11.9	9.9	18.2	54.3
114	Lexington	41.1	23.1	56.1	1.0	16.6	6.8	34.3	12.2	11.2	18.0	62.2
115	Lynchburg	44.4	25.6	57.7	1.2	14.2	6.3	38.1	13.7	12.5	18.8	66.5
116	Manassas	43.1	22.4	51.9	1.2	30.7	13.2	29.9	8.7	7.5	20.7	36.1
117	Manassas Park	43.1	22.7	52.5	1.1	29.6	12.7	30.4	8.8	7.7	20.5	37.7
118	Martinsville	46.1	26.4	57.3	1.2	22.7	10.5	35.7	10.4	9.2	19.7	46.9
119	Newport News	47.3	25.4	53.7	2.1	19.8	9.4	38.0	14.7	12.6	21.9	57.3
120	Norfolk	46.8	21.8	46.6	1.9	26.8	12.5	34.2	14.3	12.4	25.0	49.8
121	Norton	55.3	26.9	48.6	0.8	27.2	15.0	40.2	14.1	13.4	28.4	47.1
122	Petersburg	45.0	27.6	61.3	2.0	18.4	8.3	36.7	11.1	9.1	17.4	52.3
123	Poquoson	47.2	27.8	59.0	2.4	13.1	6.2	41.1	15.7	13.2	19.4	68.2
124	Portsmouth	47.2	23.9	50.6	2.1	22.6	10.7	36.5	14.7	12.6	23.3	54.1
125	Radford	38.1	22.6	59.2	0.8	17.5	6.7	31.5	9.7	8.9	15.6	57.0
126	Richmond	44.4	24.4	54.9	1.5	22.0	9.8	34.6	11.7	10.2	20.0	51.1
127	Roanoke	42.7	21.4	50.1	0.9	38.5	16.4	26.3	5.8	4.9	21.3	22.8
128	Salem	41.6	21.3	51.2	1.0	33.6	14.0	27.6	7.2	6.3	20.3	31.0
129	Staunton	38.6	23.1	59.8	0.9	13.4	5.2	33.5	11.3	10.4	15.5	66.7
130	Suffolk	48.3	31.1	64.5	2.7	10.1	4.9	43.4	15.0	12.3	17.2	71.6
131	Virginia Beach	46.1	26.4	57.1	2.6	14.9	6.9	39.3	15.5	12.9	19.8	65.2
132	Waynesboro	44.0	23.6	53.8	1.0	22.5	9.9	34.0	11.4	10.4	20.3	51.2
133	Williamsburg	48.2	29.1	60.4	1.9	14.6	7.0	41.1	13.9	12.0	19.1	63.1
134	Winchester	38.8	19.0	49.0	0.8	21.6	8.4	30.4	12.1	11.4	19.8	57.5

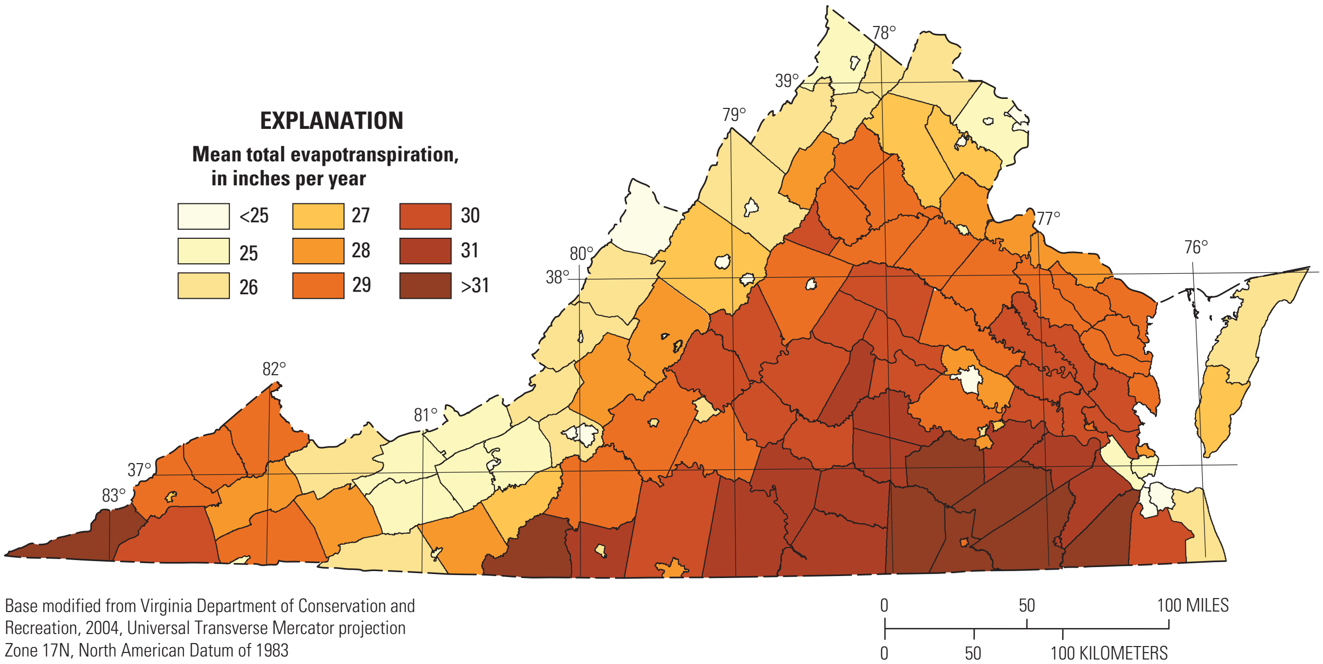


Figure 40. Mean annual total evapotranspiration in Virginia by locality, estimated by regression. See figure 2 for locality names.

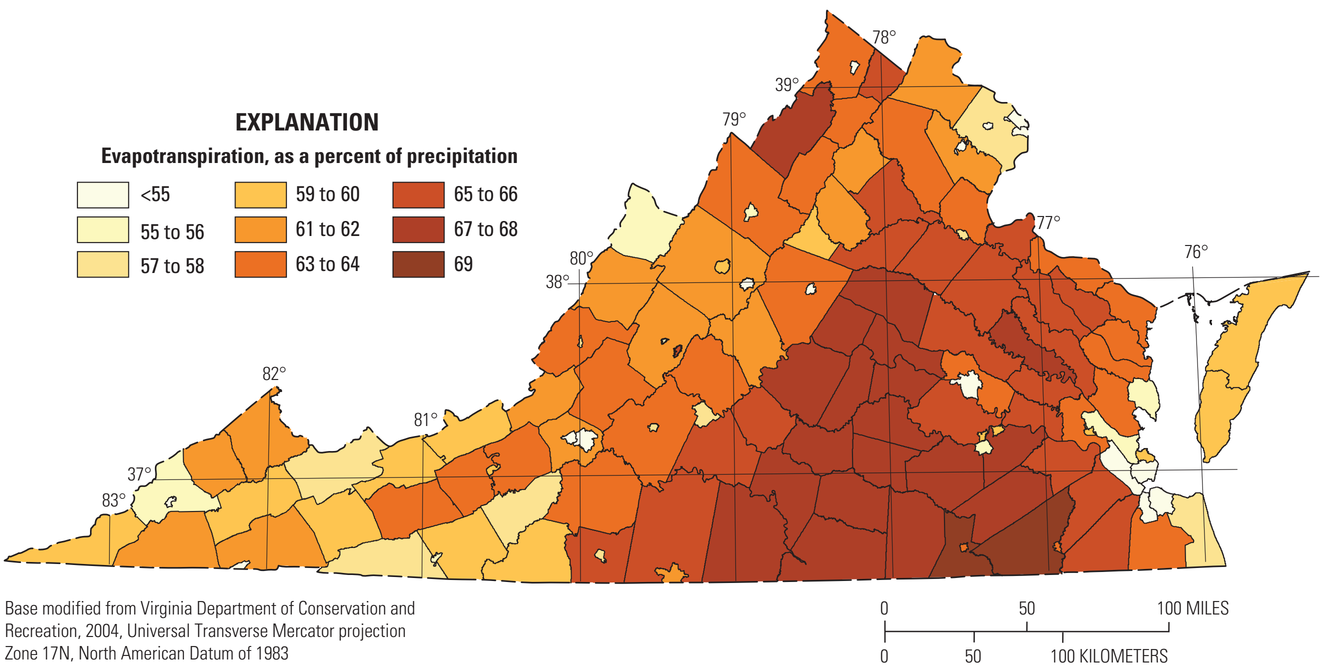


Figure 41. Mean annual percentage of precipitation lost to evapotranspiration in Virginia by locality. See figure 2 for locality names.

Riparian Evapotranspiration

Use of the seasonal SC estimates to estimate ET_{rp} on a local basis proved difficult because there was not an obvious spatial trend in the data (fig. 34). Therefore a third method was used in which three factors—the amount of riparian vegetation present, the mean annual air temperature, and the topographic relief—were used to estimate the ET_{rp}. The first factor was an indicator of the amount of riparian seepage present, and was represented by the percent marsh (or wetland) in the locality in the USGS National Land Cover Database. The second factor related to the intensity of the total ET in the watershed, and the third factor represented the relative width of the floodplains likely to occur in the locality. By including the temperature and slope rather than using the percent marsh alone, a more consistently varying estimate of ET_{rp} was developed across

Virginia. A correlation was established (R2=0.8462) between the fraction of land cover in the locality that is marsh and the slope and temperature (fig. 42), using the relation:

$$Log\ (FM) = 0.167*T - 0.067*S - 11.085, \qquad (17)$$

where

- *FM* is the fraction of land cover that is marsh,
- *T* is the mean air temperature (°F), and
- *S* is the topographic grade (dimensionless).

The riparian ET was then calculated using the formula:

$$ET_{rp} = -0.115*PS/log(FM), \qquad (18)$$

where

- *PS* is the fraction of nonimpervious surface in the locality.

The constant in this equation was adjusted such that the mean ET_{rp} of the localities was the same as that obtained for the watersheds in the other two estimates (fig. 35). This method also created a range of ET_{rp} similar to that produced by the other two methods. The uncertainty in the estimate of ET_{rp} for any given locality is relatively high compared to the magnitude of ET_{rp}, but given that the magnitude of ET_{rp} is small relative to other budget components, such as the total ET and the groundwater discharge, the effect of this uncertainty on the estimate of total recharge (which is calculated by adding the ET_{rp} to the base flow, or effective recharge) is relatively small.

The values estimated using equations 17 and 18 are strongly affected by the mean annual air temperature and topographic relief present in each locality (fig. 43). The values represent an estimate of the mean annual riparian ET for the

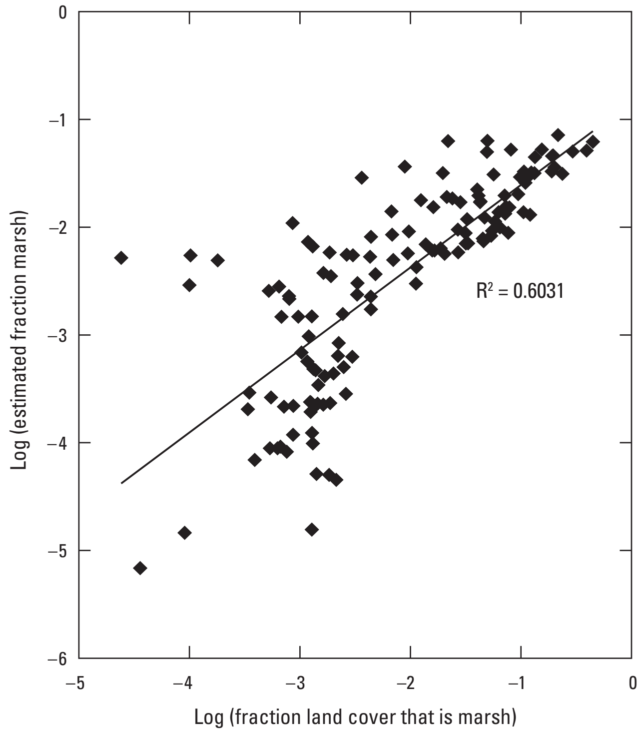


Figure 42. Comparison of fraction of locality land cover that is marsh and that estimated using temperature and topographic slope.

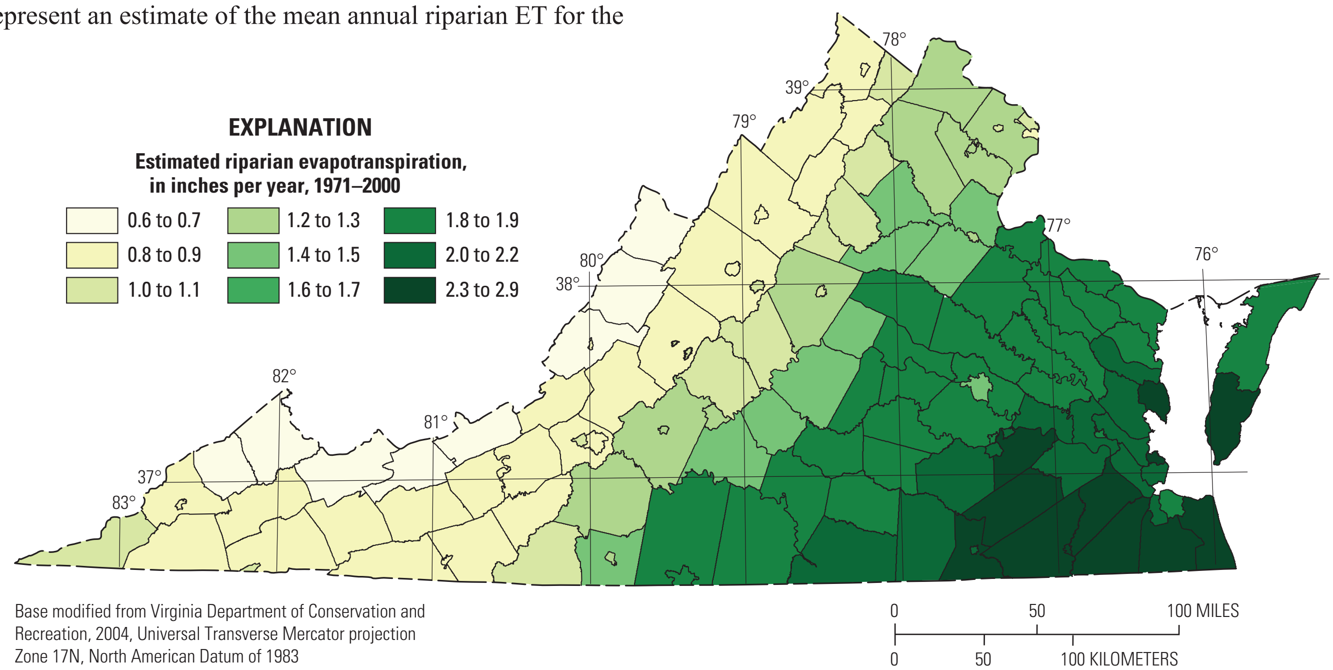


Figure 43. Estimates of mean annual riparian evapotranspiration in Virginia by locality from 1971 to 2000. See figure 2 for locality names.

entire area of the locality (not the local ET rate in the riparian zone itself). The lowest values are less than one in/yr and are consistently found across the Valley and Ridge Province. Counties in the Blue Ridge province and vicinity of Washington D.C. have values that range 1.0 to 1.4 in/yr. Values in the Piedmont Province and the northern counties of the Coastal Plain range between 1.5 and 1.9 in/yr, whereas values in southeastern Virginia and the Tidewater area are between 2 and 3 in/yr. These values all have an uncertainty associated with them that we estimate to be plus or minus one in/yr, based on the range of values that have been estimated by other methods (fig. 35).

Net Total Outflow

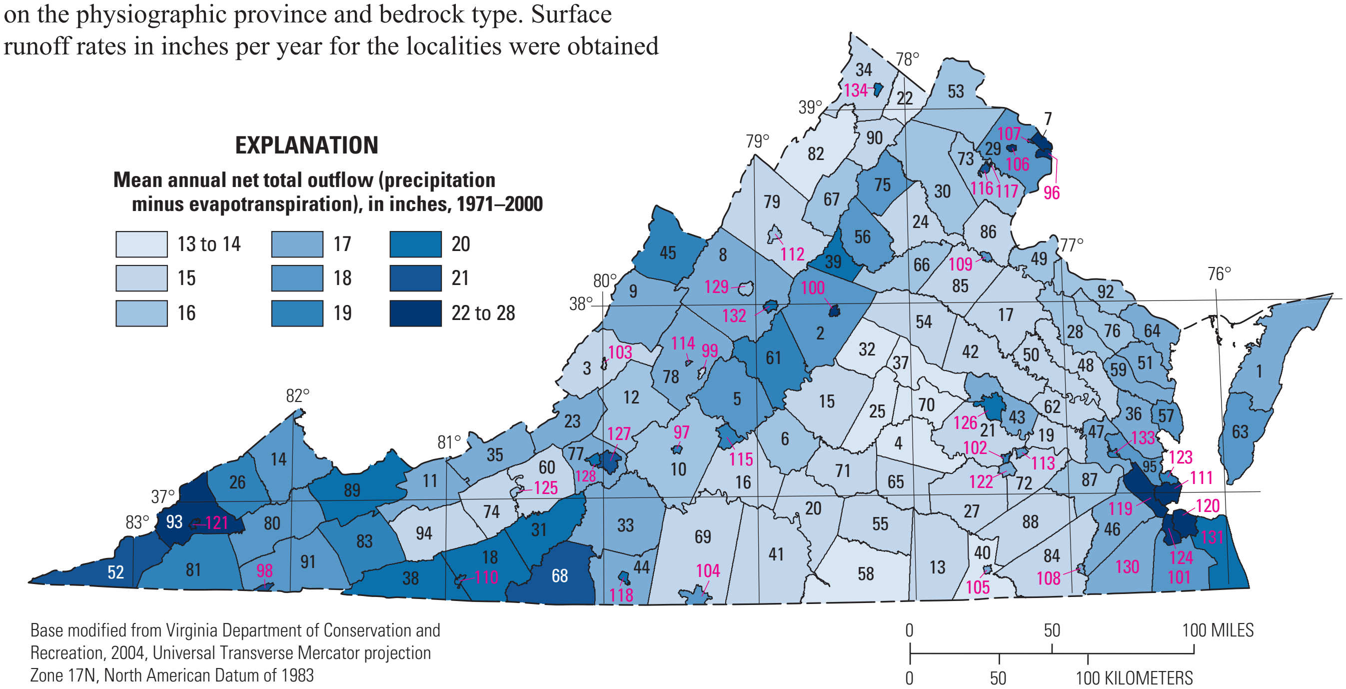
The equivalent of total streamflow for a locality is the net total outflow (table 1), which was calculated by subtracting the estimated mean annual total ET from the mean annual precipitation. This term has also been referred to as the available precipitation, because it is the fraction of precipitation that is available in terms of surface water or groundwater. Results (fig. 44) indicate that the net total outflow varies from about 13 to 14 inches (in.) in the Shenandoah Valley and Piedmont of central and southern Virginia to over 20 in. in the mountains of southwestern Virginia and the tidal regions of southeastern Virginia.

Surface Runoff

Surface runoff regression equations (table 12) were used to predict the ratio of surface runoff to precipitation based on the physiographic province and bedrock type. Surface runoff rates in inches per year for the localities were obtained by multiplying the mean annual precipitation rate (fig. 5) by the runoff ratio. The percent of precipitation that rapidly runs off is estimated to range between 6 and 39 percent, based on locality in Virginia (fig. 45). Values less than 10 percent occur typically in the Blue Ridge Province or sections of the Coastal Plain where sandy soils are prevalent. Values greater than 20 percent occur in the Appalachian Plateau in southwestern Virginia, and in independent cities where there is a relatively large fraction of impervious surface. The distribution by locality of mean annual surface runoff values (fig. 46) generally reflects the locality distribution of the fraction of precipitation that runs off (fig. 45). Values of 3 or 4 in/yr occur typically in the Blue Ridge or Coastal Plain. The carbonate rocks in the Shenandoah can produce similarly low values because precipitation is also relatively low there. Values of 9 in/yr or greater occur typically in the Appalachian Plateau and in the independent cities.

Net Groundwater Discharge

The term, base flow, was used for the watersheds to indicate the groundwater discharge from that watershed to the stream, with the assumption that the groundwater discharge across the watershed divide was negligible. Counties and cities, however, have political boundaries that frequently do not align with subsurface watershed boundaries, resulting in the potential for substantial discharge of groundwater from those localities that is not base flow to streams. For example, in some small independent cities there are no prominent streams, and in some counties along the Chesapeake Bay much of the groundwater may discharge directly to the bay or coastal



Base modified from Virginia Department of Conservation and Recreation, 2004, Universal Transverse Mercator projection Zone 17N, North American Datum of 1983

Figure 44. Amount and distribution of net total outflow (precipitation minus evapotranspiration) in Virginia by locality from 1971 to 2000. (See figure 2 for locality names and table 16 for a detailed breakdown of hydrologic budget components by locality.)

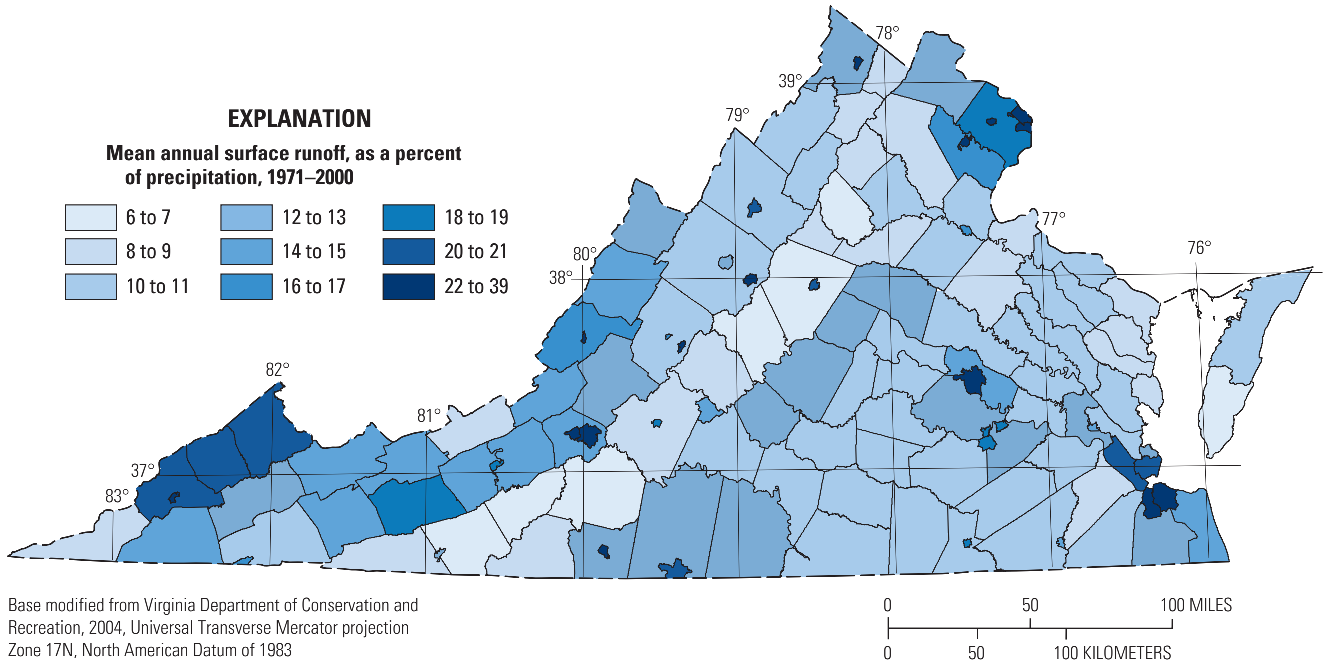


Figure 45. Estimates of mean annual runoff as a percentage of precipitation in Virginia by locality from 1971 to 2000. See figure 2 for locality names.

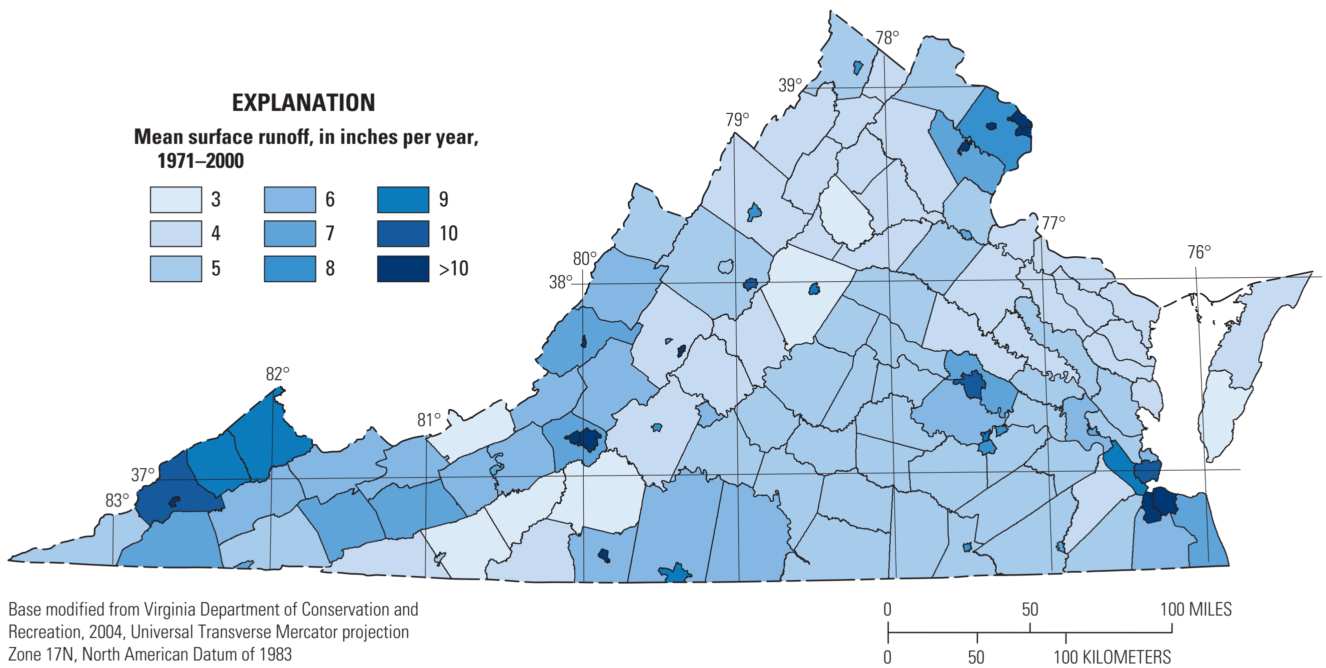


Figure 46. Estimates of mean annual surface runoff in Virginia by locality from 1971 to 2000. See figure 2 for locality names.

marshes. Both the inflow and outflow of groundwater across non-stream locality boundaries may be substantial, but only the net discharge (groundwater outflow minus inflow) is created by recharge within the locality, and is of concern in this study. Therefore, when describing discharge of groundwater from localities, the term "net groundwater discharge" is used rather than "base flow", although much of that discharge may actually occur as base flow. The estimated net groundwater discharge for the localities is calculated by subtracting the estimated surface runoff from the net total outflow.

The net groundwater discharge for the localities varies from less than 9 in/yr to approximately 16 in/yr (fig. 47). The lower values (10 in/yr or less) occur either in the regions of western Virginia where precipitation is low or surface runoff is high, or in the Piedmont Province where total ET is relatively high. Alternatively, the high values (15 in/yr or greater) occur typically either in the Blue Ridge Province where precipitation

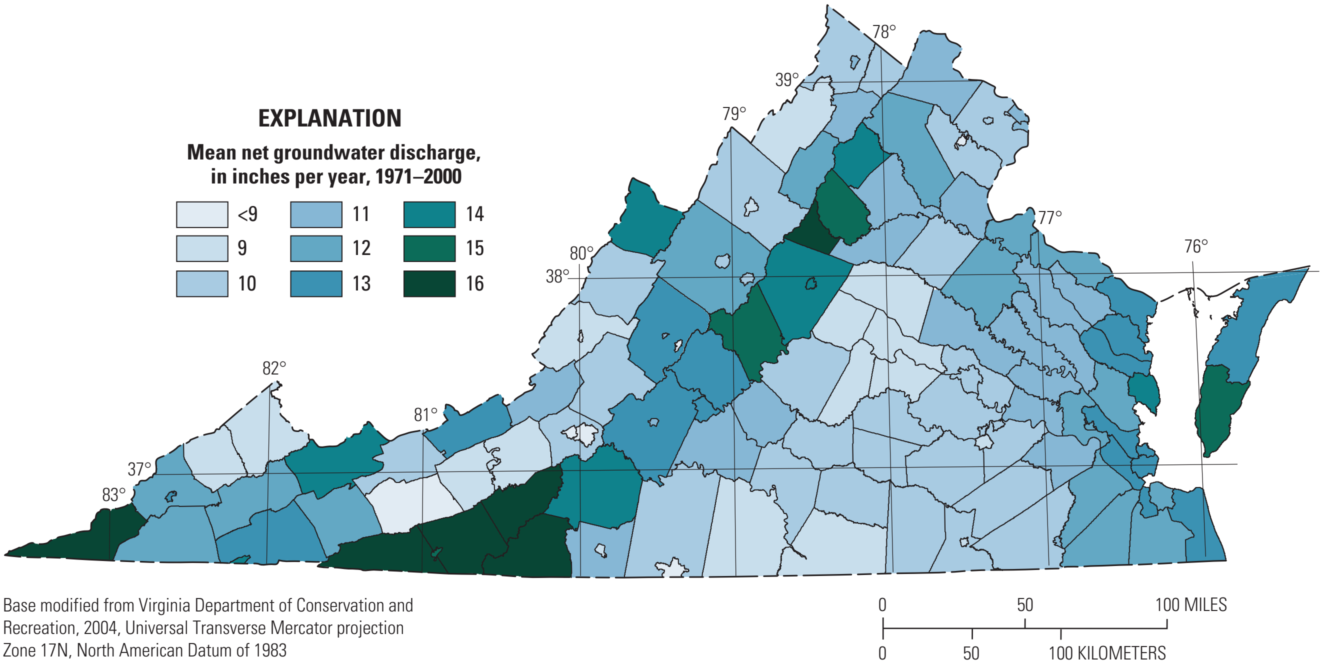


Figure 47. Mean annual net groundwater discharge in Virginia by locality from 1971 to 2000. See figure 2 for locality names.

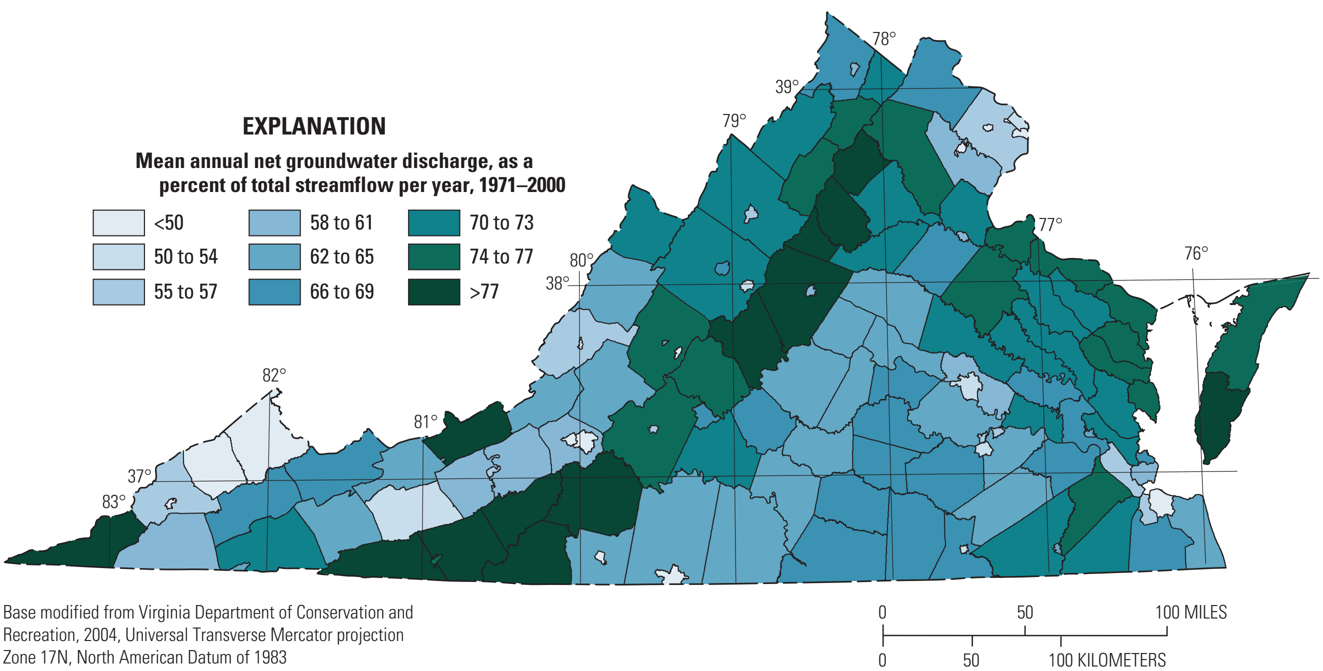


Figure 48. Mean annual net groundwater discharge as a percentage of total streamflow in Virginia by locality from 1971 to 2000. See figure 2 for locality names.

is high and surface runoff is low, or in counties where precipitation is highest, such as Lee and Patrick Counties of southwestern Virginia. Another way to evaluate the net groundwater discharge is to estimate its value as a percentage of the net total outflow from a locality (fig. 48). The remainder of the net total outflow is by shallow rapid runoff processes. The percentage of net total outflow that is net groundwater discharge is the equivalent of a base-flow index for a watershed. The areas where the percent net groundwater discharge is low (less than 60 percent) are typically in areas of high surface runoff (the Appalachian Plateau and areas with a highly impervious surface). The areas where this value is high (75 percent or greater) are those with low surface runoff (the sandy soil regions of the Blue Ridge Province and Coastal Plain).

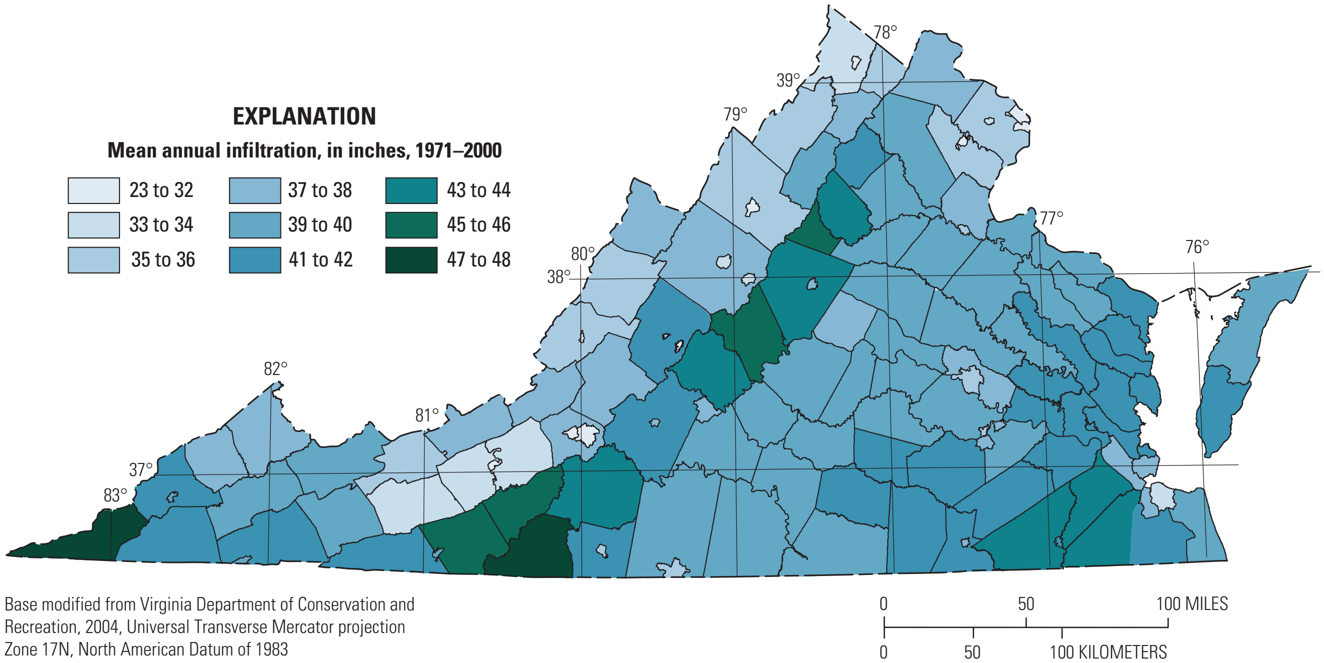


Figure 49. Estimates of mean annual infiltration in Virginia by locality from 1971 to 2000. See figure 2 for locality names.

Infiltration

This mean annual infiltration rate is calculated for the localities by subtracting the surface runoff from the precipitation (fig. 49). For this difference to represent actual infiltration, evaporation from ponded surface water must be negligible, which we believe to be the case for most localities. For localities where may not be the case (where there are large volumes of impounded water), this term includes the evaporation from ponded surface water. The rate is lowest (less than 38 in/yr) typically in the Valley and Ridge Province and in areas of high impervious surface. The rate is highest (greater than 42 in/yr) in areas of high precipitation or sandy soil (such as the Blue Ridge Province). A large fraction of infiltration is subsequently lost to vadose ET (fig. 10); the remainder is groundwater recharge.

Groundwater Recharge

The recharge rate to groundwater is important when planning for long-term groundwater resource use in any region. The first process that leads to groundwater recharge is the infiltration of rainfall into the ground. The recharge for the localities was calculated by subtracting the vadose zone ET from the infiltration. The vadose zone ET is defined here as the total ET minus the riparian ET. The exact equivalent value for recharge can be arrived at by adding the riparian ET to the groundwater discharge (fig. 50). The localities with the lowest mean recharge rates (10 in/yr or less) are those in western Virginia in the Valley and Ridge or Appalachian Plateau where siliciclastic bedrock is present. The localities with the highest recharge (15 in/yr or more) are in the Blue Ridge Province, or where precipitation is high, or where ET is relatively low (the coastal localities).

Water Use

One component of groundwater or surface water discharge from the localities is extracted for human use. These extraction rates for the localities of Virginia have been tabulated in previous water-use studies. Data were taken from the latest such study (Kenney and others, 2009) and compiled in Table 17. Values of groundwater or surface water extraction are often represented as millions of gallons per day (Mgal/d), but in this study, for comparison to the net total outflow in each locality, these values were multiplied by 365 and divided by the area of the locality to convert them to inches per year (fig. 51). For most localities this extracted water is a very small fraction of the net total outflow (less than 0.5 in/yr out of 15–20 in/yr). In some localities total fresh-water use is a small, but not insignificant (1–5 in/yr out of 15–20 in/yr), fraction of the total outflow. Typically total freshwater use is a substantial fraction (>5 out of 15–20 in/yr) of that available per area of the locality only in the most populous areas. These highly populated localities usually import water from other regions, usually through surface water diversions. In the Coastal Plain, much of the water used is extracted from storage in deep confined coastal plain aquifers and has minimal impact on the other hydrologic components calculated. The water used is discharged to local streams and Bay estuaries.

Table 17. Freshwater use in Virginia by locality in 2005.

[Data from Kenney and others, 2009; see figure 2 for map locations; Mgal/d, million gallons per day; —, not applicable]

Map number	Locality name	Area, in square miles	Groundwater withdrawals, in Mgal/d (unless noted otherwise)				Surface-water withdrawals, in Mgal/d (unless noted otherwise)				Total withdrawals	
			Public supply	Domestic	Industrial	Total, in inches	Public supply	Domestic	Industrial	Total, in inches	Mgal/d	Inches
1	Accomack County	463.5	1.47	1.48	3.31	0.44	0.00	1.47	0.00	0.10	11.5	0.54
2	Albemarle County	726.3	0.05	3.18	0.04	0.11	10.92	3.62	0.00	0.35	15.5	0.46
3	Alleghany County	448.3	0.12	0.75	0.98	0.09	3.99	0.50	40.85	2.17	47.1	2.26
4	Amelia County	358.4	0.00	0.70	0.01	0.05	0.00	0.22	0.00	0.03	1.4	0.09
5	Amherst County	478.9	0.00	1.02	0.01	0.05	11.55	1.39	6.12	0.81	19.1	0.86
6	Appomattox County	336.1	0.98	0.89	0.02	0.13	0.00	0.16	0.00	0.02	2.3	0.15
7	Arlington County	26.1	0.00	0.00	0.00	0.02	0.00	14.70	0.00	0.09	0.1	0.12
8	Augusta County	972.9	5.61	2.50	2.09	0.24	2.30	2.73	0.00	0.68	41.3	0.91
9	Bath County	535.0	0.24	0.20	0.97	0.06	0.00	0.17	0.00	10.37	259.2	10.43
10	Bedford County	769.2	0.07	3.24	0.01	0.14	3.29	1.65	9.31	0.38	18.5	0.52
11	Bland County	358.2	0.20	0.32	0.00	0.04	0.00	0.20	0.12	0.02	1.0	0.06
12	Botetourt County	545.7	0.97	1.30	0.06	0.10	16.20	1.10	0.00	0.65	19.0	0.75
13	Brunswick County	570.3	0.00	0.95	0.00	0.04	24.62	0.39	0.00	1.01	27.6	1.04
14	Buchanan County	498.7	0.00	0.56	0.00	0.03	0.00	1.30	0.42	0.03	1.4	0.06
15	Buckingham County	584.0	0.00	0.76	0.00	0.04	0.45	0.45	0.00	0.06	2.5	0.09
16	Campbell County	506.0	0.31	2.04	0.10	0.11	2.96	1.89	2.00	0.32	9.9	0.42
17	Caroline County	537.0	0.53	1.00	0.42	0.09	0.39	0.92	2.45	0.14	5.6	0.23
18	Carroll County	477.4	0.54	1.29	0.00	0.10	0.38	0.92	0.00	0.04	3.1	0.14
19	Charles City County	182.9	0.06	0.47	0.01	0.06	0.00	0.06	0.12	0.06	1.1	0.13
20	Charlotte County	477.8	0.13	0.67	0.00	0.04	0.15	0.26	0.00	0.04	1.7	0.08
21	Chesterfield County	434.2	0.00	2.46	0.20	0.13	39.99	19.20	55.26	4.81	99.6	4.94
22	Clarke County	178.4	0.10	0.73	0.00	0.12	0.43	0.34	0.08	0.10	1.8	0.22
23	Craig County	328.8	0.09	0.29	0.00	0.03	0.00	0.09	0.00	0.00	0.5	0.03
24	Culpepper County	383.1	0.10	1.76	0.00	0.11	2.00	1.43	0.08	0.16	4.7	0.27
25	Cumberland County	300.8	0.00	0.69	0.00	0.06	1.03	0.01	0.00	0.10	2.1	0.15
26	Dickenson County	332.9	0.00	0.68	0.00	0.05	4.02	0.54	0.00	0.31	5.5	0.36
27	Dinwiddie County	508.0	0.00	1.29	0.01	0.07	0.00	0.62	0.00	0.02	2.0	0.08
28	Essex County	265.7	0.37	0.53	0.01	0.08	0.00	0.26	0.00	0.01	1.1	0.09
29	Fairfax County	402.3	0.16	3.81	0.08	0.23	258.9	71.68	0.03	13.92	264.4	14.16
30	Fauquier County	653.1	1.77	2.36	0.00	0.14	1.36	2.51	0.00	0.08	6.9	0.23
31	Floyd County	381.4	0.18	0.92	0.00	0.07	0.00	0.18	0.00	0.04	1.9	0.10
32	Fluvanna County	290.5	1.12	0.74	0.00	0.14	0.00	1.12	0.00	0.01	2.1	0.16
33	Franklin County	711.4	0.22	2.70	0.00	0.09	0.92	1.08	0.00	0.07	5.2	0.16
34	Frederick County	414.8	0.31	2.31	0.05	0.15	4.00	2.88	0.00	0.23	7.3	0.38
35	Giles County	359.9	1.24	0.55	10.67	0.75	0.00	0.73	56.48	3.49	71.0	4.25

Table 17. Freshwater use in Virginia by locality in 2005.—Continued

[Data from Kenney and others, 2009; see figure 2 for map locations; Mgal/d, million gallons per day; —, not applicable]

Map number	Locality name	Area, in square miles	Groundwater withdrawals, in Mgal/d (unless noted otherwise)				Surface-water withdrawals, in Mgal/d (unless noted otherwise)				Total withdrawals	
			Public supply	Domestic	Industrial	Total, in inches	Public supply	Domestic	Industrial	Total, in inches	Mgal/d	Inches
36	Gloucester County	219.0	0.00	2.15	0.00	0.22	0.69	0.68	0.00	0.07	2.9	0.29
37	Goochland County	287.6	0.00	0.76	0.00	0.06	0.00	0.69	0.00	0.14	2.8	0.21
38	Grayson County	445.7	0.25	0.98	0.00	0.08	0.00	0.25	0.07	0.03	2.2	0.11
39	Greene County	156.8	0.00	0.63	0.02	0.09	0.00	0.67	0.00	0.02	0.8	0.12
40	Greensville County	297.3	0.03	0.58	0.00	0.04	0.00	0.25	1.58	0.29	4.6	0.33
41	Halifax County	829.8	0.10	1.78	0.01	0.05	1.77	0.94	0.00	0.08	5.0	0.13
42	Hanover County	474.5	5.89	1.41	0.09	0.34	0.00	5.89	0.72	0.14	10.5	0.47
43	Henrico County	240.7	0.05	4.45	0.24	0.42	22.74	16.60	0.00	2.57	33.5	2.99
44	Henry County	383.7	0.04	1.90	0.01	0.34	4.86	2.34	1.99	0.42	13.6	0.76
45	Highland County	415.5	0.09	0.14	6.44	0.35	0.00	0.05	0.00	0.45	15.5	0.80
46	Isle of Wight County	322.2	1.23	1.25	34.46	2.47	0.15	1.25	4.09	0.34	42.2	2.82
47	James City County	143.3	3.40	0.99	0.11	0.70	6.26	3.33	0.00	1.04	11.6	1.74
48	King and Queen County	314.5	0.02	0.49	0.00	0.03	0.00	0.02	0.00	0.02	0.8	0.05
49	King George County	178.5	1.28	0.27	0.31	0.23	0.00	1.28	0.00	0.22	3.7	0.45
50	King William County	273.0	0.53	0.70	17.57	1.49	0.00	0.41	0.00	0.06	19.6	1.55
51	Lancaster County	135.5	0.50	0.37	0.03	0.17	0.00	0.50	0.00	0.00	1.1	0.17
52	Lee County	437.1	0.35	0.96	0.00	0.10	1.40	0.82	0.00	0.09	3.8	0.19
53	Loudoun County	522.1	1.21	2.55	0.11	0.18	4.62	16.61	0.00	0.26	10.7	0.44
54	Louisa County	511.4	0.15	1.78	0.00	0.09	0.32	0.47	0.00	0.03	2.7	0.11
55	Lunenburg County	432.8	0.00	0.74	0.00	0.04	0.57	0.25	0.00	0.06	2.0	0.10
56	Madison County	322.1	0.00	0.86	0.04	0.07	1.77	0.14	0.00	0.15	3.2	0.21
57	Mathews County	85.3	0.00	0.65	0.00	0.17	0.00	0.04	0.00	0.00	0.7	0.17
58	Mecklenburg County	679.6	0.18	1.39	0.01	0.05	1.46	1.05	0.00	0.10	4.9	0.15
59	Middlesex County	132.9	0.20	0.58	0.01	0.14	0.00	0.20	0.00	0.03	1.0	0.16
60	Montgomery County	388.6	0.06	1.38	0.04	0.09	6.91	4.94	26.09	1.87	35.3	1.96
61	Nelson County	474.2	0.24	0.77	0.05	0.14	0.00	0.36	0.97	0.07	4.8	0.22
62	New Kent County	207.2	0.37	0.52	1.37	0.23	28.75	0.69	0.00	3.02	31.3	3.25
63	Northampton County	217.5	0.37	0.71	0.16	0.24	0.00	0.30	0.00	0.11	3.6	0.36
64	Northumberland County	194.7	0.40	0.56	0.15	0.14	0.00	0.40	2.47	0.27	3.7	0.41
65	Nottoway County	316.6	0.04	0.55	0.01	0.06	0.54	0.62	0.00	0.05	1.7	0.11
66	Orange County	343.7	0.04	1.12	0.00	0.07	1.10	1.14	0.00	0.13	3.3	0.21
67	Page County	313.3	1.45	0.94	0.34	0.21	0.00	0.85	0.00	0.05	3.7	0.25
68	Patrick County	486.0	0.00	1.32	0.23	0.07	0.30	0.12	0.18	0.04	2.6	0.12
69	Pittsylvania County	977.9	0.33	3.53	0.03	0.09	7.17	1.11	2.41	0.26	16.0	0.35
70	Powhatan County	264.5	0.00	1.74	0.00	0.14	0.00	0.25	0.83	0.09	2.9	0.24

Table 17. Freshwater use in Virginia by locality in 2005.—Continued

[Data from Kenney and others, 2009; see figure 2 for map locations; Mgal/d, million gallons per day; —, not applicable]

Map number	Locality name	Area, in square miles	Groundwater withdrawals, in Mgal/d (unless noted otherwise)				Surface-water withdrawals, in Mgal/d (unless noted otherwise)				Total withdrawals	
			Public supply	Domestic	Industrial	Total, in inches	Public supply	Domestic	Industrial	Total, in inches	Mgal/d	Inches
71	Prince Edward County	354.0	0.00	0.93	0.08	0.07	0.00	0.60	0.00	0.02	1.5	0.09
72	Prince George County	269.2	0.32	1.08	0.04	0.13	0.00	1.68	0.00	0.01	1.7	0.13
73	Prince William County	343.0	0.34	4.68	0.03	0.39	67.29	21.47	0.41	4.37	75.7	4.75
74	Pulaski County	329.9	0.00	0.59	0.00	0.05	4.15	2.04	1.46	0.39	6.8	0.44
75	Rappahannock County	267.1	0.05	0.53	0.00	0.07	0.00	0.01	0.00	0.02	1.0	0.08
76	Richmond County	192.4	0.26	0.42	0.12	0.09	0.00	0.26	0.00	0.00	0.8	0.09
77	Roanoke County	251.6	1.32	2.22	0.04	0.31	16.23	4.39	0.02	1.41	20.1	1.72
78	Rockbridge County	600.0	0.64	1.13	0.92	0.12	1.38	0.46	0.00	1.21	37.1	1.33
79	Rockingham County	853.7	4.70	3.25	9.35	0.48	8.19	2.09	0.00	0.59	42.5	1.07
80	Russell County	476.6	0.91	1.22	0.01	0.10	0.61	0.96	0.00	0.21	6.9	0.31
81	Scott County	538.5	0.01	0.90	0.00	0.04	1.10	0.83	0.00	0.06	2.5	0.10
82	Shenandoah County	511.4	1.42	1.58	1.72	0.21	1.47	1.36	0.21	0.58	18.8	0.79
83	Smyth County	452.0	5.69	0.67	0.00	0.32	0.54	1.78	0.00	0.91	25.8	1.23
84	Southampton County	601.7	0.66	0.70	5.84	0.26	3.78	0.62	0.00	0.16	11.9	0.42
85	Spotsylvania County	412.0	0.01	4.26	0.07	0.23	4.83	4.48	0.00	0.27	9.6	0.50
86	Stafford County	275.6	0.00	1.73	0.01	0.14	15.95	7.11	1.63	1.44	20.2	1.58
87	Surry County	281.7	0.12	0.41	0.01	0.07	0.00	0.12	0.00	0.02	1.2	0.09
88	Sussex County	494.1	0.77	0.35	0.02	0.08	0.00	0.55	0.00	0.02	2.2	0.10
89	Tazewell County	519.2	0.07	0.88	0.00	0.05	4.51	2.48	0.00	0.30	8.4	0.35
90	Warren County	218.2	0.06	1.53	0.00	0.19	9.12	1.14	0.00	0.91	11.2	1.11
91	Washington County	567.2	1.08	0.53	0.00	0.08	7.81	3.38	0.07	2.73	73.9	2.81
92	Westmoreland County	233.6	0.88	0.45	0.02	0.13	0.00	0.84	0.00	0.04	1.8	0.16
93	Wise County	403.5	0.21	0.55	0.00	0.04	5.56	2.60	0.00	0.36	7.4	0.40
94	Wythe County	464.4	0.83	0.96	0.00	0.14	2.40	1.17	0.00	0.44	12.5	0.58
95	York County	108.6	0.19	0.58	0.00	0.16	29.42	4.05	59.08	17.56	89.4	17.72
96	Alexandria	15.4	0.00	0.00	0.02	0.03	0.00	10.15	0.00	0.00	0.0	0.03
97	Bedford	6.8	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.0	0.00
98	Bristol	11.5	0.00	0.00	0.00	0.00	0.00	1.30	0.00	0.09	0.1	0.09
99	Buena Vista	6.5	1.10	0.00	0.07	4.04	0.00	0.48	0.18	0.60	1.4	4.64
100	Charlottesville	10.5	0.00	0.00	0.00	0.00	0.00	3.03	0.00	0.00	0.0	0.00
101	Chesapeake	349.1	0.46	2.88	0.30	0.24	0.00	13.54	0.00	0.01	3.9	0.24
102	Colonial Heights	7.7	0.00	0.00	0.00	0.00	0.00	1.32	0.00	0.00	0.0	0.00
103	Covington	4.4	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.0	0.00
104	Danville	43.9	0.00	0.00	0.00	0.00	1.04	3.46	2.55	1.83	3.7	1.83
105	Emporia	6.7	0.00	0.00	0.00	0.00	1.03	0.42	0.00	3.31	1.0	3.31

Table 17. Freshwater use in Virginia by locality in 2005.—Continued

[Data from Kenney and others, 2009; see figure 2 for map locations; Mgal/d, million gallons per day; —, not applicable]

Map number	Locality name	Area, in square miles	Groundwater withdrawals, in Mgal/d (unless noted otherwise)				Surface-water withdrawals, in Mgal/d (unless noted otherwise)				Total withdrawals	
			Public supply	Domestic	Industrial	Total, in inches	Public supply	Domestic	Industrial	Total, in inches	Mgal/d	Inches
106	Fairfax	6.4	0.00	0.00	0.00	0.27	0.00	1.65	0.00	0.00	0.1	0.27
107	Falls Church	2.0	0.00	0.00	0.00	0.00	0.00	0.81	0.00	0.00	0.0	0.00
108	Franklin	7.7	1.16	0.00	0.00	3.24	0.00	0.64	0.00	0.00	1.2	3.24
109	Fredericksburg	10.6	0.00	0.00	0.00	0.00	0.00	1.55	0.00	0.00	0.0	0.00
110	Galax	8.1	0.00	0.00	0.00	0.00	1.67	0.50	0.00	4.64	1.7	4.64
111	Hampton	52.0	0.00	0.00	0.08	0.11	0.00	10.92	0.00	0.00	0.3	0.11
112	Harrisonburg	17.5	0.00	0.00	0.00	0.00	0.00	3.03	0.00	0.12	0.1	0.12
113	Hopewell	10.4	0.00	0.00	0.00	0.00	21.10	1.88	140.1	332.8	161.2	332.8
114	Lexington	2.5	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.0	0.00
115	Lynchburg	49.4	0.00	0.00	0.00	0.00	0.00	5.02	0.10	0.05	0.1	0.05
116	Manassas	10.1	0.00	0.00	0.13	0.28	0.00	2.82	0.00	0.00	0.1	0.28
117	Manassas Park	1.8	0.41	0.00	0.00	5.00	0.00	0.87	0.00	0.00	0.4	5.00
118	Martinsville	10.9	0.00	0.00	0.00	0.00	0.00	1.12	0.00	0.00	0.0	0.00
119	Newport News	69.0	0.02	0.00	0.21	0.17	26.81	13.49	0.00	8.37	27.4	8.53
120	Norfolk	54.9	0.03	0.00	0.19	0.09	1.97	17.40	0.00	0.84	2.4	0.93
121	Norton	7.6	0.00	0.00	0.00	0.00	0.89	0.28	0.00	2.54	0.9	2.54
122	Petersburg	23.1	0.00	0.00	0.00	0.00	0.00	2.45	0.00	0.00	0.0	0.00
123	Poquoson	16.3	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.0	0.00
124	Portsmouth	32.7	0.00	0.00	0.48	0.36	0.00	7.51	0.00	0.04	0.6	0.40
125	Radford	10.1	0.00	0.00	0.00	0.00	2.21	1.09	0.00	4.86	2.3	4.86
126	Richmond	62.0	0.00	0.00	0.00	0.01	74.67	14.53	0.00	26.31	75.8	26.32
127	Roanoke	42.4	4.35	0.00	0.22	2.42	0.00	6.95	0.84	0.43	5.6	2.85
128	Salem	14.4	0.12	0.00	0.01	0.30	3.70	1.85	0.00	5.54	3.9	5.84
129	Staunton	19.3	0.00	0.00	0.03	0.03	0.00	1.75	0.00	0.11	0.1	0.15
130	Suffolk	411.8	5.50	1.35	0.12	0.37	88.37	4.58	0.00	4.65	96.0	5.02
131	Virginia Beach	258.0	0.00	2.77	0.04	0.26	0.04	30.11	0.00	0.08	4.1	0.34
132	Waynesboro	14.0	2.96	0.00	4.06	10.8	0.00	1.60	0.01	0.12	7.1	10.89
133	Williamsburg	9.0	0.88	0.00	0.67	3.80	0.00	0.88	0.00	0.26	1.7	4.07
134	Winchester	9.3	0.00	0.00	0.15	0.35	0.00	1.88	0.00	0.00	0.2	0.35
	Total withdrawals[a]	—	**73**	**126**	**106**	—	**889**	**442**	**421**	—	**2,167**	—

[a]Totals have been rounded.

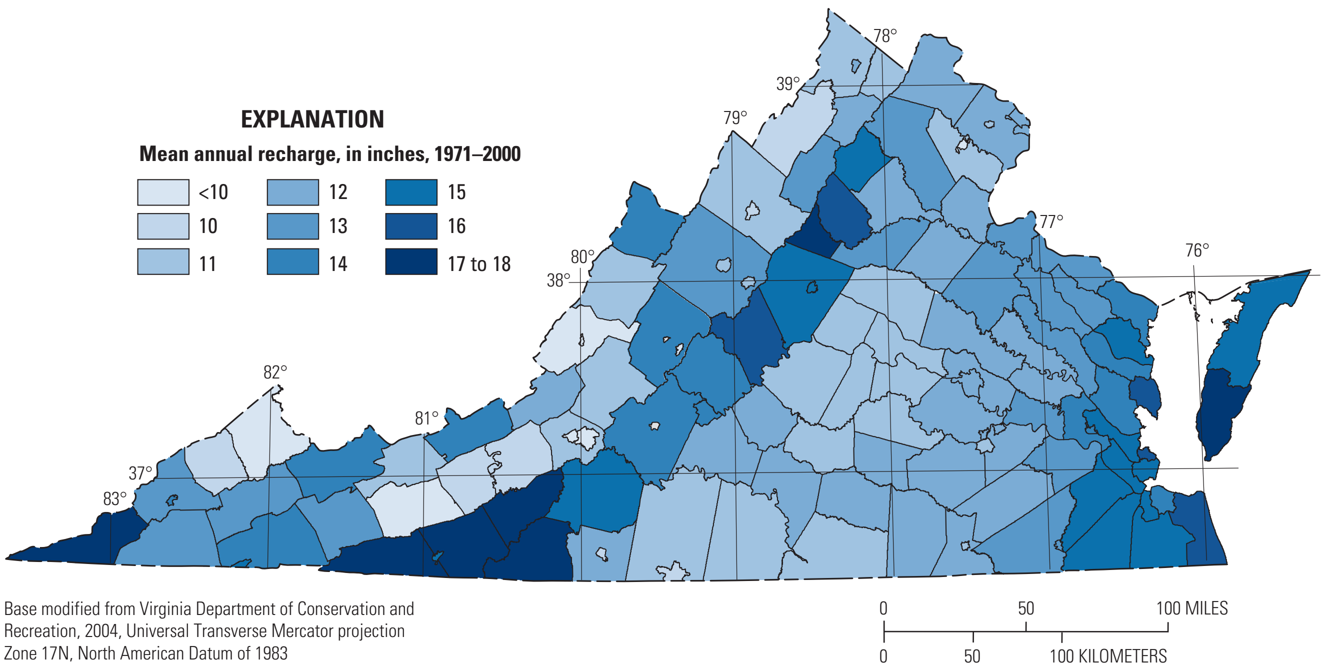


Figure 50. Estimates of mean annual effective recharge in Virginia by locality from 1971 to 2000. See figure 2 for locality names and table 16 for hydrologic budget components by locality.

Uncertainties in Estimates

There are many uncertainties inherent in a study such as this one. First, the locality estimates included in this report are averages over each locality, and actual values may vary significantly within a locality based on the character of the local bedrock, land cover, and topography. The averages are also long-term mean estimates, and actual values of many of the components can vary significantly from year to year, and even more so from month to month, based on temporal variations in precipitation and air temperature. For example, recent studies in the Shenandoah Valley of Virginia have shown that groundwater recharge rates can vary significantly with annual precipitation, resulting in recharge rates which differ by a factor of two or more for dry versus wet years, and for valleys versus ridge tops (Harlow and others, 2005; Nelms and Moberg (2010a,b).

Additionally, each component of the hydrologic budget that was measured or estimated from existing data is no more accurate than the assumptions that went into interpreting those measurements or data. Therefore, the precipitation data that was obtained from the PRISM climate group is limited to the accuracy of those data that are based on algorithms that interpolate precipitation data at stations throughout Virginia and attempt, for example, to account for changes in elevation. Watershed ET estimates were based on the assumption that long-term precipitation minus streamflow equals ET, and locality estimates were based on the ET regression derived from the watershed ET values and climatic factors. Therefore, individual ET averages for localities may vary by an inch or two (associated with potential error in the watershed ET and regression). There are two uncertainties inherent in the surface runoff estimates: (1) the assumptions in the chemical hydrograph separation technique, and (2) uncertainty in the regression that estimates surface runoff based on province and rock type. Although the chemical hydrograph method provides additional information in comparison to that of standard graphical methods, estimates are made during the analysis, such as the base-flow specific conductance that is estimated by visual inspection. Also, recharge is assumed to be not so rapid that ET does not intercept the infiltration; this may not be the case in every type of terrain. The regression can easily include an uncertainty of one inch per year, and two inches per year in the Valley and Ridge Province. Given that the other components, such as recharge, are estimated by combining other components, these errors are potentially cumulative. The estimates of ET and surface runoff in the regions with high impervious surface (many of the independent cities) have been adjusted based on a somewhat general observation of the behavior of ET and runoff in such areas (Lull and Sopper, 1969). Different impervious surfaces can behave very differently hydrologically, and scaling up these behaviors into more regional estimates of system response can often be critical (Mejia and Moglen, 2010). Thus the estimates for many of the independent cities have a higher degree of uncertainty than those localities with low percentages of impervious surface. Given all of these uncertainties, however, we believe that the estimates for the localities presented here are generally reliable because they are based on the sound principle of water balance. The user must simply be aware of the uncertainties when using specific values presented in this report.

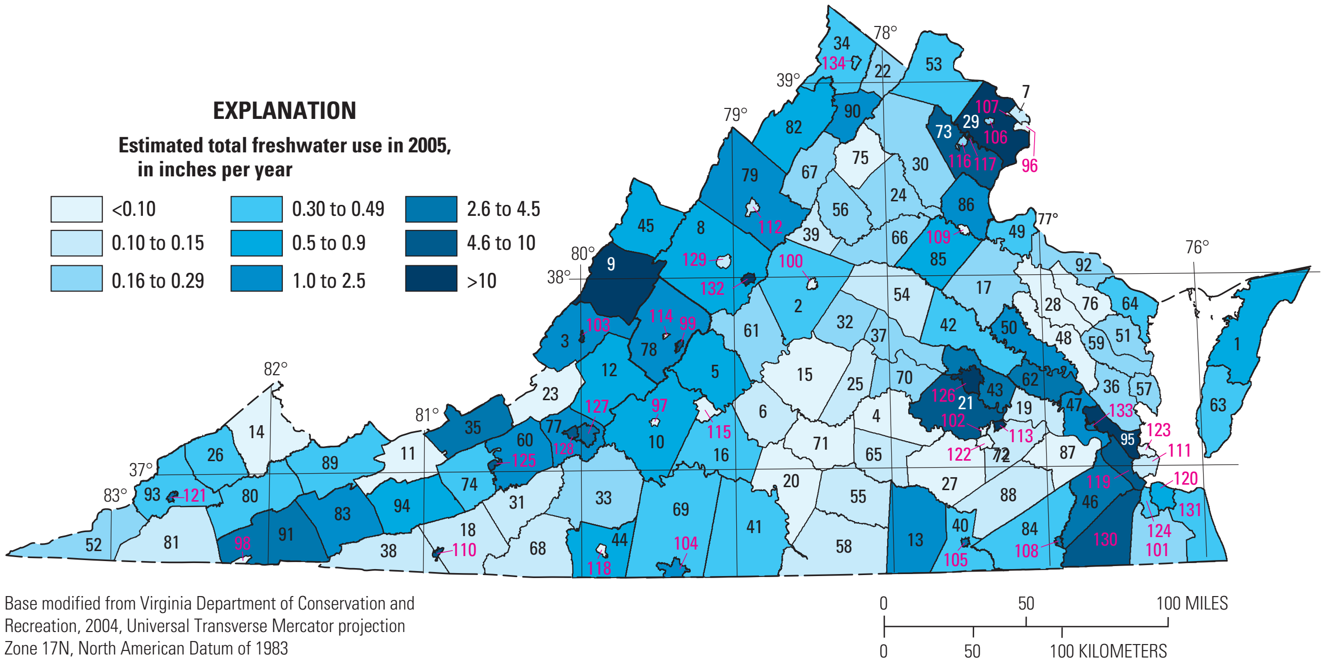


Figure 51. Map showing estimates of total freshwater use in Virginia by locality in 2005. Modified from Kenney and others, 2009. See figure 2 for locality names and table 17 for a detailed breakdown of hydrologic budget components by locality.

Summary and Conclusions

A study was undertaken to estimate the components of the hydrologic cycle for watersheds and localities (counties and independent cities) across Virginia. The components were estimated as long-term mean annual fluxes for each watershed or locality. Flux estimates of components of the hydrologic cycle were made by creating water and solute budgets in which the various components balanced. The water and solute balance approach was combined with regression equations that were developed based on climatic and land-surface characteristics. Mean annual precipitation was estimated for watersheds using the PRISM climate data from 1971–2000. Mean annual total ET was estimated for watersheds by subtracting the long-term mean annual streamflow from the area of the watershed multiplied by the long-term mean annual precipitation. Surface runoff and base flow for the watersheds were estimated by using chemical hydrograph separation on real-time streamflow records for approximately 18 months during March 2007 through August 2008. These separations were performed using specific conductance. The results of the separation revealed that the average base flow using this chemical separation was 72 percent of streamflow, as compared to 61 percent using a graphical separation technique. This difference is consistent with previous chemical hydrograph studies, but is the first time this has been demonstrated to be consistent on a large scale and with a large number of watersheds. Riparian ET for the watersheds was estimated by comparing the mean summer versus mean winter specific conductance values of the base flows. Infiltration and recharge for the watersheds were calculated using the water balance assumption.

Mean annual precipitation for each locality was estimated using the PRISM climate data from 1971–2000. Mean annual total ET for the localities was calculated using a regression equation based on precipitation, the mean minimum daily temperature, the mean maximum daily temperature, and how these parameters varied with the ET values calculated for the watersheds. The surface runoff for the localities was estimated as a percent of precipitation by developing a regression equation, based on the relative area within any given physiographic province or rock type. Parameters for this equation were calculated by fitting these land characteristics to the surface runoff percentages observed in the watersheds. Net total outflow for the localities was estimated by subtracting the total ET from the precipitation. Net groundwater discharge for the localities was estimated by subtracting the surface runoff from the total net outflow. Riparian ET for the localities was estimated from a regression that estimated the percent marsh based on mean air temperature and topographic slope. Infiltration for the localities was estimated by subtracting surface runoff from precipitation. Recharge for the localities was calculated by adding the riparian ET to the net groundwater discharge.

The following estimates were made for the component fluxes across Virginia. As an annual long-term average for all of Virginia (table 16), 44.7 in. of precipitation falls on the land surface, of which 5.8 in. runs off the surface into streams, with the remaining 38.9 in. infiltrating into the soil zone. After infiltration, 27.4 in. evapotranspires from the vadose zone, leaving 12.5 in. to recharge the groundwater system at the water table. This groundwater migrates to the stream valleys where 1.4 in. evapotranspires in the riparian zone and the remaining 11.1 in. discharges to the stream. The 11.1 in.

in the stream joins the 5.8 in. of surface runoff to result in 16.9 in. of mean annual streamflow. This streamflow plus the 27.8 in. of total ET balance the 44.7 in. of precipitation. Dividing the 11.1 in. of groundwater discharge by 16.9 in. of total streamflow indicates that 65.7 percent of streamflow is groundwater discharge on average. These budget component estimates vary across Virginia. Preciptation estimates vary between approximately 38 in/yr in the Shenandoah Valley, and approximately 50 in/yr along the Blue Ridge Province and in extreme southwestern Virginia (fig. 5). Total ET estimates vary between approximately 25 in/yr in western Virginia and the independent cities, and approximately 31 in/yr in the southern Piedmont and Coastal Plain Provinces (fig. 40). Surface runoff estimates varied between 3 in/yr along the Blue Ridge Province and the Eastern Shore of Virginia, and approximately 10 or more in/yr in the independent cities and the Appalachian Plateau Province (fig. 46). Riparian ET estimates vary between <1 in/yr in the Valley and Ridge Province to >2.5 in/yr in the southern Coastal Plain (fig. 43). Net total outflow (or streamflow) estimates vary between approximately 14 in/yr in the central Piedmont Province and the northern Shenandoah Valley and >20 in/yr in the independent cities and in southwestern Virginia (fig. 44). Net groundwater discharge (or base flow) estimates vary between approximately 9–10 in/yr in the central and southern Piedmont Province and the siliciclastic regions of western Virginia, and 15–16 in/yr along the Blue Ridge Province (fig. 47). Recharge estimates vary between approximately 10 in/yr in the siliciclastic regions of western Virginia and 16–18 in/yr in the Blue Ridge Province and coastal Virginia (fig. 50). These estimates represent long-term mean values. Actual values will likely vary substantially around these means within localities based on land-surface characteristics, and will vary substantially temporally based on changing weather and climatic conditions.

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