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Estimating Mean Long-term Hydrologic Budget Components for Watersheds and Counties: An Application to the Commonwealth of Virginia, USA

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Abstract

Mean long-term hydrologic budget components, such as recharge and base flow, are often difficult to estimate because they can vary substantially in space and time. Mean long-term fluxes were calculated in this study for precipitation, surface runoff, infiltration, total evapotranspiration (ET), riparian ET, recharge, base flow (or groundwater discharge) and net total outflow using long-term estimates of mean ET and precipitation and the assumption that the relative change in storage over that 30-year period is small compared to the total ET or precipitation. 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 (SC) 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. A new approach to estimate riparian ET using seasonal SC data gave results consistent with those from other methods. 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. Final results for the study are presented as component flux estimates for all counties and independent cities in Virginia. The method has the potential to be applied in many other states in the U.S. or in other regions or countries of the world where climate and stream flow data are plentiful.

Keywords: Hydrologic budget; Evapotranspiration; Runoff; Recharge; Hydrograph separation

Introduction

Water-resource managers 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 recurring droughts and water shortages, many places often attempt to develop comprehensive water-supply plans. In 2005 in Virginia (USA), localities (counties and independent cities) were required to develop either local or regional water-supply plans in response to the Virginia Local and Regional Water Supply Planning Regulation (9 VAC 25-780). Although recent studies within the state [1-5] focused on the resources of the Virginia Coastal Plain, reliable information is frequently lacking on water availability west of the coastal plain (Figure 1), 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 an entire state, such as Virginia, because most other methods used to estimate recharge (such as the use of environmental tracers or water levels) are highly dependent on local measurements in both space and time [5,6]. New datasets, 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 in the United States to assess water availability at a regional level, such as for the Commonwealth of Virginia. Such assessments would be valuable for water resource managers at the state, county, and local planning levels and the method is applicable to other regions as well.

Water budgets are quantified routinely for watersheds, but to quantify budgets for county units for which managers off make decisions requires results from watersheds to be transferrable to counties through some type of regression. Along these lines, the purpose of this study was to demonstrate such a method by quantifying components of the hydrologic budget on a large number of watersheds across the entire Commonwealth of Virginia, and using 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.

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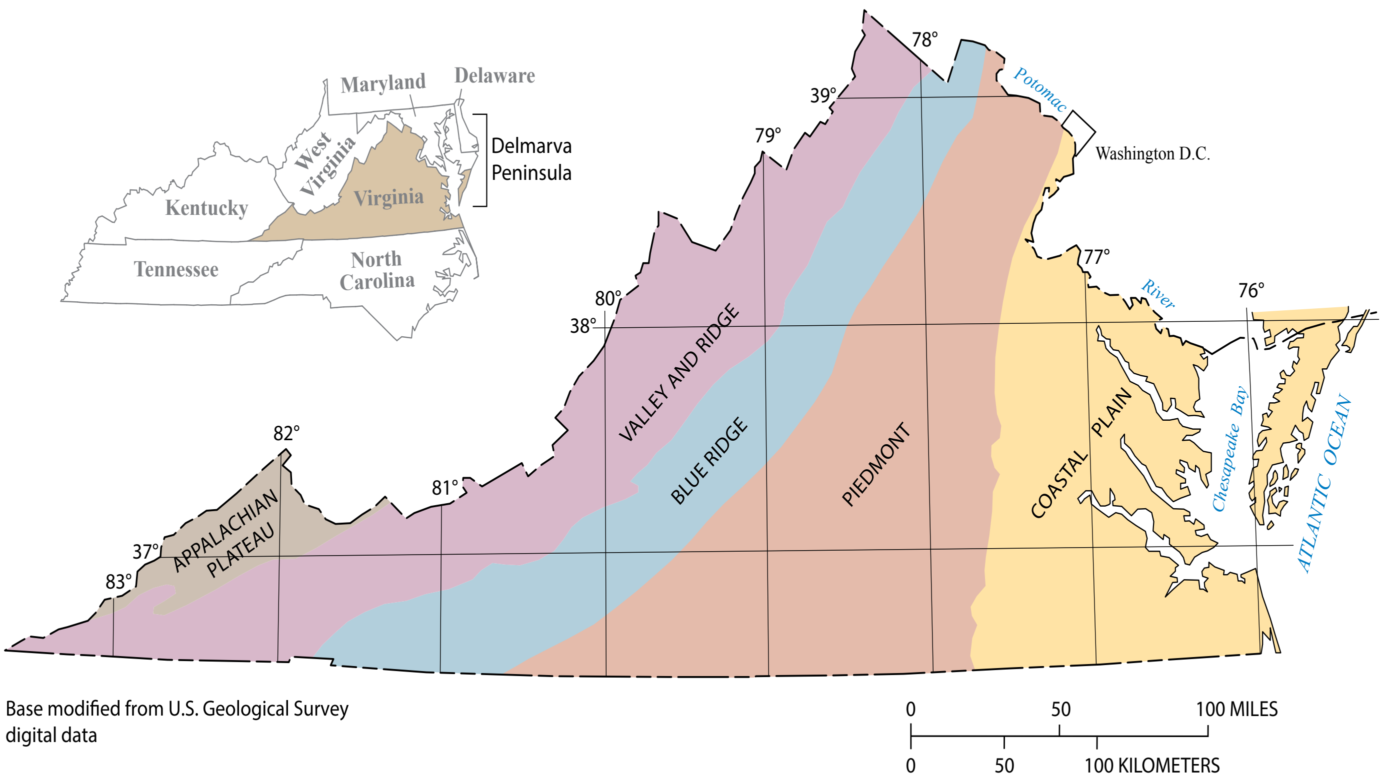


Figure 1: Physiographic provinces of Virginia [40].

The latter were adjusted to long-term conditions based on historical stream flow data. Within watersheds or counties values are expected to deviate, both temporally and locally, from the calculated mean values. 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. Detailed data associated with the study have been included in an earlier USGS report [7].

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 (Figure 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 (Figure 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. The mountains of the Blue Ridge, Valley and Ridge Provinces, and Appalachian Plateau in Virginia frequently reach up to 600 to 900 meters (m) above sea level, with local relief frequently exceeding 300 m.

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 15 degrees Celsius (°C) in Virginia Beach in the southeast to 9°C in Highland County in the west. 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 100 centimeters per year (cm/yr) at many locations, and highest along the southwestern ridges where average values can exceed 125 cm/yr. 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. 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.

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 [8], effects of mining [9], water quality [10,11], geochemistry [12], and hydraulic characteristics [13]. 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 that of the hydrogeology [14], groundwater quantity [15], and shallow hydrologic characteristics through stream

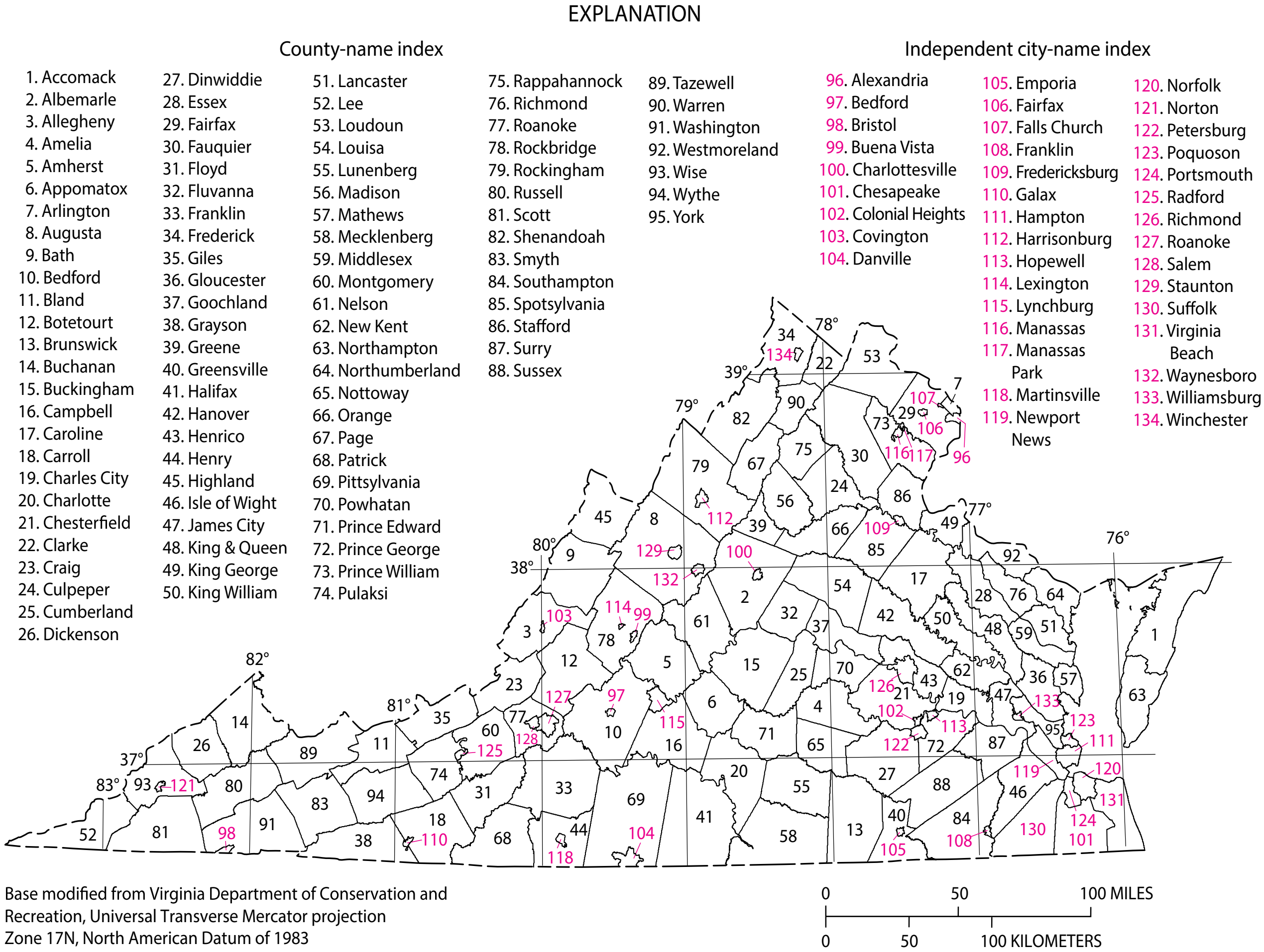


Figure 2: Names and locations of counties and independent cities in the Commonwealth of Virginia.

flow recession analysis [16]. In addition, base-flow [17] and low-flow [18] characteristics have been determined for these provinces. In the Coastal Plain of Virginia, descriptions of the hydrogeologic framework, groundwater quality, and groundwater discharge have been published elsewhere [1,4,19]. A similar regression approach was developed for the State of Minnesota [20], 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 [5,6,21] 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. 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 [22].

The Piedmont Province is underlain by polydeformed rocks believed to be of late Proterozoic age that were metamorphosed 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 to the Mid-Atlantic Ridge; they filled with siliciclastic and carbonate sediments which later were lithified. A few of these Mesozoic Rift Basins 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 [23]. The section north of the Roanoke River 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 an anticlinorium [17]. 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 [23].

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. 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. Shale's 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 [24]. 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.

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, and evapotranspiration (ET), infiltration, recharge, riparian ET, and base flow. The use of long-term (30-year) mean averages for precipitation and ET allowed change in storage to be neglected. 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 the region (Table 2 and Figure 3), and two multiple-parameter regression equations were developed that allowed the results to be transferred from the watersheds to the entire Commonwealth of Virginia. Long-term mean precipitation and stream flow 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.

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 (Figure 4). In general, the difference between these inflow and outflow terms leads to a change in water stored within the watershed. On a monthly or annual time scale these changes in storage can be significant fractions of the inflow or outflow. The annual change is storage, however, will never exceed the total inflow or outflow for one year. Thus if the water balance is applied to a period of three decades using long term mean inflows and outflows, the change in storage should not exceed 1/30th of the total inflow or outflow for that time period. So for long time periods the change in storage term becomes relatively small and can be neglected and a steady-state condition assumed. This steady-state water-balance approach for long-time periods has been recognized as valid in other hydrologic studies [25,26]. Based on the principle of conservation and

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 2 different values of runoff concentration. Values were then adjusted for 1971-2000 conditions via 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 3) 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 17) relating riparian ET to the estimated fraction of marsh area (FM), which was estimated from (EQ 16) 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 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.

Table 2. Real-time watersheds included in this study. See figure 3 for map locations.
(ET=evapotranspiration, SC=specific conductance, CP=Coastal Plain, VR=Valley and Ridge, BR=Blue Ridge, PM=Piedmont, unk=unknown)

Map number	USGS Gage Number	Stream gage and watershed name and location	Physiographic Province	Area in square kilometers	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, DE	CP	194				X
2	01613900	Hogue Creek near Hayfield, VA	VR	41	X		X	X
3	01614830	Opequon Creek near Stephens City, VA	VR	39			X	
4	01615000	Opequon Creek near Berryville, VA	VR	151	X		X	X
5	01616075	Fay Spring near Winchester, VA	VR	unk		X	X	
6	01616100	Dry Marsh Run near Berryville, VA	VR	28			X	
7	01616500	Opequon Creek at Martinsburg, WV	VR	707	X	X	X	
8	01622000	North River near Burketown, VA	VR	974	X	X	X	X
9	01625000	Middle River near Grottoes, VA	VR	966	X	X	X	X
10	01626000	South River near Waynesboro, VA	BR	329	X	X	X	X
11	01627500	South River at Harriston, VA	BR	549	X	X	X	X
12	01629500	S F Shenandoah River near Luray, VA	VR	3566		X	X	X
13	01630700	Gooney Run near Glen Echo, VA	BR	54			X	
14	01631000	S F Shenandoah River at Front Royal, VA	VR	4232	X		X	X
15	01632000	N F Shenandoah River at Cootes Store, VA	VR	544	X	X	X	X
16	01632082	Linville Creek at Broadway, VA	VR	119			X	X
17	01632900	Smith Creek near New Market, VA	VR	242	X		X	X
18	01633000	N F Shenandoah River at Mount Jackson, VA	VR	1316	X	X	X	X
19	01634000	N F Shenandoah River near Strasburg, VA	VR	1994	X		X	X
20	01634500	Cedar Creek near Winchester, VA	VR	264	X		X	X
21	01635090	Cedar Creek above Hwy 11 near Middletown, VA	VR	396		X	X	X
22	01635500	Passage Creek near Buckton, VA	VR	224	X		X	X
23	01636242	Crooked Run below Hwy 30 at Riverton, VA	VR	122			X	
24	0163626650	Manassas Run at Rt 645 near Front Royal, VA	BR	28			X	
25	01636316	Spout Run at RT 621 near Millwood, VA	VR	54			X	X
26	01643700	Goose Creek near Middleburg, VA	BR	316	X	X	X	X
27	01644280	Broad Run near Leesburg, VA	PM	197		X	X	
28	01646000	Difficult Run near Great Falls, VA	PM	150	X	X	X	X
29	01649500	NE Branch Anacostia River at Riverdale, MD	CP	189				X
30	01651000	NW Branch Anacostia River near Hyattsville, MD	PM	127				X
31	01656000	Cedar Run near Catlett, VA	PM	242	X	X	X	X
32	01658000	Mattawoman Creek near Pomonkey, MD	CP	142				X
33	01660400	Aquia Creek near Garrisonville, VA	PM	91	X	X	X	X
34	01663500	Hazel River at Rixeyville, VA	BR	743		X	X	
35	01664000	Rappahannock River at Remington, VA	BR	1603	X			
36	01665500	Rapidan River near Ruckersville, VA	BR	298	X	X	X	X

Table 2 (continued). Watersheds included in this study. See figure 3 for locations.
(ET=evapotranspiration, SC=specific conductance, CP=Coastal Plain, VR=Valley and Ridge, BR=Blue Ridge, PM=Piedmont)

Map number	USGS Gage Number	Stream gage and watershed name and location	Physiographic Province	Area in square kilometers	Used to estimate ET	SC probe installed for this study	Samples collected for chloride analysis	SC data used for base flow estimate
37	01666500	Robinson River near Locust Dale, VA	BR	464	X	X	X	X
38	01667500	Rapidan River near Culpeper, VA	BR	1212	X	X	X	X
39	01669000	Piscataway Creek near Tappahannock, VA	CP	73		X	X	
40	01669520	Dragon Swamp at Mascot, VA	CP	280		X	X	X
41	01671020	North Anna River at Hart Corner near Doswell, VA	PM	1199		X	X	
42	01671100	Little River near Doswell, VA	PM	277		X	X	
43	01672500	South Anna River near Ashland, VA	PM	1023	X	X	X	X

44	01673000	Pamunkey River near Hanover, VA	PM	2792	X			
45	01673638	Cohoke Mill Creek near Lestor Manor, VA	CP	23		X	X	
46	01674000	Mattaponi River near Bowling Green, VA	PM	666		X	X	
47	01674500	Mattaponi River near Beulahville, VA	CP	1559	X			
48	02011400	Jackson River near Bacova, VA	VR	409		X	X	X
49	02011500	Back Creek near Mountain Grove, VA	VR	347		X	X	X
50	02013000	Dunlap Creek near Covington, VA	VR	420	X	X	X	X
51	02013100	Jackson River BL Dunlap Creek at Covington, VA	VR	1590		X	X	
52	02014000	Potts Creek near Covington, VA	VR	396	X	X	X	X
53	02015700	Bullpasture River at Williamsville, VA	VR	285		X	X	X
54	02016000	Cowpasture River near Clifton Forge, VA	VR	1194	X	X	X	
55	02016500	James River at Lick Run, VA	VR	3556		X	X	X
56	02017500	Johns Creek at New Castle, VA	VR	272	X	X	X	X
57	02018000	Craig Creek at Parr, VA	VR	852	X	X	X	X
58	02020500	Calfpasture River above Mill Creek at Goshen, VA	VR	365	X	X	X	X
59	02021500	Maury River at Rockbridge Baths, VA	VR	852	X	X	X	X
60	02024000	Maury River near Buena Vista, VA	VR	1676	X	X	X	X
61	02025500	James River at Holcomb Rock, VA	VR	8440		X	X	
62	02026000	James River at Bent Creek, VA	VR	9538		X	X	
63	02030000	Hardware River BL Briery Run near Scottsville, VA	BR	300		X	X	
64	02032640	N F Rivanna River near Earlysville, VA	BR	280		X	X	X
65	02039500	Appomattox River at Farmville, VA	PM	785		X	X	
66	02040000	Appomattox River at Mattoax, VA	PM	1878	X	X	X	X
67	02041000	Deep Creek near Mannboro, VA	PM	409	X	X	X	X
68	02042500	Chickahominy River near Providence Forge, VA	CP	650	X			
69	02044500	Nottoway River near Rawlings, VA	PM	821	X	X	X	X
70	02045500	Nottoway River near Stony Creek, VA	PM	1499		X	X	
71	02046000	Stony Creek near Dinwiddie, VA	PM	290		X	X	
72	02047500	Blackwater River near Dendron, VA	CP	751	X	X	X	X

Table 2 (continued): Watersheds included in this study. See figure 3 for locations.
(ET=evapotranspiration, SC=specific conductance, CP=Coastal Plain, VR=Valley and Ridge, BR=Blue Ridge, PM=Piedmont)

Map number	USGS Gage Number	Stream gage and watershed name and location	Physiographic Province	Area in square kilometers	Used to estimate ET	SC probe installed for this study	Samples collected for chloride analysis	SC data used for base flow estimate
73	02049500	Blackwater River near Franklin, VA	CP	1588	X			
74	02051500	Meherrin River near Lawrenceville, VA	PM	1430	X	X	X	X
75	02052000	Meherrin River at Emporia, VA	PM	1927	X			
76	02053800	S F Roanoke River near Shawsville, VA	BR	282	X	X	X	
77	02054500	Roanoke River at Lafayette, VA	VR	658	X			
78	02055000	Roanoke River at Roanoke, VA	VR	994	X			
79	02056000	Roanoke River at Niagara, VA	VR	1318	X	X	X	
80	02056900	Blackwater River near Rocky Mount, VA	BR	298		X	X	
81	02059485	Goose Creek at Rt 747 near Bunker Hill, VA	BR	324			X	
82	02059500	Goose Creek near Huddleston, VA	BR	487	X	X		X
83	02061000	Big Otter River near Bedford, VA	BR	295			X	
84	02061500	Big Otter River near Evington, VA	BR	816	X	X	X	X
85	02062500	Roanoke (Staunton) River at Brookneal, VA	BR	6254		X	X	
86	02064000	Falling River near Naruna, VA	PM	448		X	X	
87	02065500	Cub Creek at Phoenix, VA	PM	253	X	X	X	
88	02070000	North Mayo River near Spencer, VA	PM	280		X	X	
89	02072000	Smith River near Philpott, VA	BR	559		X	X	
90	02073000	Smith River at Martinsville, VA	PM	984		X	X	
91	02074500	Sandy River near Danville, VA	PM	290		X	X	
92	02075045	Dan River STP near Danville, VA	BR	5451		X	X	
93	02077000	Banister River at Halifax, VA	PM	1417	X	X	X	
94	02079640	Allen Creek near Boydton, VA	PM	139	X	X	X	

95	03165500	New River at Ivanhoe, VA	BR	3470		X	X	
96	03167000	Reed Creek at Grahams Forge, VA	VR	668	X	X	X	X
97	03168000	New River at Allisonia, VA	BR	5703		X	X	
98	03170000	Little River at Graysontown, VA	BR	800	X			
99	03171000	New River at Radford, VA	BR	7117		X	X	
100	03173000	Walker Creek at Bane, VA	VR	774	X	X	X	
101	03175500	Wolf Creek near Narrows, VA	VR	578		X	X	
102	03207800	Levisa Fork at Big Rock, VA	AP	769	X			
103	03208500	Russell Fork at Haysi, VA	AP	741	X	X	X	
104	03473000	S F Holston River near Damascus, VA	BR	785	X			
105	03475000	M F Holston River near Meadowview, VA	VR	533	X	X	X	
106	03488000	N F Holston River near Saltville, VA	VR	572	X			
107	03524000	Clinch River at Cleveland, VA	VR	1380	X	X	X	X
108	03531500	Powell River near Jonesville, VA	VR	826	X	X	X	X

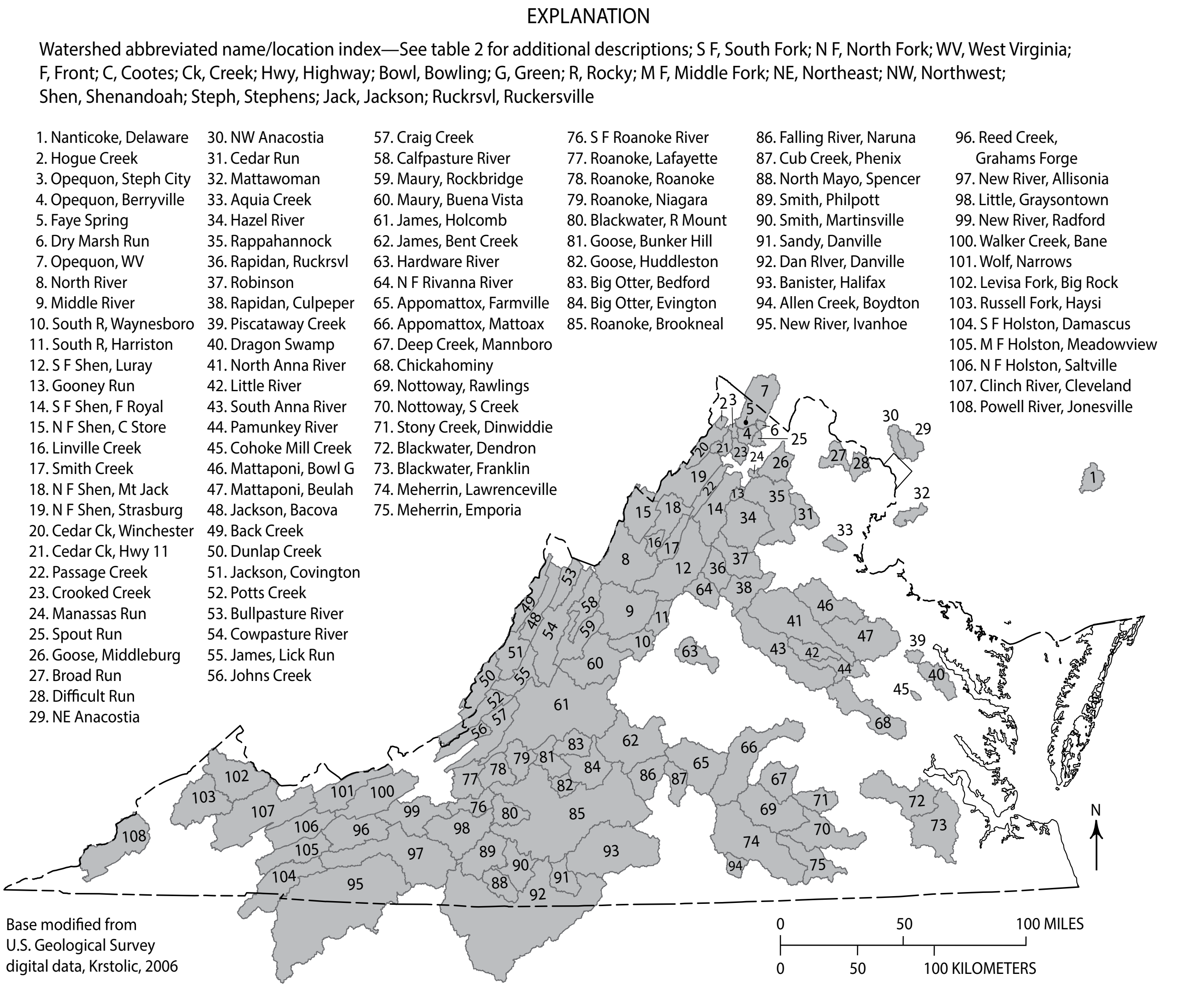


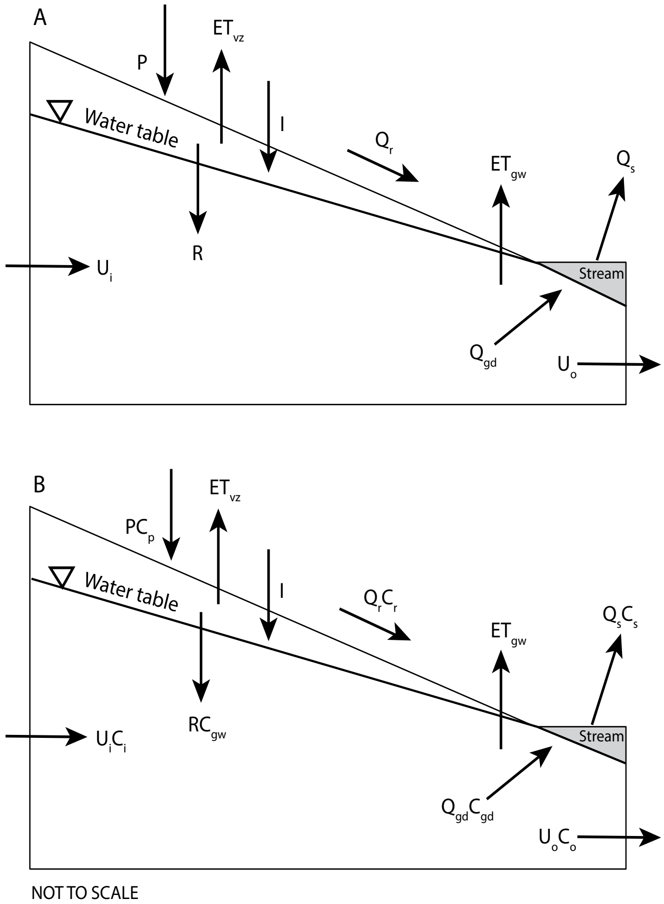
Figure 3: Names and locations of watersheds referenced in this study.

the steady state assumption, a number of equations can be written that represent the balance of mass moving into and/or out of the watershed. A total steady-state water balance across the watershed can be written as:

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

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

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



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_{gw}	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 4: An idealized watershed showing components of the (A) water, and (B) conservative-solute budget.

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

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],

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],

L is the dimension of length, and

t is the dimension of time.

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 C_p is the average concentration of the solute in precipitation, [M/L^3],

C_s is the average concentration of the solute in the stream at the outflow point, [M/L^3],

C_i is the average concentration of the solute in the groundwater flowing into the watershed, [M^3/t],

C_{vz} is the average concentration of the solute in the water evapotranspiring from the vadose zone, [M/L^3],

C_{rp} is the average concentration of the solute in the water evapotranspiring from the riparian zone, [M/L^3],

C_o 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 Q_r is the surface runoff, and

$$RC_{gw} = I\,C_p \quad (6)$$

where C_{gw} is the average concentration of the solute in the groundwater [M/L^3]. The thirty-year time over which the ET is represented allows for the change in storage in the unsaturated zone to be neglected. 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 Q_r at the site location is zero [27]. 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:

$$Q_sC_s = Q_{gd}C_{gd} + Q_rC_r \quad (9)$$

where C_{gd} is the concentration of the solute in the groundwater discharge to the stream, [M/L^3]; and C_r is the concentration of the solute in the runoff, [M/L^3]; 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 [20]. 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 stream flow, 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:

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

That represents the fraction of stream flow 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 2007 and August 2008 was used during this study to estimate the fraction of surface runoff in watersheds. The average groundwater discharge component of stream flow was then calculated using water balance eq 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 Cr, 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 no solutes in the stream water originate by mineral dissolution in the subsurface, but rather are either originally present in the precipitation or originate by minerals (fertilizer, road salt, etc.) that dissolve into the precipitation on the land surface. Then mass balance equation 4 can be rewritten as:

$$C_r = Q_sC_s/PA \quad (12)$$

This first assumption leads to a second assumption—that the solute concentrations of the surface runoff and infiltration are equal.

Based on this latter 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 second end-member process that can explain solute concentrations in streams is the opposite of the first-that virtually all of the solute in the stream was derived from subsurface mineral reactions, and that C_r is that of rainwater, C_p. In most watersheds, the conditions are likely to lie somewhere between these two end-member processes, so in this study we made calculations 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 C_{gw} 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. This relatively small value of ET_{rp} relative to ETvz is supported by the fact that in the Piedmont and Valley and Ridge Provinces the depth to the water table is greater than one meter in all regions that are not immediately adjacent to streams [7].

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:

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

where ET_{rps} is the riparian ET rate during the summer, [L/t], and

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 estimated watershed mean-annual riparian ET calculation becomes that calculated for the summer (equation 13) divided by three:

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

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 other estimates [14,28] in the Mid-Atlantic region (see later in Riparian ET section), 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.

Total evapotranspiration estimation

Total evapotranspiration for the watersheds of interest was estimated by subtracting stream flow from total precipitation using eq 3 [29]. A total of 60 watersheds were selected (Table 2) 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 [30] 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 article, 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. A multiple-regression equation was created that related the mean total evapotranspiration rate of each watershed to the precipitation rate, the mean maximum daily temperature, and the mean daily minimum temperature. All PRISM climate data averaged for the 1971-2000 data period were available as a raster grid for the entire Commonwealth on 800-meter spacing. A geographical information system was used to calculate an average temperature and precipitation value 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:

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

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, and have the values 0.370, 0.957, –0.383, and –34.277, respectively. The regression had an R^2 value of 0.844 and a slope of 0.91. Land cover data were also considered as a potential variable in the regression, but it did not substantially improve the regression and therefore was not included in the final equation [7]. For the remainder of Virginia, equation 15 was used to estimate total evapotranspiration by locality, along with a correction for percent impervious surface

Chemical hydrograph separation

The components of stream flow-surface runoff and base flow-are represented in the hydrologic budget in equations 7 and 11. We use the term base flow 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 [31,32]. 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 [33], 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 installed on 75 streams (and one spring) across Virginia at real-time gaging sites (Table 2) for SC. Data were transferred to spreadsheets where both stream flow and SC could be plotted together [7]. 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 in 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. On occasion, there was observed high-frequency variability in SC during low-flow periods that was attributed to causes other than rainfall. 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. SC of rainwater was not measured directly in the study area, but rather the former value was used to represent the SC of average rainwater [34]. Data collection began in March 2007 and continued for 18 months, through August 2008.

During 2007-2008, water samples were also collected at approximately six-week intervals (during normal gage maintenance visits) from 90 stream gage sites and analyzed for SC and anion concentrations of chloride (Cl), sulfate, and nitrate [7]. Chloride tends to be the most conservative ion in the subsurface for most regions [34] 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. A plot of chloride concentration versus SC for the Difficult Run samples and all of the other watershed samples [7] revealed 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. Conversely, many streams had a ratio below 0.03, indicating a low average surface-salt composition.

The mean specific conductance of the streams measured in Virginia is a reflection, in large part, of the solubility of minerals in the soils and rocks through which the groundwater passes [34]. Watersheds in the Valley and Ridge Province had the highest mean SC values; especially the watersheds that were underlain by carbonate rocks, frequently have mean SC values in excess of 300 µS/cm [7]. 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.

Regression analysis

In order to estimate the hydrologic budget components for all of Virginia, the results from the watersheds analysis were transferred to other localities using two regression equations. The first equation was that used to estimate total evapotranspiration, described previously. The second equation expressed the fraction of the precipitation that results in surface runoff as 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 (as described 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, land cover, rock type, median topographic slope, mean soil permeability, and percent impervious surface. After examination of each of these factors in the regression equation it was concluded that physiographic province, rock type, 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 [35] on 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.

Results

Estimates of hydrologic budget components

The components of the hydrologic budgets were first calculated for the watersheds based on the stream flow, climatic data, and chemical hydrograph separations in the watersheds (Table 1). These watershed 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 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 surface runoff and recharge may be particularly useful for water managers.

The hydrologic budget components were estimated for a number of watersheds across Virginia as an average annual rate in centimeters 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 range from less than 100 cm/yr in the watersheds in the Shenandoah Valley to more than 125 cm/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 sections 2.1 and 2.3 of this article in which the mean annual stream flow from 1971-2000 is subtracted from the mean annual precipitation of the same period multiplied by the watershed area. Results indicate that mean annual total ET rates in the watersheds evaluated in Virginia range from 60 cm/yr in some of the higher elevation watersheds in western Virginia to 80 cm/yr in some of the wetter and warmer watersheds in southwestern and southern Virginia (Figure 5). 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. 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 (equation 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. A plot of the ET calculated using the water balance versus that estimated by the regression (equation 15) (Figure 6) indicates a relatively good fit (R^2=0.844, slope=0.91) and that ET in Virginia is controlled predominantly by variations in climate.

Chemical hydrograph separation

Hydrographs and records of specific conductance during the same period were obtained and plotted for 100 watersheds across the region [7]. 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 was estimated using the chemical hydrograph separation method described in section 2.4 of this article. 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-

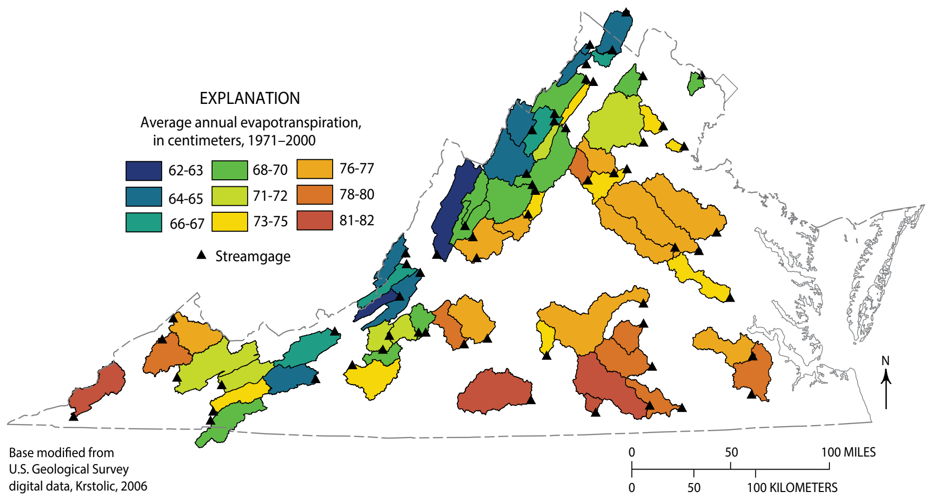


Figure 5: Evapotranspiration from 1971 to 2000 calculated by mass balance for watersheds of Virginia in this study.

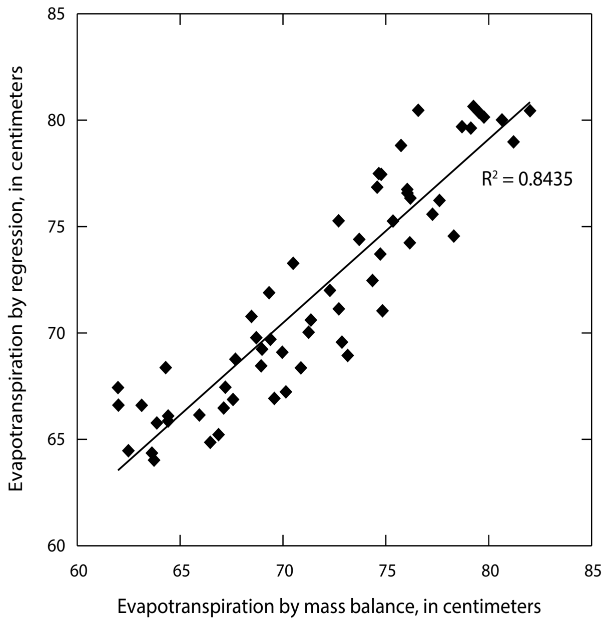


Figure 6: Comparison of evapotranspiration calculated by mass balance versus that estimated through the regression equation.

term flow conditions for the watershed. Upon examination of streamflow 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 [7] 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, where BF equals the base-flow fraction and Q equals the mean monthly stream flow 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 section 2.4 of this article). An average base flow was then calculated from the two end-members based on a weighting term that is a function of the SC/Cl ratio.

Results of the base-flow analyses demonstrated a substantial difference in base-flow indices across Virginia (Figure 7). The base-flow index is the percentage of the mean annual stream flow 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. The results revealed that the average base flow using this chemical separation was 72% of stream flow, as compared to 61% using a graphical separation technique. The latter value is typical of those presented in earlier studies for this region [16]. 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 section 2.5 of this paper). The range of base-flow indices in the individual watersheds 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-

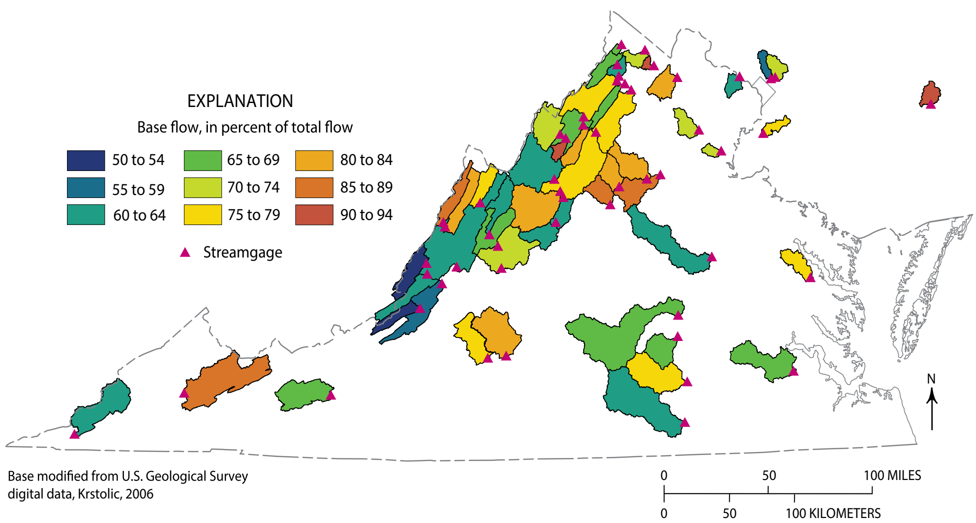


Figure 7: Estimates of mean base flow as percent of total streamflow in selected watersheds in Virginia, Maryland, and Delaware.

Citation: Sanford WE, Nelms DL, Pope JP, Selnick DL (2015) Estimating Mean Long-term Hydrologic Budget Components for Watersheds and Counties: An Application to the Commonwealth of Virginia, USA. Hydrol Current Res 6: 191. doi:10.4172/2157-7587.1000191

term base-flow component (base flow) from the total stream flow. The surface runoff values for the different watersheds across Virginia range from 5 cm/yr or less in the Valley and Ridge Province carbonate rocks and the Blue Ridge Province to 20 or more cm/yr in some of the siliciclastic rocks of the Valley and Ridge Province (Figure 8). The regression equation described in section 2.4 was used to estimate the surface runoff as a percentage of the precipitation depending on the physiographic province and rock type within that province (Table 3). 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 run off. When the regression was later applied to the localities, the effect of impervious surfaces was reintroduced, as described in section 2.5. The estimated percent of precipitation estimated to end up as surface runoff varied between approximately 4 and 16 percent.

Riparian evapotranspiration

Riparian Evapotranspiration, ET_{rp}, 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 1.2 cm/yr to more than 10 cm/yr (Figure 9). Estimates of ET_{rp} from an earlier investigation based on a combination of graphical hydrograph separation methods [16] also yielded a similar distribution of values of ET_{rp} for watersheds in Virginia (Figure 9).

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 values now for the latter two we could calculate the infiltration and then the recharge. 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 20 and 45 cm/yr.

Estimates for localities

In order to apply the ET regression equations to the localities,

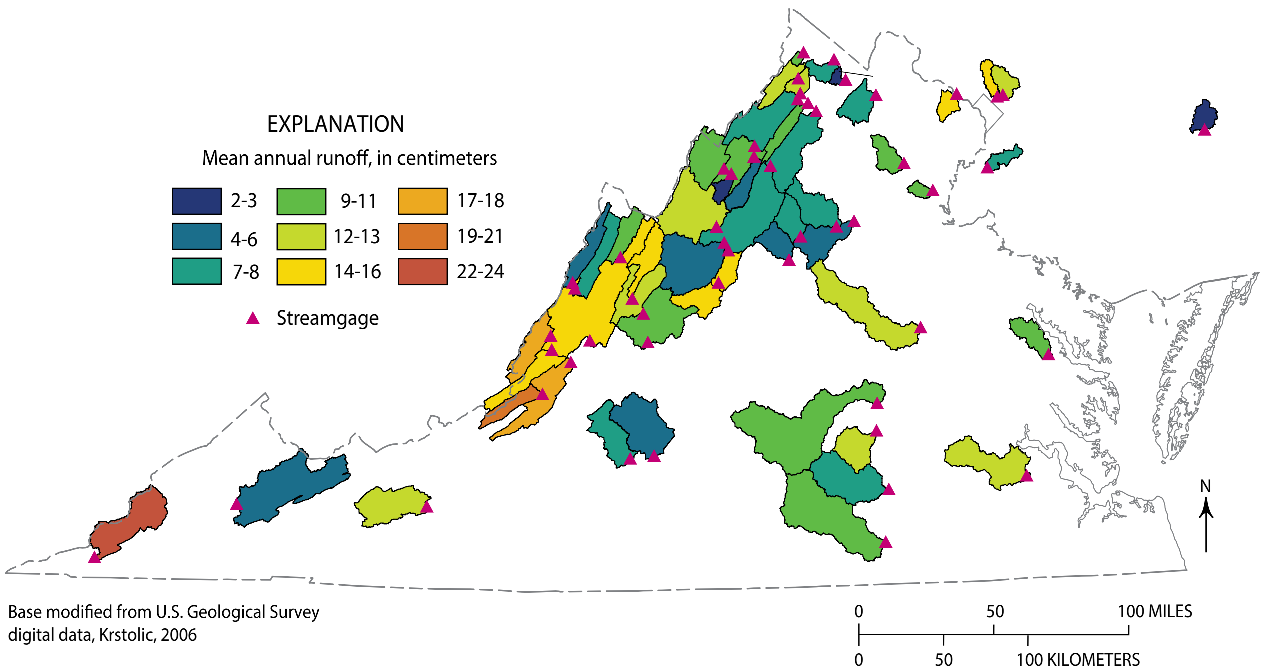


Figure 8: Estimates of mean annual surface runoff for selected watersheds of Virginia, Maryland, and Delaware.

Physiographic Province	Regression equations with linear constants and rock type variables*	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**	2.8	7.1	13.1	---	---	---	---
Coastal Plain	R = aFG+bMG+cCG	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**	4.6	8.1	2.8	24.4	11.2	17.8

*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 dolomostones, COL=fraction Cambrian-Ordovician limestones, OD=fraction Ordovician Dolostones, OS=fraction Ordovician siliciclastics, SSL=fraction Silurian siliciclastics and limestones, S=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. **Values of 1.0 were assigned when the regression attempted to fit a value below zero.

Table 3: Runoff regession equations and their parameter values.

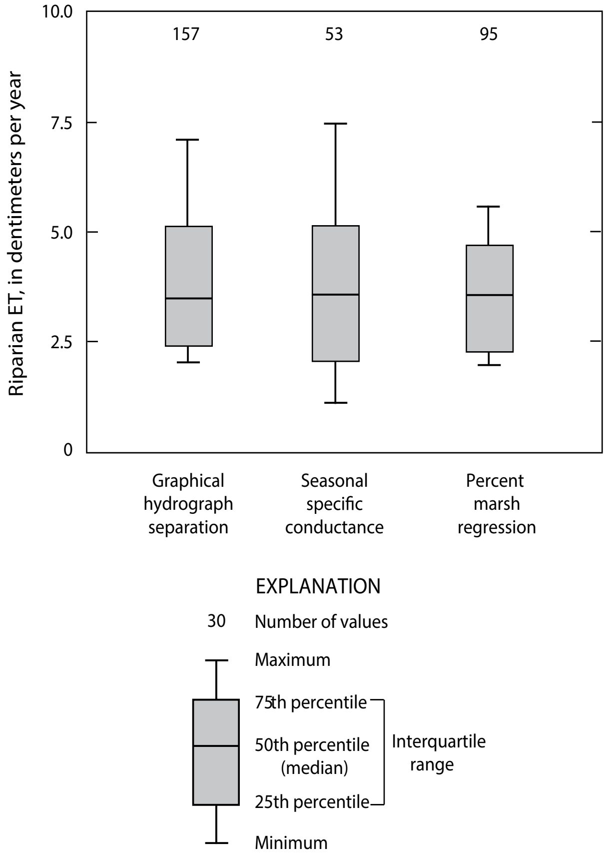


Figure 9: Comparison of different methods for estimating riparian evapotranspiration (ET).

certain climatic and land cover (marsh) variables were first needed for each locality. The climatic variables needed included the mean annual temperature, the mean annual precipitation, the mean daily maximum temperature, the mean daily minimum temperature, and the mean difference in daily temperature. In addition, the percentage of physiographic province and rock types in each county were required in order to apply the regression used to calculate the percent of precipitation that becomes surface runoff [7]. 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 2).

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 (Figure 10). The lowest values are 62 cm/yr or less in some of the far western and northern counties; 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 62 cm/yr or lower because of the relatively high amounts of impervious surface (Figure 10). The highest evapotranspiration values are > 80 cm/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 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. The values of ET estimated in this study agree reasonably well with other regional estimate of ET in Virginia [36].

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. 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 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 (R^2=0.6031)

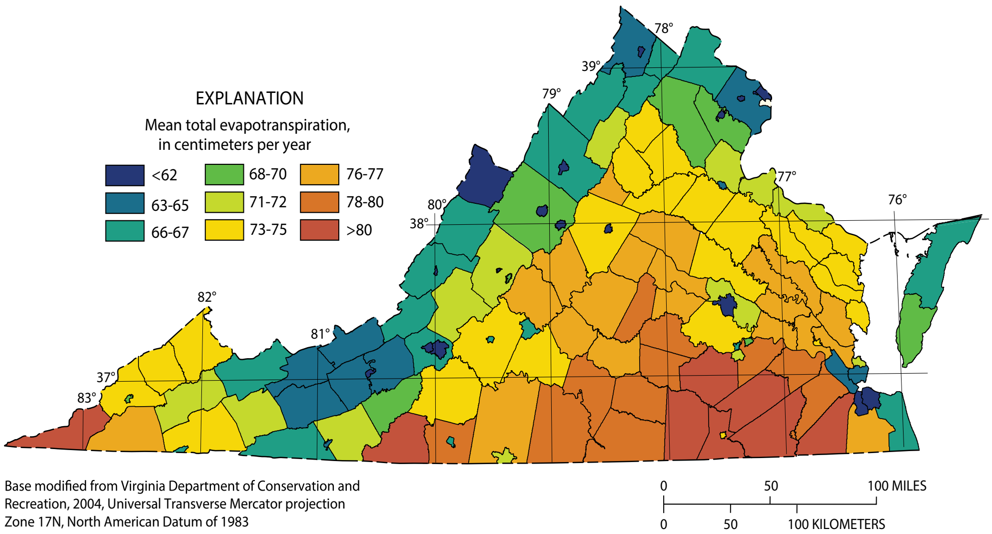


Figure 10: Mean annual total evapotranspiration by locality in Virginia estimated by regression.

between the slope and temperature in each of the 134 localities and the fraction of land cover that is marsh, using the relation:

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

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) (Figure 11). The riparian ET was then calculated using the formula:

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

where PS is the fraction of pervious 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. This method also created a range of ET_{rp} similar to that produced by the other two methods (Figure 9). 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 (Figure 12). The values represent an estimate of the mean annual riparian ET for the entire area of the locality (not the local ET rate in the riparian zone itself). The lowest values are less than 2.5 cm/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 2.5 to 3.4 cm/yr. Values in the Piedmont Province and the northern counties of the Coastal Plain range between 3.5 and 5.7 cm/yr, whereas values in southeastern Virginia and the Tidewater area are between 5.8 and 7.4 cm/yr. These values all have an uncertainty associated with them that we estimate to be plus or minus 2 cm/yr, based on the range of values that have been estimated by other methods (Figure 9).

Net total outflow

The equivalent of total stream flow 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 indicate that the net total outflow varies from about 30 to 50 cm in the Shenandoah Valley and Piedmont of central and southern Virginia to over 50 cm in the mountains of southwestern Virginia and the tidal regions of southeastern Virginia.

Surface runoff

Surface-runoff regression equations were used to predict the ratio of surface runoff to precipitation based on the physiographic province and bedrock type (Figure 13). Surface runoff rates in cm/yr for the localities were obtained by multiplying the mean annual precipitation rate 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 (Figure 14). 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 mean annual values of surface runoff are controlled partly by the fraction of precipitation that runs off. Values of 8 to 10 cm/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 22 cm/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 marshes. Both the inflow and outflow of ground water across non-stream locality boundaries may

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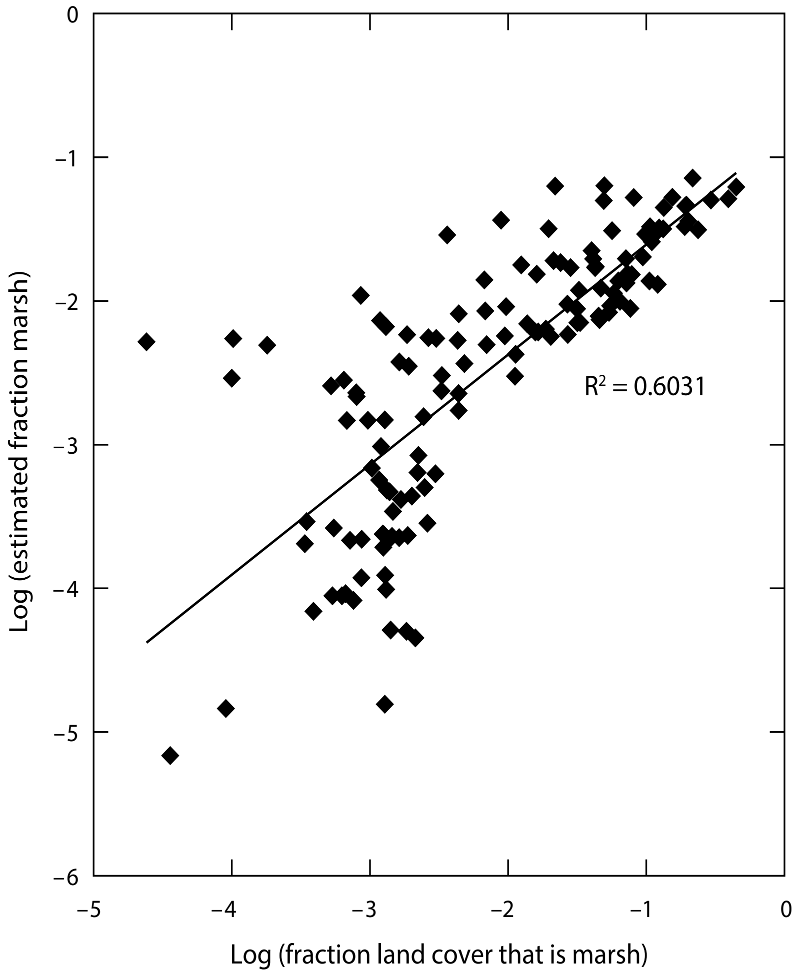

Figure 11: Comparison of fraction of locality land cover that is marsh and that estimated using temperature and topographic slope.

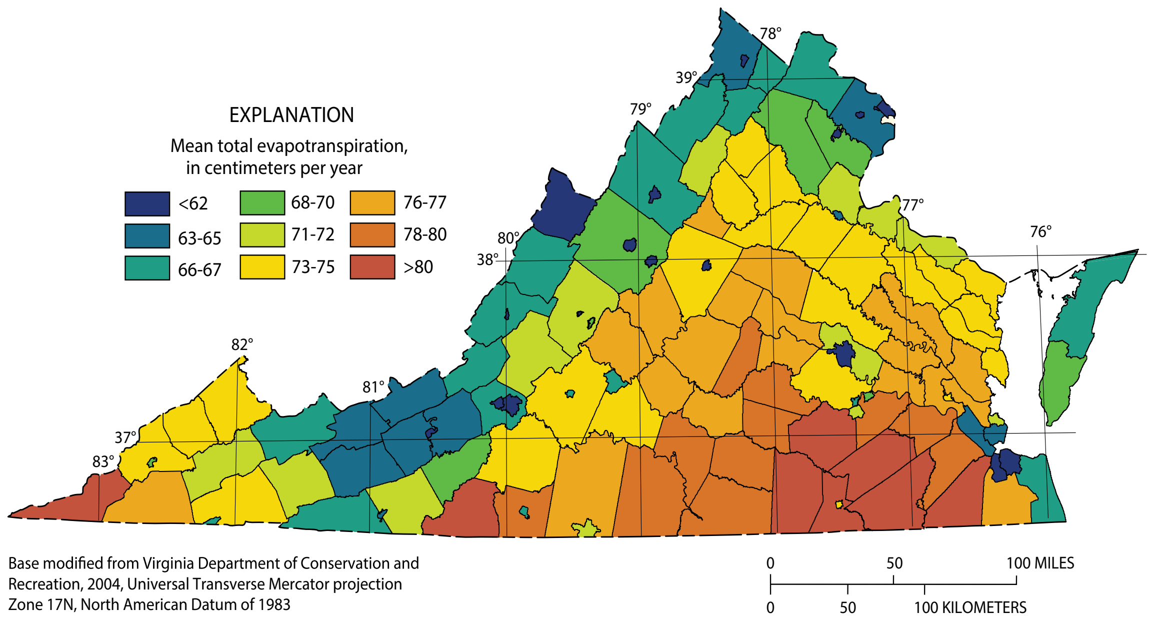

Figure 12: Estimates of mean annual riparian ET in Virginia from 1971 to 2000 by locality.

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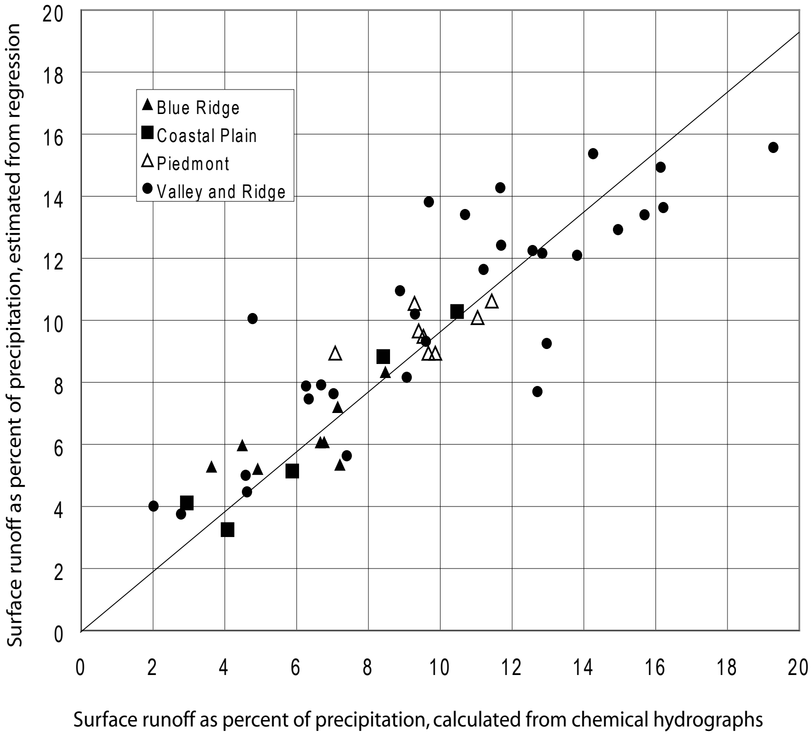

Figure 13: Comparison of calculated surface runoff versus that estimated by the regression.

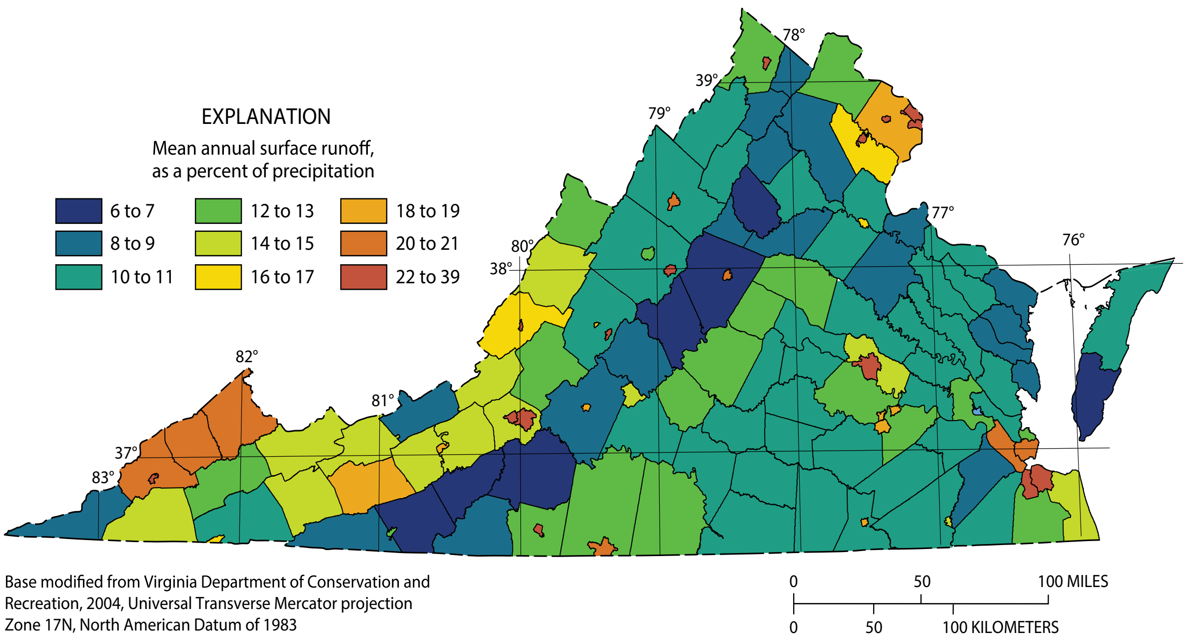

Figure 14: Estimates of surface runoff as a percent of precipitation in Virginia from 1971-2000 by locality.

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 22 cm/yr to approximately 40 cm/yr. Low values (<22 cm/yr) occur in the regions of western Virginia where precipitation is low or surface runoff is high, and in the Piedmont Province where total ET is relatively high. Alternatively, high values (>30 cm/yr) occur in the Blue Ridge Province where precipitation is high and surface runoff is low, and in counties where precipitation is high, 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. 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 (Figure 15). 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).

Infiltration

This means annual infiltration rate is calculated for the localities by subtracting the surface runoff from the precipitation. 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 (<95 cm/yr) typically in the Valley and Ridge Province and in areas of high impervious surface. The rate is highest (>105 cm/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; 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. The localities with the lowest mean recharge rates (<25 cm/yr) are those in western Virginia in the Valley and Ridge or Appalachian Plateau where siliciclastic bedrock is present (Figure 16). The localities with the highest recharge (>35 cm/yr) are in the Blue Ridge Province, or where precipitation is high, or where ET is relatively low (the coastal localities).

Uncertainties in estimates

There are many uncertainties inherent in a study such as this one. First, the locality estimates included in this article 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 [28,37,38].

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 stream flow 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 a few centimeters (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

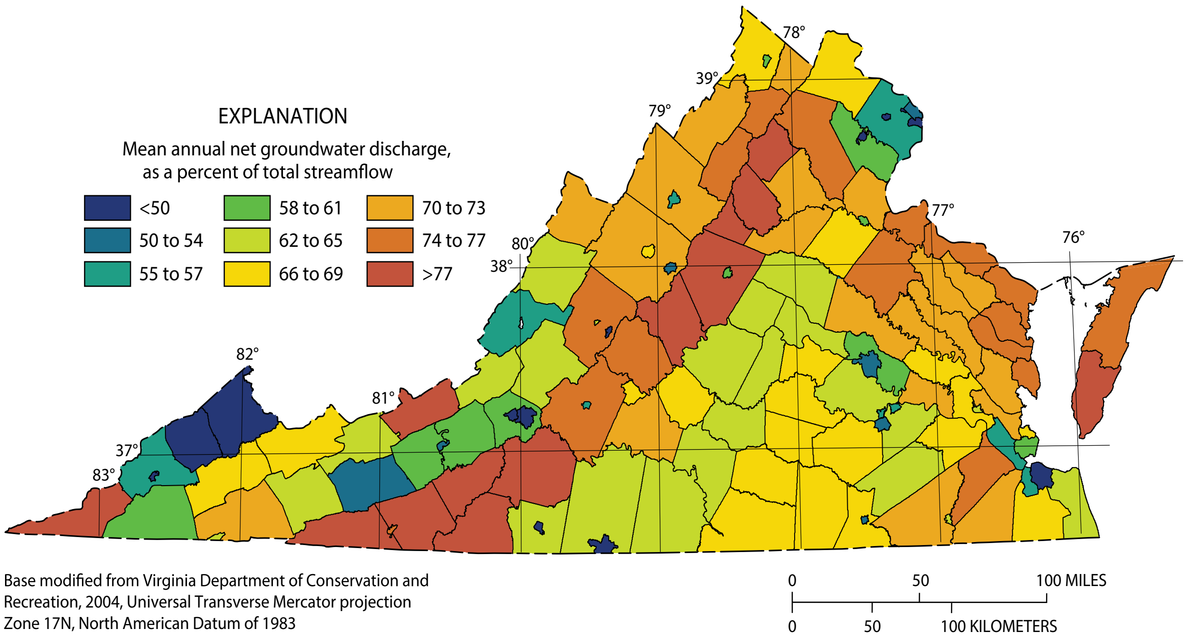

Figure 15: Mean annual net groundwater discharge as a percent of total streamflow in Virginia from 1971- 2000 by locality.

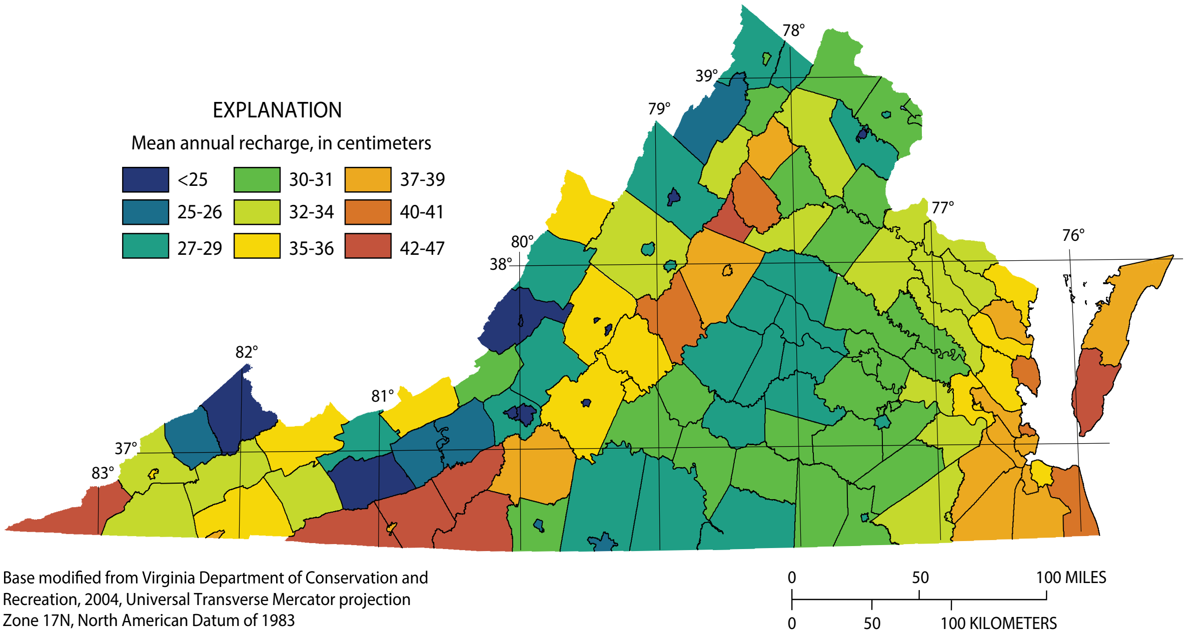

Figure 16: Estimates of mean annual recharge in Virginia from 1971-2000 by locality.

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 2 cm/yr, and 5 cm/yr 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 [35]. Different impervious surfaces can impart very different hydrological effects, and scaling up these behaviors into more regional estimates of system response can often be critical [39]. Thus the estimates for many of the independent cities have a higher degree of uncertainty than those localities with low percentages of impervious surface. Withdrawals of water for human use were not included for in this study, as the magnitude of the natural fluxes to the withdrawals [7] showed that the latter are usually quite small relative to the former.

Overall, given the relative reliability of the precipitation data [40], the agreement of the ET estimates with other recent estimates [26], and the long history of streamgaging by the U. S. Geological Survey, we believe the values of the budget components for the localities determined in this study are very useful estimates.

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 because such values are often needed by water-resource planners. The actual values can, or course, vary greatly in time and space within localities. 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 evapotranspiration (ET) was estimated for watersheds by subtracting the long-term mean annual stream flow 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 stream flow 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% of stream flow, as compared to 61% 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, 113 cm of precipitation falls on the land surface, of which 16 cm runs off the surface into streams, with the remaining 97 cm infiltrating into the soil zone. After infiltration, 65 cm evapotranspires from the vadose zone, leaving 32 cm to recharge the groundwater system at the water table. This groundwater migrates to the stream valleys where 4 cm evapotranspires in the riparian zone and the remaining 28 cm discharges to the stream. The 28 cm in the stream joins the 16 cm of surface runoff to result in 44 cm of mean annual stream flow. This stream flow plus the 69 cm of total ET balance the 113 cm of precipitation. Dividing the 28 cm of groundwater discharge by 44 cm of total stream flow indicates that 64 percent of stream flow is groundwater discharge on average.

The methods used in this study could easily be used in other regions of the United States or the world where (1) streams have been gaged for the last few decades, (2) there is plentiful climate data from the last few decades to estimate long-term average ET, and (3) specific conductance probes can be installed in the streams. In the western United States lack of continuous stream flow in many arid and semi-arid regions might make the implementation of this approach more difficult. In the eastern United States the physiographic provinces that are present in Virginia also extend north and south along most of the Atlantic coastline. Thus the base-flow and surface-runoff regressions might be able to be applied even without installing additional specific conductance probes. Alternatively, graphical hydrograph separation could be used in place of the more costly specific conductance approach. This study provides one example of how a water census could be developed for the United States or other countries where long-term climate and stream flow data sets exist.

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Many individuals worked to install specific conductance probes, and collect and process stream flow and chemistry data during this study, including Gary K. Speiran, Roger M. Moberg, Jr., Donal C. Hayes, and George E. Harlow, Jr. This study would not have been possible without their tireless contributions in the field.

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