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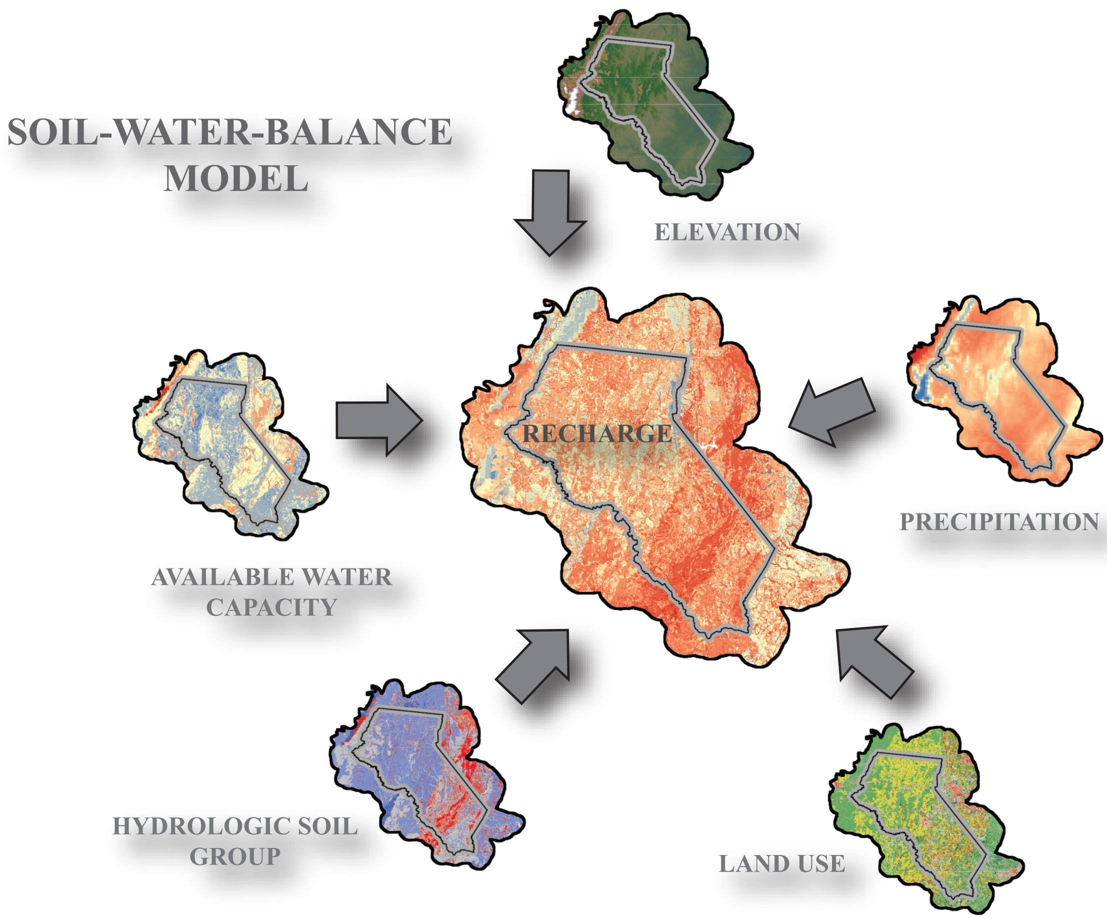
Prepared in cooperation with the Fauquier County Department of Community Development

Documentation of a Soil-Water-Balance Model to Estimate Recharge to Blue Ridge, Piedmont, and Mesozoic Basin Fractured-Rock Aquifers, Fauquier County, Virginia, 1996 through 2015



Scientific Investigations Report 2019–5056

U.S. Department of the Interior
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Cover: Image of the Soil-Water-Balance model of Fauquier County includes an area of 1,498 square miles, divided into 1,076-square-foot (100-square-meter) grid cells on which daily groundwater recharge was estimated using existing elevation, meteorological, land-use, and soil property datasets.

Documentation of a Soil-Water-Balance Model to Estimate Recharge to Blue Ridge, Piedmont, and Mesozoic Basin Fractured-Rock Aquifers, Fauquier County, Virginia, 1996 through 2015

By Kurt J. McCoy and David E. Ladd

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DAVID BERNHARDT, Secretary

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Conversion Factors

U.S. customary units to International System of Units

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)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01093	cubic meter per second per square kilometer ($[m^3/s]/km^2$)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AWC	available water capacity
DEM	digital elevation model
ET	evapotranspiration
gSSURGO	gridded Soil Survey Geographic (dataset)
HUC	hydrologic unit code
RET	riparian evapotranspiration
SWB	Soil-Water-Balance (model)
USDA-NRCS	U.S. Department of Agriculture, Natural Resources Conservation Service
USGS	U.S. Geological Survey

Documentation of a Soil-Water-Balance Model to Estimate Recharge to Blue Ridge, Piedmont, and Mesozoic Basin Fractured-Rock Aquifers, Fauquier County, Virginia, 1996 through 2015

By Kurt J. McCoy and David E. Ladd

Abstract

This report documents a Soil-Water-Balance (SWB) model that was developed for an area covering the Blue Ridge, Piedmont, and Mesozoic basin fractured-rock aquifers in Fauquier County, Virginia, for the calendar years 1996–2015. The SWB model includes an area of 1,498 square miles, divided into 1,076-square-foot (100-square-meter) grid cells on which daily groundwater recharge was estimated using existing elevation, meteorological, land-use, and soil property datasets.

Daily groundwater recharge estimates obtained from the model were summarized annually, and annual model output was compared to the results of the hydrograph separation method, PART, on streamflow data from two streamgages in Fauquier County with periods of continuous record overlapping those of the SWB model period (01643700 Goose Creek near Middleburg, Virginia, and 01656000 Cedar Run near Catlett, Virginia). Spatially distributed groundwater recharge results from the SWB model represent annual conditions and the 20-year average values for the years 1996–2015, including estimated recharge during a previously defined drought in 2001. The 20-year average recharge in Fauquier County from the SWB model ranged from 8.1 inches per year (in/yr) in Blue Ridge aquifers to 5.3 in/yr in Mesozoic basin aquifers. Although mean annual precipitation volumes vary slightly across the County, the contrast in recharge among the Blue Ridge and western Piedmont aquifers with that of the Mesozoic basin aquifers is largely a result of differences in soil infiltration capacity. Precipitation totals 20 percent below mean annual precipitation from 1996–2015 produced drought recharge rates that were less than 50 percent of mean annual recharge.

The SWB model and model output, including spatially distributed annual estimates of groundwater recharge, evapotranspiration, and gross precipitation for the 1996 through 2015 model period, are publicly available as a U.S. Geological Survey data release.

Introduction

This report documents a Soil-Water-Balance (SWB) model developed to estimate the mean annual water budget for the period 1996 through 2015 and the annual water budget for a drought year in 2001 for Fauquier County, Virginia. Fauquier County is a rural 651-square-mile (mi^2) county adjacent to rapidly growing suburban areas near Washington, D.C. (fig. 1). The County includes parts of three distinct geologic provinces: (1) the Blue Ridge, (2) the western Piedmont, and (3) the Mesozoic basin, each of which consist of fractured-rock aquifers that currently supply about 4.3 million gallons per day (Mgal/d) of groundwater for public supply and domestic use (Dieter and others, 2018).

Groundwater recharge, the amount of water infiltrating soils in excess of evapotranspiration (ET) losses, is a critical hydrologic boundary condition affecting the volume of water stored and the rates of water movement in aquifers. Numerous techniques are available to estimate groundwater recharge from streamflow, water-level, and water-quality datasets (Barlow and others, 2017; Nimmo and others, 2014; Sanford and others, 2015). In Virginia, hydrograph separation has been the most commonly used method to estimate watershed-scale recharge (McCoy and others, 2015a; Nelms and Moberg, 2010; Nelms and others, 1997). Hydrograph separation has been used for calibration of recharge estimates derived from chemograph separation (Sanford and others, 2015) and groundwater-flow models (McCoy and others, 2015a).

SWB models covering parts of Virginia have been used at regional scales to derive water budgets and estimate recharge to fractured-rock and unconsolidated aquifers (McCoy and others, 2015b; Masterson and others, 2015). This initial application of a SWB model at a sub-regional scale in Virginia was developed as part of a countywide assessment of fractured-rock aquifers underlying Fauquier County and hydrologic boundary conditions influencing long-term groundwater availability. The SWB model of Fauquier County was used to calculate gridded estimates of recharge at a 1,076-square-foot (ft^2; 100-square-meter)

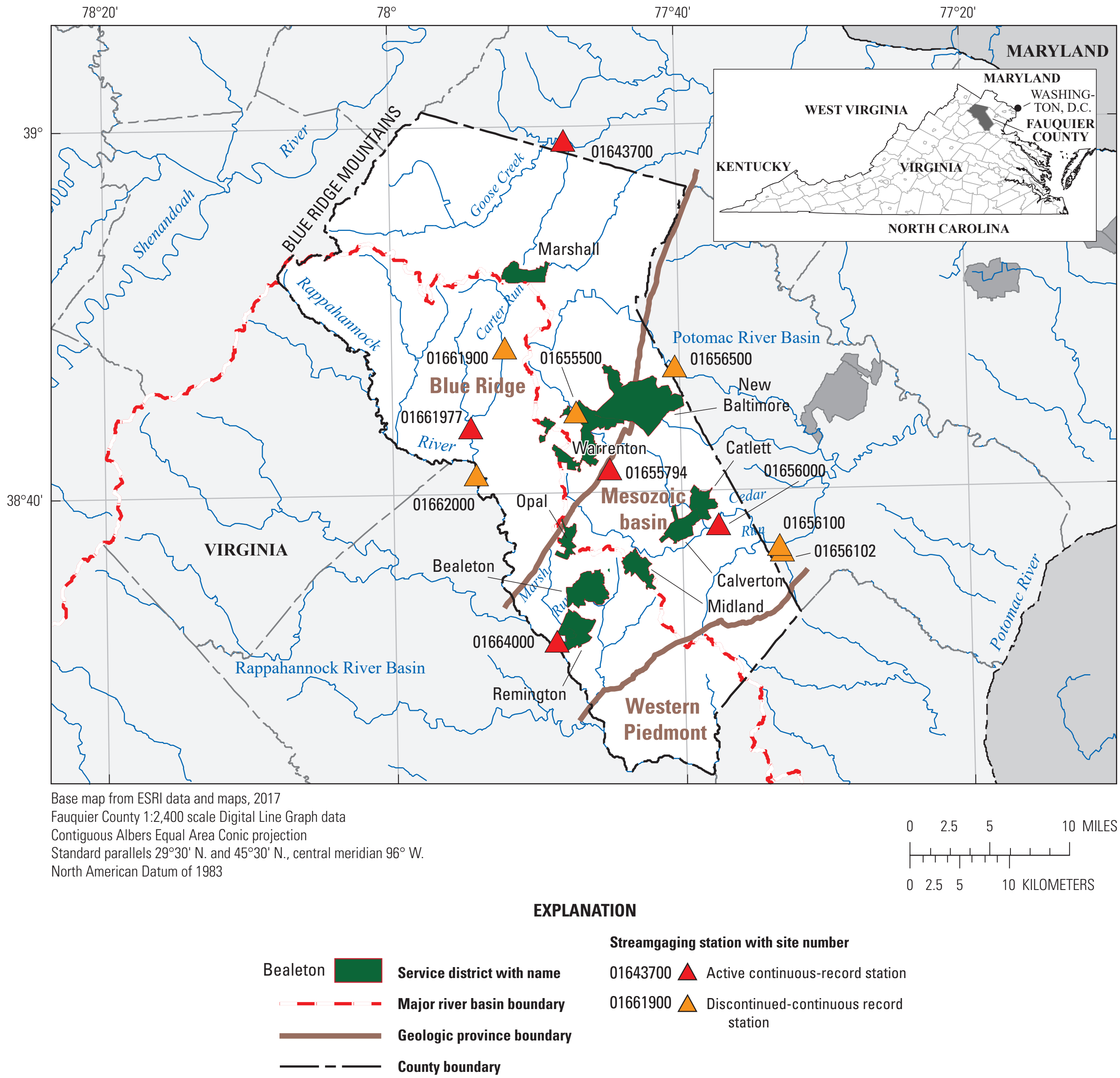


Figure 1. Location of Fauquier County, Virginia, service districts, and hydrologic data-collection sites.

resolution for a 1,498-mi^2 area including a 1.9-mile (mi) buffer around 34 12-digit hydrologic unit code (HUC) watersheds using existing elevation, land-cover, soil property, and daily meteorological data. Annual base-flow estimates also were computed using the hydrograph separation method, PART (Rutledge, 1998), using data collected from two continuous streamgages monitoring non-regulated flow in the Blue Ridge (01643700 Goose Creek near Middleburg, Virginia) and Mesozoic basin (01656000 Cedar Run near Catlett, Virginia) geologic provinces. The drainage areas for the two streamgages are 122 mi^2 and 93.4 mi^2, respectively. The SWB model for Fauquier County was calibrated by comparing the annual base-flow estimates derived from PART for these streamgages to the SWB-derived grid of recharge across the drainage area upstream of the streamgages. The SWB model and model output, including spatially distributed annual estimates of groundwater recharge, ET, and gross precipitation, are publicly available as a USGS data release (Ladd, 2019).

Purpose and Scope

The purpose of this report is to document a 1,076-ft^2 resolution SWB model of groundwater recharge to aquifers of Fauquier County, Virginia, for the calendar years 1996–2015. A sensitivity analysis was conducted to compare changes in model recharge to changes in selected model parameters. Recharge from the SWB model was calibrated using base-flow estimates derived from hydrograph separation results using PART at two streamgages that have been in operation since 1990. To adequately characterize the range of past and current hydrologic conditions affecting aquifers, model output is summarized to provide the 20-year average recharge and annual recharge for the model period, including recharge during a previously defined drought in 2001 affecting northern parts of Virginia (Nelms and Moberg, 2010). Model limitations and results of sensitivity analysis also are discussed.

Description of Study Area

Fauquier County is in north-central Virginia along the drainage divide between the north flowing tributaries of the Potomac River and south flowing tributaries of the Rappahannock River (fig. 1). The Blue Ridge Mountains rise to elevations over 3,300 feet (ft) along the County's western boundary and separate the Shenandoah River drainage from smaller headwater tributaries of the Potomac River and the Rappahannock River Basins. Elevations drop to below 200 ft where Cedar Run and Marsh Run exit the County east and southeast of the City of Warrenton, respectively (fig. 2). Mean annual precipitation for the 20-year period from 1996–2015 varies with elevation and averaged between 41 and 57 inches per year (in/yr; fig. 3; Thornton and others, 2016).

Warrenton is one of nine public service districts along major highways that provide water and sewer utilities to low- and medium-intensity development areas. The majority of Fauquier County lies outside of service districts and is rural with major land-cover classes consisting of deciduous forest or pasture/hay (fig. 4; U.S. Geological Survey, 2014).

Fauquier County includes parts of the Blue Ridge Physiographic Province and the Piedmont Upland and Piedmont Lowlands sections of the Piedmont Physiographic Province (Fenneman and Johnson, 1946). Crystalline rocks underlying the Blue Ridge Province and the northwestern part of the Piedmont Upland section within Fauquier County are combined in this study and referred to as the Blue Ridge geologic province (fig. 1). The Piedmont Lowlands section is underlain by Mesozoic-age sedimentary rocks and is referred to as the Mesozoic basin geologic province for this study. Mesozoic basin rocks were deposited in a series of northeast-southwest trending rift basins that extend along a broad swath of the eastern United States. The southeastern corner of Fauquier County, part of the Piedmont Upland section, is underlain by crystalline rocks of multiple island-arc and volcanic origins (Davis and others, 2001) and is referred to as the western Piedmont geologic province in this study.

Prior to 1986, as many as seven continuous streamgages were operating in or just outside of Fauquier County. The 1952–84 period of record average recharge rates for the Fauquier County area, determined through analysis of streamflow data from five of the seven streamgages, ranged from 5.0 in/yr to 10.7 in/yr (Nelms and others, 1997). From 2002 through 2015, streamflow was measured at only the two streamgages used for calibration in this study: stations 01643700 and 01656000 (fig. 2).

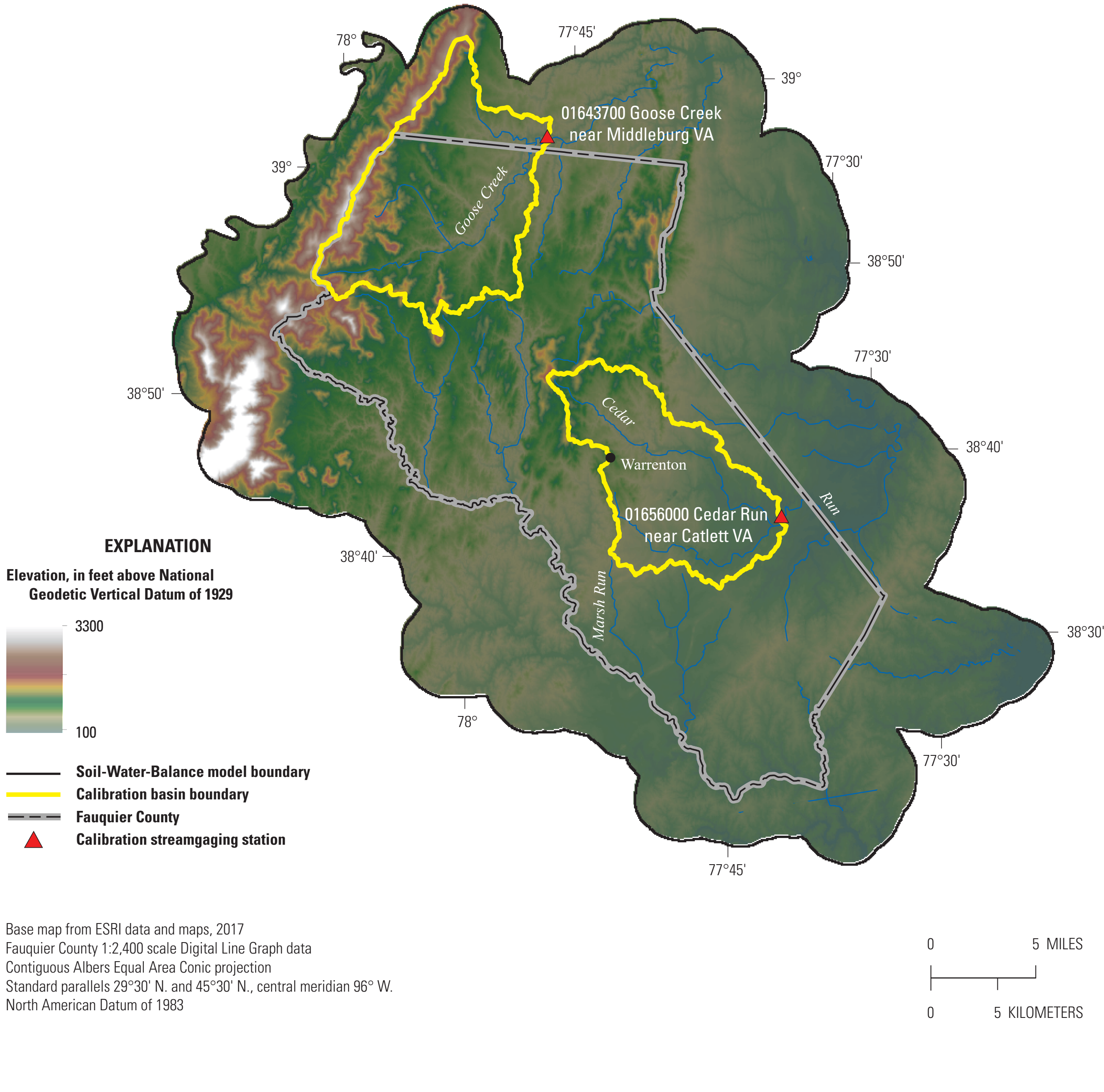


Figure 2. Digital elevation model of the Fauquier County Soil-Water-Balance model area and the location of two calibration basins.

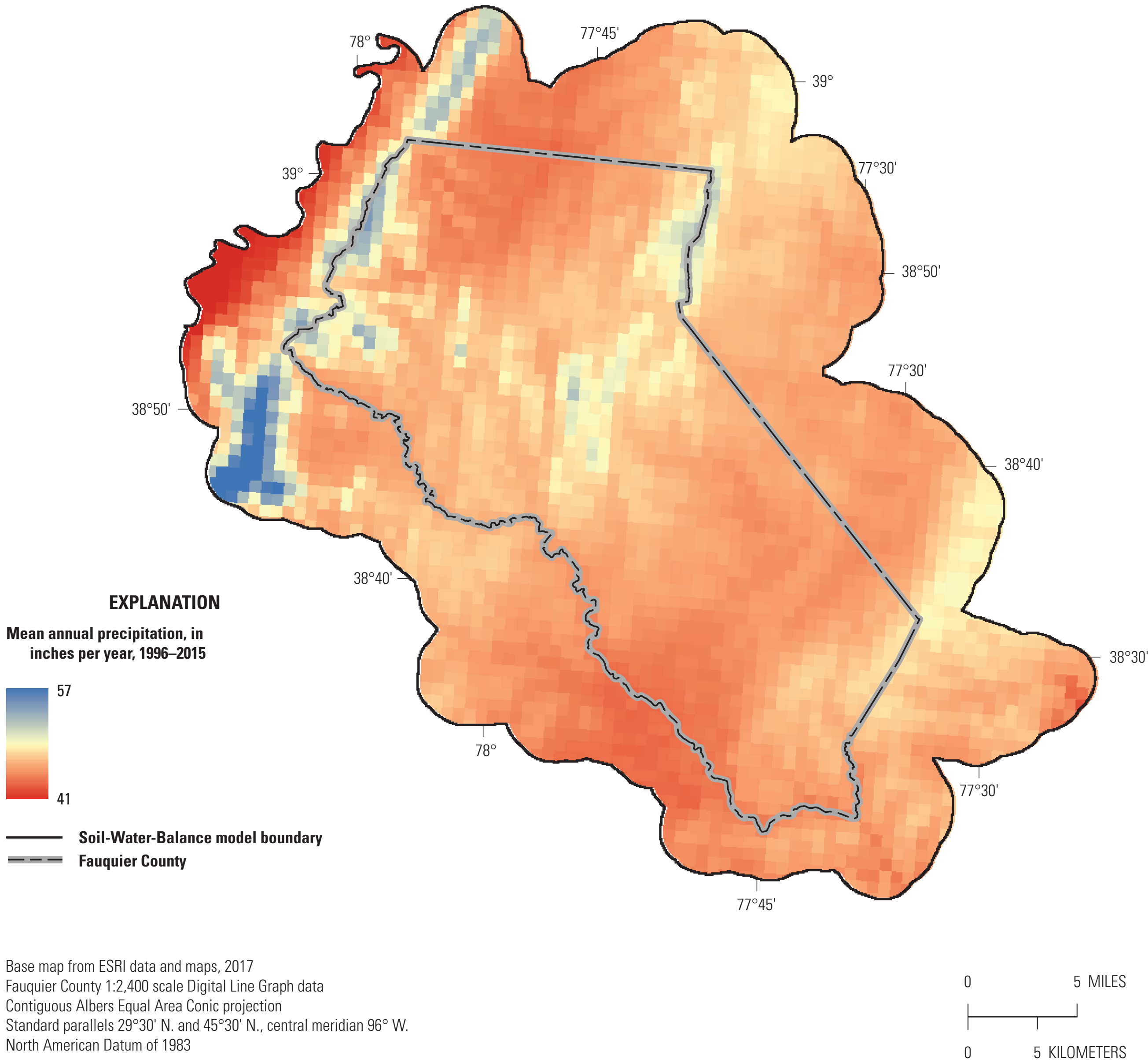
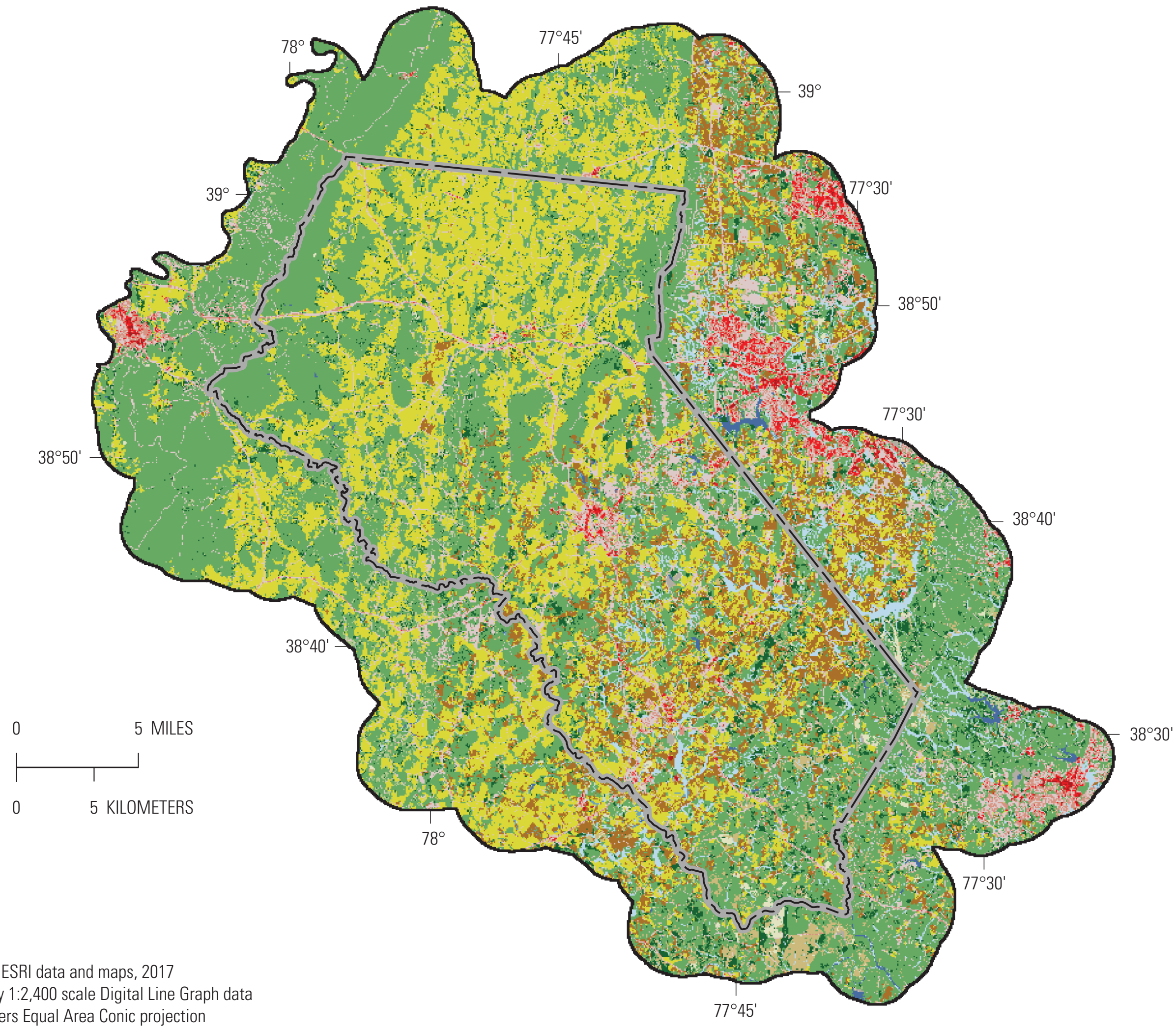


Figure 3. Mean annual precipitation within the Fauquier County Soil-Water-Balance model domain, 1996–2015.



Base map from ESRI data and maps, 2017
Fauquier County 1:2,400 scale Digital Line Graph data
Contiguous Albers Equal Area Conic projection
Standard parallels 29°30' N. and 45°30' N., central meridian 96° W.
North American Datum of 1983

Land-use data from U.S. Geological Survey (2014)

EXPLANATION

Land-Cover Classification

Water
- Open water

Developed
- Open space
- Low intensity
- Medium intensity
- High intensity

Forest
- Deciduous
- Evergreen
- Mixed

Shrubland
- Shrub/scrub
- Grassland/herbaceous

Planted/cultivated
- Pasture/hay
- Cultivated crops

Wetlands
- Woody wetlands
- Emergent herbaceous wetlands

Barren
- Barren land (rock/sand/clay)

Soil-Water-Balance model boundary

Fauquier County

Figure 4. Land-cover classes within the Fauquier County Soil-Water-Balance model area.

Methods

A water budget is a quantitative expression of the various components of the hydrologic cycle. The water budget for any basin must balance the quantity of water entering the basin with the quantity of water leaving the basin. A hydrologic landscape approach was used in Fauquier County to estimate groundwater recharge at a 1,076-ft^2 resolution using SWB and by comparing output with base flow estimated from PART. This comparison includes the assumption that recharge to Fauquier County aquifers is equivalent to groundwater discharge as base flow to streams. In the SWB model, this assumption is satisfied once the maximum soil-water capacity in a model cell is reached. At that time, excess water in the soil column, computed as the difference in water-budget sources (precipitation, snowmelt, and runoff from upstream cells) and water-budget sinks (interception, ET, and runoff to downstream cells), conceptually exits the model as recharge to underlying aquifers. The annual sum of recharge in a basin of the SWB model was assumed to be comparable to base-flow estimates from PART. In the field, recharge could occur prior to reaching maximum soil-water capacity through macropore processes, or as direct infiltration in streambeds. SWB explicitly represents flow through the soil matrix that originates from precipitation and does not account for point source recharge originating from other processes (such as loss of streamflow to aquifers).

Hydrograph Separation

Variability in annual recharge rates was evaluated using annual base-flow estimates from PART (table 1). PART is a hydrograph-separation technique that divides streamflow into its groundwater discharge and surface-runoff components (Rutledge, 1998). PART estimates a daily record of base flow from streamflow records by using a form of streamflow partitioning based on antecedent streamflow recession. Base-flow discharge is commonly assumed to be equivalent to effective recharge in fractured-rock terrains of the eastern United States (Nelms and others, 1997); however, effective recharge is not equivalent to the total recharge for a basin. Total recharge is always greater than effective recharge and includes riparian evapotranspiration, which is the quantity of water evaporated or transpired by plants in the riparian zone adjacent to streams. The Groundwater Toolbox (Barlow and others, 2017) was used to estimate annual base flow at the two continuous-record streamflow-gaging stations within the Fauquier County SWB model area. Streamgage data covered calendar years 1996 through 2015, however, individual periods of record varied between the two streamgaging stations during that period. Nelms and others (2015) and McCoy and others (2015b) described the limitations and assumptions of applying hydrograph separation methods in the eastern United States.

Fauquier County Soil-Water-Balance (SWB) Model

The magnitude and distribution of water-budget components in Fauquier County was computed using regionally available spatial datasets and the SWB model (Westenbroek and others, 2010). The SWB model of Fauquier County consists of 387,969 grid cells (1,076-ft spacing) across a 1,498-mi^2 study area that includes a 1.9-mi buffer around 34 HUC12 watersheds completely or partially within Fauquier County. Climatological data specified for each grid cell, including daily values of precipitation and maximum and minimum temperature, were obtained from the Daymet database (Thornton and others, 2016) for the period 1996 through 2015. The SWB model calculates spatial and temporal variations in groundwater recharge based on climatological data, soil, and landscape properties. SWB is a deterministic model that uses gridded data and physically based parameters to apportion water derived from daily precipitation and snowmelt into surface runoff, ET, recharge, and water storage in the soil column. Model output includes gridded distributions of actual ET and recharge at a specified cell size within the study area. Computation of water-budget components relies on relations between surface runoff, land cover, and hydrologic soil group (Cronshey and others, 1986), and estimated values of ET and temperature (Hargreaves and Samani, 1985). Water storage in the soil column is estimated using a modified Thornwaite-Mather accounting method on a daily basis (Westenbroek and others, 2010). For the SWB model input, landscape data, including land cover (fig. 4) and surface flow directions, were obtained from the National Land Cover Database (U.S. Geological Survey, 2014) and derived from a 98-ft (30-meter) digital elevation model (DEM; U.S. Geological Survey, 2015), respectively. The DEM was processed to eliminate all closed depressions in the elevation data to prevent internal drainage. Deciduous forest covers 42.4 percent of the model area (table 2). Pasture and hay or cultivated crops cover 25.7 and 8.1 percent, respectively.

Hydrologic soil groups (fig. 5) and available water capacity (AWC; fig. 6) were derived primarily from gridded Soil Survey Geographic (gSSURGO) data (U.S. Department of Agriculture, Natural Resources Conservation Service, 2016). Local data from the Digital General Soil Map of the U.S. (U.S. Department of Agriculture, Natural Resources Conservation Service, 2006) were used in areas where gSSURGO data were unavailable. The gSSURGO data for soils in Rappahannock County were updated for consistency with recent map units in Fauquier County (table 3). The soil survey data define four hydrologic soil groups, A through D, that range from low to high runoff potential, high to low infiltration capacity, and less than 10 percent to greater than 40 percent clay content, respectively (U.S. Department of Agriculture, 2007). Hydrologic soil groups B and C underlie

Table 1. Annual base flow and percent streamflow from PART for two basins used in the calibration of the Fauquier County, Virginia, Soil-Water-Balance model, 1996–2015

[--, no data]

Year	1643700 Goose Creek near Middleburg, VA		1656000 Cedar Run near Catlett, VA	
	Annual base flow from PART, inches per year	Percent annual streamflow from PART	Annual base flow from PART, inches per year	Percent annual streamflow from PART
1996	19.7	66	9.9	40
1997	--	--	5.1	53
1998	--	--	7.0	35
1999	--	--	2.9	39
2000	--	--	3.4	46
2001	--	--	3.0	41
2002	3.3	65	2.1	36
2003	23.1	60	11.6	36
2004	11.7	67	5.7	45
2005	10.5	65	5.7	41
2006	7.2	75	4.4	39
2007	6.3	73	3.7	51
2008	5.9	58	3.1	32
2009	9.4	66	4.1	40
2010	10.8	64	4.2	47
2011	9.2	57	5.6	41
2012	7.9	60	3.7	44
2013	10.9	67	5.5	32
2014	12.6	69	8.8	46
2015	9.3	68	5.6	47

three-quarters of the Fauquier County SWB model area (table 4). The remainder of the area is mostly underlain by soil group D, or is composed of dual soil groups in which the water table is within 24 inches of relatively permeable soils in groups A, B, or C.

Water from precipitation and snowmelt is either diverted to surface runoff, intercepted by the plant canopy, consumed by ET, or allowed to infiltrate the soil column. Surface runoff either infiltrates the soil column in downslope cells, discharges to open water bodies, or accumulates in closed surface depressions. Daily accounting of the volume of water stored in the soil column in each grid cell is calculated from the estimated ET for distinct combinations of hydrologic soil group and land cover. Recharge is computed as surplus water in excess of the maximum soil-water capacity, a product of AWC and root depth in the soil column. Surplus water in excess of a specified maximum recharge rate, which may be assigned to any combination of hydrologic soil group and land cover, is rejected as recharge and passed to downslope cells.

The SWB model was calibrated by comparing annual base-flow estimates from the hydrograph separation technique PART to annual recharge estimates from the SWB model for available years of record at streamgages 01643700 and 01656000 within the model area. Selected SWB model parameters were adjusted to improve model fit.

Table 2. Distribution of 2011 land cover in the Fauquier County Soil-Water-Balance model area.

[2011 land cover data from U.S. Geological Survey (2014)]

Land-cover class	Code	Percentage of total study area
Open water	11	0.5
Developed, open space	21	8.3
Developed, low intensity	22	2.0
Developed, medium and high intensity	23/24	1.1
Barren land	31	~0.2
Deciduous forest	41	42.4
Evergreen forest	42	4.3
Mixed forest	43	1.4
Shrub/Scrub	52	1.8
Grassland/Herbaceous	71	0.7
Pasture/Hay	81	25.7
Cultivated crops	82	8.1
Woody wetlands	90	3.2
Emergent herbaceous wetlands	95	~0.2

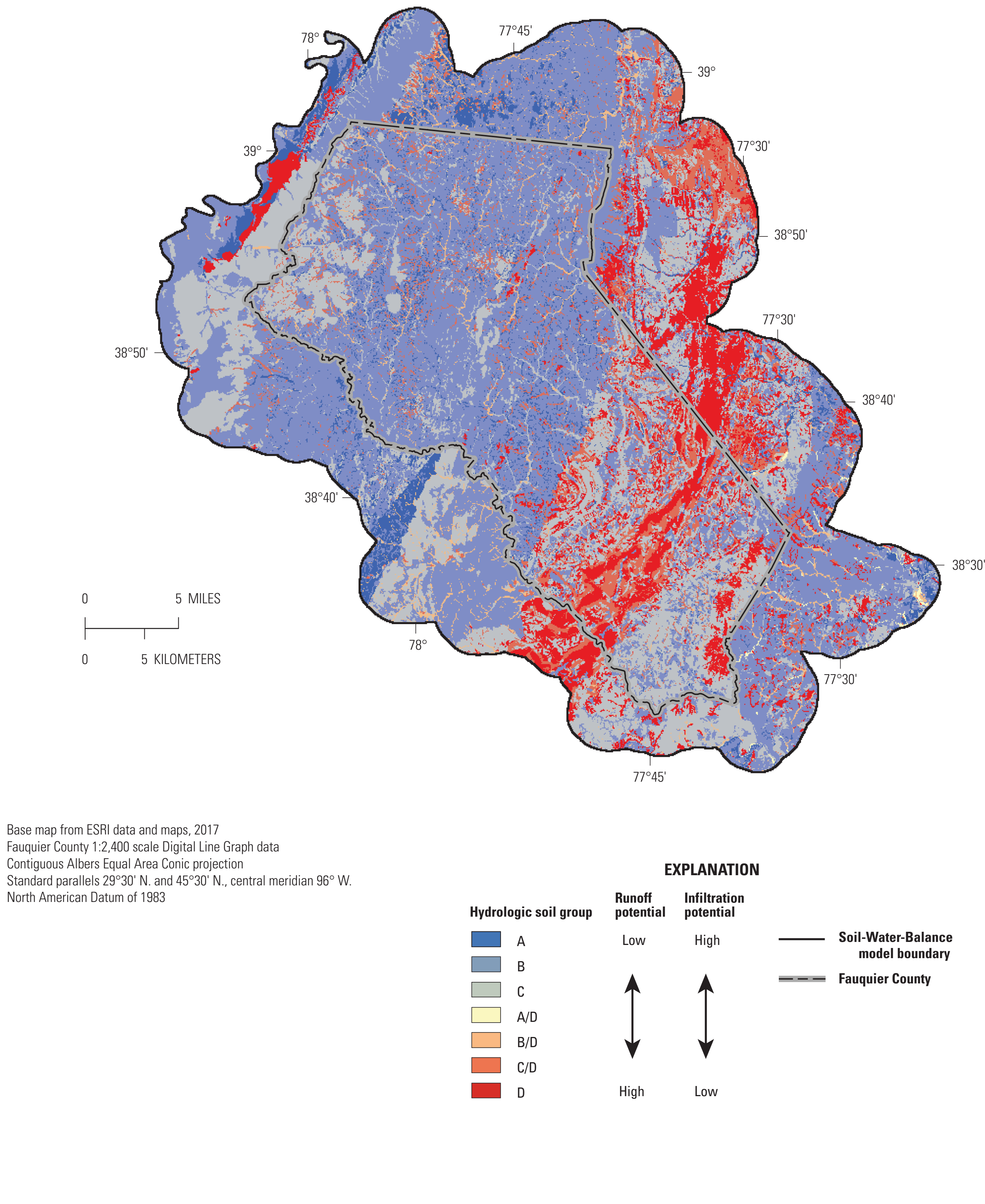


Figure 5. Hydrologic soil groups within the Fauquier County Soil-Water-Balance model area derived from soil survey data (U.S. Department of Agriculture, Natural Resources Conservation Service, 2006, 2016).

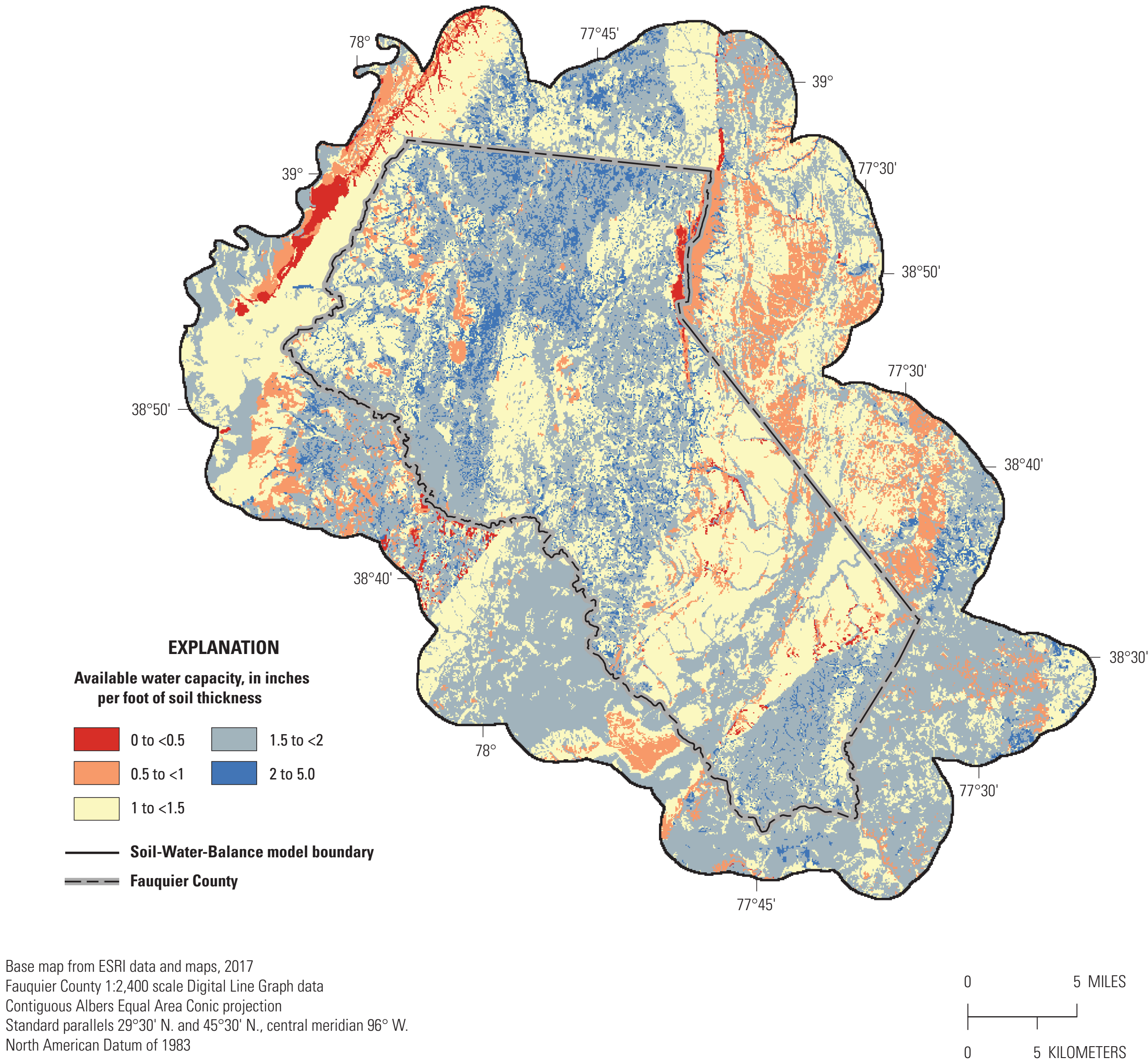


Figure 6. Available water capacity of soils within the Fauquier County Soil-Water-Balance model area derived from soil survey data (U.S. Department of Agriculture, Natural Resources Conservation Service, 2006, 2016).

Table 3. Correlation table for Rappahannock County and Fauquier County, Virginia, map unit symbols.

[Data from U.S. Department of Agriculture, Natural Resources Conservation Service (2016)]

Map unit symbol	
Rappahannock County	**Fauquier County**
Ad	1A
Be	38B
BgC	30C
BoC	20C
BoD	20D
BoE	20E
BrC	18C
BrD	19D
BrE	19E
BwC2	20C
ByC	20C
ByD	20D
ByE	20E
CdB	23B
CdC2	23C
CeB2	31B
CeC2	31C
Ch	2A
Co	3A
DyB	83C
DyC2	83C
EbC	31C
EbD2	20D
EcB	31B
EcC	31C
ElC3	28C
EuB	28C
EuC2	28C
EyD2	28C
HtC3	97B
Me	17B
MyC	40C
MyD	40D
RaE	25E
RkD	19D
RkE	19E
RoD	42D
RoE	42E
Sa	1A
Sc	59C
StB	87C
StC	87C
StD	87C
UcB	87C
UcC	87C
UnC2	87C
Ve	42E
We	4A
Wo	10A
Ws	9A

Table 4. Distribution of hydrologic soil groups in the Fauquier County Soil-Water-Balance model area.

[Data derived from U.S. Department of Agriculture, Natural Resources Conservation Service (2006, 2016)]

Hydrologic soil group	Percentage of total model area
A	5.3
B	50.1
C	25.2
D	9.8
A,B,C/D[a]	9.5

[a]Saturated soils with shallow water table.

Recharge Results

The 20-year average recharge in Fauquier County from the SWB model ranged from 8.1 in/yr in Blue Ridge aquifers to 5.3 in/yr in Mesozoic basin aquifers (table 5; fig. 7). Countywide, recharge averaged 23.1 Mgal/d for the period 1996–2015. Although mean annual precipitation volumes vary slightly across the County (fig. 3), the contrast in recharge among the Blue Ridge and western Piedmont aquifers with that of the Mesozoic basin aquifers is largely a result of differences in soil infiltration capacity (fig. 5). Land-use differences result in local differences in recharge rates that are less prominent. Recharge rates are generally highest in deciduous forest areas and lowest in pasture/hay and developed areas. Within multiple stream valleys in the model area, recharge rates for individual cells locally exceed 14 in/yr where the stream is underlain by A group soils (fig. 5). Cedar Run, southeast of

Table 5. Soil-Water-Balance model estimates of recharge for Fauquier County by geologic province.

[in/yr, inches per year]

Geologic province	1996–2015 mean annual recharge, in/yr	2001 drought annual recharge, in/yr
Blue Ridge	8.1	3.2
Mesozoic basin	5.3	2.2
western Piedmont	8.0	3.1

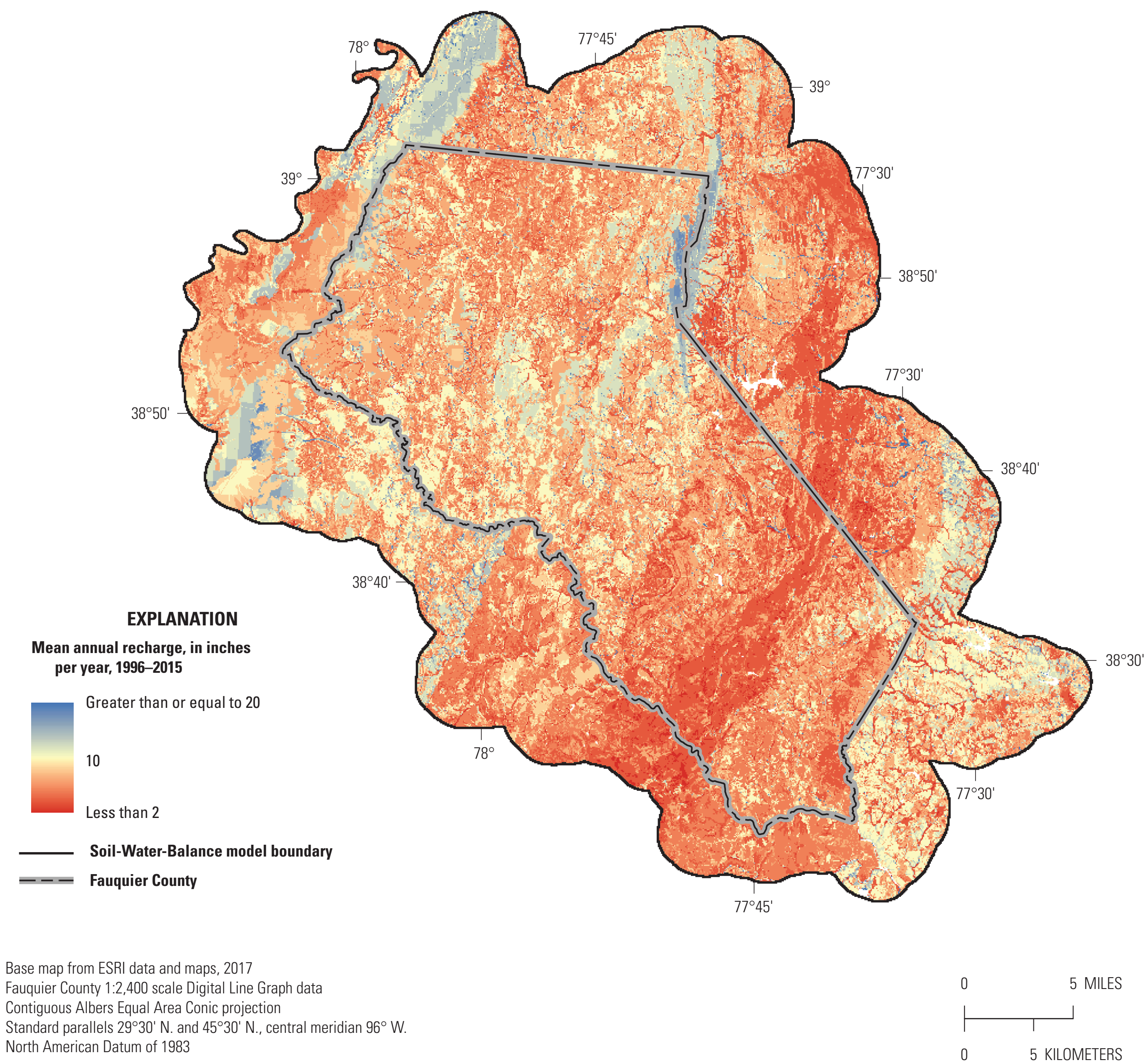


Figure 7. Mean annual recharge from the Fauquier County Soil-Water-Balance model, 1996–2015.

the New Baltimore Service District, is a particularly good example of model predicted recharge greater than 10 in/yr in several locations where the stream crosses the Mesozoic basin aquifers, where recharge is expected to be relatively low. These results contrast with the conceptualization of streams as areas of discharge; however, the SWB model can be expected to perform poorly in areas where the water table is close to land surface, as there is no provision for recharge rejection due to saturation beyond explicitly limiting the maximum recharge rate for specific combinations of land cover and soil type (Westenbroek and others, 2010). Additional recharge from losing stream reaches or pumping-induced capture of stream water are processes that are not explicitly represented by the SWB model and require other techniques to quantify.

Large parts of northern Virginia were affected by drought in 2001 (Nelms and Moberg, 2010). Precipitation across Fauquier County averaged 36.5 inches in 2001, or an amount equivalent to 80 percent of the 1996–2015 average of 45.3 inches. Recharge in 2001 ranged from 3.2 in/yr in the Blue Ridge aquifer to 2.2 in/yr in the Mesozoic basin aquifers (fig. 8). Precipitation totals 20 percent below mean annual precipitation from 1996–2015 produced drought recharge rates that were less than 50 percent of mean annual recharge. Countywide, 2001 drought recharge from the SWB model averaged 9.0 Mgal/day.

Model Sensitivity Analysis

The sensitivity of SWB-modeled annual recharge to changes in various model parameters was analyzed to determine which parameters should be adjusted for model calibration. Curve number, root-zone depth, and growing season plant-canopy interception were altered independently over a range of values within two calibration basins with measured streamflow at gages 01643700 and 01656000 for the modeled years 2003 through 2007. Curve number determines modeled runoff based on the U.S. Department of Agriculture, Natural Resources Conservation Service curve number rainfall-runoff relation (Cronshey and others, 1986; Westenbroek and others, 2010), and is assigned within the SWB model to various combinations of hydrologic soil group and land-use class. Root-zone depth, which also is assigned within the SWB model to various combinations of hydrologic soil group and land-use class, is used in combination with an input AWC grid to determine the maximum soil water capacity for each cell in the model area (Westenbroek and others, 2010). Plant-canopy interception is assigned for growing and non-growing seasons to individual land-use classes within the SWB model and represents the amount of water trapped by vegetation prior to reaching the soil (Westenbroek and others, 2010). The period from 2003 through 2007 was chosen for the sensitivity analysis because precipitation covered a wide range of conditions; annual precipitation during the model period was highest (63.5 inches) in 2003, lowest (33.7 inches) in 2007, and average annual precipitation for the entire model period (45.4 inches) was close to 2006 precipitation (44.8 inches). Curve number and root-zone depth were altered independently for each unique combination of deciduous forest and pasture/hay land-use classes in hydrologic soil groups B and C. Plant-canopy interception, which is assigned exclusively to land cover, was altered independently over a range of values in deciduous forest and pasture/hay land-use classes. Modeled recharge and differences in modeled recharge resulting from changes in these parameters are shown in table 6 and figure 9, respectively. For mean-annual conditions and all years from 2003 through 2007, except 2003, the largest changes in modeled recharge occurred due to changes in curve number and root-zone depth in both deciduous forest and pasture/hay land-use classes in hydrologic soil type B (table 6; figs. 9*A* and *B*). High model recharge sensitivity to canopy interception in deciduous forest and pasture/hay land-use classes in 2003 (figs. 9*A* and *B*) is likely due to the high precipitation that year. Model recharge in the calibration basins was less sensitive to changes in model parameters apportioned to hydrologic soil group C than hydrologic soil group B (figs. 9*A* and *B*).

In the two basins selected for calibration, modeled annual recharge values were compared to annual base-flow values computed by the hydrograph separation program, PART. The differences between PART base-flow estimates and SWB modeled recharge for the two calibration basins were computed on an annual basis for each year during the model period, 1996 through 2015. During the model period, station 01643700 had 15 years of available streamflow record and station 01656000 had 20 years of available streamflow record from which to derive PART base-flow estimates (table 1). The annual differences between the PART base-flow estimates and SWB recharge estimates, known as residuals, were squared and summed for each watershed to determine the sum-of-square errors (*SSE*). The standard error (*SE*) for each watershed was computed using equation 1.

$$SE = \sqrt{\frac{SSE}{n}} \quad , \qquad (1)$$

where

n is the number of years of available record used in the PART hydrograph separation analysis.

For the initial comparison, previously published values (Westenbroek and others, 2010; McCoy and others, 2015b) were used for most model parameters in the SWB model. Some initial model parameters were altered from previously published values to fit conceptual models of runoff and infiltration in the study area. The initial comparisons showed that SWB annual recharge estimates generally underestimate PART annual base-flow estimates from station 01643700 in the Goose Creek basin (predominantly positive residuals), and generally overestimate PART annual base-flow estimates from station 01656000 in the Cedar Run basin (predominantly negative residuals; fig. 10; table 7). Changes to the model parameters to which SWB model recharge is most sensitive

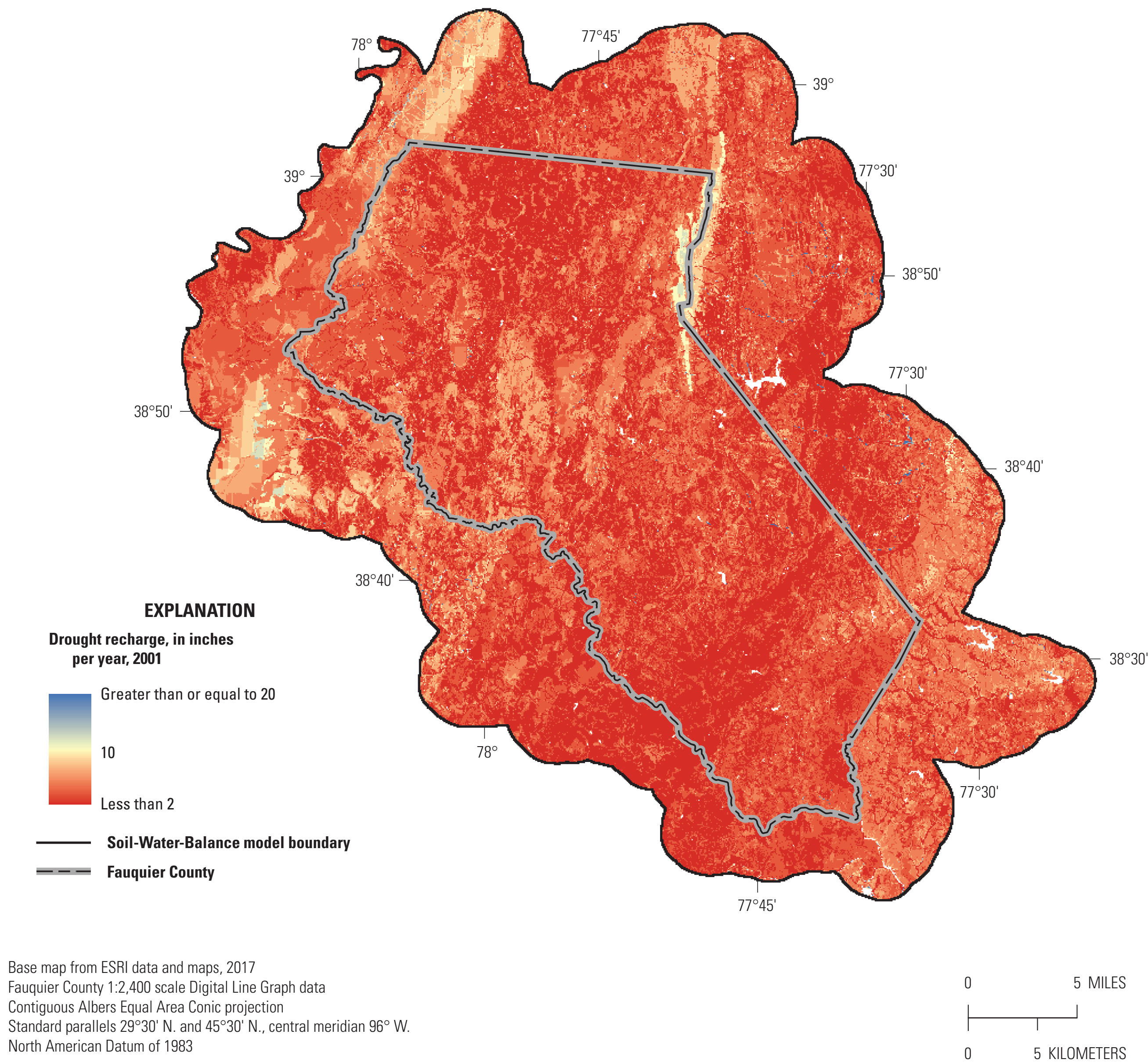


Figure 8. Drought recharge from the Fauquier County Soil-Water-Balance model, 2001.

Table 6. Soil-Water-Balance (SWB) recharge in calibration basins for various model parameter values.

Basin	Parameter	Parameter value	Hydrologic soil group	Land-use class	SWB recharge[a], in inches per year					
					2003	2004	2005	2006	2007	Mean-annual conditions (2003–07)
1643700	Root-zone depth	1.5	B	Deciduous forest	13.22	7.06	6.10	6.97	5.57	7.78
1643700	Root-zone depth	6	B	Deciduous forest	12.80	6.58	5.05	5.87	4.70	7.00
1643700	Root-zone depth	1.5	B	Pasture/hay	13.72	7.49	6.95	7.76	6.19	8.42
1643700	Root-zone depth	6	B	Pasture/hay	12.81	6.47	5.55	6.18	5.26	7.25
1643700	Root-zone depth	1.5	C	Deciduous forest	13.12	6.93	5.97	6.83	5.44	7.66
1643700	Root-zone depth	6	C	Deciduous forest	12.99	6.79	5.75	6.61	5.24	7.47
1643700	Root-zone depth	1.5	C	Pasture/hay	13.12	6.91	6.00	6.85	5.45	7.67
1643700	Root-zone depth	6	C	Pasture/hay	13.05	6.87	5.90	6.74	5.38	7.59
1643700	Plant-canopy interception	0.03	Both	Deciduous forest	13.33	6.96	5.99	6.87	5.43	7.72
1643700	Plant-canopy interception	0.12	Both	Deciduous forest	12.35	6.77	5.86	6.63	5.42	7.40
1643700	Plant-canopy interception	0.03	Both	Pasture/hay	13.76	6.96	6.02	6.94	5.45	7.83
1643700	Plant-canopy interception	0.12	Both	Pasture/hay	12.72	6.87	5.93	6.75	5.42	7.54
1643700	Curve number	40	B	Deciduous forest	13.09	6.90	5.95	6.80	5.42	7.63
1643700	Curve number	90	B	Deciduous forest	11.87	6.40	4.98	5.81	4.68	6.75
1643700	Curve number	40	B	Pasture/hay	14.11	7.36	6.70	7.54	6.13	8.37
1643700	Curve number	90	B	Pasture/hay	12.42	6.53	5.66	6.53	5.16	7.26
1643700	Curve number	40	C	Deciduous forest	13.09	6.90	5.95	6.80	5.42	7.63
1643700	Curve number	90	C	Deciduous forest	13.09	6.92	5.92	6.78	5.42	7.63
1643700	Curve number	40	C	Pasture/hay	13.10	6.89	6.00	6.83	5.43	7.65
1643700	Curve number	90	C	Pasture/hay	13.09	6.90	5.95	6.80	5.42	7.63
1656000	Root-zone depth	1.5	B	Deciduous forest	12.30	5.57	6.14	6.45	4.70	7.03

Table 6. Soil-Water-Balance (SWB) recharge in calibration basins for various model parameter values.—Continued

Basin	Parameter	Parameter value	Hydrologic soil group	Land-use class	SWB recharge[a], in inches per year					
					2003	2004	2005	2006	2007	Mean-annual conditions (2003–07)
1656000	Root-zone depth	6	B	Deciduous forest	12.02	5.33	5.51	5.78	4.26	6.58
1656000	Root-zone depth	1.5	B	Pasture/hay	12.44	5.68	6.43	6.73	4.91	7.24
1656000	Root-zone depth	6	B	Pasture/hay	12.09	5.39	5.86	6.14	4.54	6.80
1656000	Root-zone depth	1.5	C	Deciduous forest	12.23	5.52	6.06	6.36	4.64	6.96
1656000	Root-zone depth	6	C	Deciduous forest	12.10	5.42	5.94	6.24	4.52	6.84
1656000	Root-zone depth	1.5	C	Pasture/hay	12.25	5.52	6.09	6.39	4.66	6.98
1656000	Root-zone depth	6	C	Pasture/hay	12.13	5.46	5.95	6.26	4.55	6.87
1656000	Plant-canopy interception	0.03	Both	Deciduous forest	12.37	5.54	6.07	6.40	4.63	7.00
1656000	Plant-canopy interception	0.12	Both	Deciduous forest	11.76	5.45	5.98	6.17	4.61	6.79
1656000	Plant-canopy interception	0.03	Both	Pasture/hay	12.55	5.54	6.08	6.45	4.64	7.05
1656000	Plant-canopy interception	0.12	Both	Pasture/hay	12.05	5.49	6.04	6.30	4.62	6.90
1656000	Curve number	40	B	Deciduous forest	12.21	5.50	6.05	6.34	4.63	6.95
1656000	Curve number	90	B	Deciduous forest	11.56	5.25	5.41	5.67	4.27	6.43
1656000	Curve number	40	B	Pasture/hay	12.60	5.66	6.51	6.75	4.87	7.28
1656000	Curve number	90	B	Pasture/hay	11.91	5.38	5.92	6.23	4.54	6.80
1656000	Curve number	40	C	Deciduous forest	12.21	5.50	6.05	6.34	4.63	6.95
1656000	Curve number	90	C	Deciduous forest	12.17	5.50	5.99	6.32	4.61	6.92
1656000	Curve number	40	C	Pasture/hay	12.24	5.50	6.11	6.39	4.64	6.98
1656000	Curve number	90	C	Pasture/hay	12.20	5.50	6.04	6.33	4.62	6.94

[a]Other than parameter values specified in the table, recharge values were calculated using model parameter values from Ladd (2019).

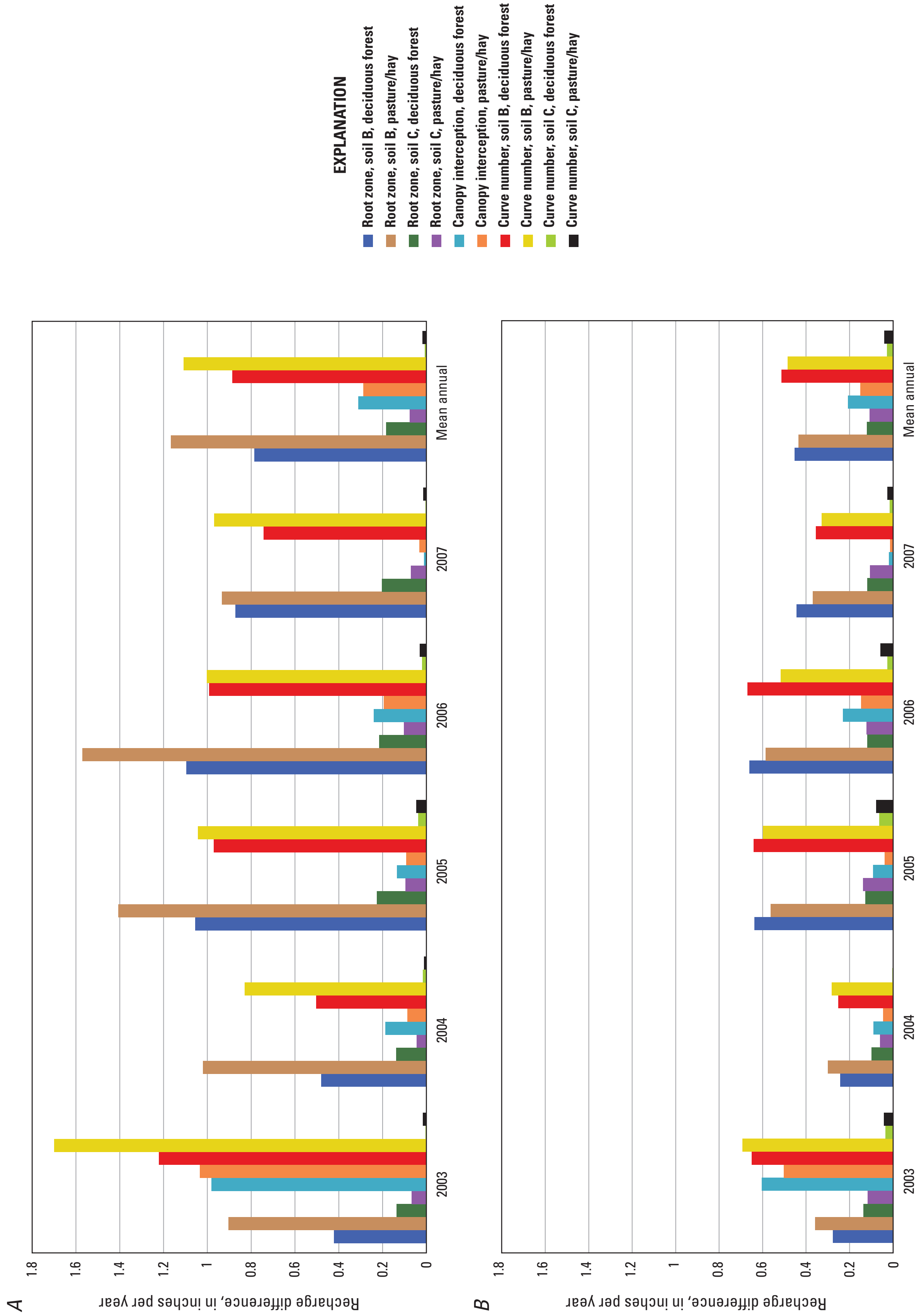


Figure 9. Changes in Soil-Water-Balance modeled recharge in (*A*) basin 01643700 and (*B*) basin 01656000 due to changes in selected model parameters.

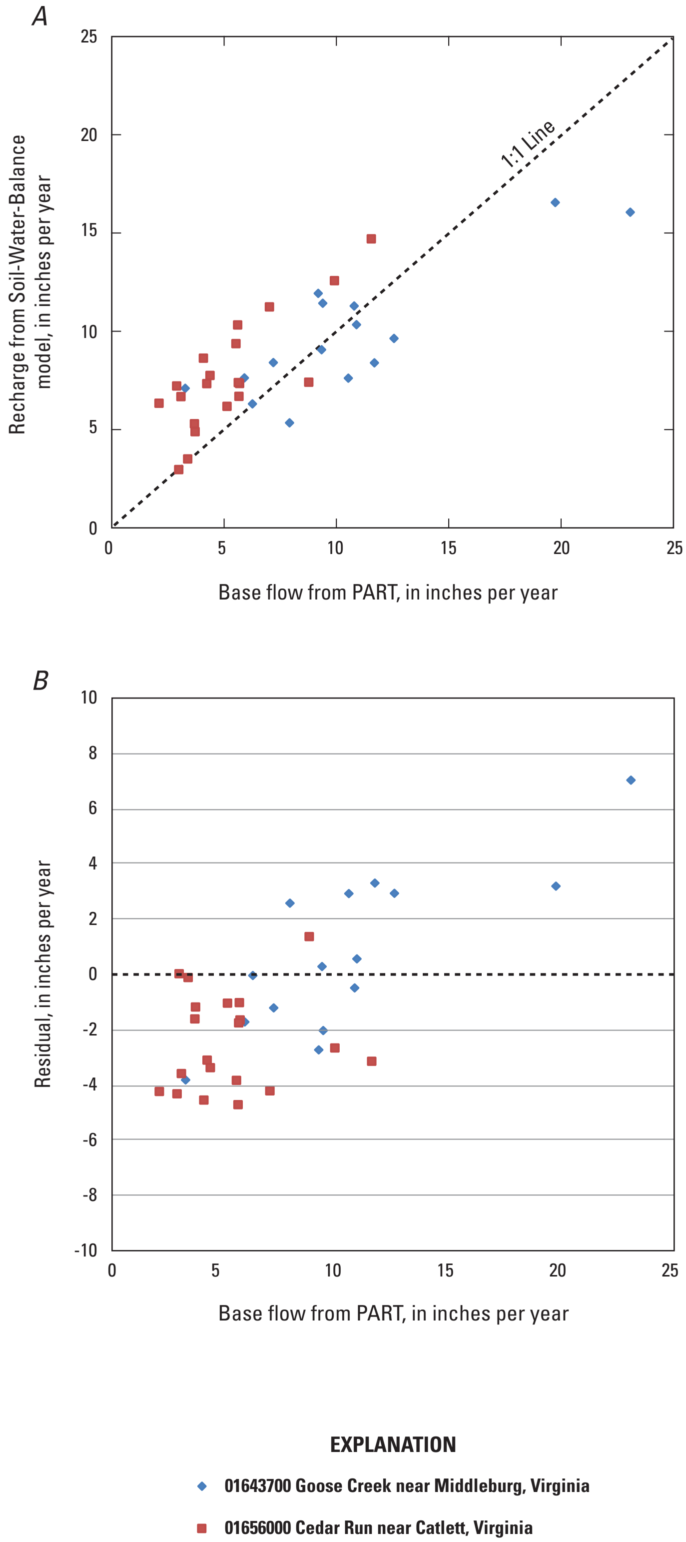


Figure 10. Annual base flow from PART compared to Soil-Water-Balance model simulated recharge for two calibration basins: (*A*) 1:1 plots and (*B*) residuals.

caused opposing changes to the SE in the calibration basins, requiring the calculation of a single value for the SE representative of both basins. The area-weighted SWB annual recharge estimate and the area-weighted PART annual base-flow estimate representing both basins for each of the 15 years of concurrent record (1996, 2002–2015) were determined. Area-weighted annual residuals for concurrent years of record in the calibration basins were determined using the area-weighted SWB annual recharge and PART annual base-flow estimates, and an area-weighted standard error (SE_{AW}) was determined from equation 1 by using the area-weighted residuals for the concurrent years of record.

The model was calibrated by adjusting curve number and root-zone depth associated with hydrologic soil group B in areas of deciduous forest and pasture/hay land-use classes, which are the parameters and areas to which SWB-modeled recharge was determined to be most sensitive (figs. 9*A* and *B*). The model parameter values were adjusted to values above and below those from the initial values to determine which parameter-value combinations produced minimal bias (departure of the mean of area-weighted residuals from zero) and low SE_{AW} (table 7). Two calibration model runs produced similar values of minimal bias and low SE_{AW}. The chosen model run possessed a root-zone depth of 1.5 ft in deciduous forest and 4.5 ft in pasture/hay land-use classes, and a curve number of 45 in deciduous forest and 80 in pasture/hay land-use classes. This model run produced a slightly higher SE_{AW} and slightly less bias than a similar model run in which the curve number was 90 in the pasture/hay land-use class (table 7).

Model Limitations

SWB results can be used to construct a generalized representation of recharge throughout the study area, and to estimate the magnitude of monthly and annual recharge for years when daily climatological data are available. An assumption of the SWB model is that soil infiltration is the sum of net water-budget sources (precipitation, snowmelt, and runoff from upstream cells) minus water budget sinks, which include runoff calculated using the Natural Resources Conservation Service curve number method (Cronshey and others, 1986). Runoff calculated at a plot or grid-cell scale may be beyond the limits of the curve number method (Garen and Moore, 2005; Westenbroek and others, 2010). Overland-flow routing in the Fauquier County SWB model ensures that runoff and rejected recharge have an opportunity to contribute to infiltration in downslope cells on a daily timestep. In areas where the water table is close to land surface, the SWB model can be expected to perform poorly and locally provide anomalously high recharge estimates; there is no provision for recharge rejection due to saturation beyond explicitly limiting the maximum recharge rate for specific combinations of land cover and soil type (Westenbroek and others, 2010). The SWB model should be capable of providing reasonable annual or monthly recharge estimates at the scale of a small catchment (Dripps and Bradbury, 2007; Westenbroek and others, 2010).

Table 7. Model parameters adjusted in hydrologic soil group B for calibration of the Fauquier County Soil-Water-Balance model.

[Yellow shading indicates initial model-parameter values and associated statistics. Gray shading indicates final calibrated model-parameter values and associated statistics]

Root-zone depth (feet) in deciduous forest	Root-zone depth (feet) in pasture/hay	Curve number in deciduous forest	Curve number in pasture/hay	01643700 Basin		01656000 Basin		Combined basins (area weighted)	
				Standard error[a] (inches)	Average residual[b] (inches)	Standard error[a] (inches)	Average residual[b] (inches)	Standard error[a] (inches)	Average residual[b] (inches)
1.97	3.61	50	86	3.67	1.99	2.03	-1.66	2.26	0.35
1.5	3	45	80	3.35	1.32	2.22	-1.93	2.25	-0.15
1.5	3	45	90	3.76	2.06	2.04	-1.67	2.31	0.38
1.5	3	55	80	3.35	1.33	2.22	-1.93	2.25	-0.15
1.5	3	55	90	3.76	2.06	2.03	-1.67	2.31	0.39
1.5	4.5	45	80	3.46	1.68	2.12	-1.80	2.20	0.11
1.5	4.5	45	90	3.91	2.43	1.93	-1.54	2.31	0.66
1.5	4.5	55	80	3.46	1.69	2.12	-1.80	2.20	0.11
1.5	4.5	55	90	3.92	2.44	1.93	-1.54	2.31	0.66
3	3	45	80	3.49	1.72	2.07	-1.70	2.22	0.17
3	3	45	90	3.96	2.45	1.89	-1.44	2.35	0.70
3	3	55	80	3.50	1.73	2.06	-1.69	2.22	0.18
3	3	55	90	3.96	2.46	1.88	-1.43	2.35	0.72
3	4.5	45	80	3.63	2.08	1.97	-1.57	2.21	0.43
3	4.5	45	90	4.14	2.83	1.79	-1.31	2.39	0.98
3	4.5	55	80	3.64	2.09	1.97	-1.56	2.21	0.44
3	4.5	55	90	4.15	2.84	1.79	-1.30	2.39	0.99

[a]Residual between base flow computed by PART and recharge computed by SWB model.

[b]A positive average residual indicates that the SWB recharge estimates are lower on average than the PART base-flow estimates. A negative residual indicates that the SWB recharge estimates are higher on average than the PART base-flow estimates.

The SWB model is designed to simulate several processes that affect the infiltration of precipitation through the soil column. As a result, it is necessary to specify values for many parameters in the model to cover the complete range of soil groups and land covers that are present within the study area. Although model discretization (1,076 ft) is sufficient to represent the relatively detailed spatial distribution of soils and land cover, only general information is available concerning the properties of the soils themselves (for example, hydrologic soil group and saturated vertical hydraulic conductivity). Some of the properties for the combinations of soil groups and land cover that compose most of the study area could be estimated through calibration against the base flows computed by PART, but many other parameters were insensitive and required specified values. In addition, the properties associated with a particular soil group and land-cover combination could vary from one part of the study area to another. The disparity between the SWB and PART results reflects the spatial differences in soil properties within the study area, and the uncertainty in the values of those properties. The difference in results from basins 01643700 and 01656000 (fig. 10) indicate that other hydrologic properties or processes are not explicitly accounted for in the SWB model or are misrepresented by PART.

Summary

Recharge to aquifers underlying Fauquier County, Virginia, was computed using the Soil-Water-Balance model and hydrograph separation at two continuous streamgages with at least 15 years of record between 1996 and 2015. Recharge is highest and most variable in deciduous forest areas overlying crystalline rock aquifers in the Blue Ridge geologic province. Annual recharge to aquifers in the Blue Ridge geologic province was strongly influenced by annual differences in precipitation. The lowest and least variable rates of recharge for the period of simulation were computed for pasture/hay or developed areas overlying sedimentary rock aquifers in the Mesozoic basin. Higher than expected rates of recharge occurred in type A soils underlying streams in the Mesozoic basin are considered model errors derived from shallow water tables and model inability to reject recharge due to saturation. An example drought year (2001) showed that below normal precipitation can result in severe drought conditions as measured by reduction in annual recharge rates. Precipitation totals 20 percent below mean annual precipitation from 1996–2015 produced drought recharge rates that were less than 50 percent of mean annual recharge. Further work is needed to assess the influence of stream loss or pumping-induced stream capture in areas where recharge from streams may be occurring.

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