U.S. Department of the Interior
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Prepared in cooperation with:

Virginia Department of Conservation and Recreation

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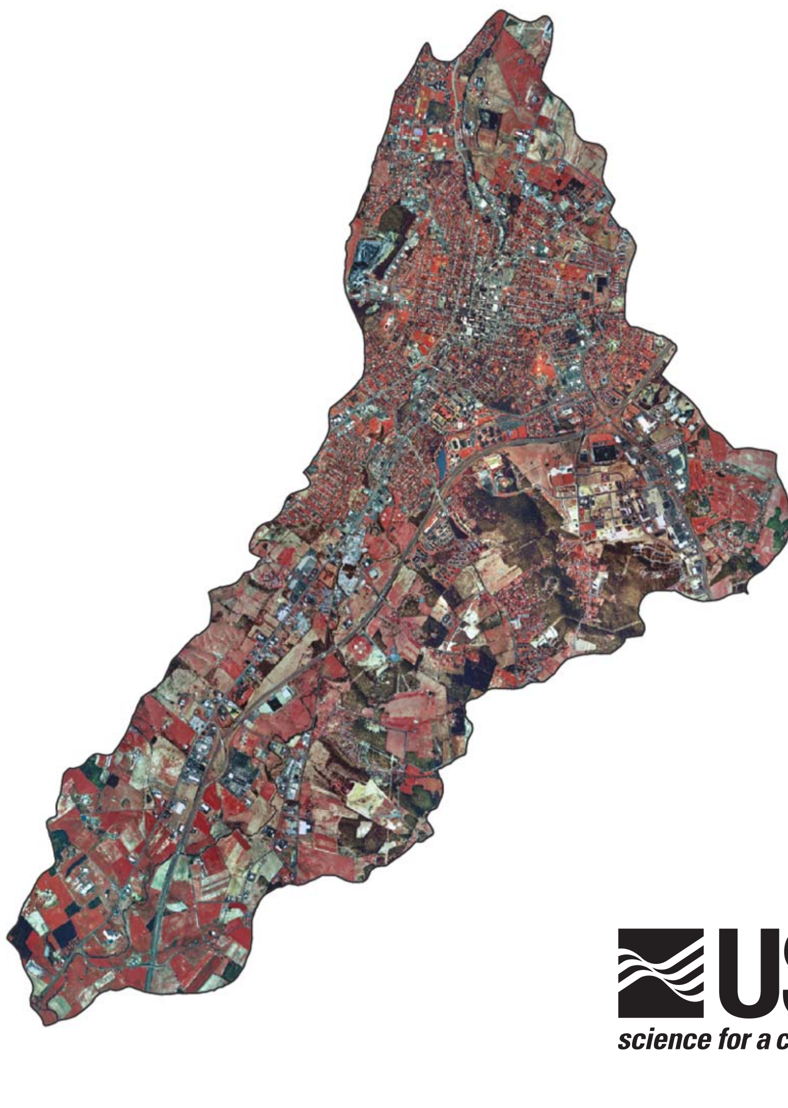
Water-Resources Investigations Report 03-4161



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Cover image of Blacks Run watershed from U.S. Department of Agriculture-Farm Service Agency-Aerial Photography Field Office, Digital Orthophoto Quadrangle, MrSID mosaic

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By Douglas L. Moyer and Kenneth E. Hyer

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Richmond, Virginia
2003

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CONVERSION FACTORS, DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
acre	0.4047	hectare
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.028317	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per hour	0.0254	meter per hour
inch per year	2.54	centimeter per year
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram
pound per acre (lb/acre)	1.121	kilogram per hectare

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Temperature: Temperature is reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 (°C) + 32°

Abbreviated water-quality units: Bacterial concentrations are reported in units of colonies per 100 milliliters (col/100 mL).

Use of the Hydrological Simulation Program–FORTRAN and Bacterial Source Tracking for Development of the Fecal Coliform Total Maximum Daily Load (TMDL) for Blacks Run, Rockingham County, Virginia

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ABSTRACT

Impairment of surface waters by fecal coliform bacteria is a water-quality issue of national scope and importance. Section 303(d) of the Clean Water Act requires that each State identify surface waters that do not meet applicable water-quality standards. In Virginia, more than 175 stream segments are on the 1998 Section 303(d) list of impaired waters because of violations of the water-quality standard for fecal coliform bacteria. A total maximum daily load (TMDL) will need to be developed by 2006 for each of these impaired streams and rivers by the Virginia Departments of Environmental Quality and Conservation and Recreation. A TMDL is a quantitative representation of the maximum load of a given water-quality constituent, from all point and nonpoint sources, that a stream can assimilate without violating the designated water-quality standard. Blacks Run, in Rockingham County, Virginia, is one of the stream segments listed by the State of Virginia as impaired by fecal coliform bacteria. Watershed modeling and bacterial source tracking were used to develop the technical components of the fecal coliform bacteria TMDL for Blacks Run. The Hydrological Simulation Program–FORTRAN (HSPF) was used to simulate streamflow, fecal coliform concentrations, and source-specific fecal coliform loading in Blacks Run. Ribotyping, a bacterial source tracking technique, was used to identify the dominant sources of fecal coliform bacteria in the Blacks Run watershed. Ribotyping also was used to determine the relative contributions of specific sources to the observed fecal coliform load in Blacks Run. Data from the ribotyping analysis were incorporated into the calibration of the fecal coliform model.

Study results provide information regarding the calibration of the streamflow and fecal coliform bacteria models and also identify the reductions in fecal coliform loads required to meet the TMDL for Blacks Run. The calibrated streamflow model simulated observed streamflow characteristics with respect to total annual runoff, seasonal runoff, average daily streamflow, and hourly stormflow. The calibrated fecal coliform model simulated the patterns and range of observed fecal coliform bacteria concentrations. Observed fecal coliform bacteria concentrations during low-flow periods ranged from 40 to 7,000 colonies per 100 milliliters, and peak concentrations during storm-flow periods ranged from 33,000 to 260,000 colonies per 100 milliliters. Simulated source-specific contributions of fecal coliform bacteria to instream load were matched to the observed contributions from the dominant sources, which were cats, cattle, deer, dogs, ducks, geese, horses, humans, muskrats, poultry, raccoons, and sheep. According to model results, a 95-percent reduction in the current fecal coliform load delivered from the watershed to Blacks Run would result in compliance with the designated water-quality goals and associated TMDL.

INTRODUCTON

Background

Surface-water impairment by fecal coliform bacteria is a water-quality issue of national scope and importance. Section 303(d) of the Clean Water Act requires that each State identify surface waters that do not meet applicable water-quality standards. In Virginia, more than 175 stream segments are on the 1998 Section 303(d) list of impaired waters because of violations of the fecal coliform bacteria standard (an instantaneous water-quality standard of 1000 col/100 mL, or a geometric mean water-quality standard of 200 col/100 mL). Blacks Run, in Rockingham County, Virginia (fig. 1), is one of these impaired streams. Fecal coliform bacteria concentrations that are elevated above the State water-quality standard indicate an increased risk to human health when these waters are contacted through swimming or other recreational activities.

In Virginia, total maximum daily load (TMDL) plans will need to be developed by 2006 for impaired waterbodies on the State 1998 Section 303(d) list. TMDLs are a quantitative representation of all the contaminant contributions to a stream and are defined as

$$TMDL = \Sigma WLAs + \Sigma LAs + MOS \qquad (1)$$

where $\sum$ WLAs (waste-load allocations) represents the sum of all the point-source loadings, $\sum$ LAs (load allocations) represents the sum of all the nonpoint-source loadings, and MOS represents a margin of safety. The sum of these loading terms and assigned margin of safety constitute the TMDL and represent the loading of a particular constituent that the surface waterbody can assimilate without violating the State water-quality standard. The TMDL must meet eight conditions in order to be approved by the U.S. Environmental Protection Agency (USEPA). These conditions ensure that the TMDL (1) is designed to implement applicable water-quality standards; (2) includes a total allowable load as well as individual waste-load allocations and load allocations; (3) considers the effect of background contaminant contributions; (4) considers critical environmental conditions (periods when water quality is most affected); (5) considers seasonal variations; (6) includes a margin of safety; (7) has been subject to public participation; and (8) can be met with reasonable assurance. Once a TMDL is established, source-load contributions then can be reduced through implementation of source-control management practices until the target TMDL is achieved.

In Virginia, the primary tool for developing TMDLs in impaired watersheds has been the Hydrological Simulation Program–FORTRAN (HSPF) watershed model. HSPF is a continuous simulation watershed model designed to simulate the transport and storage of water and associated water-quality constituents by linking surface, soil, and instream processes (Donigian and others, 1995). HSPF recently has been demonstrated to be an effective tool for the simulation of fecal coliform bacteria for TMDL development (U.S. Environmental Protection Agency, 2000). HSPF has been used extensively to simulate watershed hydrology (Ng and Marsalek, 1989; Donigian and others, 1995; Berris, 1996; Dinicola, 1997; Srinivasan and others, 1998; Zarriello, 1999) and water-quality constituents such as nutrients in agricultural runoff (Bicknell and others, 1985; Donigian, 1986; Moore and others, 1988; Linker and others, 1996), sediment (Sams and Witt, 1995; Fontaine and Jacomino, 1997), atrazine (Laroche and others, 1996), and water temperature (Chen and others, 1998).

One of the major difficulties in developing TMDLs for waters contaminated by fecal coliform bacteria is that the potential sources of bacteria are numerous and the magnitude of their contributions commonly is unknown. Potential sources of fecal coliform bacteria include all warm-blooded animals (humans, pets, domesticated livestock, birds, and wildlife). The lack of information on the bacteria sources hinders the development of accurate load allocations and the identification of appropriate source-load reduction measures. Information about the major fecal coliform sources that impair surface-water quality would improve the ability to develop effective watershed models and may lead to more scientifically defensible TMDLs.

Bacterial source tracking (BST) is a recently developed tool for identifying the sources of fecal coliform bacteria that are found in surface waters (Hyer and Moyer, 2003). This technology identifies specific differences among fecal coliform bacteria present in the feces of different animal species. Time, diet, environment, and many other factors may have contributed to produce these evolutionary distinctions; BST uses these species-specific distinctions to identify the ani

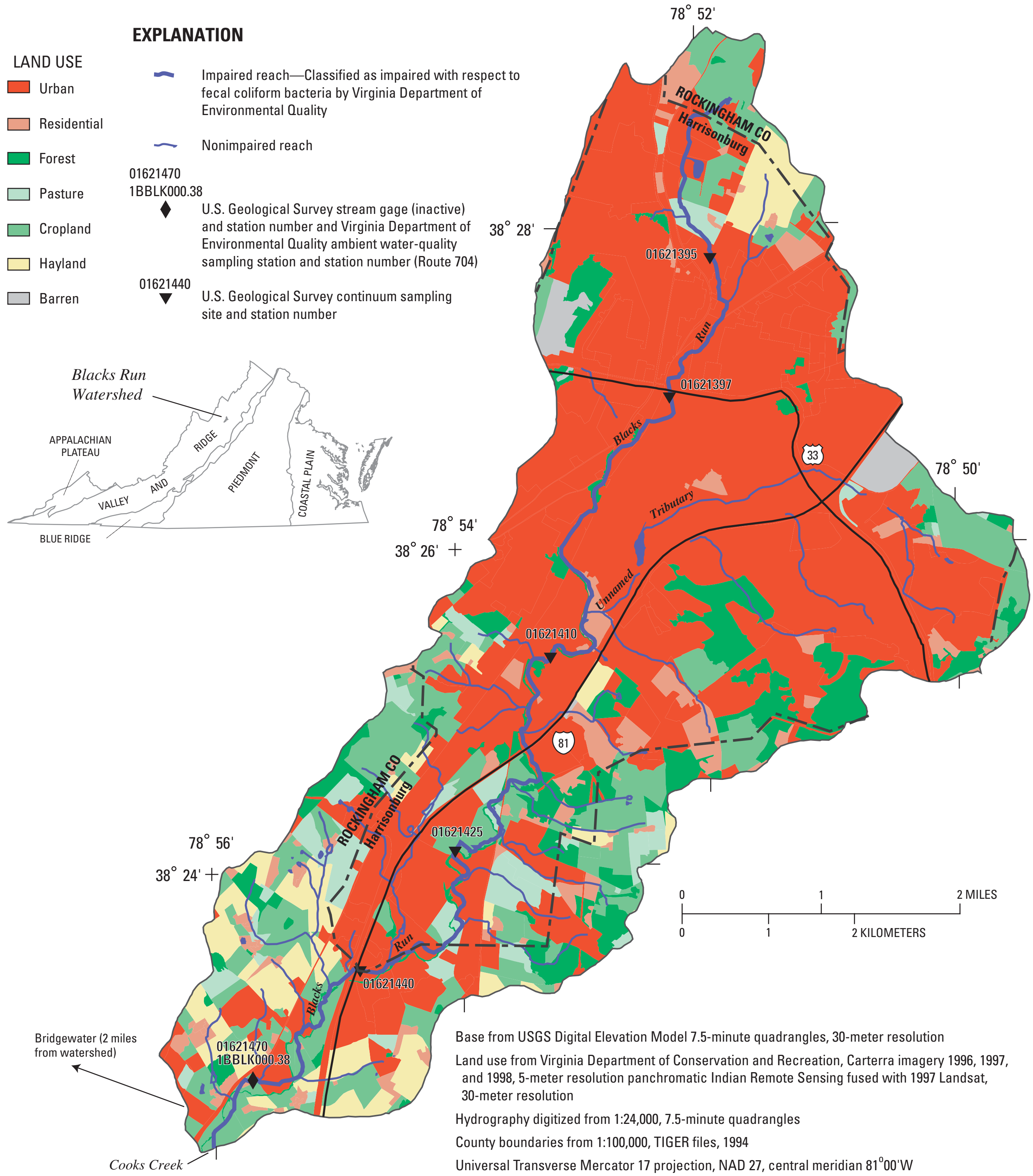


Figure 1. Land use, streams, stream-gaging station, and water-quality sampling stations in the Blacks Run watershed, Rockingham County, Virginia.

mal source of an unknown fecal coliform that has been isolated from a waterbody. The BST method chosen to identify the dominant sources of fecal coliform bacteria in the Blacks Run watershed is ribotyping (Hyer and Moyer, 2003), which involves an analysis of the specific DNA (deoxyribonucleic acid) sequence that codes for the production of ribosomal RNA (ribonucleic acid). Ribotyping identifies bacteria sources with a degree of precision that makes it well suited for use in the development of a fecal coliform TMDL.

In 1999, the U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Conservation and Recreation (DCR), began a 3-year study to develop a fecal coliform bacteria TMDL for the Blacks Run watershed. The primary objective was to develop a HSPF model to simulate streamflow and the transport of fecal coliform bacteria within the watershed. Specific project objectives were to (1) produce calibrated models of watershed streamflow and fecal coliform bacteria transport, (2) incorporate BST information into the fecal coliform model calibration process, (3) estimate fecal coliform source-load reductions required to meet State water-quality standards, and (4) define the TMDL for fecal coliform bacteria for Blacks Run. These objectives ensure that the Blacks Run TMDL would (1) include a total allowable load as well as individual waste load and load allocations; (2) consider the effect of background contaminant contributions; (3) consider critical environmental conditions; (4) consider seasonal variations; and (5) include a margin of safety. The primary objectives for DCR were to ensure that the Blacks Run TMDL was designed to implement applicable water-quality standards; was developed with public participation; and can be met with reasonable assurance.

Purpose and Scope

This report describes the development and calibration of the HSPF model for streamflow and fecal coliform bacteria as part of determining the TMDL for the Blacks Run watershed. The model simulation period is from February 1999 to January 2001. This report also documents the methodology for incorporating BST data into the calibration of the fecal coliform model and demonstrates how these data enhance TMDL development. Current source-specific fecal coliform bacteria loads in Blacks Run are presented as well as the load reductions needed to meet the designated TMDL and associated State water-quality standard.

Blacks Run Watershed Characteristics

Blacks Run, located in Rockingham County, Va., originates on the north side of the city of Harrisonburg, Va., and extends to the confluence of Cooks Creek. The entire 10.7-mi-long reach is classified as impaired with respect to fecal coliform bacteria (Virginia Department of Environmental Quality, 1998). The basin has a drainage area of 20 mi^2, and an estimated population of 34,700 (1990 Census). The city of Harrisonburg is the primary urban area within the watershed. No stream gage was available for Blacks Run; therefore, a stream gage was installed by the USGS (USGS station number 01621470) at Route 704 (Cecil Wampler Road) for this study. DEQ has performed monthly sampling for fecal coliform bacteria at this site since 1991.

The Blacks Run watershed lies within the Valley and Ridge physiographic province. Underlying the watershed are seven geologic formations dominated by limestone and dolomite; information about each formation is summarized from the work of Gathright and Frischmann (1986). The primary formations within the watershed include the Martinsburg Formation (calcareous slate, argillite, and sandstone), Beekmantown Group (limestone and dolomite), New Market Limestone (limestone with dolomite beds near the base), Lincolnshire Formation (cherty limestone), Oranda Formation (limestone and calcareous shale), and Edinburg Formation (limestone and calcareous shale). Karst features are evident in portions of the watershed. Alluvial material (composed of unconsolidated fine sand, silt, and minor clay) is present in portions of the floodplain adjacent to Blacks Run.

The soils of the Blacks Run watershed have been described thoroughly (Hockman and others, 1979) and are best classified from the material from which they were formed. Most of the soil in the watershed has formed from the residuum of limestone, dolomite, and calcareous shale. Three soil assemblages have been identified in this category. The Frederick-Lodi-Rock outcrop assemblage consists of deep, well-drained, silt loam soils with limestone or dolomite outcrop areas. The Endcav-Carbo-Rock outcrop assemblage consists of deep and moderately deep, well-drained, silt loam soils; sinkholes and limestone outcrops are common in this assemblage. The Chilhowie-Edom assemblage consists of deep to moderately deep, well-drained, silt loam or silty clay loam soils with occasional bedrock outcrops. On floodplains and terraces, soils have formed in the alluvial or colluvial material. Although not extensive within the watershed, these soils are part of the Monongahela-Unison-Cotaco assemblage, which consists of deep, well-drained or moderately well-drained soils. These generally are fine sandy loam soils, although some areas are cobbly.

Land use in the Blacks Run watershed consists primarily of urban and agricultural practices. Approximately two-thirds of the basin (generally the portion closer to the headwaters) is dominated by urban land uses. In this urban area, potentially major contributors of fecal coliform bacteria include human-related (cross-pipes, failing septic systems, and leaking or overflowing sewer lines), domestic animals (dogs and cats), waterfowl (geese, ducks, and sea gulls), and other wildlife (such as raccoons, opossum, rats, squirrels, and deer). The remaining one-third of the watershed (the lower portion of the watershed, closer to the stream gage) is dominated by agricultural land uses. Major components of the animal husbandry in this watershed include the production of beef cattle, dairy cattle, heifers, chickens, broilers, and turkeys.

Modeling Approach

Streamflow and bacterial transport in the Blacks Run watershed were simulated by means of the Hydrological Simulation Program–FORTRAN (HSPF) version 11 (Bicknell and others, 1997). HSPF is a continuous simulation and lumped parameter watershed model that is used to simulate the transport and storage of water and associated water-quality constituents by linking surface, soil, and instream processes (Donigian and others, 1995). HSPF represents these mechanisms of transport and storage for three unique land segments or model elements: pervious land segments (PERLND), impervious land segments (IMPLND), and stream channels (RCHRES). Natural variability in these hydrologic transport mechanisms occurs because of spatial changes in watershed characteristics such as topography, land use, and soil properties; HSPF accounts for this variability by simulating runoff from smaller, more homogeneous portions of the watershed. Thus, for modeling purposes, the watershed is disaggregated into subwatersheds with similar land-use and topographical features. Each subwatershed is refined further into hydrologic response units (HRU) that represent areas within each land segment with similar watershed characteristics such as land use (Leavesley and others, 1983). HSPF links the movement of water and constituents from each HRU to generate an overall watershed response.

Acknowledgments

We thank DCR for their cooperation, input, and assistance with this study. The Virginia Department of Environmental Quality (DEQ) is acknowledged for their technical support and assistance. The authors also would like to thank Tom Jobes (Aqua Terra Consultants) for his help with the development of the model. Michael J. Gearheart, Trisha L. Baldwin, and Robert R. Lotspeich provided outstanding technical support on this project. Allison A. Shipp and Michael E. Lewis are acknowledged for providing technical reviews of this report. Lastly, we are indebted to the residents of and stakeholders in the Blacks Run watershed for their enthusiastic participation in this study. Without their cooperation, this study would not have been possible.

DESCRIPTION OF MODELS

The following sections describe the streamflow and fecal coliform bacteria models used in this study for development of the fecal coliform TMDL for the Blacks Run watershed.

Streamflow Model

The first step in generating a watershed-scale bacterial transport model is the simulation of streamflow. The mechanisms by which precipitation is routed from the land surface, through the various soil layers, and to the stream channel must be represented accurately in order to build a bacterial transport model. The following sections summarize the transport mechanisms associated with the PERLND, IMPLND, and RCHRES modules. A detailed description of the hydrologic portion of HSPF is in Bicknell and others (1997).

Pervious and Impervious Land Segments

The dominant feature of the pervious land segment (PERLND) module is the component for calculating

Table 1. Hydrologic parameters used in the simulation of streamflow in Blacks Run, Rockingham County, Virginia

[ET, evapotranspiration; PET, potential evapotranspiration]

Parameter	Definition	Unit
AGWETP	Active ground-water ET. Represents the fraction of stored ground water that is subject to direct evaporation and transpiration by plants whose roots extend below the active ground-water table. Accounts for the fraction of available PET that can be met from active ground-water storage.	none
AGWRC	Active ground-water recession rate. Represents the ratio of current ground-water discharge to that from 24 hours earlier.	1 per day
BASETP	Base flow ET. ET by riparian vegetation from active ground water entering the stream channel. Represents the fraction of PET that is fulfilled only as ground-water discharge is present.	none
CEPSC	Interception storage capacity of vegetation.	inches
DEEPFR	Fraction of infiltrating water that is lost to deep aquifers. Represents the fraction of ground water that becomes inactive ground water and does not discharge to the modeled stream channel.	none
INFEXP	Infiltration equation exponent.	none
INFILD	Ratio of maximum and mean soil-infiltration capacities.	none
INFILT	Index to mean soil infiltration rate. INFILT governs the overall division of available moisture between surface and subsurface flow paths. High values of INFILT divert more water to the subsurface flow paths.	inches per hour
INTFW	Interflow coefficient that governs the amount of water that enters the ground from surface detention storage.	none
IRC	Interflow retention coefficient. Rate at which interflow is discharged from the upper-zone storage.	1 per day
KVARY	Ground-water recession flow parameter. Describes nonlinear ground-water recession rate.	1 per inch
LSUR	Length of the overland flow plane.	feet
LZETP	Lower-zone evapotranspiration ET. Percentage of moisture in lower-zone storage that is subject to ET.	none
LZSN	Lower-zone nominal storage. Defines the storage capacity of the lower-unsaturated zone.	inches
NSUR	Surface roughness (Manning’s n) of the overland flow plane.	none
RETS	Retention-storage capacity of impervious surfaces.	inches
SLSUR	Average slope of the overland flow path.	none
UZSN	Upper-zone normal storage. Defines the storage capacity of the upper-unsaturated zone.	inches

the hydrologic water budget (PWATER). PWATER includes parameters that represent storage (vegetative, surface, shallow subsurface, and deep subsurface) and transport (evaporation, transpiration, inflow, and outflow) components of the hydrologic cycle (table 1). PWATER simulates the storage and transport of precipitation along three flow paths: overland flow, interflow (shallow subsurface flow), and base flow (active ground-water discharge). Storage and transport parameters are refined to simulate the hydrologic routing through each HRU, generating a simulated watershed response between and during precipitation events.

The simulated hydrologic cycle indicates how these storage and transport parameters govern the overall stream response within the watershed (fig. 2). Precipitation falling on the watershed is first intercepted (CEPSC) and stored by the vegetation. Most of the precipitation then is routed to the land surface because the surface area of the intercepting vegetation is small relative to the total volume of precipitation. The volume of water that remains on the vegetation is lost to the atmosphere through evaporation.

Water that falls on the land surface is captured and stored temporarily (SURS) before being transported along three potential pathways: (1) Stored water begins to infiltrate the subsurface (INFILT). The infiltrating water is distributed among the upper-zone storage (UZSN), lower-zone storage (LZSN), active ground-water storage (AGWS), and inactive ground-water storage. (2) Water also is routed to interflow storage (IFWS) just beneath the land surface. This pathway is active when the deeper subsurface storages are full and the rate of precipitation approaches the rate of infiltration. Water held in interflow storage is released as interflow to the stream. The residence time for the stored water is governed by the interflow recession constant (IRC). (3) The stored water is routed directly to the stream through overland flow. This pathway is active when all subsurface storages are full and/or the precipitation rate exceeds the infiltration capacity of the soils. Overland flow is governed by the length (LSUR), slope (SLSUR), and roughness (NSUR) of the overland flow path.

Water in upper-zone storage (UZSN) ultimately is lost to the atmosphere (through evapotranspiration) and the deeper subsurface (through delayed infiltration). Water that infiltrates to the deeper subsurface will be divided among lower-zone storage (LZSN), inactive ground-water storage, and active ground-water storage (AGWS). Water stored in the lower zone can be lost to the atmosphere through evapotranspiration (LZETP). Water that is transported to inactive ground-water storage is lost from the simulated basin and is never transported to the simulated stream reach. The portion of infiltrating water that is allocated to inactive ground-water storage is governed by DEEPFR. Water that enters AGWS either through delayed infiltration from UZSN or through direct infiltration from surface storage is either lost to the atmosphere through evapotranspiration (AGWETP) or transported to the simulated stream reach through base flow. The residence time for water in AGWS storage is controlled by AGWETP and the active ground-water recession constant (AGWRC). Finally, a portion of the base flow is removed through evapotranspiration (BASETP) prior to entering the stream channel.

The component under the impervious land segment (IMPLND) module that calculates the hydrologic water budget is IWATER. Simulation of the flux and storage of precipitation falling on impervious land segments is less complex than for pervious land segments because there are no infiltration and subsurface processes. Similar to PWATER, IWATER contains parameters that represent the storage (rooftop and surface) and transport (evaporation and runoff) components of the hydrologic cycle. These parameters are unique to each impervious HRU so that precipitation runoff may be simulated accurately.

The routing of precipitation in IWATER is similar to the surface runoff routing in the PERLND module. Precipitation that falls on the watershed is first intercepted by impervious surfaces (building tops, urban vegetation, and asphalt wetting) that extend above the land surface (impervious retention storage – RETS). Most of the precipitation is passed to the land surface because the storage capacity of the intercepting surfaces is relatively small compared to the volume of incoming precipitation. The water that remains in RETS is lost to the atmosphere through evaporation. Water that is routed to the land surface is captured and momentarily stored in surface-detention storage (SURS). This stored water then is transported to the simulated stream reach as surface runoff. Overland flow is governed by the length (LSUR), slope (SLSUR), and roughness (NSUR) of the overland flow path.

The urban and residential land segments represented in the model contain both pervious and impervious features. The main objective associated with the calibration of the impervious area represented in the

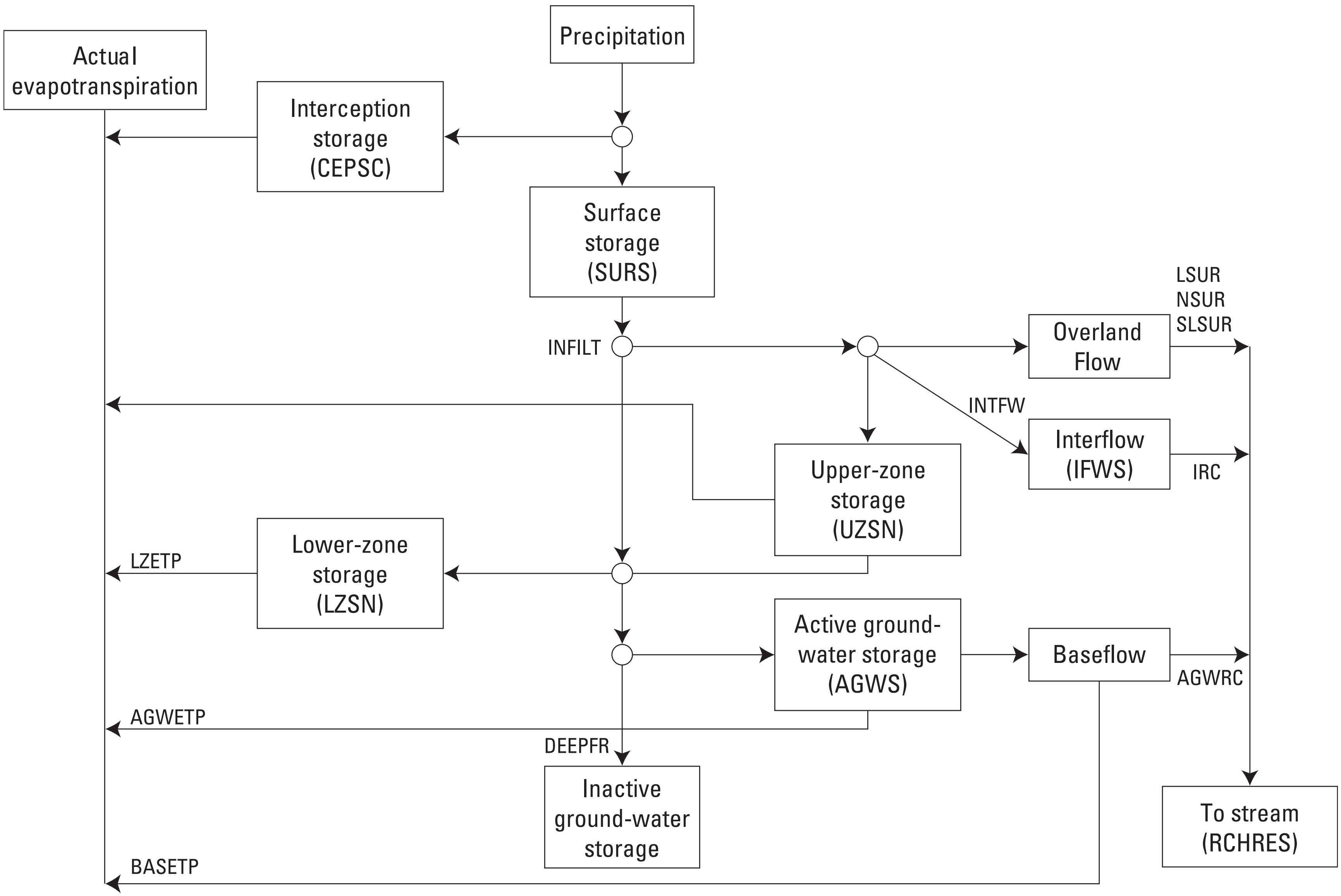


Figure 2. Rainfall-routing processes, associated with pervious land segments, represented by the Hydrological Simulation Program-FORTRAN for the simulation of streamflow in Blacks Run, Rockingham County, Virginia. (See table 1 for definition of hydrologic parameters.)

model is to determine the fraction of impervious area within urban and residential land types. This impervious fraction can be broken into two categories, “hydrologically effective” or “hydrologically ineffective” (Zarriello, 1999). Hydrologically effective areas drain directly to stream channels and are represented by the IMPLND module. Hydrologically ineffective areas drain onto pervious land types, such as grassland or forest, and are better represented by the PERLND module. For example, rain that falls on a rooftop, and then is transported to a grassy lawn, would be considered hydrologically ineffective. Initial estimates were that urban land use contains between 18- and 50-percent effective impervious area and residential land use contains between 6- and 18-percent effective impervious area, (Northern Virginia Planning District Commission, 1980). This initial estimate was refined during model calibration of stormflow timing and magnitude. For instance, overestimating the impervious area will cause a greater volume of water to be routed directly to the stream through surface runoff (in contrast to the delayed response associated with pervious land segments) during a storm event; thus, the simulated storm response will be earlier and of greater magnitude than the observed storm response.

Stream Channels

The RCHRES module in HSPF is used to simulate the routing of water and associated water-quality constituents through a stream channel network that consists of a series of connected stream reaches. For this study, only one reach was simulated within each subwatershed. Water is supplied to a reach from PERLND (overland flow, interflow, and base flow), IMPLND (overland flow), point sources (sewage-treatment plants or STPs), and upstream segments. These inflows are assumed to enter the reach at a single upstream point and the water is transported downstream in a unidirectional manner. Actual channel properties (width, depth, cross-sectional area, slope, and roughness) are measured in order to develop the relation among stage (water depth), surface area, volume, and discharge (streamflow). Stage, surface area, volume, and discharge information are specified in a function table (FTABLE) and are used to govern stream discharge for a given inflow. Water transported down a reach is assumed to follow the kinematic wave function (Martin and McCutcheon, 1999).

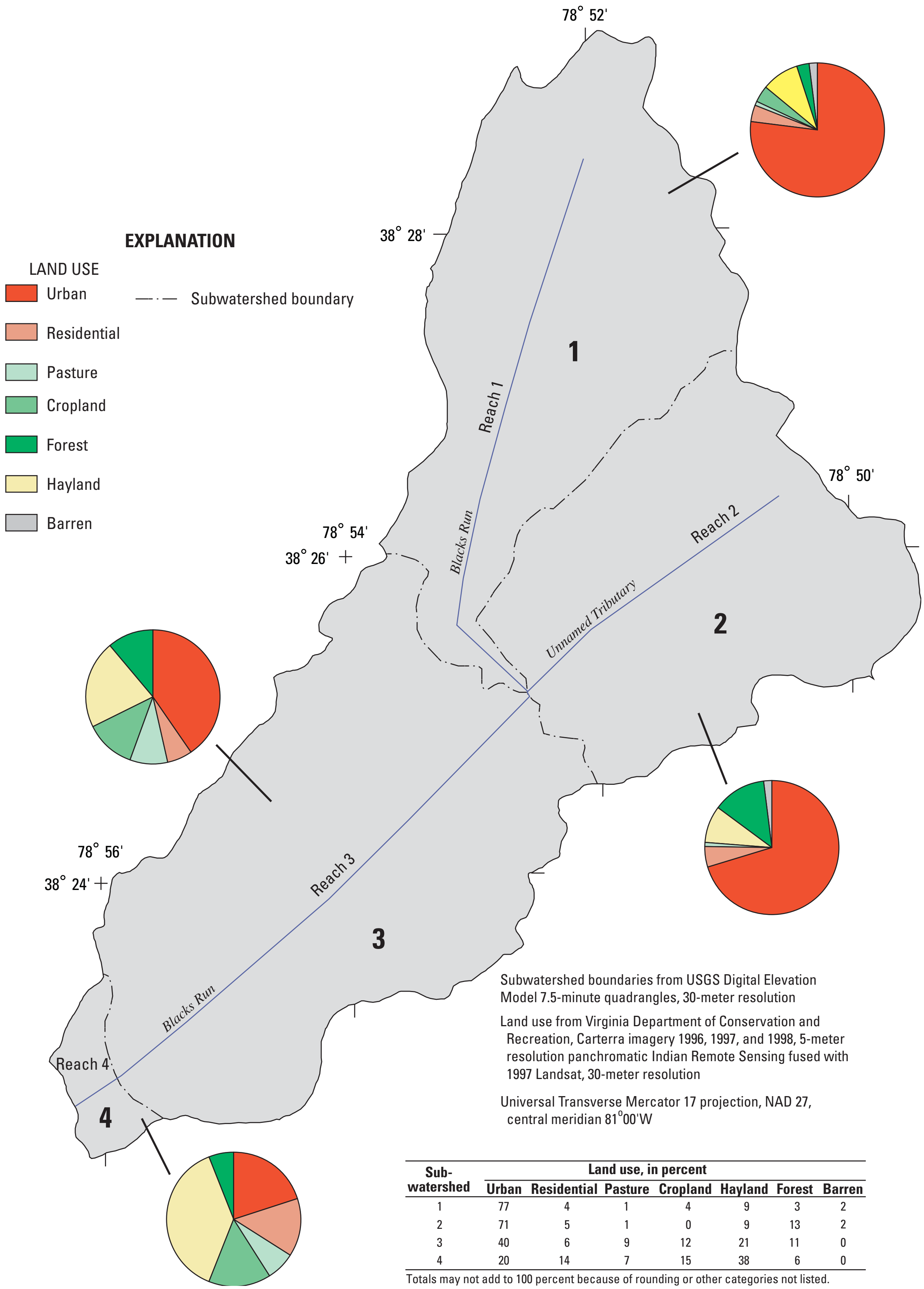
Subwatershed Delineation

A critical step in the simulation of streamflow and bacterial transport within a watershed is characterization of the watershed morphology. The morphology consists of watershed characteristics such as topography (slope, aspect, and elevation), soil types, and land use. Within the watershed boundary, each of these characteristics typically is highly variable. For example, the northern portion of the Blacks Run watershed has a higher elevation and steeper slopes than the southern portion. To account for these topographical variations within HSPF, the watershed is broken into smaller, more homogeneous subwatersheds. There also may be variations in land use within each subwatershed; land uses with similar hydrologic responses are grouped into a single HRU. For example, high-intensity residential and high-intensity commercial are assumed to have similar hydrologic responses and were grouped to form an urban HRU. The following section documents the methods used to delineate subwatersheds, aggregate land uses, and establish the stream channel network for the Blacks Run watershed.

Four subwatersheds were identified within the Blacks Run watershed on the basis of variations in land use, land-surface elevation and slope (fig. 3). The area of each subwatershed was determined by delineating along the natural drainage boundary. These drainage boundaries were identified using the USGS Digital Elevation Model (DEM) from the Harrisonburg, Bridgewater, and Mount Sidney 7.5-minute quadrangles. The DEM coverage has a cell size of 30 meters.

Land Use

DCR provided land-use data in the form of a Geographic Information System (GIS) coverage for the Blacks Run watershed. The GIS coverage provides land-use/land-cover information. The land-use coverage identifies 22 possible land-use types, which were combined into 7 general types based on hydrological routing similarities: urban, residential, cropland, hayland, pasture, forested, and barren (table 2). Each of these general land-use types represents the HRUs for each subwatershed.



Sub-watershed	Land use, in percent						
	Urban	Residential	Pasture	Cropland	Hayland	Forest	Barren
1	77	4	1	4	9	3	2
2	71	5	1	0	9	13	2
3	40	6	9	12	21	11	0
4	20	14	7	15	38	6	0

Totals may not add to 100 percent because of rounding or other categories not listed.

Figure 3. Hydrologic subwatersheds, land use, and reaches as represented in the streamflow and fecal coliform models for Blacks Run, Rockingham County, Virginia.

Table 2. Aggregated hydrologic resposnse units used to develop the streamflow and fecal coliform models for Blacks Run, Rockingham County, Virginia

[Land-use data from Virginia Department of Conservation and Recreation]

Hydrologic Response Unit	Area	
	Acres	Percent of watershed
Urban[1]	7,296	59.5
Residential[2]	659	5.4
Cropland	752	6.1
Hayland[3]	1,767	14.4
Pasture[4]	531	4.3
Forested	1,107	9.0
Barren	144	1.2

[1] Includes urban impervious, medium density residential, high density residential, commercial and services, industrial, transportation, mixed urban or built up, open urban land.

[2] Includes residential impervious, low density residential, mobile home park, wooded residential, cattle operations, poultry operations, farmstead, and large dairy waste facility.

[3] Includes improved pasture, permanent hay, and rotational hay.

[4] Includes pasture impervious, unimproved pasture, grazed woodland, and overgrazed pasture.

Channel Network

A single stream channel (reach) is represented in each of the four subwatersheds simulated in HSPF. The routing of runoff from one reach to a connected downstream reach is governed by the stage, cross-sectional area, storage, and discharge information contained in the FTABLE. An FTABLE was created for each stream reach by first collecting data on stream channel morphology. Stream-channel surveys (transects) were performed by USGS at both the upstream and downstream ends of each reach, based on techniques described in Davidian (1984). At each transect, coordinate data (depth at a given position along the transect) were recorded. Estimates of channel roughness (Manning's n) were made on the basis of channel median grain size, irregularity (width to depth ratios), alignment (abrupt changes in channel width), obstructions (debris), vegetation (instream and bank vegetation), and meandering (Barnes, 1967; Arcement and Schneider, 1989; Coon, 1998). Channel slope was estimated by dividing the change in elevation from the upstream and downstream transects by the reach length. Transect coordinate data were loaded into the Channel Geometry Analysis Program (CGAP) to identify the area, width, wetted perimeter, and hydraulic radius of cross sections at successive water-surface elevations (Regan and Schaffranek, 1985). These data from CGAP along with channel roughness and channel slope were loaded into the program Generate F-Table (GENFTBL, provided with CGAP). GENFTBL creates an FTABLE for each stream reach as required by HSPF. The stage and discharge information (rating table) from the stream gage at Route 704 (USGS station 01621470) was incorporated into the FTABLE for reach segment 3.

Four subwatersheds (1–4) represent the morphological features of the Blacks Run watershed (fig. 3). Within each subwatershed there are 9 HRUs, including 7 pervious (urban, residential, cropland, hayland, pasture, forest, and barren) and 2 impervious (urban and residential). Each subwatershed has a single reach that is governed by an FTABLE. Reaches 1, 3, and 4 represent Blacks Run. Reach 2 represents an unnamed tributary to Blacks Run.

Meteorological and Streamflow Data

Rainfall data were obtained from both the Virginia Polytechnic Institute and State University (VPI) and the USGS. VPI collected rainfall data at the Mossy Creek rain gage, which is approximately 4.8 mi southwest of the Blacks Run watershed from September 15, 1998, to August 3, 2000 (table 3). Annual rainfall measured during 1999 was 33.7 in., which is consistent with the annual rainfall amount of 33.5 in. measured during 1999 at the nearby National Climatic Data Center (NCDC) gage at the Staunton Sewage Treatment Plant (SSTP) (Climatological Data Annual Summary for Virginia, 1999). The USGS collected rainfall data at the Blacks Run streamflow gage (USGS station number 01621470) from December 30, 1999, to January 23, 2001 (table 3). Annual rainfall measured during 2000 was 30.5 in. This value is less than the annual rainfall amount of 38.9 in. measured at SSTP (Climatological Data Annual Summary for Virginia, 2000). Rainfall data from both Mossy Creek (February 20, 1999–December 31, 1999) and Blacks Run (January 1, 2000–January 23, 2001) were used for the streamflow simulation. The precipitation dataset was quality checked by comparison with the observed streamflow record. Discrepancies identified in the precipitation record were corrected using rainfall data collected by Mr. Clayton Towers (written commun., 2000), Weather Watcher for the Town of Bridgewater, Va., and Rockingham County Sewer Authority.

Daily minimum and maximum temperatures were obtained from the NCDC weather station at Dale Enterprise for the time period January 1, 1999, to January 31, 2001 (table 3). These data were required for calculating potential evapotranspiration (PET). Daily PET values were calculated using the Hamon equation (Hamon, 1961), which is part of the USEPA software package WDMUtil (U.S. Environmental Protection Agency, 2001). The average of the annual PET values was compared and calibrated to average annual evaporation from a Class A Pan (Kohler and others, 1959). A Class A Pan coefficient of 76 percent was applied to the calculated PET values, because values of evaporation from a Class A Pan generally overestimate actual evapotranspiration (Kohler and others, 1959). Daily values of PET were disaggregated to hourly values using WDMUtil.

Streamflow data for Blacks Run for the period February 20, 1999–January 23, 2001, were collected by the USGS every 15 minutes at the Blacks Run near Mount Crawford stream gage (USGS station number 01621470) (table 3). Hourly streamflow values were used for the streamflow simulation. Streamflow values over the 23-month period of monitoring ranged from a peak flow of 516 ft^3/s to a low flow of 0.28 ft^3/s.

All model input (meteorological, streamflow, and water-quality) time-series datasets were loaded into the Watershed Data Management format (WDM) using the computer program WDMUtil. WDMUtil provides the functionality of summarizing, listing, and graphing datasets in the WDM format. Input datasets can be retrieved in HSPF from and output datasets (simulated streamflow and fecal coliform bacteria) written to the WDM file.

Calibration Approach

The objective of the streamflow modeling effort was to simulate the observed water budget and hydrologic response in the Blacks Run watershed. The 23-month simulation period extended from February 20, 1999, to January 23, 2001. Commonly, a simulation period covers at least 5 years and is divided into a calibration period and a verification period. The calibration period is used to adjust model parameters to better simulate the water budget and hydrologic response. The verification period is used to verify the accuracy of the model calibration without adjusting model parameters. Because of the limited simulation period (23 months), however, the entire period was used for model calibration and the calibrated model was not verified. Key steps in the development of a calibrated model of streamflow for the Blacks Run watershed included collection of historical and current meteorological and

Table 3. Meteorological and streamflow data in the streamflow model for Blacks Run, Rockingham County, Virginia

[in., inches; VPI, Virginia Polytechnic Institute and State University; °F, degrees Fahrenheit; NCDC, National Climatic Data Center; ft^3/sec, cubic feet per second]

Type of data	Location of data collection	Latitude Longitude	Source	Recording frequency	Period of record
Rainfall (in.)	Mossy Creek	38°22′30″ 79°01′02″	VPI	10 minutes	9/15/98–8/3/00
Rainfall (in.)	Blacks Run	38°22′43″ 78°55′42″	USGS	10 minutes	12/30/99–1/23/01
Minimum air temperature (°F)	Dale Enterprise Weather Station	38°27′19″ 78°56′07″	NCDC	daily	8/1/48–1/31/01
Maximum air temperature (°F)	Dale Enterprise Weather Station	38°27′19″ 78°56′07″	NCDC	daily	8/1/48–1/31/01
Minimum air temperature (°F)	Staunton Sewage Treatment Plant	38°10′52″ 79°05′25″	NCDC	daily	8/1/48–1/31/01
Maximum air temperature (°F)	Staunton Sewage Treatment Plant	38°10′52″ 79°05′25″	NCDC	daily	8/1/48–1/31/01
Streamflow (ft^3/sec)	Blacks Run at Route 704 near Mount Crawford	38°22′43″ 78°55′42″	USGS	hourly daily	2/20/99–1/23/01 2/20/99–1/23/01

streamflow data, determination of the effective impervious area, calibration of hydraulic parameters, and evaluation of model results.

A suite of physically based hydraulic parameters governs the streamflow simulation in HSPF. These hydraulic parameters are categorized as fixed and adjusted parameters. Fixed hydraulic parameters can be measured or are well documented in the literature and can be used with a high degree of confidence, such as the length, slope, width, depth, and roughness of a stream channel. Fixed hydraulic parameters are held constant in HSPF during model calibration. Adjusted hydraulic parameters are highly variable in the environment or are immeasurable, such as the infiltration rate and the extent of the lower zone storage area. These adjusted hydraulic parameters represent the hydrologic transport and storage components in HSPF; each parameter is adjusted/calibrated until simulated streamflow closely represents observed streamflow. Eleven parameters were adjusted to obtain a calibrated model of streamflow for the Blacks Run watershed (table 4).

Results from the streamflow model were evaluated for the calibration period (February 20, 1999, to January 23, 2001). Results from the model calibration were evaluated on the basis of comparisons between simulated and observed streamflow with respect to water budget (total runoff volume), high-flow and low-flow distribution (comparison of low-flow and high-flow periods), stormflow (comparison of stormflow volume, peak, and recession), and season (seasonal runoff volume). These comparisons were performed using Expert System for the Calibration of the Hydrological Simulation Program–FORTRAN (HSPEXP) (Lumb and others, 1994). Seven calibration criteria, expressed as a percent difference, were established in HSPEXP to aid in the evaluation of simulated and observed runoff:

Calibration criterion	Percent difference
Total annual runoff	10
Highest 10-percent flows	10
Lowest 50-percent flows	15
Winter runoff	15
Spring runoff	15
Summer runoff	15
Fall runoff	15

Finally, graphs were used to compare simulated and observed streamflow with respect to daily and hourly streamflow, flow-duration curves, and residuals.

Typically, the calibrated streamflow model is verified by simulating streamflow during a time period not used for model calibration. The results from the model verification are then used as a final evaluation of the calibrated model. A simulation period of at least five

Table 4. Initial streamflow model parameters and percent imperviousness in four subwatersheds represented in the streamflow model for Blacks Run, Rockingham County, Virginia

[HRU, Hydrologic Response Unit; see table 1 for definitions of parameters; U, Urban; R, Residential; P, Pasture; H, Hayland; C, Cropland; F, Forest; B, Barren; UI, Urban impervious; –, not applicable]

HRU	Imperviousness (percent)	AGWETP	AGWRC (1 per day)	BASETP	DEEPFR	INFILT (inches per hour)	INTFW	IRC (1 per day)	KVARY (1 per inch)	LZETP	LZSN (inches)	UZSN (inches)
U	–	0.00	0.972	0.00	0.15	0.08	3.00	0.60	0.00	0.60	8.00	1.00
R	–	.00	.972	.00	.15	.10	3.00	.60	.00	.60	8.00	1.00
P	–	.00	.972	.00	.15	.10	3.00	.60	.00	.60	9.00	1.00
C	–	.00	.972	.00	.15	.12	3.00	.60	.00	.60	9.00	1.00
H	–	.00	.972	.00	.15	.12	3.00	.60	.00	.60	9.00	1.00
F	–	.00	.972	.00	.15	.15	3.00	.60	.00	.60	10.00	1.00
B	–	.00	.972	.00	.15	.08	3.00	.60	.00	.60	7.00	1.00
UI	45	–	–	–	–	–	–	–	–	–	–	–
RI	6	–	–	–	–	–	–	–	–	–	–	–

years typically is used to calibrate and verify a watershed model. The longer the simulation period, the better the model will be able to simulate annual variations in environmental conditions. However, because of the limited time period (February 20, 1999 to January 23, 2001) for which streamflow data in the Blacks Run watershed were available, verification was not performed.

Fecal Coliform Model

After the streamflow model is calibrated, the next step in generating a watershed-scale bacterial transport model is to simulate the transport of bacteria from the land surface, to the stream channel, and through the stream network. In HSPF, this is accomplished by linking the fecal coliform simulation to the streamflow simulation. The following sections summarize the simulation of fecal coliform bacteria in the PERLND, IMPLND, and RCHRES modules. Additional information regarding the simulation of fecal coliform bacteria using HSPF can be found in Bicknell and others (1997).

Pervious and Impervious Land Segments

The PQUAL module is used to simulate the transport of fecal coliform bacteria from pervious land segments. Similar to the PWATER module, PQUAL simulates storages and fluxes of bacteria along three flow paths: overland flow, interflow, and base flow. There are 11 model parameters used to simulate fecal coliform bacteria (table 5). Collectively, these parameters govern the total fecal coliform loading from each HRU to a given stream reach.

The processes by which the transport of fecal coliform bacteria is simulated can be split into two categories: surface and subsurface (interflow and base flow) (fig. 4). The surface processes begin with deposition of feces containing fecal coliform bacteria onto the land surface by numerous sources in the watershed (people, pets, livestock, and wildlife). Fecal coliform deposition is established by the accumulation rate (ACCUM). These bacteria are stored on the surface (SQO) and are allowed to accumulate until the storage limit (SQOLIM) is reached. Bacteria are removed from surface storage by either die-off or washoff. The removal rate (REMQOP) of the stored bacteria through die-off is defined by the ratio of the accumulation rate

Table 5. Parameters used in the simulation of the transport and storage of fecal coliform bacteria in Blacks Run, Rockingham County, Virginia

[ft^3, cubic feet]

Parameter	Definition	Unit
ACCUM	Accumulation rate of fecal coliform bacteria on the land surface.	number of colonies per acre per day
AOQUAL	Transport of fecal coliform bacteria through base flow (ground-water discharge).	number of colonies per day
AQO	Storage of fecal coliform bacteria in active ground water.	number of colonies per ft^3
IOQUAL	Transport of fecal coliform bacteria through interflow.	number of colonies per day
IQO	Storage of fecal coliform bacteria in interflow.	number of colonies per feet
REMQOP	Removal rate (die-off) for fecal coliform bacteria stored on the land surface. Removal rate is based on the ratio of ACCUM/SQOLIM.	1 per day
SOQUAL	Transport of fecal coliform bacteria through overland flow.	number of colonies per acre per day
SQO	Storage of fecal coliform bacteria on the land surface.	number of colonies per acre
SQOLIM	Asymptotic limit for the storage of fecal coliform bacteria on the land surface if no washoff occurs.	number of colonies per acre
WSFAC	Susceptibility of fecal coliform bacteria to washoff. Susceptibility is defined by 2.30/WSQOP.	per inch
WSQOP	Rate of surface runoff that results in 90-percent washoff of the stored fecal coliform bacteria in one hour.	inches per hour

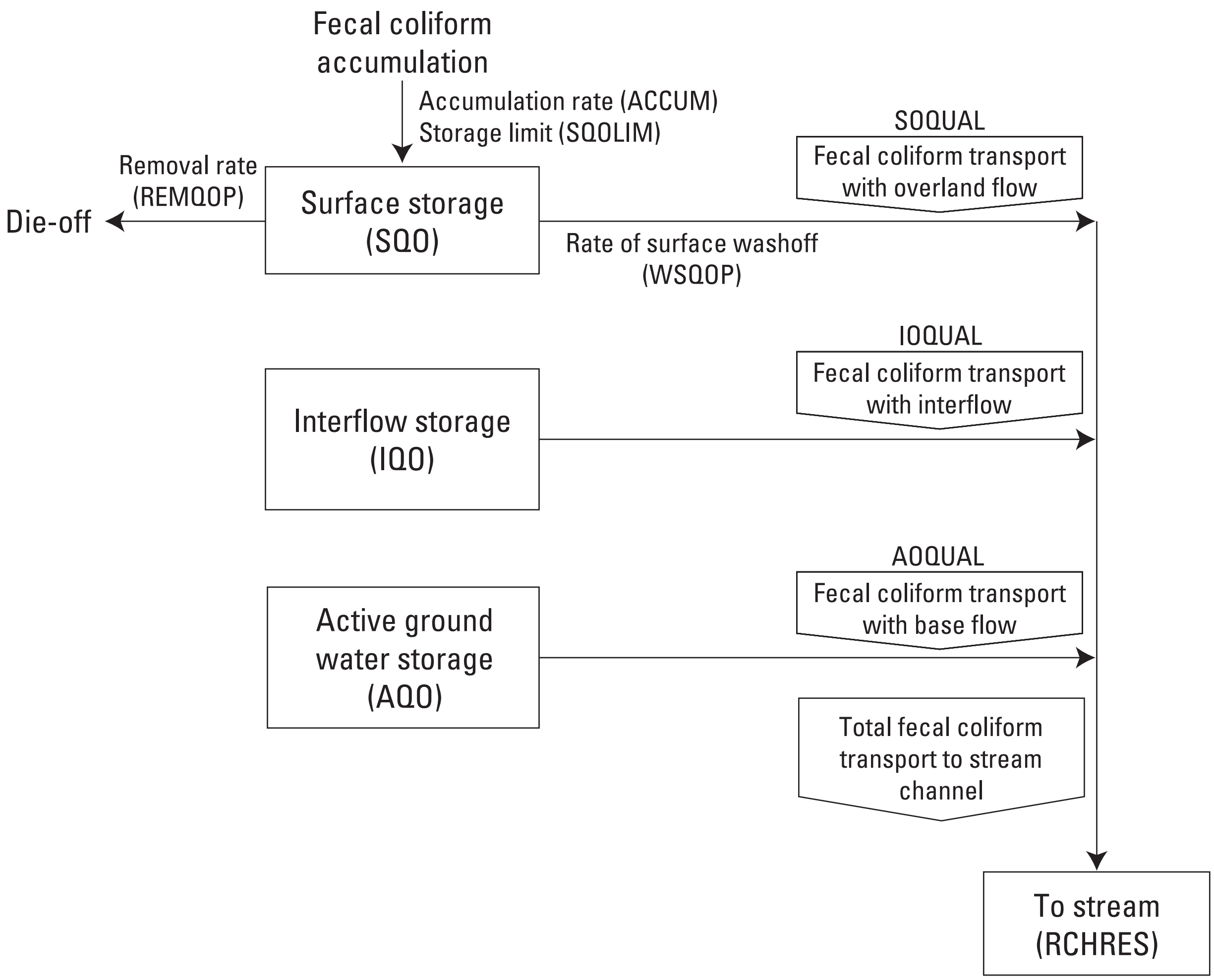


Figure 4. Routing processes represented by the Hydrological Simulation Program-FORTRAN for the simulation of fecal coliform bacteria transport in Blacks Run, Rockingham County, Virginia. (See table 5 for definition of fecal coliform bacteria transport and storage parameters.)

(ACCUM) and the storage limit (SQOLIM). Bacteria remaining in storage are removed through washoff by overland flow. The amount of bacteria removed from surface storage (SOQUAL) during a given storm event is controlled by both the amount of overland flow generated (SURO) and the susceptibility of the bacteria to washoff by overland flow (WSFAC). SURO is identified for each HRU during the hydrologic calibration. WSFAC is a function of the rate of runoff that results in 90 percent washoff of stored fecal coliform bacteria in a given hour (WSQOP). Below are the governing equations for the release of fecal coliforms from storage on the land surface to the receiving stream channel:

$$SOQUAL = SQO*(1 - e^{(-SURO*WSFAC)}) \quad (2)$$

$$WSFAC = \frac{2.30}{WSQOP} \quad (3)$$

where SOQUAL is the amount of fecal coliform bacteria washed off the land surface (number of colonies/acre/interval),

SQO is surface storage of fecal coliform bacteria (number of colonies/acre),

SURO is the total amount of surface runoff (in/interval), WSFAC is susceptibility of fecal coliform bacteria to washoff (per inch), and

WSQOP is the rate of surface runoff that results in 90 percent washoff of fecal coliform bacteria in 1 hour (in/hr).

In the simulation of the transport of fecal coliform bacteria through the subsurface, PQUAL allows for the storage and release of bacteria from interflow (IQO) and active ground-water (AQO) storages. The subsurface transport processes represented are simplified considerably compared to those used to represent surface transport. A concentration of fecal coliform bacteria is assigned to both IQO and AQO and is held constant during the simulation. These bacteria are transported to the stream channel with interflow and base flow. The total volume of interflow and base flow that discharges to the stream channel is established during the streamflow model calibration.

IQUAL is used to simulate the transport of fecal coliform bacteria from impervious land segments. The IQUAL module only simulates surface washoff of fecal coliform bacteria because impervious land segments do not have a subsurface component. The transport processes and governing equations (2, 3) used in IQUAL are identical to those used in the surface washoff component of PQUAL. Generally, bacteria stored on an impervious land segment are more susceptible to washoff than those stored on pervious land segments; thus, WSFAC for impervious land segments is greater than WSFAC for pervious land segments.

Stream Channels

GQUAL is the component in the RCHRES module used to simulate the transport of fecal coliform bacteria through the channel network. Bacteria are routed to the simulated stream channels from the various PERLND and IMPLND HRUs, point source inputs (sewage-treatment plants and instream animals), and upstream stream segments. These bacteria enter the simulated stream segment at a single upstream point and are either transported to the next downstream stream segment or are removed through die-off. The portion of bacteria removed from the simulated stream channel through die-off is based on a first-order decay rate of 1.1 day $^{-1}$ (U.S. Environmental Protection Agency, 1985) and is determined by the following equations:

$$DDQALT = DQAL*(1 - e^{(-KGEN)})*VOL \qquad (4)$$

$$KGEN = (KGEND)(THGEN)^{(TW20)} \qquad (5)$$

where DDQALT is the number of bacteria removed through die-off (number of colonies/interval),

DQAL is the concentration of bacteria for the time interval (number of colonies/100 mL),

KGEN is the generalized first-order decay rate corrected for temperature (number of colonies/interval), and

VOL is the volume of water in the reach (ft^3).

KGEND is the base first-order decay rate (number of colonies/interval),

THGEN is the temperature correction parameter, dimensionless, and

TW20 is the temperature of the water (°C) for interval minus 20.

Limitations of the Fecal Coliform Model

The most critical limitation associated with the fecal coliform model is that fecal coliform bacteria are simulated as a dissolved constituent. Fecal coliform bacteria, however, are particulate constituents and are deposited and resuspended once delivered to the active stream channel. The transport mechanisms associated with deposition and resuspension are not simulated explicitly. However, mechanisms that mimic deposition and resuspension are simulated through interflow and base-flow pathways (see Fecal Coliform Bacteria in the Subsurface).

Point and Nonpoint Source Representation

A key step in simulating the transport of fecal coliform bacteria is to determine the total amount of bacteria deposited on the land surface (representing nonpoint sources) or deposited directly in the stream channel (representing point sources). For this study, the total amount of bacteria deposited by each of the dominant sources of fecal coliform bacteria was estimated. This information was the primary input dataset for the fecal coliform model; the fecal coliform deposition information is analogous to rainfall data used in the runoff model. The following sections explain how the fecal coliform deposition rate was established for the various point sources (for example, STPs) and nonpoint sources (people, pets, livestock, and wildlife) within the Blacks Run watershed.

There are two private permitted dischargers in the Blacks Run watershed: one family residence and one small business (table 6). Both of these private permits govern the treatment and release of treated human waste generated by the establishments. According to the permit, the treated wastewater may not contain fecal coliform bacteria concentrations that exceed 200 col/100 mL. Each discharger is represented in the fecal coliform model at the maximum permitted level, and together contribute 5.52×10^9 col/year to Blacks Run.

Table 6. Private permitted point-source dischargers of fecal coliform bacteria in Blacks Run, Rockingham County, Virginia

Permit number	Discharge rate (million gallons per day)	Fecal coliform limit (number of colonies per 100 milliliters)	Annual fecal coliform load (number of colonies per year)
VAG401217	1,000	200	2.76×10^9
VAG401944	1,000	200	2.76×10^9
Total			5.52×10^9

Most of the fecal coliform bacteria in Blacks Run are derived from and represented as nonpoint sources. These bacteria are deposited on the land surface by many different sources (people, pets, livestock, and wildlife) and subsequently are transported to the stream network with rainfall runoff. Two critical pieces of information must be obtained to simulate the transport of fecal coliform bacteria derived from nonpoint sources using HSPF. First, the dominant sources of fecal coliform bacteria in the watershed must be identified. A survey was conducted of fecal coliform sources in the Blacks Run watershed, and 12 sources were identified as potentially dominant and represented in the model. These 12 sources are cats, cattle, deer, dogs, ducks, geese, horses, humans, muskrats, poultry, raccoons, and sheep. Second, the total daily amount of fecal coliform bacteria deposited on the land surface or directly in streams (for example, cattle in streams) by each of the identified sources must be determined for both pervious and impervious land segments.

General Quantification of Fecal Coliform Bacteria

The amount of fecal coliform bacteria deposited on the land surface daily is represented by ACCUM in HSPF. Every source represented in the model has a specific fecal coliform accumulation rate. The following equation is used to calculate ACCUM for each fecal coliform source:

$$ACCUM = \frac{(Fprod*FCden)POPN}{HAB} \qquad (6)$$

where ACCUM is the fecal coliform bacteria accumulation rate (number of colonies/acre/day),

Fprod is the feces produced per day (g/day),

FCden is the number of fecal coliform bacteria per gram of feces produced (number/g),

POPN is the population size, dimensionless, and

HAB is the habitat area (acres).

The calculation of ACCUM is based on values of Fprod, FCden, HAB, and POPN that are source specific, and selection of these values is challenging. Information on Fprod and HAB generally is well documented for individual species. Therefore, single values of Fprod and HAB are used and held constant throughout the entire modeling effort. Values of FCden and POPN, however, generally are more variable and poorly documented compared to values of Fprod and HAB. For example, dog, cat, and human feces have measured FCden ranges from 4.1×10^6 col/g to 4.3×10^9 col/g; 8.9×10^4 col/g to 2.6×10^9 col/g; and 1.3×10^5 col/g to 9.0×10^9 col/g, respectively (Mara and Oragui, 1981). This wide range in measured values of FCden is typical of most of the sources represented in the model; therefore, considerable uncertainty is associated with choosing a single value of FCden to represent a given species. Additionally, exact population numbers commonly are unknown for the human, pet, and wildlife populations, and the proportion of the population that contributes to the instream fecal coliform load also is unknown. Because of the uncertainty associated with values of FCden and POPN, two decision rules were established that limit the number of parameters adjusted while refining ACCUM for each source:

(1) When the population size for a given source is well documented, then that value will be used and held constant.

(2) When the population size for a given source is unknown, POPN will be treated as an adjusted parameter and potentially modified during the model-calibration process while FCden is held constant.

Under the first decision rule, FCden will be treated as an adjusted variable and potentially modified during the model-calibration process. Adjustments to FCden account for the uncertainty associated with fixed values of Fprod, POPN, and HAB. Under the second decision rule, adjustments to POPN account for the uncertainty associated with the fixed values of Fprod, FCden, and HAB. The resulting POPN value, following calibration, will be identified as an "effective" value that accounts for the uncertainty associated with the fixed values of Fprod, FCden, and HAB.

In HSPF, the total accumulation rate of fecal coliform bacteria on the land surface is bounded by a storage limit (SQOLIM). This storage limit enables the model to account for the natural die-off of bacteria stored on the land surface. For this study, the storage limit was set to 9 times the accumulation rate, which represents a decay rate of 0.1 day^{-1} (U.S. Environmental Protection Agency, 1985).

Source-Specific Quantification of Fecal Coliform Bacteria

The quantification of fecal coliform bacteria generated by the various sources within the Blacks Run watershed is documented in the following section. The sources described in this section are humans, dogs, cats, beef cattle, dairy cattle, heifers, broilers, turkeys, horses, sheep, deer, geese, ducks, raccoons, and muskrats. These sources are described with respect to their contribution to the pervious and impervious land segments within the basin.

Pervious Land Segments

The Blacks Run watershed has a human population of approximately 34,700 (1990 Census). Within the watershed, many pathways can allow human-derived fecal coliform bacteria to enter Blacks Run. These pathways include failing septic systems, overflowing sewer lines, and leaking sewer lines, the cumulative effect of which was represented by a land application of human waste. The fecal coliform bacteria accumulation rate for the land-applied bacteria was calculated using equation 6. The values used to calculate the initial accumulation rate are in table 7. On average, one person generates approximately 150 g of feces per day (Geldreich and others, 1962) and an estimated 4.66 x 10^8 col/g of human feces (Mara and Oragui, 1981). The initial population value (POPN) used was based on an

Table 7. Initial values of the total amount of feces produced daily and fecal coliform per gram of feces generated by the human population in the residential hydrologic response unit represented in the streamflow model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces; POPN, population size; HAB, habitat area]

Subwatershed[1]	Fprod (grams)	FCden	POPN (number)	HAB (acres)
1	150	4.66 x 10^8	119	131
2	150	4.66 x 10^8	159	165
3	150	4.66 x 10^8	194	288
4	150	4.66 x 10^8	0	37

[1]See figure 3 for location of subwatersheds.

estimated septic-system failure rate of 15 percent, which is consistent with failure rates determined for nearby communities (Virginia Polytechnic Institute and State University, 2000). In the Blacks Run watershed, 1,169 houses have septic systems. The average household occupancy rate for Rockingham County is 2.69 people (1990 Census). POPN is the most uncertain value in equation 6 and, therefore, is adjusted during the model-calibration process. These bacteria then are distributed over the residential land type (HAB) (table 7).

Fecal coliform bacteria derived from dogs were represented as a land application to both urban and residential land types. The accumulation rate for these bacteria was calculated using equation 6. Initial values used to calculate ACCUM are listed in table 8. On average, one dog generates 450 g of feces per day (Weiskel and others, 1996), and an estimated 4.11×10^6 col/g of feces (Mara and Oragui, 1981). The initial value for the total number of dogs in the watershed was based on the estimate of one dog per four people. This estimate was refined further to account for the approximately 20 percent of dog waste that is picked up and disposed of. Additionally, 1 percent of the dog waste was assumed to be deposited on impervious surfaces such as parking lots and roads. The POPN value in table 8 represents the initial estimated number of dogs whose feces are deposited outdoors and are picked up and disposed of. Because the actual number of dogs in the watershed is unknown, POPN is treated as a fitted value during the model-calibration process.

Fecal coliform bacteria derived from cats were represented as a land application to both urban and residential land types. The accumulation rate for these bacteria was calculated using equation 6. Initial values used to calculate ACCUM are listed in table 8. On average, one cat generates 20 g of feces per day (Jutta Schneider, Virginia Department of Conservation and Recreation, written commun., 2000), and an estimated 1.49×10^7 col/g of feces (Mara and Oragui, 1981). The initial value for the total number of cats in the watershed was based on an estimate of two cats per three people. It was assumed that 70 percent of the estimated number of cats deposits their feces outdoors. The POPN value in table 8 represents the initial estimated number of cats that deposit their feces outdoors. Because the actual number of cats that deposit their feces outdoors is unknown, POPN is treated as a fitted value during the model-calibration process.

There are approximately 900 beef cattle, 300 dairy cattle, and 300 heifers in the Blacks Run watershed. Each of these cattle types has different estimated daily

Table 8. Initial values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by the initial dog and cat populations in the urban and residential hydrologic response units represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces; POPN, population size; HAB, habitat area]

Subwatershed[1]	Fprod (grams)	FCden	POPN (number)		HAB (acres)	
			Residential impervious	Urban impervious	Residential impervious	Urban impervious
Dogs						
1	450	4.11×10^6	146	4,101	125	2,581
2	450	4.11×10^6	195	1,489	167	2,183
3	450	4.11×10^6	239	696	205	1,753
4	450	4.11×10^6	0	7	0	49
Cats						
1	20	1.49×10^7	345	9,713	125	2,581
2	20	1.49×10^7	461	3,527	167	2,183
3	20	1.49×10^7	565	1,648	205	1,753
4	20	1.49×10^7	0	16	0	49

[1]See figure 3 for location of subwatersheds.

fecal production rates (American Society of Agricultural Engineers, 1998) and associated fecal coliform densities (Mara and Oragui, 1981) (table 9). The fecal coliform bacteria derived from cattle feces can be transported to Blacks Run along three possible pathways: (1) Feces generated while cattle are confined are stored and later distributed over the various croplands in the watershed, and then transported to the stream network with surface runoff. (2) Feces are deposited directly on the pastureland by grazing cattle, and then transported to the stream network through surface runoff. (3) Feces are deposited directly in Blacks Run and associated tributaries by cattle standing in these streams. Each of these three pathways is represented in HSPF.

Table 9. Initial values of the total amount of feces produced daily and fecal coliform per gram of feces generated by dairy cattle, beef cattle, and heifers represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces]

Source	Average daily Fprod (grams)	FCden
Dairy cattle	54,545	8.18×10^5
Beef cattle	20,909	1.87×10^6
Heifers	39,091	6.40×10^4

Dairy cattle are confined in or around milking parlors between 7.2 and 18.0 hr/day during the summer and winter months, respectively (table 10). The feces generated by confined dairy cattle are collected and stored in anaerobic lagoons. Fecal coliform bacteria stored in anaerobic lagoons are subject to die-off; the die-off rate was simulated using the equation

$$C_t = C_o e^{-Kt} \quad (7)$$

where C_t is the fecal coliform bacteria load at time t,

C_o is the initial fecal coliform bacteria load,

t is the time in days, and

K is the first order decay rate (day^{-1}).

C_o was set to the number of fecal coliform bacteria produced yearly by dairy cattle in confinement. The time (t) these bacteria were stored was set to 100 days, which represents the average storage capacity of dairy lagoons in the Blacks Run watershed. A decay rate (K) of 0.375 day^{-1} was used to represent the decay rate observed in an anaerobic lagoon (Crane and Moore, 1986). The amount of fecal coliform bacteria remaining after the 100 days of storage (C_t), which then is available for manual application to croplands, is incorporated into equation 6 to determine the accumulation rate per acre of cropland. Because the number of dairy cattle in the watershed is known, FCden is adjusted during the model-calibration process. The percentage of stored dairy waste applied to cropland varies from month to month (table 11); the monthly field application rate and the number of cattle in confinement were represented by means of monthly ACCUM values. The fecal coliform bacteria from the dairy waste applied to cropland are treated as a nonpoint source in the model simulation.

Beef cattle and heifers spend an average of 9.6 hours per day in confinement during the months of December, January, and February (table 12). During these months, the cattle are not confined to a small area but are housed in barns where they deposit feces and associated fecal coliform bacteria. The accumulating manure is removed routinely and stored until it can be applied to cropland. Fecal coliform bacteria are subject to die-off during the manure storage phase. Equation 7 was used to determine the total amount of bacteria removed from the stored manure through die-off. C_o was set to the total number of fecal coliform bacteria produced by beef cattle and heifers in confinement. The total time (t) these bacteria were stored was set to 30 days. A decay rate (K) of 0.066 day^{-1} was used to represent the decay rate in an uncovered manure pile (Crane and Moore, 1986). The amount of fecal coliform bacteria remaining after the 30 days of storage (C_t), which then is available for manual application to croplands, is incorporated into equation 6 to determine the accumulation rate per acre of cropland. Because the number of beef cattle and heifers in the watershed is known, FCden is treated as an adjusted value during the model-calibration process. The percentage of stored manure applied to cropland varies from month to month (table 13); the monthly field application rate and number of cattle in confinement were represented in the model by means of monthly ACCUM values. The

Table 10. Initial values of the total hours per day dairy cattle spend in a given month in the pasture, with access to a stream, and in confinement in the Blacks Run watershed, Rockingham County, Virginia

Month	Time (hours)		
	Pasture	Access to stream	Confinement
January	5.5	0.5	18.0
February	5.5	0.5	18.0
March	13.4	1.0	9.6
April	15.8	1.0	7.2
May	15.8	1.0	7.2
June	13.8	3.0	7.2
July	13.8	3.0	7.2
August	13.8	3.0	7.2
September	15.8	1.0	7.2
October	15.8	1.0	7.2
November	13.4	1.0	9.6
December	5.5	.0	18.0

Table 11. Percentage of the total stored dairy cattle waste applied to cropland in the Blacks Run watershed, Rockingham County, Virginia

Month	Application amount[1] (percent)
January	0
February	5
March	25
April	20
May	5
June	7.5
July	2.5
August	5
September	12.5
October	7.5
November	10
December	0

[1]From Virginia Department of Conservation and Recreation

Table 12. Total hours per day beef cattle and heifers spend in a given month in the pasture, with access to a stream, and in confinement in the Blacks Run watershed, Rockingham County, Virginia

Month	Time (hours per day)		
	Pasture	Access to stream	Confinement
January	13.9	0.5	9.6
February	13.9	.5	9.6
March	23.0	1.0	.0
April	23.0	1.0	.0
May	22.5	1.5	.0
June	20.5	3.5	.0
July	20.5	3.5	.0
August	20.5	3.5	.0
September	22.5	1.5	.0
October	23.0	1.0	.0
November	23.0	1.0	.0
December	13.9	.5	9.6

Table 13. Percentage of stored beef cattle and heifer manure and poultry litter applied to cropland in the Blacks Run watershed, Rockingham County, Virginia

Month	Application amount[1] (percent)
January	0
February	5
March	25
April	20
May	5
June	5
July	5
August	5
September	10
October	10
November	10
December	0

[1] From Virginia Department of Conservation and Recreation

bacteria from the manure applied to cropland are treated as a nonpoint source in the model simulation.

Dairy cattle spend between 5.5 and 15.8 hours per day in the pasture (table 10) while beef cattle and heifers spend between 13.9 and 23.0 hours per day in the pasture (table 12). In the model, pasture is represented by both pasture and hayland with 80 percent of the cattle distributed on pasture and 20 percent distributed on hayland. These cattle deposit feces with associated fecal coliform bacteria directly onto the pasture. The daily total number of bacteria deposited on the pasture is determined by the time cattle spend in the pasture and the daily fecal coliform production rate. Monthly values of ACCUM were used to represent the monthly varying number of cattle in the pastures, and the bacteria from the feces deposited directly to the pasture are treated as a nonpoint source in the model simulation.

When stream access is provided, cattle spend an average of 0.5 hr/day during cold months to 3.5 hr/day during warm months (table 12) in and near streams. In order to determine and simulate the total amount of feces that is deposited directly to the stream, the number of cattle with direct access to a stream must be identified. This number is estimated by first identifying the total number of pasture and hayland land segments (pastures) that are bordered by Blacks Run or its major tributaries (fig. 1). GIS coverages for land use and stream networks in the Blacks Run watershed revealed that 58 percent of all pastures are bordered by a major stream. The number of cattle in the major streams is determined by the equation

$$Cattle_{Instream} = (Cattle_{Total}(0.58))\left[\frac{T_{Access}}{24hrs}\right] \qquad (8)$$

where $Cattle_{Instream}$ is the number of dairy cattle, beef cattle, or heifers in the stream,

$Cattle_{Total}$ is the total number of dairy cattle, beef cattle, or heifers in the pastures, and

T_{Access} is the estimated time spent in the stream (hrs).

In the model, 30 percent of the fecal coliform bacteria generated by $Cattle_{Instream}$ are represented as deposited directly in the stream whereas the remaining 70 percent is allocated to pastures. This 70 percent represents the feces that are deposited near but not directly in the stream channel. The 30 percent that is directly deposited into the stream is represented using monthly values to account for varying time cattle spend in the stream each month. This direct deposition is represented in the model as a point source.

There are 143,000 broilers and 143,000 turkeys in the Blacks Run watershed. The resident broiler and turkey population was represented in the model as combined poultry. A fecal production rate for turkey of 231 g/day (American Society of Agricultural Engineers, 1998) and an estimated fecal coliform density of 1.82×10^9 col/g (Mara and Oragui, 1981) were used to determine the total number of fecal coliform bacteria produced per day. Because the entire poultry population is confined to poultry houses, the generated poultry litter is stored and later applied to cropland. The extent of fecal coliform bacteria die-off during poultry litter storage was determined using equation 7. C_o was set to the total number of fecal coliform bacteria produced yearly by poultry. The time (t) these bacteria were stored was set to 90 days, which is the average poultry litter storage time. A decay rate (K) of 0.08 day^{-1} was used to represent the decay rate observed for poultry litter applied to the soil surface (Giddens and others, 1973). The amount of fecal coliform bacteria remaining (C_t) after the 90 days of storage is incorporated into equation 6 to determine ACCUM. The percentage of stored poultry litter applied to cropland varies from month to month (table 13); the monthly field application rate was represented in the model by means of monthly ACCUM values. Because the number of poultry in the watershed is known, FCden is adjusted during the model-calibration process. The fecal coliform bacteria from the poultry litter applied to cropland are treated as a nonpoint source in the model simulation.

There are 165 horses and 175 sheep in the Blacks Run watershed. The average fecal production rate for horses and sheep is 23,182 g/day and 1,091 g/day, respectively (American Society of Agricultural Engineers, 1998). The fecal coliform density assumed for horse feces is 1.81×10^5 col/g (American Society of Agricultural Engineers, 1998) and 1.80×10^5 col/g for sheep (Mara and Oragui, 1981). ACCUM values for horses and sheep are adjusted during the calibration process, as needed, through the FCden parameter. Horses and sheep deposit their waste directly onto pasture. The bacteria applied to pasture are treated as a nonpoint source in the model simulation.

DCR provided information on the numbers and housing of livestock, as well as application rates of liquid dairy waste and manure to cropland and pasture in the Blacks Run watershed (Jutta Schneider, Virginia Department of Conservation and Recreation, written commun., 2000).

The wildlife sources represented in the model are deer, geese, ducks, raccoons, and muskrats. These sources were selected on the basis of information from the Virginia Department of Game and Inland Fisheries (VDGIF) and watershed surveys performed by the USGS as part of this study. The population of each of these wildlife species was estimated on the basis of habitat area, species density within the specified habitat, and seasonal migration (table 14). GIS coverages for animal habitat and land use were used to determine the size of each animal's habitat. For example, Canada geese prefer to be within 300 ft of streams on all land segments except forested; therefore, the total acres of Canada geese habitat is equal to the sum of the acres of all land segments within 300 ft of a stream, except forested, in the habitat area. The population density for geese and ducks increases during the winter months (December, January, and February) because of migration. The amount of fecal coliform bacteria produced daily by each wildlife species (table 15) is used in equation 6 to identify ACCUM for each wildlife species represented in the model. POPN for all wildlife species except deer, and FCden for deer, are adjusted during the model-calibration process. Monthly values of ACCUM are adjusted for geese and ducks in order to account for migration. The feces of all wildlife species are applied directly to the land segments in their habitat; therefore, these sources of fecal coliform bacteria are represented in the model as nonpoint sources.

Impervious Land Segments

Dogs are the only source in the model that is assumed to deposit feces on impervious surfaces. One percent of the total waste generated by dogs is assumed to fall directly on the impervious portions of the residential and urban land-use types (table 16). The bacteria from the feces directly deposited on impervious surfaces are modeled as a nonpoint source. The fecal coliform accumulation rate is calculated using equation 6 and is based on the fecal production from 1 percent of the dog population.

Fecal Coliform Bacteria in the Subsurface

The decision to represent fecal coliform bacteria in the subsurface was based primarily on results from intensive monitoring of fecal coliform bacteria during stormflow and base-flow conditions in Blacks Run (Hyer and Moyer, 2003). Data collected by Hyer and Moyer (2003) support two hypotheses regarding the transport of fecal coliform bacteria. First, in addition to the surface runoff, fecal coliform bacteria may be transported along subsurface pathways. Other studies have found that bacteria can infiltrate and move through the shallow subsurface (Rahe and others, 1978; Wright, 1990; Miller and others, 1991; Pasquarell and Boyer, 1995; Howell and others, 1995; Felton, 1996; McMurry and others, 1998). Second, fecal coliform bacteria may be transported by other mechanisms that mimic subsurface pathways, such as resuspension of fecal coliforms from streambed sediments by animals walking in the stream, sloughing of fecal coliforms from the surface of streambed sediments, or advective transport of fecal coliforms from the streambed sediment by ground-water recharge (Goyal and others, 1977; LaLiberte and Grimes, 1982; Burton and others, 1987; Sherer and others, 1988; Marino and Gannon, 1991). These bacteria transport mechanisms were simulated by incorporating the subsurface modules for interflow and base flow.

Interflow represents water that is transported through the shallow subsurface (soil water). The travel time for soil water to reach the stream is greater than water transported as surface runoff; thus, soil water affects the stream hydrograph by decreasing the rate of recession following a storm event. Similarly, fecal coliform bacteria transported with interflow will extend the period of elevated fecal coliform bacteria concentrations following a storm event. Hyer and Moyer (2003) observed elevated fecal coliform concentrations for up to 2 days following storm events in Blacks Run. Fecal coliform bacteria associated with instream suspended sediment may contribute to post-storm elevated fecal coliform concentrations and are represented by simulation of the interflow component. Hyer and Moyer (2003) observed similar post-storm responses for streamflow, suspended sediment, and fecal coliform bacteria. In HSPF, the post-storm response for fecal coliform bacteria concentration was represented by assigning a concentration of 1,500 col/100 mL (424,800 col/ft^3) to interflow. These bacteria were linked to the top four fecal coliform bacteria sources

Table 14. Initial population values of wildlife sources of fecal coliform bacteria in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[F, Forest; P, Pasture; U, Urban; R, Residential; H, Hayland; C, Cropland; B, Barren]

Wildlife source	Land-use type	Habitat[1]	Population density[2] (number per acre)	POPN (number)
Deer	F, P	Entire watershed	0.040	64
Goose–Summer	U, R, P, H, C, B	Within 300 feet of streams and ponds	.70	887
Goose–Winter	U, R, P, H, C, B	Within 300 feet of streams and ponds	.89	1,129
Duck–Summer	U, R, P, H, C, B	Within 300 feet of streams and ponds	.20	253
Duck–Summer	F	Within 300 feet of streams and ponds	.047	14
Duck–Winter	U, R, P, H, C, B	Within 300 feet of streams and ponds	.375	475
Duck–Winter	F	Within 300 feet of streams and ponds	.078	24
Raccoon	F	Within 2,640 feet of streams and ponds	.055	69
Raccoon	R, P, H, C	Within 2,640 feet of streams and ponds	.023	95
Muskrat	U, R, P, H, C, B	Within 60 feet of streams and ponds	.500	331

[1]Paul Bugas, Virginia Department of Game and Inland Fisheries, oral commun., 1999, and U.S. Department of Agriculture, Forest Service, Rocky Mount Research Station, Fire Sciences Laboratory, Fire Effects Information System (January, 2000).
[2]Paul Bugas, Virginia Department of Game and Inland Fisheries, oral commun., 1999.

Table 15. Initial values of the total amount of feces produced per day and fecal coliform bacteria per gram of feces generated by deer, goose, duck, raccoon, and muskrat represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gramof feces]

Wildlife source	Fprod (grams)	FCden
Deer	772	3.30×10^{6}
Goose	225	3.55×10^{6}
Duck	150	4.90×10^{7}
Raccoon	450	1.11×10^{7}
Muskrat	100	2.50×10^{5}

Table 16. Initial values of the total amount of feces produced per day and fecal coliform bacteria per gram of feces generated by the dog population in the urban and residential impervious hydrologic response unit represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces; POPN, population size; HAB, habitat area]

Subwatershed[1]	Fprod (grams)	FCden	POPN (number)		HAB (acres)	
			Residential impervious	Urban impervious	Residential impervious	Urban impervious
			Dogs			
1	450	4.11×10^6	1	42	8	287
2	450	4.11×10^6	2	15	11	243
3	450	4.11×10^6	2	7	18	195
4	450	4.11×10^6	0	0	2	6

[1]See figure 3 for location of subwatersheds.

identified by Hyer and Moyer (2003). These sources are cattle, dogs, humans, and poultry.

Base flow, which represents the portion of ground water that enters the stream, is the dominant component of the stream hydrograph during periods of extended dry weather. Fecal coliform bacteria observed during these base-flow periods typically are transported through diffuse ground-water input or pathways that mimic this diffuse input, such as resuspension of fecal coliforms from streambed sediments by animals walking in the stream, sloughing of fecal coliforms from the surface of streambed sediments, and advective transport of fecal coliforms from the streambed sediment by ground water inputs. Results from Hyer and Moyer (2003) indicate that bacteria linked to poultry, pet, and other nonpoint sources were present in base-flow samples from Blacks Run. Although the transport mechanism is unknown, nonpoint source signatures in base flow are represented through the ground-water module. In HSPF, a fecal coliform bacteria concentration of 100 col/100 mL (28,320 col/ft^3) was assigned to base flow. These bacteria also were linked to cattle, dogs, humans, and poultry identified by Hyer and Moyer (2003).

Water-Quality Data

DEQ monitors water quality in streams and rivers across the State. One constituent monitored is fecal coliform bacteria, which are derived from the intestinal tract of warm-blooded animals. These bacteria are used as an indicator organism for identifying the presence of fecal contamination and associated pathogens such as *Salmonella* and *Shigella*. The predominant form of fecal coliform bacteria is *Escherichia coli (E. coli)*. DEQ collects and analyzes water samples to determine if a particular stream or river is in compliance with the State water-quality standard for fecal coliform bacteria, which is an instantaneous concentration of 1,000 col/100 mL. Sites with fecal coliform bacteria concentrations greater than 1,000 col/100 mL pose a risk to individuals who are in direct contact with the contaminated water because of the increased likelihood of encountering a pathogen (U.S. Environmental Protection Agency, 1986). DEQ established an upper detection limit of 8,000 col/100 mL for enumeration of fecal coliform bacteria during 1991–93. The upper detection limit was then increased to 16,000 col/100 mL from 1994–99. In 2000, the upper detection limit was dropped to 2,000 col/100 mL. Therefore, historical fecal coliform data values equal to the upper detection limit, for each respective time period, had actual concentrations equal to or greater than the respective detection limit. DEQ generally collects water-quality samples monthly under low-flow or post stormflow conditions; peak stormflow water-quality samples are not collected routinely.

DEQ collects monthly water-quality samples at a long-term monitoring station on Blacks Run (fig 1; table 17). Samples are analyzed for fecal coliform bacteria using the membrane filtration technique. Results

Table 17. Fecal coliform bacteria concentrations for water-quality samples collected by the Virginia Department of Environmental Quality at a water-quality monitoring station on Blacks Run, Rockingham County, Virginia

Station number[1]	Station name	Latitude Longitude	Period of record	Fecal coliform bacteria concentration, in colonies per 100 milliliters			
				Minimum	Maximum	Mean	Median
1BBLK000.38	Route 704	38°22′39″ 78°55′49″	1991-2001	45	16,000	5,057	2,000

[1]See figure 1 for location of station.

of monitoring during 1991-2001 show that fecal coliform bacteria concentrations were greater than the State instantaneous water-quality standard in 72.4 percent of the samples taken (fig. 5). Seasonal patterns also were identified in the data (fig. 6). Generally, fecal coliform concentrations are higher during the warmer months (April–November) and lower during the cooler months (December–March). This seasonal pattern is consistent with the animal practices in the watershed (increased animal density and activity around the streams during the hot summer months) and possible seasonal differences in bacteria survivorship. Similar seasonal patterns have been observed in other studies of fecal coliform concentrations and loads (Christensen and others, 2001; Baxter-Potter and Gilliland, 1988).

The USGS collected water-quality data for this study at six sites in Blacks Run from March 1999 to October 2000 (Hyer and Moyer, 2003). All stream-water samples were analyzed for the enumeration of fecal coliform bacteria following standard USGS methods for the membrane filtration technique (Myers and Sylvester, 1997). Stream-water samples were collected over a wide range of flow conditions (table 18).

Low-flow samples were collected every 6 weeks at Route 704. Some of these low-flow sampling events were on the recession limbs of storm events. Typically, between four and eight depth-integrated samples were collected during each low-flow sampling event. Consecutive sample were collected at three locations across the stream width (the center of the channel and approximately halfway to each stream bank). The depth-integrated samples were collected at 5-minute intervals, providing a degree of time-integration during each sampling event. Results of the water-quality samples collected under low-flow and recession-flow conditions indicate that 75 percent of the low-flow samples exceeded the State fecal coliform bacteria standard (fig. 7). Recession-flow samples generally had fecal coliform concentrations that were elevated relative to the low-flow samples. These fecal coliform data also exhibited a seasonal pattern; higher concentrations were observed during the summer and fall than during the winter and spring. This seasonal pattern for concentrations of fecal coliform bacteria is consistent with the pattern identified in the historical data.

Stormflow samples were collected during five storm events (May 8, 1999; September 16, 1999; November 2, 1999; January 10, 2000; and June 14, 2000) at Route 704. At least 10 water samples were collected across the storm hydrograph (rising limb, plateau, and falling limb) during each storm event. The fecal coliform concentrations observed during these storm events are elevated considerably relative to the State water-quality standard (fig. 8) and the low-flow concentrations. A large range of concentrations was observed during each storm because sampling was done over the entire hydrograph. Peak fecal coliform concentrations observed during these storms ranged from 33,000 to 260,000 col/100 mL. These elevated fecal coliform concentrations during storm events have been observed in previous studies (Christensen and others, 2001; Bolstad and Swank, 1997). In general, these elevated stormflow concentrations are interpreted as resulting from a combination of a flushing response (whereby fecal coliform bacteria that have been deposited near the stream are washed off the land surface and into the stream) and a resuspension of streambed sediments containing fecal coliform bacteria (Hunter and others, 1992; McDonald and Kay, 1981).

Five continuum sampling sites in addition to Route 704 were established along Blacks Run (fig. 1; table 18). These six sites were sampled 13 times (March 22, 1999; July 22, 1999; August 19, 1999; September 5, 1999; October 4, 1999; November 17, 1999; December 17, 1999; January 22, 2000; February 25, 2000; March 3, 2000; April 27, 2000; May 13, 2000; and August 15, 2000) to examine how well the intensive sampling at Route 704 represented the entire

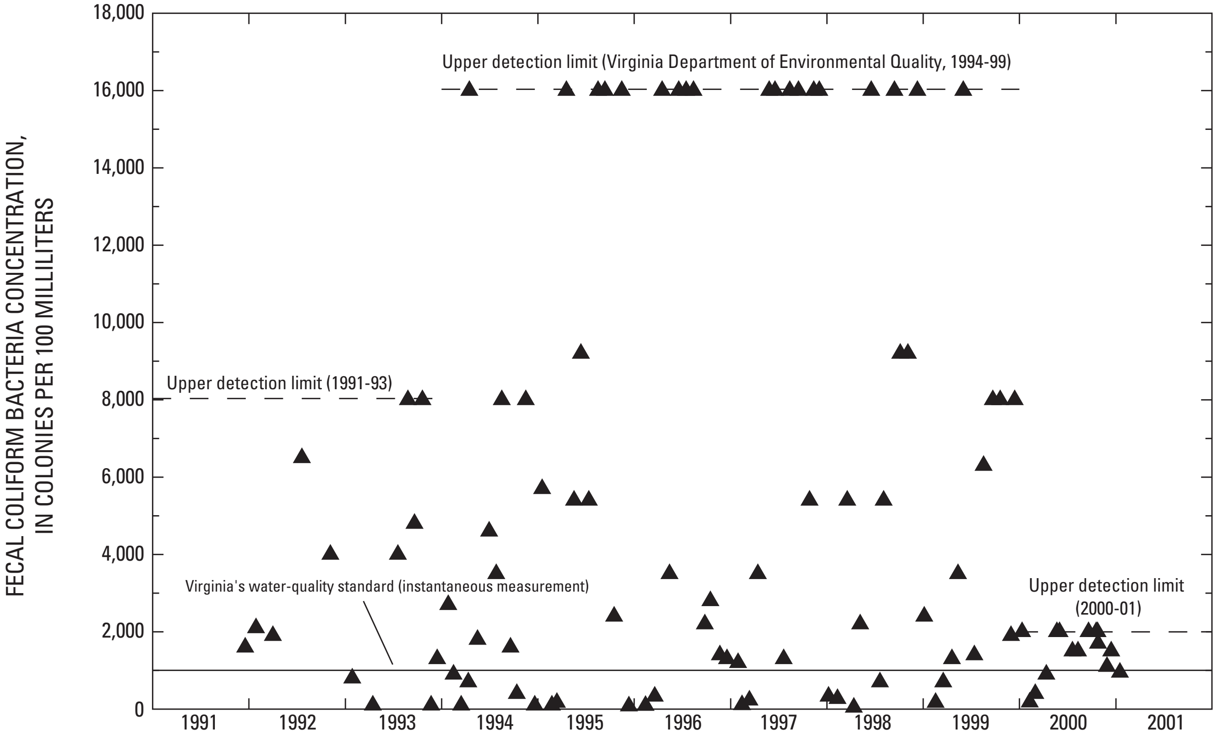


Figure 5. Observed fecal coliform bacteria concentrations for Blacks Run at Route 704, Rockingham County, Virginia, 1991-2001. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

Table 18. Fecal coliform bacteria concentrations for water-quality samples collected by the U. S. Geological Survey during low-flow and stormflow conditions at Route 704 (01621470) and at five other sites along the continuum of Blacks Run, Rockingham County, Virginia

Station number[1]	Station name	Latitude Longitude	Number of samples	Fecal coliform bacteria concentration, in colonies per 100 milliliters			
				Minimum	Maximum	Mean	Median
Low-flow samples							
01621470	Route 704	38°22′43″ 78°55′42″	105	28	97,272	10,244	3,400
Stormflow samples							
01621470	Route 704	38°22′43″ 78°55′42″	57	3,400	260,000	45,704	31,000
Continuum samples							
01621395	Route 753	38°27′47″ 78°51′55″	6	16	290,000	63,161	1,375
01621397	Water Street	38°26′56″ 78°52′16″	12	120	62,000	10,083	1,550
01621410	Route 726	38°25′18″ 78°53′18″	12	26	54,000	8,481	345
01621425	Route 679	38°24′07″ 78°54′04″	13	13	81,000	8,554	610
01621440	Route 988	38°23′23″ 78°54′49″	13	10	39,000	4,928	160
01621470	Route 704	38°22′43″ 78°55′42″	13	20	65,000	8,542	700

[1]See figure 1 for location of stations.

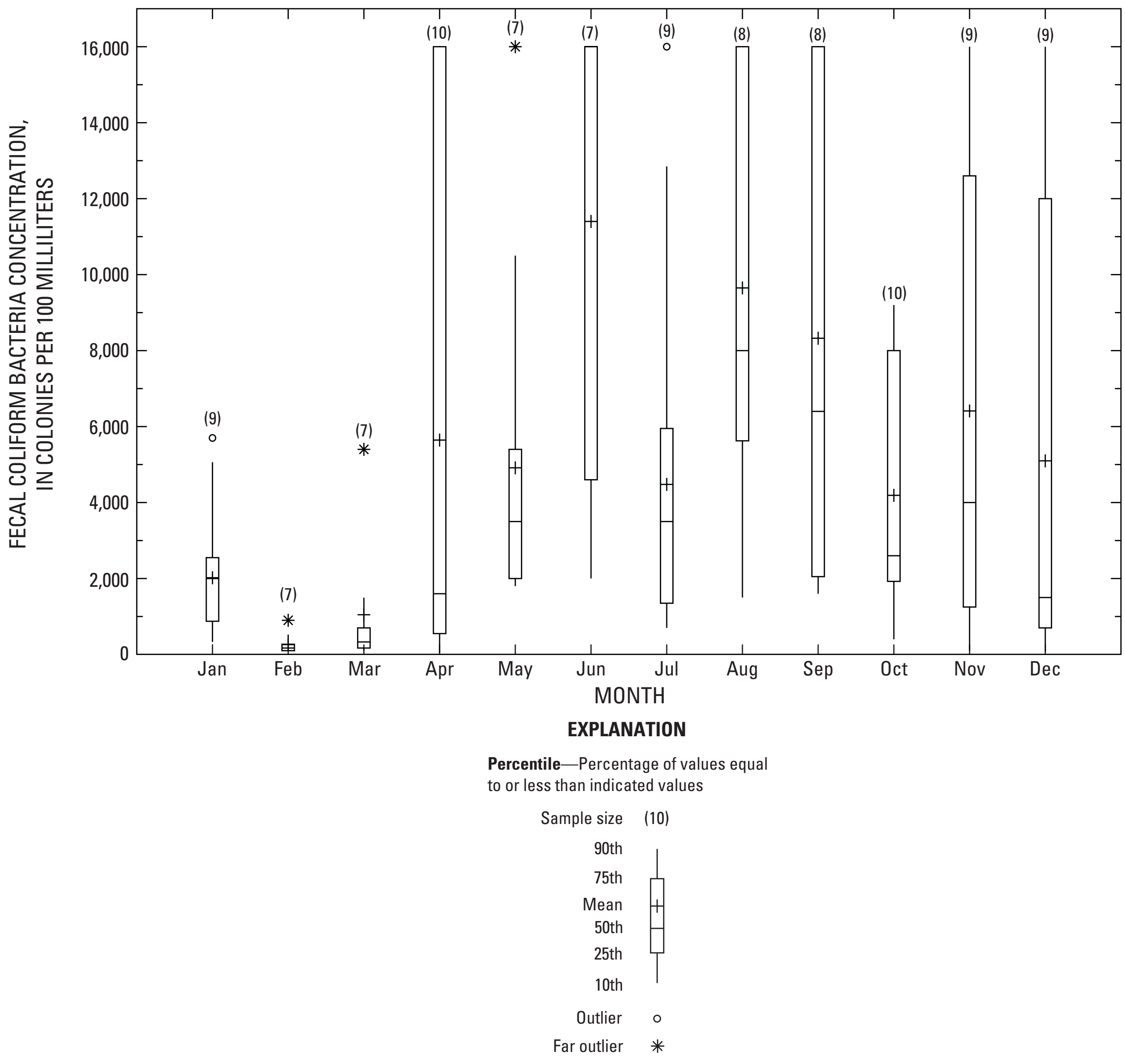


Figure 6. Monthly distribution of observed fecal coliform bacteria concentrations for Blacks Run at Route 704, Rockingham County, Virginia, 1991-2001. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

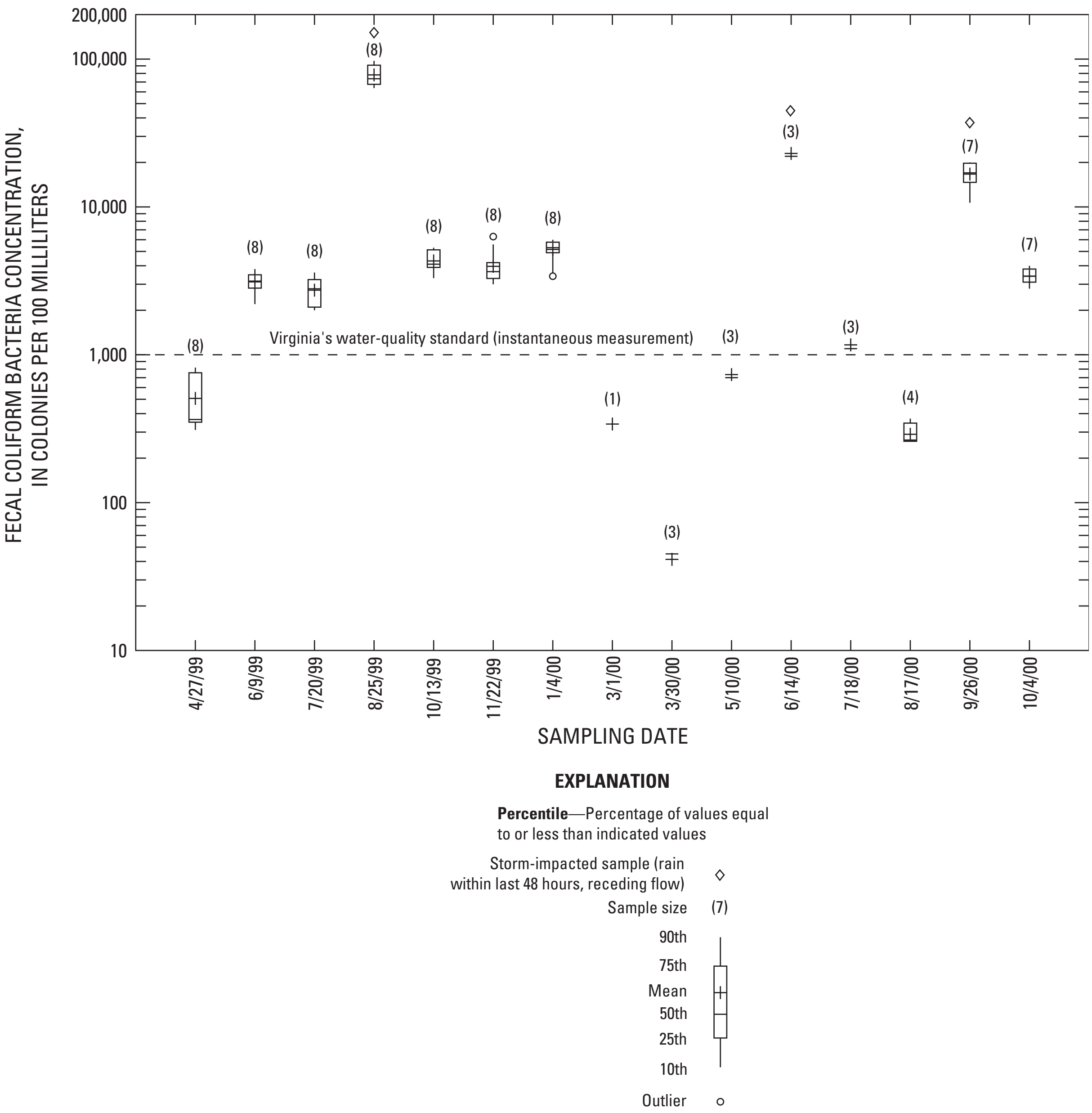


Figure 7. Observed fecal coliform bacteria concentrations from stream-water samples for Blacks Run at Route 704 during low-flow periods, Rockingham County, Virginia.

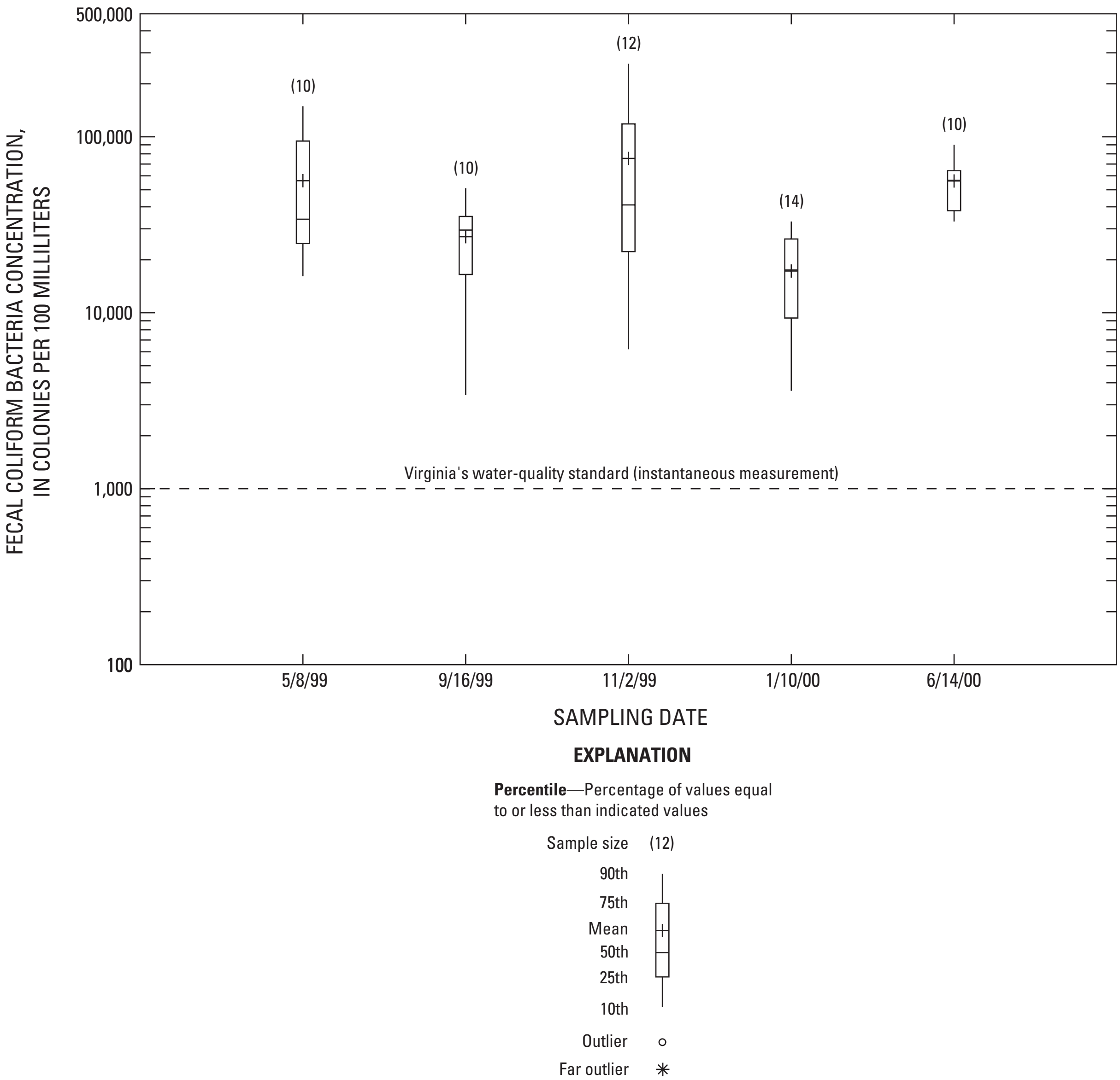


Figure 8. Observed fecal coliform concentrations from stream-water samples for Blacks Run at Route 704 during storm-flow periods, Rockingham County, Virginia.

watershed. These samples were collected as a single, depth-integrated sample from the approximate center of the stream channel. Additionally, data from these continuum sites provided information on the spatial variability observed in concentrations of fecal coliform bacteria. These data are consistent with patterns observed in the fecal coliform bacteria collected by DEQ at Route 704.

Bacterial Source Tracking

BST is a rapidly growing technology with various analytical techniques; the technique used depends on the study goals. In general, these techniques are based on molecular, genetics-based approaches (also known as “genetic fingerprinting”) or phenotypic (relating to the physical characteristics of an organism) distinctions among the bacteria of different sources. There are three primary genetic techniques for bacterial source tracking. Ribotyping characterizes a small, specific portion of the bacteria’s DNA sequence (Samadpour and Chechowitz, 1995). Pulsed-field gel electrophoresis (PFGE) is similar to ribotyping but typically is performed on the entire genome of the bacteria (Simmons and others, 1995). Polymerase chain reaction (PCR) amplifies selected DNA sequences in the bacteria’s genome (Makino and others, 1999). Phenotypic techniques generally involve an antibiotic resistance analysis, in which resistance patterns for a suite of different concentrations and types of antibiotics are developed (Wiggins, 1996; Hagedorn, and others, 1999).

Although all the techniques described above are promising for identifying bacteria sources, the ribotyping technique was used to identify the sources of fecal coliform bacteria impairing Blacks Run (Hyer and Moyer, 2003). Ribotyping involves an analysis of the specific DNA sequence that codes for the production of ribosomal RNA (ribonucleic acid). Ribotyping has been demonstrated to be an effective technique for distinguishing bacteria from the feces of multiple animal species (Carson and others, 2001). This technique has been performed successfully and used to identify bacteria sources in both freshwater (Samadpour and Chechowitz, 1995) and estuarine systems (Ongerth and Samadpour, 1994). Furthermore, the technique has been used to identify the species-specific sources of bacteria contributing to impairments in both urban (Herrera Environmental Consultants, Inc., 1993) and wilderness systems (Farag and others, 2001). The broad applicability of ribotyping makes it well suited for use in this study.

The Microbial Source Tracking Laboratory at the University of Washington (UWMSTL) performed the bacterial source tracking for all samples in this study. Refer to Hyer and Moyer (2003) for specific details regarding the ribotyping technique used in Blacks Run.

The results from the BST study indicate that a diverse collection of organisms contributes to the impairment of Blacks Run (Hyer and Moyer, 2003). Hyer and Moyer (2003) identified 21 different sources of fecal coliform bacteria; the top 10 contributors identified by ribotyping are cattle, poultry, human, dog, and cat, with raccoon, horse, deer, goose, and possum considered minor sources, making up less than 5 percent of the total contributors (fig. 9).

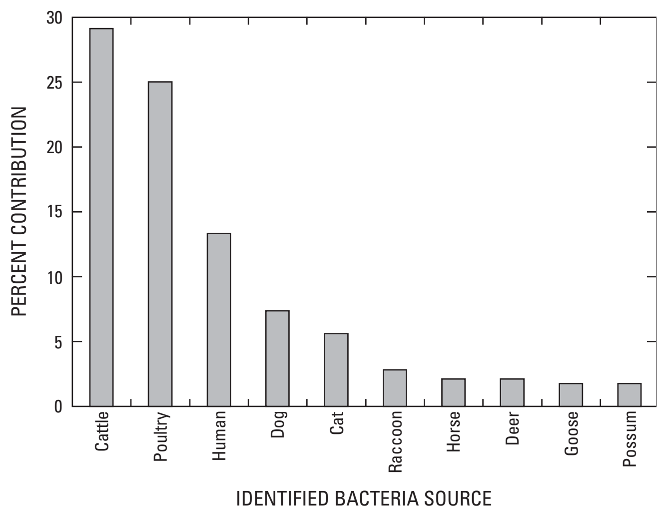


Figure 9. Distribution of the top ten contributors of fecal coliform bacteria identified by bacterial source tracking in the Blacks Run watershed, Rockingham County, Virginia.

The poultry category (fig. 9) was adjusted to improve the data interpretation. The poultry category represents a combination of chicken, turkey, and other poultry sources. The ribotyping technique sometimes can be used to distinguish chickens from turkeys (and, in these cases, the two are identified separately), whereas, in other cases, an unknown isolate can be identified only as either a chicken or a turkey isolate (in this case, the isolate is labeled as poultry). Additionally, a general avian category was identified by the ribotyping analysis. The avian category represents strains of fecal coliform bacteria that can occur in multiple bird species. Whereas the poultry category was specific to chickens and turkeys, the avian category is more extensive, encompassing all birds, including chickens and turkeys. For data interpretation and watershed modeling purposes, this avian category was distributed among all the observed bird species. Quantitatively, the avian category was assumed to be distributed proportionally, according to the occurrence of each individual bird species. For example, the poultry contribution to Blacks Run is 83 percent of all the bird species that are identified uniquely; therefore, 83 percent of the avian category was attributed to poultry. A detailed description of the manipulation of the avian category is in Hyer and Moyer (2003).

Calibration Process

The calibrated fecal coliform model can be used to simulate the range of observed fecal coliform concentration data as well as observed BST data from the Blacks Run watershed. The simulations cover a 23-month period from February 20, 1999, to January 23, 2001.

A suite of water-quality transport and storage parameters governs the simulation of fecal coliform bacteria in HSPF. As with the streamflow simulation, these parameters are categorized as fixed and adjusted. Fixed parameters can be measured or are well documented in the literature, and can be used with a high degree of confidence. The fecal coliform model parameters that were fixed (held constant) during the calibration process were the bacteria die-off rates associated with bacteria on the land surface (REMQOP) and instream (KGEN). Adjusted parameters exhibit a high degree of variability and uncertainty in the environment. Four parameters representing fecal coliform bacteria transport and storage components were adjusted to obtain a calibrated fecal coliform model for the Blacks Run watershed: fecal coliform accumulation rate (ACCUM); susceptibility of bacteria to surface runoff (WSFAC); storage of fecal coliform bacteria in interflow (IQO); and storage of fecal coliform bacteria in active ground water (AQO). The fecal coliform model was calibrated to (1) low-flow fecal coliform concentrations, (2) stormflow fecal coliform concentrations, and (3) BST data.

The fecal coliform model first was calibrated to the data collected by DEQ and USGS during low-flow periods. The primary sources represented in the model that contribute fecal coliform bacteria during low-flow periods include direct deposition by instream cattle and active ground-water discharge (AQO). The low-flow periods represented in the model were calibrated by adjusting the inputs from instream cattle and active ground-water discharge.

Next, the fecal coliform model was calibrated to data collected by the USGS during stormflow and recession-flow periods. This step, which focused on the range of fecal coliform bacteria concentrations during peak stormflow and stormflow recession, was achieved by adjusting ACCUM and WSFAC. WSFAC was adjusted by revising the rate of surface runoff required to remove 90 percent of the surface-stored bacteria (WSQOP). The initial values of WSQOP ranged from 0.3 to 0.7 in/hr (table 19). Lower values of WSQOP result in more bacteria being washed off the land surface per unit rate of surface runoff than do higher values. Thus, decreasing WSQOP will generate increased fecal coliform concentrations during individual storm events. However, when changes to WSQOP did not produce sufficient adjustments to resulting peak fecal coliform concentrations, then ACCUM was adjusted. The post-storm fecal coliform recession rate was calibrated by adjusting the fecal coliform concentration in interflow storage (IQO). Increasing the amount of bacteria in IQO decreases the fecal coliform bacteria recession rate. The initial value of IQO was set to 1,500 col/100 mL.

Table 19. Initial values of WSQOP used for the various land-use types represented in the fecal coliform model for Blacks Run, Rockingham County, Virginia

[WSQOP, Rate of surface runoff required to remove 90 percent of the surface-stored fecal coliform bacteria]

Land-use type	WSQOP (inch per hour)
Urban	0.5
Residential	.5
Cropland	.6
Hayland	.6
Pasture	.6
Forest	.7
Urban impervious	.3
Residential impervious	.3

Finally, the model was calibrated to BST data collected by Hyer and Moyer (2003). These data provide information on the sources of fecal coliform bacteria to Blacks Run and are treated as being representative of the percent contribution by each source to the total instream fecal coliform load. Not all bacteria sources identified by means of BST were included explicitly in the model because the fecal coliform model was developed before the results of the BST study (Hyer and Moyer, 2003) were available. The minor sources identified by Hyer and Moyer (2003) not included in the model contributed a total of 7.6 percent of the *E. coli* isolates identified. However, 92.4 percent of the *E. coli* isolates identified by means of BST (including cattle, poultry, humans, dogs, cats, raccoons, horses, deer, sheep, ducks, geese, and muskrats) were represented in the model. Source-specific instream fecal coliform loads are determined by simulating each source independently. Each source-specific instream fecal coliform load is a product of bacteria transported through surface runoff, interflow, base flow, and various point sources. The sum of the source-specific fecal coliform contributions is equal to the total fecal coliform contribution used to calibrate the model to observed concentration data. The fecal coliform accumulation rate (ACCUM) is adjusted for each source represented in the model in order to calibrate the simulated source-specific instream load to observed BST data. This calibration step helps to reduce the inherent error in the calculated ACCUM value for each source. As a result, the dominant contributing sources in the watershed identified by means of BST are represented in the model.

The calibration of the fecal coliform model was evaluated through graphical comparisons and comparisons of the observed historical geometric mean concentrations to the simulated geometric mean concentrations. Plots were compared of (1) simulated daily minimum and maximum fecal coliform concentrations and observed fecal coliform concentrations, and (2) simulated and observed percent contributions to instream fecal coliform load. The geometric mean is a measure of central tendency that is unbiased by extreme high and low values and is defined as

$$GM = [(a_1)\ldots(a_n)]^{1/n} \tag{9}$$

where *GM* is the geometric mean,

$[(a_1)\ldots(a_n)]^{1/n}$ is n^{th} root of the product of the n quantities, $a_1, \ldots, a_n$.

The geometric mean of the simulated daily fecal coliform concentrations was compared to the geometric mean of the monthly samples collected by DEQ. The comparison of the simulated and observed geometric mean concentrations was done after model calibration and was not a part of the iterative calibration process.

Data Limitations

Model calibration was hindered by limitations associated with the historical fecal coliform bacteria data from DEQ. These limitations include (1) censoring of the data by upper and lower detection limits, and (2) lack of data during peak stormflow periods. DEQ collects these data to determine if a particular stream is in compliance with the State water-quality standard, not to determine the actual fecal coliform bacteria concentration. Quantitative data, however, are preferred for use during model calibration. In addition, DEQ collects these data primarily under low-flow and recession-flow conditions. The lack of data during stormflow periods limits model calibration of simulated stormflow responses. Therefore, data collected by the USGS for this study were incorporated into the model calibration process to provide information on the response of fecal coliform bacteria concentrations during stormflow periods.

The model-construction and -calibration process also was limited by the uncertainty associated with the fecal coliform accumulation rate (ACCUM) for each source. This uncertainty is linked to the four parameters used to calculate ACCUM: feces produced per day (Fprod), number of fecal coliform bacteria per gram of feces produced (FCden), population size (POPN), and habitat area (HAB). Most of this uncertainty is associated with FCden and POPN. The range of observed FCden values in previous studies (Hussong and others, 1979; Smith, 1961; Wheater and others, 1979) commonly extends over 2–5 orders of magnitude. For example, Mara and Oragui (1981) found FCden for dogs, cats, and humans ranges from 4.1×10^6 col/g to 4.3×10^9 col/g; 8.9×10^4 col/g to 2.6×10^9 col/g; and 1.3×10^5 col/g to 9.0×10^9 col/g, respectively (Mara and Oragui, 1981). Values of POPN commonly are unknown for the human, pet, and wildlife populations, and the proportion of the population that contributes to the instream fecal coliform load also is unknown. This uncertainty for each animal type is of major concern because ACCUM is the primary input parameter for the simulation of fecal coliform bacteria; ACCUM values are analogous to precipitation data in the streamflow model. As a result of the uncertainty associated with ACCUM, BST data collected by the USGS (Hyer and Moyer, 2003) were incorporated into the model-calibration process. By using BST data, the simulated contributions to instream fecal coliform bacteria load from each represented source were matched to the observed contributions.

REQUIREMENTS FOR THE FECAL COLIFORM TMDL

After the fecal coliform model was calibrated, the TMDL for Blacks Run was determined. The TMDL is defined as the sum of all waste-load allocations (WLAs) from point sources and load allocations (LAs) from nonpoint sources and natural background (equation 1). The TMDL includes a margin of safety (MOS) that explicitly accounts for uncertainties incorporated into the TMDL development process. In addition, the TMDL is set at a level that ensures that the fecal coliform loads from the point sources and nonpoint sources can be assimilated without exceeding the State water-quality standard.

Designation of Endpoint

Prior to identifying the TMDL for Blacks Run, a numeric endpoint was established by DEQ; this value is used to evaluate the attainment of acceptable water quality and represents the water-quality goal that will be targeted through load reduction strategies designated in the TMDL plan. The numeric endpoint for the Blacks Run TMDL was determined by DEQ and DCR on the basis of the State water-quality standards, which specify a maximum fecal coliform concentration of 1,000 col/100 mL at any time, or a geometric mean criterion of 200 col/100 mL for two or more samples over a 30-day period. The geometric mean criterion was used as the TMDL endpoint because continuous simulation modeling generates more data points than the minimum number of samples required for the calculation of the geometric mean.

Margin of Safety

An explicit 5-percent MOS, as required by DEQ and DCR, was incorporated into the TMDL for Blacks Run. Thus, the numeric endpoint was decreased from a 30-day geometric mean of 200 col/100 mL to 190 col/100 mL.

Scenario Development

The objective of load-reduction scenario development was to generate a series of scenarios that, if implemented, would generate water-quality conditions that meet the State standard, including the designated MOS, thus establishing the TMDL for Blacks Run. Each load-reduction scenario was simulated over the time period used for model calibration (1999–2000). During scenario development, the fecal coliform load from a given source(s) was reduced iteratively until the target water-quality conditions were met. These load reduction scenarios then were provided to the State and local watershed managers, who then selected a scenario and designated it as the TMDL for Blacks Run.

Reductions from Point and Nonpoint Sources

Fecal coliform load reductions from permitted point sources are not required by DEQ as part of the TMDL development for Blacks Run because the dischargers operate at or below the geometric mean water-quality standard of 200 col/100 mL. These permitted dischargers are represented in the TMDL at their current permit limits.

Fecal coliform loads were reduced from nonpoint sources, including direct instream deposition and land-surface runoff, which affect water quality during low-flow and stormflow periods. Direct instream deposition was reduced through reductions from instream cattle. The fecal coliform load associated with surface runoff was reduced through source-specific reductions from the 12 sources represented in the model. As represented in the HSPF model, any source-specific fecal coliform load reduction on the land surface has a comparable reduction in both interflow and base flow. For example, a 75-percent reduction of dog-derived fecal coliform bacteria on the land surface will result in a 75-percent reduction of these bacteria in both interflow and base flow.

RESULTS FROM THE STREAMFLOW AND FECAL COLIFORM MODELS

Streamflow Model Calibration Results

The calibrated streamflow model was assessed initially by comparing simulated and observed streamflow against predefined criteria (table 20). Observed and simulated total annual runoff for the time period February 20, 1999, to January 23, 2001, was 10.98 and 10.97 in., respectively. The percent difference of -0.09 percent is within the designated 10-percent criterion and indicates that the simulated water budget closely approximates the observed water budget. The total range of observed and simulated flows during the calibration period was evaluated by comparing the total of the highest 10-percent flows and the lowest 50-percent flows. The highest 10-percent flows category is representative of major storm events, whereas the lowest 50-percent is representative of base-flow conditions. The percent difference between the total of the highest 10-percent and lowest 50-percent simulated and observed flows was within the designated criteria of 10- and 15-percent difference. Additionally, the seasonality inherent in the observed and simulated seasonal flows was compared. Simulated total winter (January, February, and March) and fall (October, November, and December) runoff nearly were identical to the respective observed seasonal runoff with a percent difference of –1.44 and 0.00 percent. Simulated and observed spring and summer runoff differed by 0.59 in. (20.70 percent) and –0.58 in. (–14.57 percent), respectively.

Similar to total amount of runoff simulated, the pathways by which the streamflow model routes incoming rainfall is important. Total simulated runoff was derived from surface runoff, interflow, and base flow (table 21). Base flow (ground-water inputs) contributed 49.04 percent to the total simulated annual runoff in Blacks Run. Rutledge and Mesko (1996) calculated a base-flow index of 45.7 percent for an adjacent watershed from streamflow data at North Fork Shenandoah River at Cootes Store, Va. (station number 01632000), for the period 1981–90. Base-flow contribution to streamflow in Blacks Run varies seasonally from 61.35 percent during the fall to 37.35 percent during the summer and contributions from surface runoff during fall and summer range from 19.81 to 47.65 percent, respectively (table 21).

Various graphical comparisons provided information on the quality of the calibrated streamflow model. The hydrographs for the calibration period (February 1999 to January 2001) show the simulated and observed streamflow response to individual precipitation events (fig. 10). These hydrographs show generally good agreement between simulated and observed daily mean streamflow values. A strong correlation was observed between simulated and observed streamflow where 79 percent of the variability in observed streamflow is explained by the simulated streamflow (fig. 11). Residual plots display the measured difference between simulated and observed streamflow; no difference will generate a residual equal to zero. Residuals between simulated and observed streamflow in Blacks Run from February 1999 to January 2001 are distributed uniformly around zero, indicating no bias in the model simulation (fig. 12). Flow-duration curves show the percentage of time a particular streamflow is equaled or exceeded and represent the combined effects of watershed characteristics such as climate, topography, and hydrogeologic conditions on the distribution of flow magnitude through time (Searcy, 1959). Flow-duration curves for simulated and observed daily flows in Blacks Run are similar over the majority of flow conditions (fig. 13).

Graphical comparisons also were used to further evaluate the observed and simulated seasonal hydrologic response in Blacks Run. The distribution of simulated and observed daily flows during the winter, spring, summer, and fall months shows that simulated and observed flows for each season have similar means, medians, and variability (fig. 14). In addition, simulated flow-duration curves for winter, spring, summer, and fall closely approximate the seasonal observed flow-duration curves (fig. 15).

The streamflow model calibration also was evaluated using hourly simulated and observed streamflow data. This shortened time step allows for detailed evaluation of stormflow characteristics such as timing, peak flows, volume, and flow recession. For a storm event during August 13–14, 1999, the simulated and observed stormflow characteristics are similar except for stormflow timing (fig. 16A). The simulated stormflow response occurs approximately 3 hours before the observed response. This time lag is present because the Mossy Creek rain gage is approximately 4.8 miles to the south and west of the Blacks Run watershed. Storm movement in the Shenandoah Valley generally is from the southwest to the northeast; therefore, rain falls at

Table 20. Observed and simulated runoff values for Route 704, Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001

Runoff category	Observed (inches)	Simulated (inches)	Difference (percent)	Criterion (percent)[1]
Total annual runoff	10.98	10.97	-0.09	10
Highest 10-percent flow[2]	4.79	4.82	.63	10
Lowest 50-percent flow[3]	2.11	2.13	.95	15
Winter runoff	2.09	2.06	-1.44	15
Spring runoff	2.85	3.44	20.70	15
Summer runoff	3.98	3.40	-14.57	15
Fall runoff	2.07	2.07	.00	15

[1]Value calculated as simulated minus observed divided by observed times 100.
[2]The sum of all streamflow values with a 10-percent chance or less of being equaled or exceeded, and converted to runoff values (indicative of stormflow conditions).
[3]The sum of all streamflow values with a 50-percent chance or greater of being equaled or exceeded, and converted to runoff values (indicative of base-flow conditions).

Table 21. Simulated total annual and seasonal runoff, surface runoff, interflow and base flow for calibration period, Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001

Water year	Total runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
2/20/99–1/23/01	10.97	3.78	0.85	5.38	49.04
Water years 1993-97	**Total runoff (inches)**	**Surface runoff (inches)**	**Interflow (inches)**	**Base flow (inches)**	**Base-flow index (percent)**
Winter	2.06	.47	.16	1.24	60.19
Spring	3.44	1.28	.31	1.61	46.80
Summer	3.40	1.62	.25	1.27	37.35
Fall	2.07	.41	.13	1.27	61.35
Total[1]	10.97	3.78	.85	5.38	49.04

[1]May not add to indicated value because of rounding.

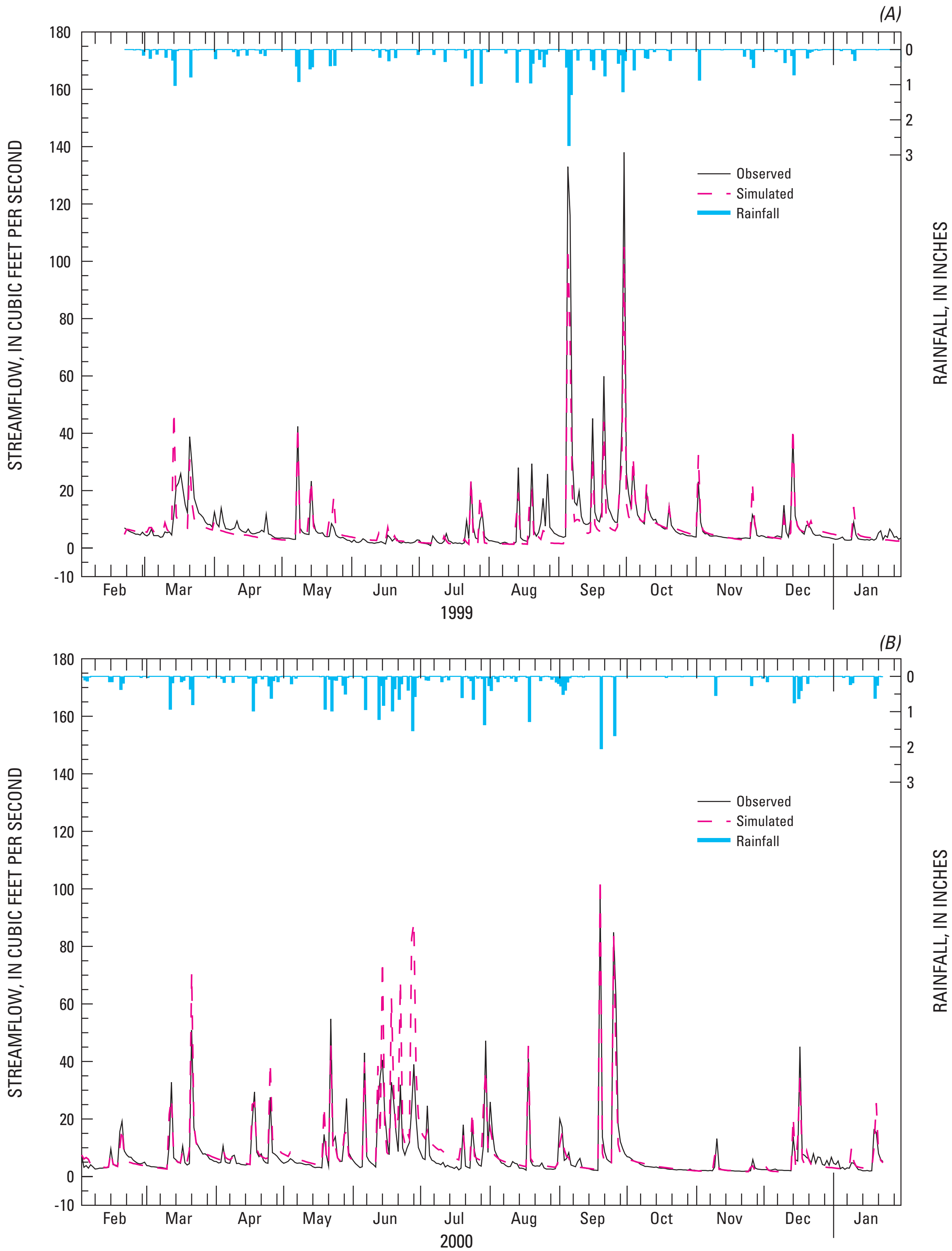


Figure 10. Daily rainfall and observed and simulated daily mean streamflows for February 20, 1999-January 23, 2000 *(A)*, February 1, 2000-January 31, 2001 *(B)*, Blacks Run, Rockingham County, Virginia.

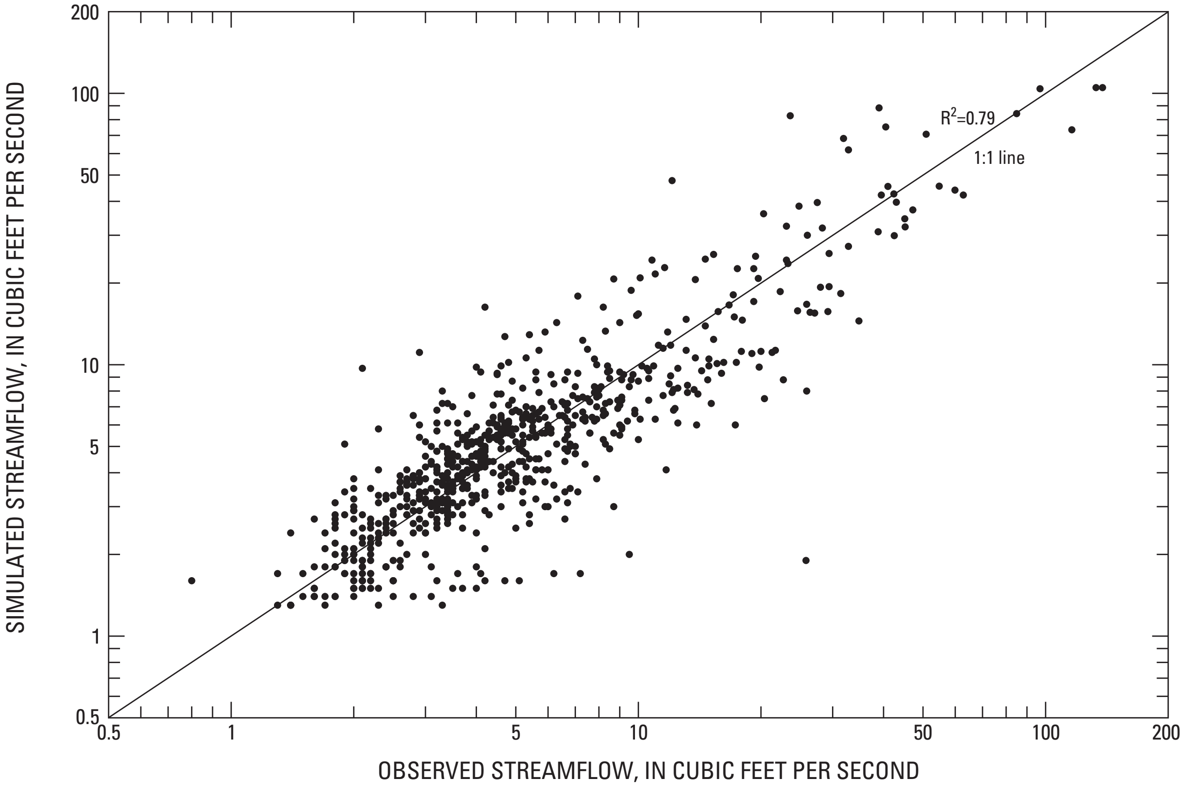


Figure 11. Simulated daily streamflow in relation to observed daily streamflow, Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001.

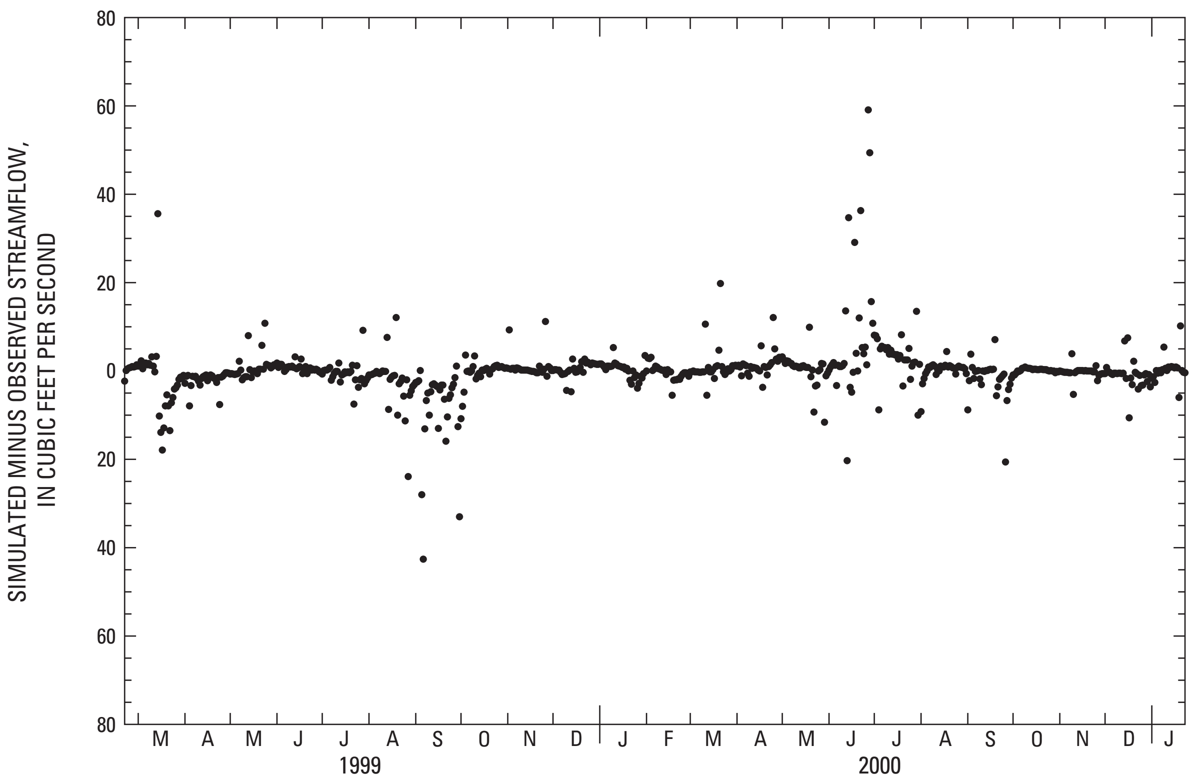


Figure 12. Residuals for simulated minus observed daily streamflow, Blacks Run, Rockingham County, Virginia, February 1999-January 2001.

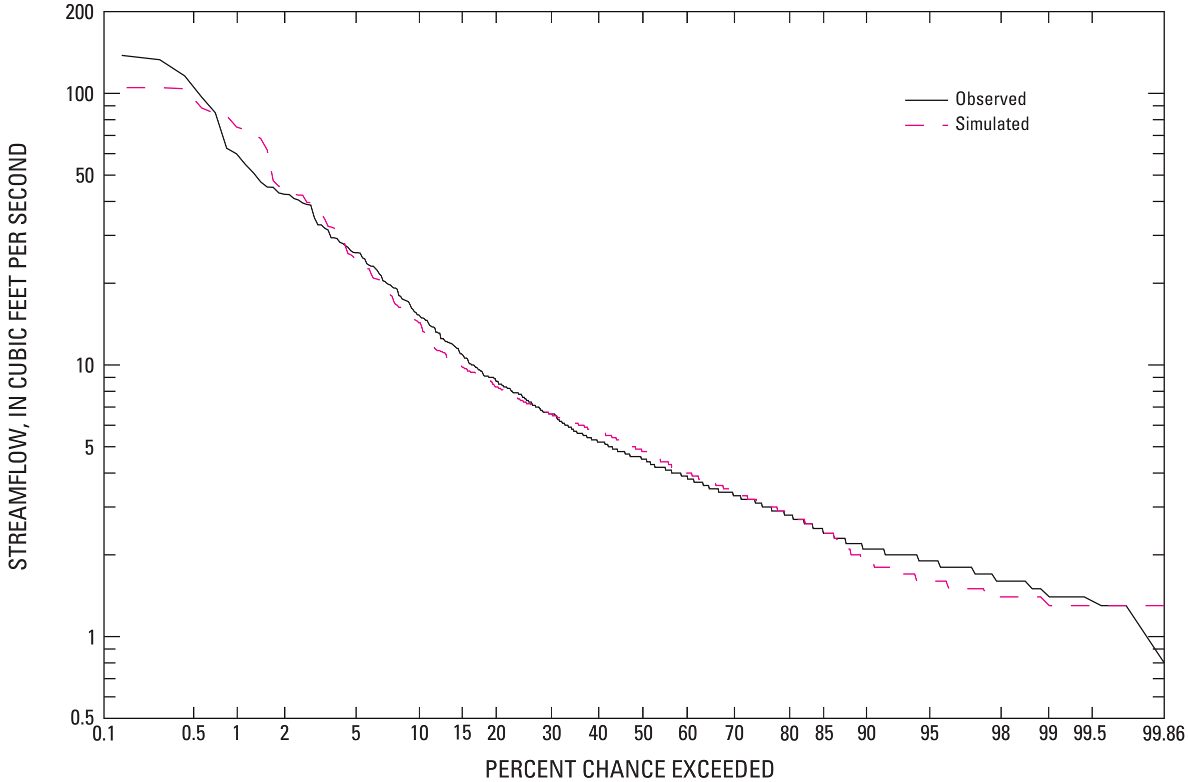


Figure 13. Flow-duration curves for observed and simulated daily mean streamflow, Blacks Run, Rockingham County, Virginia, February 20, 1999-January 31, 2001.

the Mossy Creek rain gage before falling over the Blacks Run watershed. For a large storm event on September 19, 2000 (fig. 16B), simulated and observed streamflow are similar with respect to storm volume, and recession, although an approximate 3-hour lag results. Rainfall data for this storm event were collected at the Blacks Run rain gage. The Blacks Run rain and streamflow gages are in the southernmost portion of the watershed. General storm patterns suggest that the rainfall likely was collected at the gage before falling over the majority of the watershed. As a result, there is an observed time lag between the rainfall collection and stormflow response times that the model is not simulating.

An example of a storm event for which the stormflow response was not well simulated resulted during June 27–28, 2000 (fig. 16C). On June 27, approximately 1.54 in. of rain fell, in association with a convective storm event, at the Blacks Run rain gage. Measured rainfall totals of 0.08, 0.71, 0.95, 1.35, and 1.62 in. were measured at nearby Cootes Store, Briery Branch, Lynwood, Swift Run, and Stoney Creek rain gages (operated by the National Oceanic and Atmospheric Administration), respectively. These rainfall totals from nearby gages illustrate the variability associated with convective storms. The discrepancies in the simulated and observed stormflow characteristics can be linked to the variability between the volume of rainfall measured at the Blacks Run rain gage and the volume of rainfall that fell over the rest of the watershed.

Input-Source Error

Three factors account for many of the differences between simulated and observed streamflow. The primary factor is the quality and representativeness of the input (rainfall) data. Other factors are the occurrence of snow in the watershed and model error that results because extreme events cannot be simulated in the model. Model error is increased by the limited (23 months) streamflow data set.

The most important input dataset to the streamflow model is rainfall. Because of the spatial and temporal

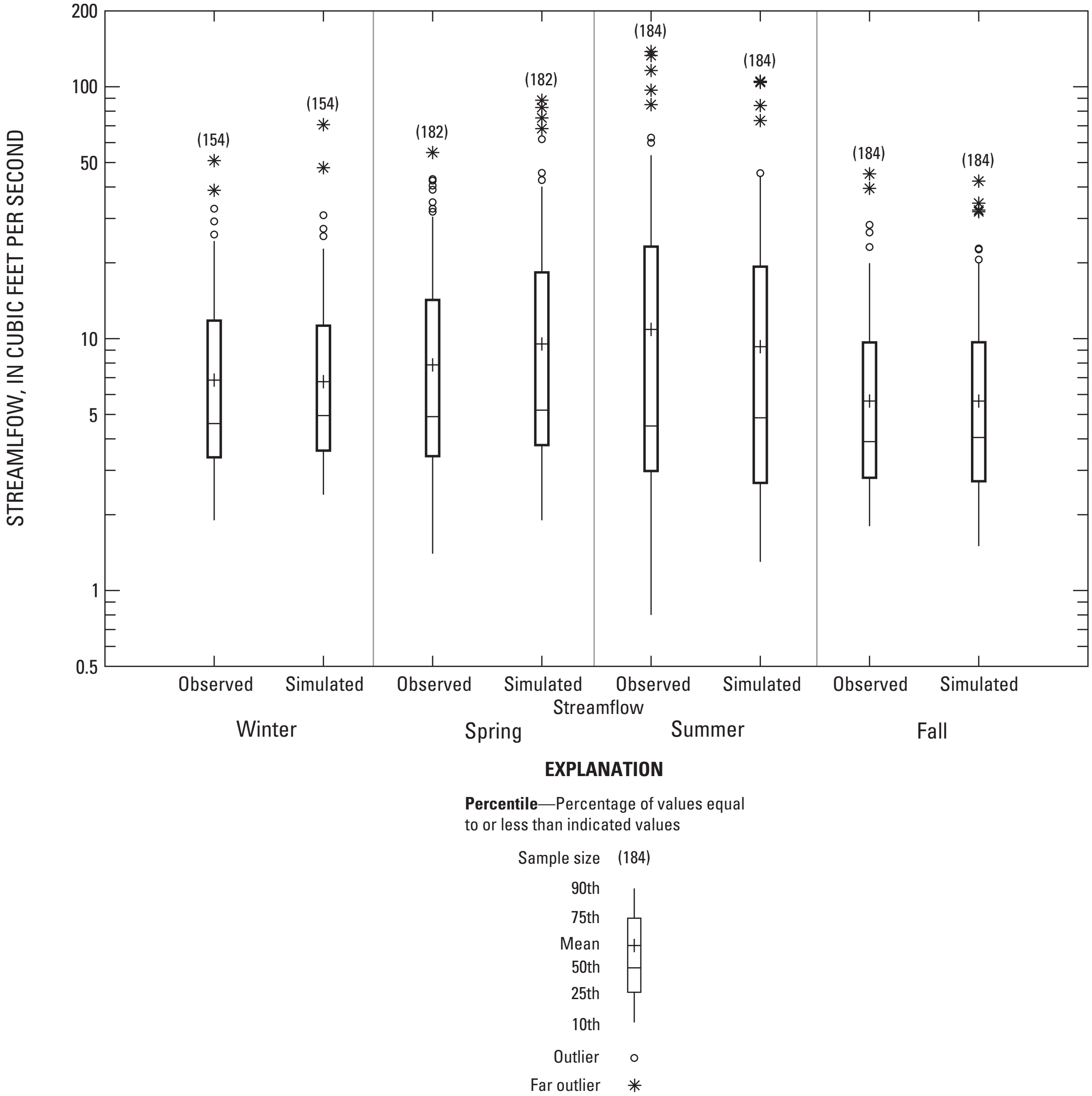


Figure 14. Observed and simulated daily streamflow (Winter, January-March; Spring, April-June; Summer, July-September; Fall, October-December), Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001.

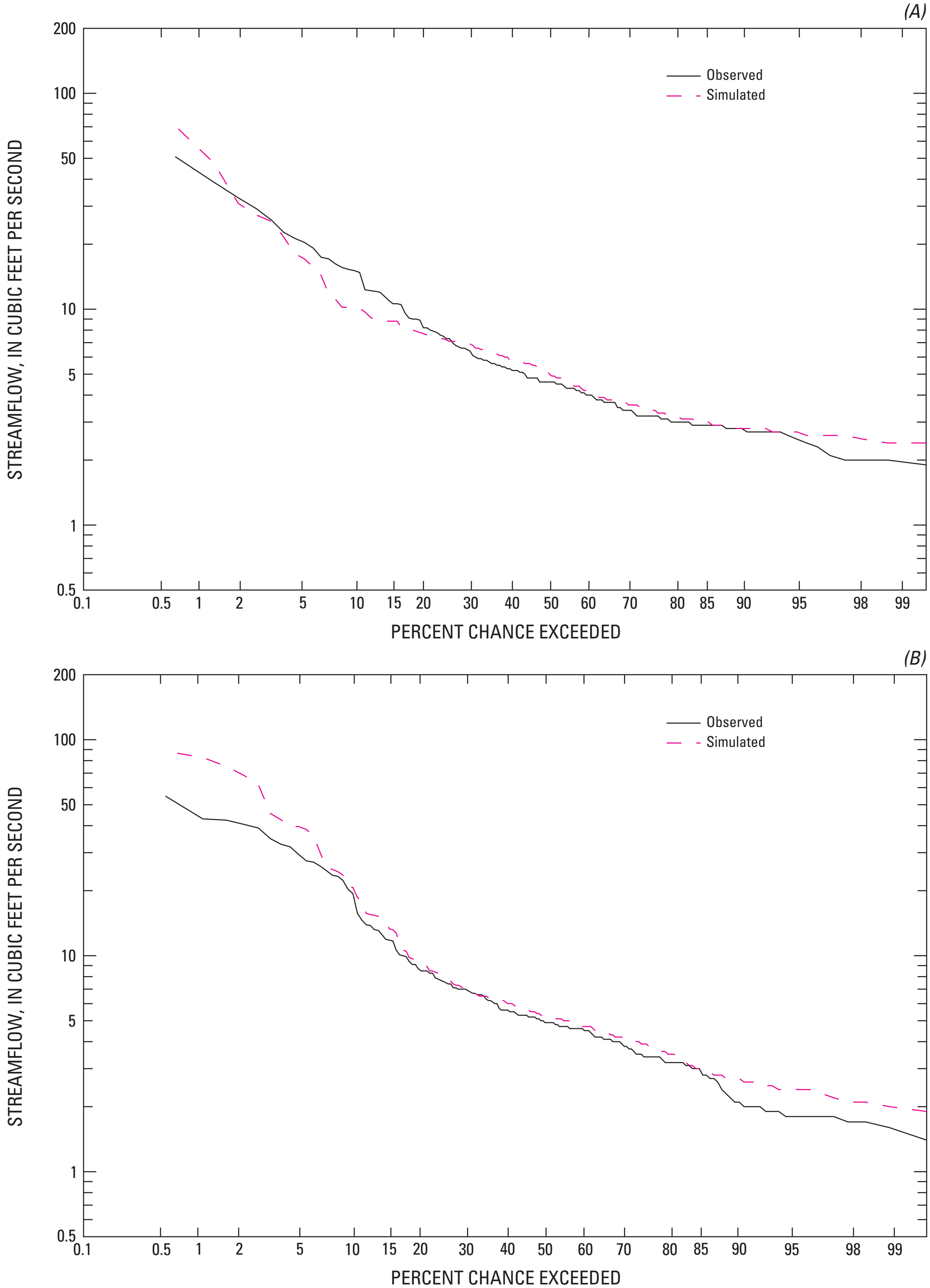
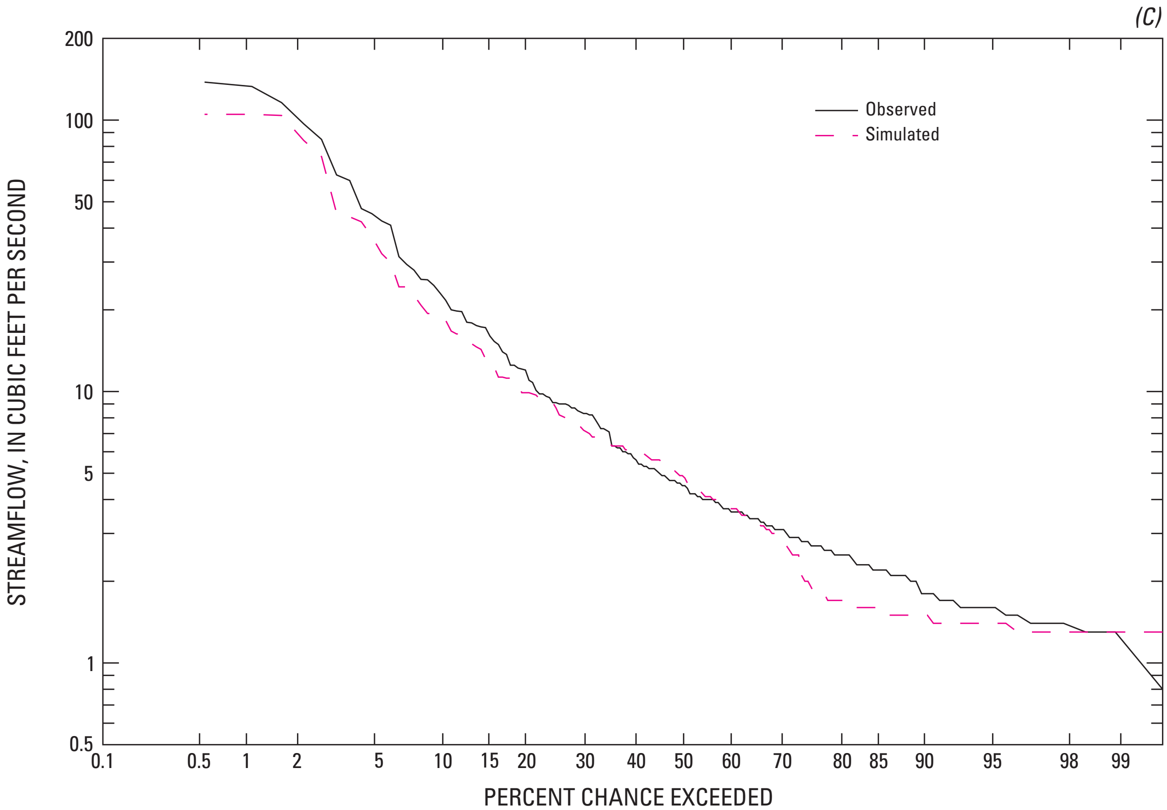


Figure 15. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001



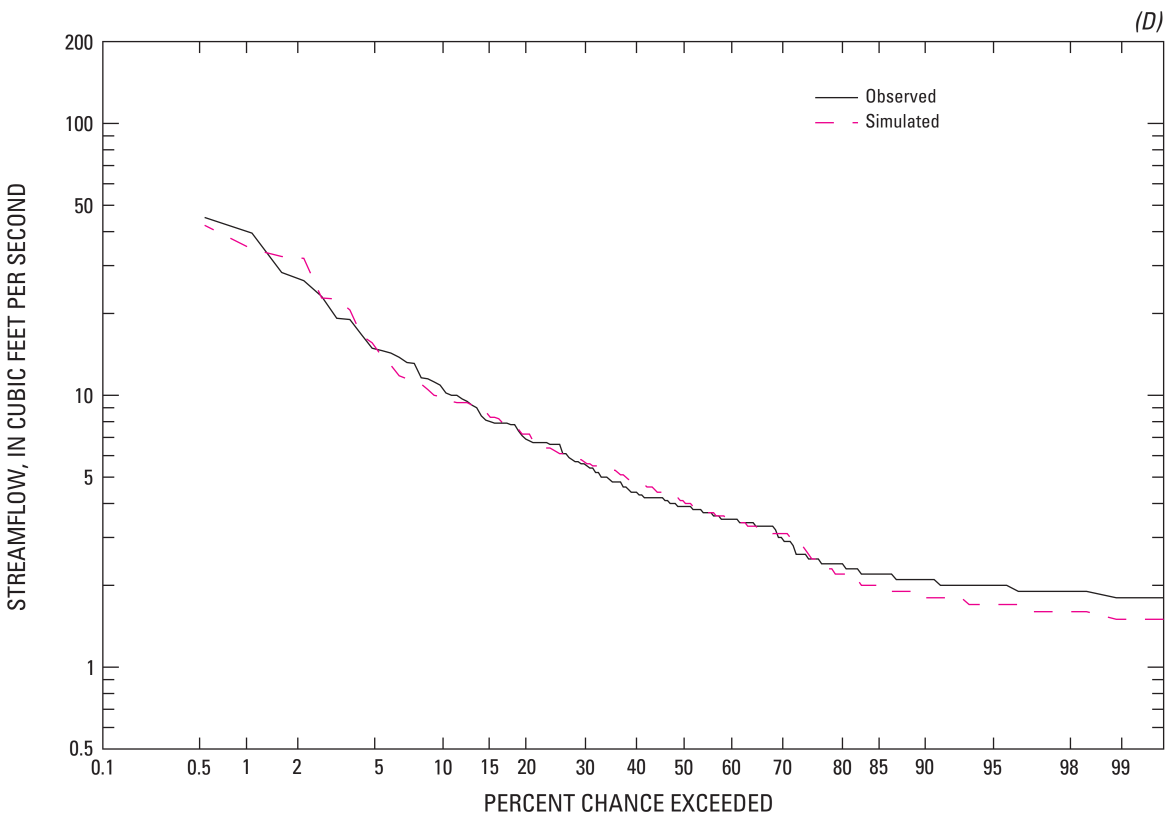
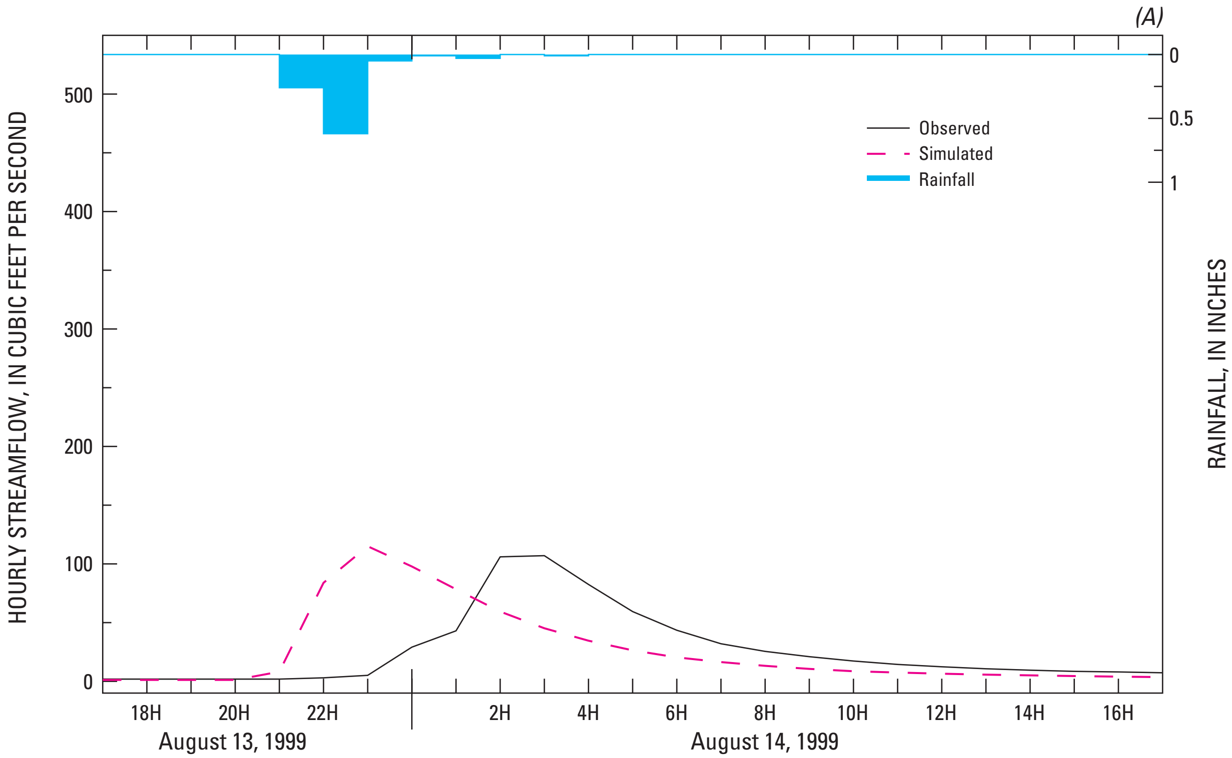


Figure 15. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001—Continued.



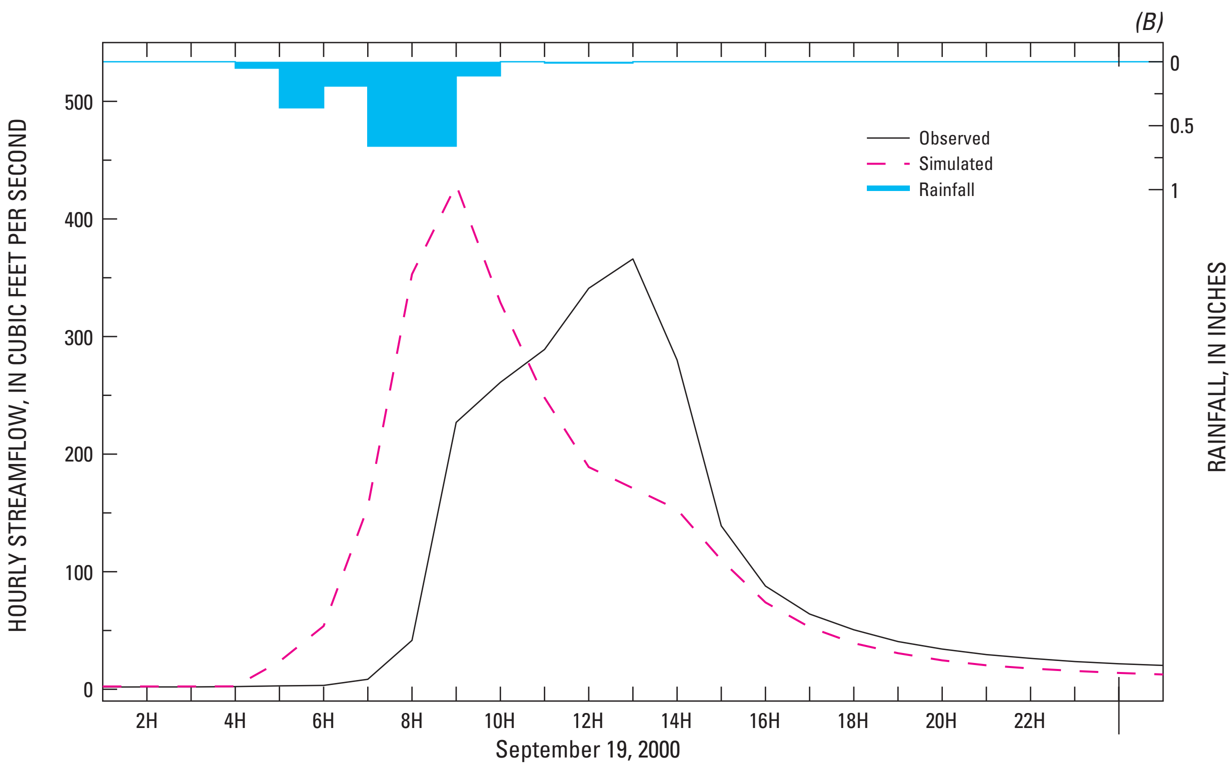


Figure 16. Hourly rainfall and observed and simulated daily mean streamflow, August 13-14, 1999 (*A*), September 19, 2000 *(B)*, and June 27-28, 2000 *(C)*, Blacks Run, Rockingham County, Virginia.

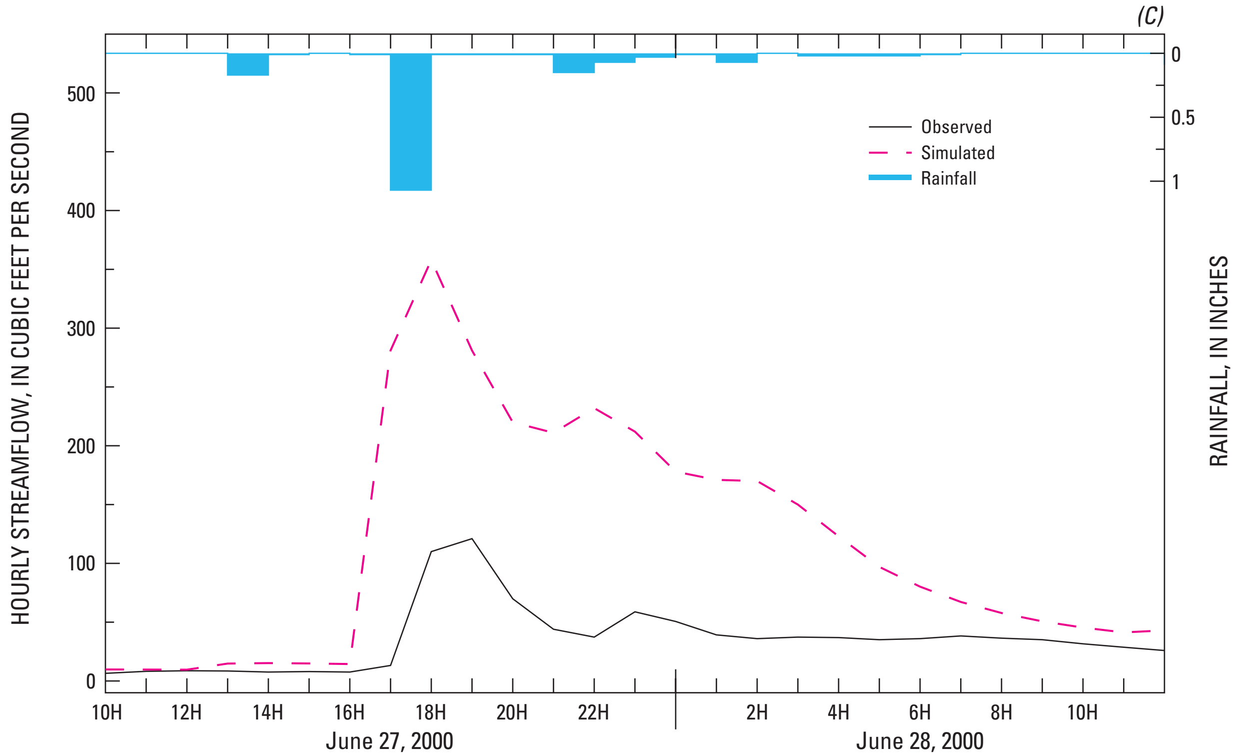


Figure 16. Hourly rainfall and observed and simulated daily mean streamflow, August 13-14, 1999 (*A*), September 19, 2000 *(B)*, and June 27-28, 2000 *(C)*, Blacks Run, Rockingham County, Virginia—Continued.

variability associated with rainfall, however, data collected at a rain gage may not always be representative of the rainfall in the surrounding areas/watershed. In some instances during the calibration period, in addition to the examples discussed previously, rainfall data were not representative of the actual rainfall distribution over the entire watershed. For example, 0.82, 0.98, and 0.65 in. of rain were recorded at the Blacks Run gage on June 14, 18, and 21, 2000, respectively. These three rainfall events were associated with convective thunderstorms similar to the thunderstorm discussed previously. The amounts of rainfall measured at the Blacks Run gage were within the wide range of rainfall data collected at nearby gages. However, the observed streamflow data during this period indicate that rainfall values actually were less than those measured within the ungaged areas of the Blacks Run watershed (fig. 10B).

Snowfall on the watershed also caused differences between simulated and observed streamflow. Snow accumulation and melt were not included in the streamflow model for Blacks Run because winter is not a critical water-quality season with respect to fecal coliform bacteria exceedances, and snowmelt is not a dominant feature of annual runoff in the watershed. Typically, during a snowfall event the volume of water in the snow is recorded at the rainfall gage. This recorded volume is treated as a volume of rain and used in the streamflow model. The resulting simulated streamflow response is an initial oversimulated peak followed by an extended period of undersimulated storms. The initial oversimulation is caused by the recorded volume of snow being treated like rainfall instead of the snow accumulating on the land surface. The extended period of undersimulated storms occurs because of the additional volume of water stored in the snow on the ground that is not accounted for by the model. Therefore, greater amounts of runoff per volume of incoming rain are observed than are simulated. These discrepancies resulted during the following time periods: March 10–20, 1999; January 20–31, 2000; and December 20–31, 2001 (fig. 10).

Final Streamflow Model Parameters

The results of the streamflow model calibration demonstrate its effectiveness for simulating streamflow response in Blacks Run. Final values for the 11 hydraulic parameters used to calibrate the streamflow model and the urban and residential effective impervious area are used in the fecal coliform model simulation (table 22).

Fecal Coliform Model Calibration Results

The fecal coliform model is the primary tool for quantifying loads, simulating transport mechanisms, and identifying load-reduction strategies for fecal coliform bacteria in the Blacks Run watershed. Direct comparisons are made between simulated and observed fecal coliform bacteria concentrations and percent contribution from each source to instream fecal coliform bacteria load; these comparisons evaluate the effectiveness of the calibrated fecal coliform model in simulating the fate and transport of fecal coliform bacteria in the watershed.

The fecal coliform model calibration results were evaluated initially by comparing graphs of simulated and observed fecal coliform concentrations. However, observed fecal coliform concentrations are representative only of instream conditions at the time of sample collection, whereas the fecal coliform model simulates 24 concentrations within a 1-day period. Therefore, simulated daily maximum and minimum concentrations were plotted against the observed data from Route 704 (fig. 17). Spikes in simulated fecal coliform concentrations are the result of rainfall events where bacteria are washed off the land surface. Increases in simulated fecal coliform concentrations when spikes do not occur are the result of point source (instream cattle) and diffuse ground-water inputs. The capacity of the model to simulate fecal coliform concentrations during low-flow, stormflow and post-stormflow conditions was evaluated (fig. 17). In general, these conditions were well represented in the model. Simulated maximum fecal coliform concentrations during storm events generally ranged from 10,000–500,000 col/100 mL. Observed maximum fecal coliform concentrations in water samples collected by the USGS at Route 704 during 1999-2000 storm events ranged from 33,000 to 260,000 col/100 mL (Hyer and Moyer, 2003). Hyer and Moyer (2003) observed maximum fecal coliform concentrations during storm events in other watersheds as high as 730,000 col/100 mL. The simulated recession of fecal coliform concentrations following a storm event ranged from 1 to 4 days (fig. 17). This range is consistent with the findings from Hyer and Moyer (2003) that elevated fecal coliform concentrations are maintained for 1 to 5 days following a storm event.

The calibrated fecal coliform model also was evaluated by comparing simulated with observed BST data

Table 22. Final parameters and percent imperviousness in four subwatersheds represented in the streamflow model for Blacks Run, Rockingham County, Virginia

[HRU, Hydrologic Response Unit; see table 1 for definition of parameters; U, Urban; R, Residential; P, Pasture; H, Hayland; C, Cropland; F, Forest; B, Barren; UI, Urban impervious; RI, Residential impervious; –, not applicable; vm, varies monthly]

HRU	Imperviousness (percent)	AGWETP	AGWRC (1 per day)	BASETP	DEEPFR	INFILT (inches per hour)	INTFW	IRC (1 per day)	KVARY (1 per inch)	LZETP	LZSN (inches)	UZSN (inches)
U	–	0.00	0.968	0.00	0.30	0.03	1.00	0.30	1.00	vm	8.00	1.00
R	–	.00	.968	.00	.30	.04	1.00	.30	1.00	vm	8.00	1.00
P	–	.00	.968	.00	.30	.04	1.00	.30	1.00	vm	8.00	1.00
C	–	.00	.968	.00	.30	.04	1.00	.30	1.00	vm	8.00	1.00
H	–	.00	.968	.00	.30	.05	1.00	.30	1.00	vm	8.00	1.00
F	–	.00	.968	.00	.30	.08	1.00	.30	1.00	vm	8.00	1.00
B	–	.00	.968	.00	.30	.05	1.00	.30	1.00	0.60	8.00	1.00
UI	10	–	–	–	–	–	–	–	–	–	–	–
RI	6	–	–	–	–	–	–	–	–	–	–	–

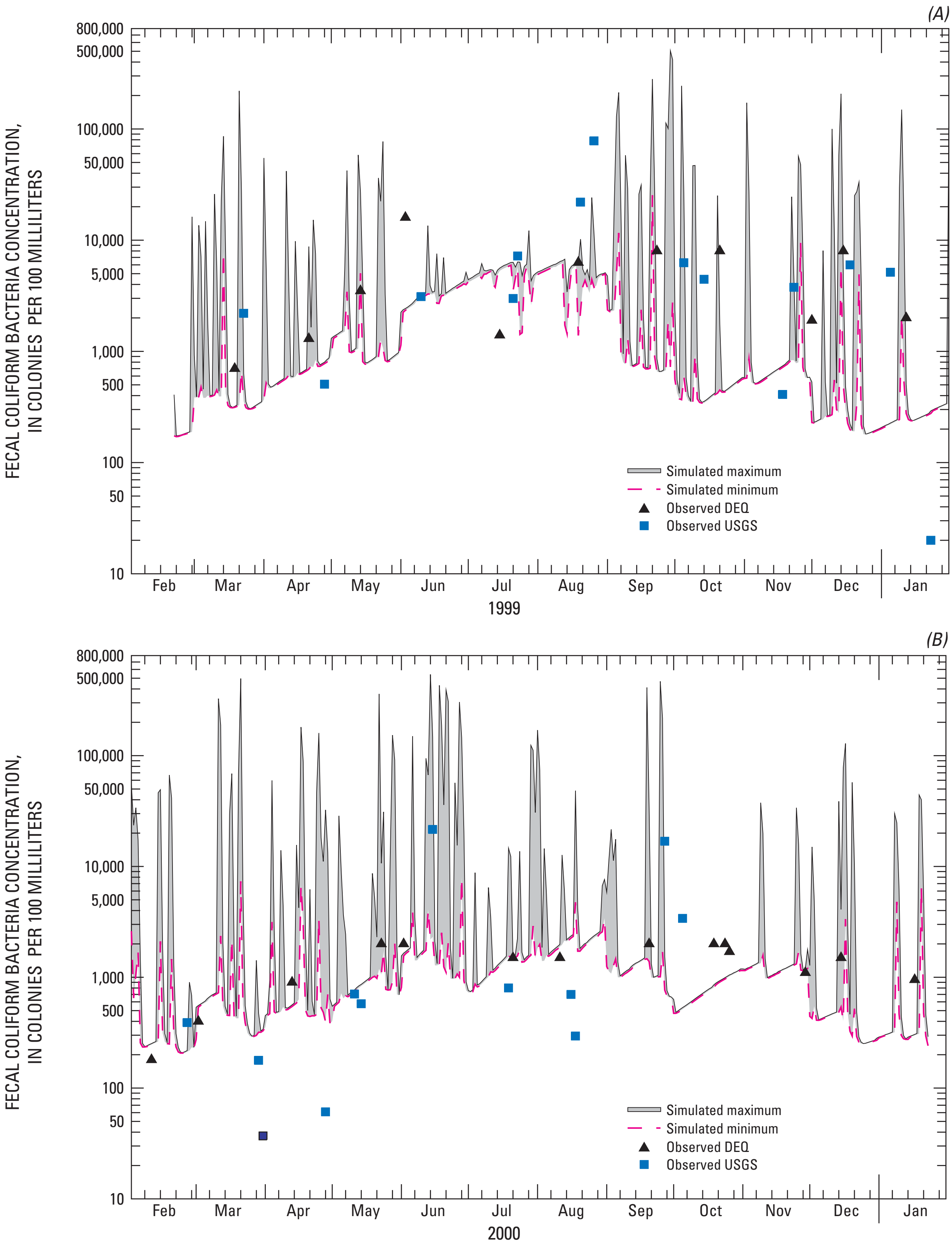


Figure 17. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 704, February 20, 1999-January 23, 2001 *(A)*, and February 1, 1999-January 31, 2001 *(B)*, Blacks Run, Rockingham County, Virginia. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality (DEQ), written commun., 1999.)

collected at Route 704. These data describe the percent contribution of fecal coliform bacteria from various sources to Blacks Run during an 18-month time period. The mean annual percent contribution to the total instream fecal coliform load from each represented source was simulated using the fecal coliform model. The initial comparison following model calibration between the simulated and observed BST data to observed concentration data revealed that simulated contributions from humans, dogs, and ducks were overestimated, whereas the simulated contributions from cattle, poultry, raccoons, horses, deer, and sheep were underestimated (fig. 18A). This initial comparison of simulated and observed BST data revealed that the input sources to the model were not represented accurately. Adjustments were made to the ACCUM values for each source until the simulated BST signature closely approximated the observed BST signature (fig. 18B).

The calibrated fecal coliform model also was evaluated by comparison of the 30-day geometric mean for the simulated fecal coliform bacteria with the geometric mean of observed concentrations (1994-2000). This comparison was a final check on the calibrated fecal coliform model but was not part of the iterative calibration process. The geometric means of the observed and simulated fecal coliform bacteria data at Route 704 are 2,322 and 2,008 col/100 mL, respectively.

The fecal coliform bacteria data used to calculate a geometric mean affect the resulting mean concentration. The simulated geometric mean concentration is calculated using daily mean concentrations of fecal coliform bacteria; thus, elevated concentrations generated during stormflow periods are represented, increasing the geometric mean. The observed geometric mean concentration is calculated using instantaneous monthly concentrations, so that not all of the elevated fecal coliform bacteria concentrations generated during stormflow periods are represented, and the resulting geometric mean is lower. Nonetheless, the comparison between simulated and observed geometric mean concentrations provides additional data on the accuracy of the fecal coliform model for simulating the fate and transport of fecal coliform bacteria in the Blacks Run watershed.

Final Fecal Coliform Model Parameters

WSQOP (rate of surface runoff that results in 90-percent washoff of fecal coliform bacteria in 1 hour) was the only non-source-specific fecal coliform model parameter adjusted during the calibration process. WSQOP was used to adjust the washoff response of the fecal coliform bacteria to rainfall events. Also, WSQOP was used during the calibration of simulated storm peaks. The final calibrated values of WSQOP for each land-use type represented in the model range from 0.2 to 0.6 in. per hour (table 23).

Table 23. Final values of WSQOP used for the land-use types represented in the fecal coliform model for Blacks Run, Rockingham County, Virginia

[WSQOP, Rate of surface runoff required to remove 90 percent of the surface-stored fecal coliform bacteria]

Land segment	WSQOP (inch per hour)
Urban	0.3
Residential	.3
Cropland	.5
Hayland	.5
Pasture	.5
Forest	.6
Urban impervious	.2
Residential impervious	.2

The two source-specific model parameters adjusted during the calibration process were the fecal coliform accumulation rate on the land surface (ACCUM) and the limit of storage of fecal coliform bacteria on the land surface (SQOLIM). ACCUM for each source was manipulated during calibration; SQOLIM was maintained at 9 times ACCUM. The total fecal coliform contributions from humans, dogs, and cats were calibrated by adjusting their initial estimated population (POPN) values (table 24). ACCUM values for cattle, poultry, horses, and sheep were calibrated by adjusting FCden (number of bacteria per gram of feces produced) (table 25). ACCUM for deer was calibrated by adjusting the FCden, whereas ACCUM values for geese, ducks, raccoons, and muskrats were calibrated through adjustments to the effective population numbers (table 26). POPN values for humans, dogs, cats, geese, ducks, raccoons, and muskrats are a result of model calibration and represent the populations needed to account for the uncertainty associated with the fixed values of Fprod, FCden, and habitat area (HAB); POPN values do not represent the actual populations in the watershed.

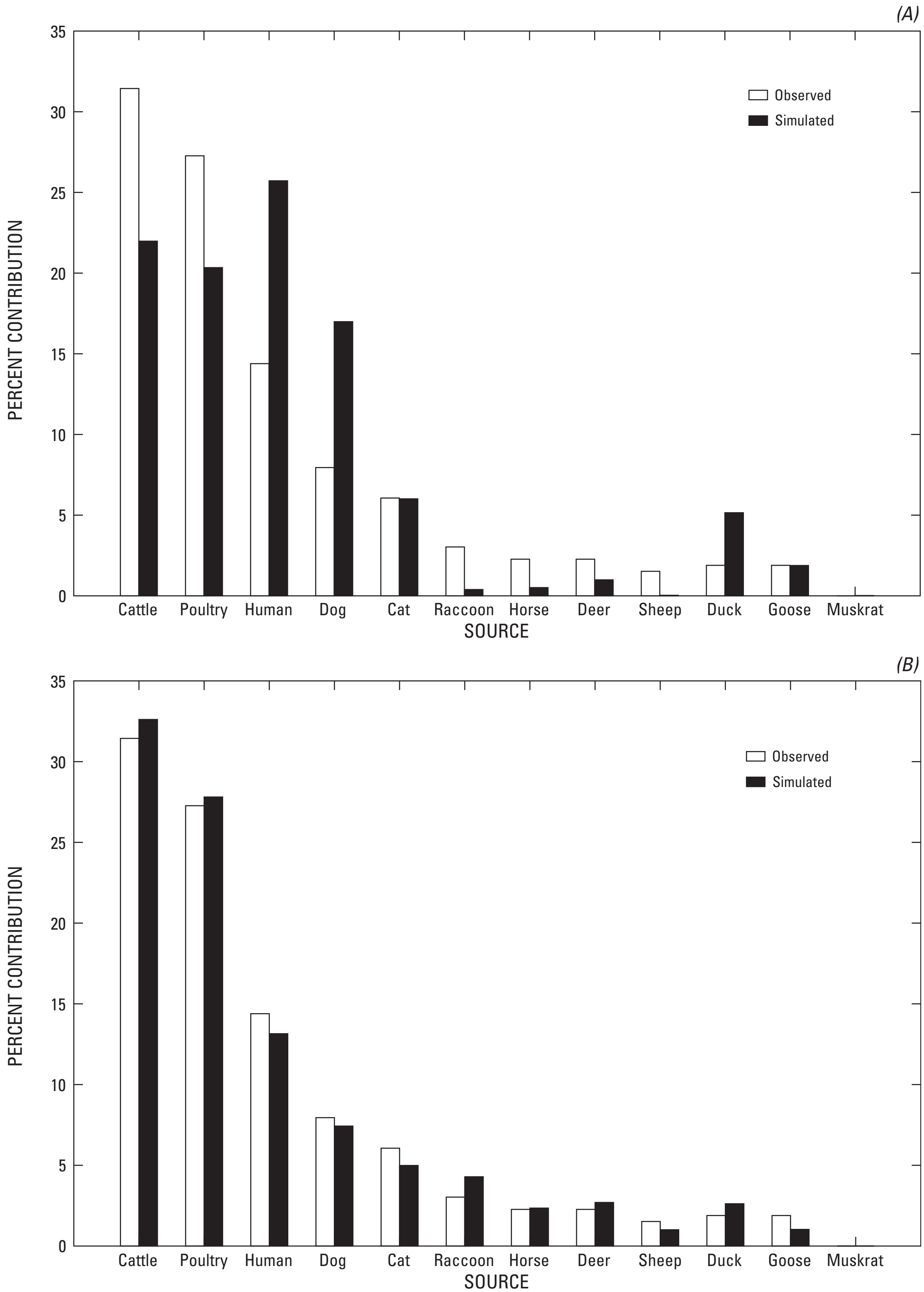


Figure 18. Observed and simulated percent contribution from the simulated sources in the watershed to the total instream fecal coliform bacteria load at Route 704, initial calibration (A), and final calibration (B), Blacks Run, Rockingham County, Virginia.

FECAL COLIFORM TMDL

Present Conditions

The simulated fecal coliform bacteria concentrations for Blacks Run, February 1999 to January 2001, were converted to 30-day geometric mean concentrations. The 30-day geometric mean concentrations indicate that predicted fecal coliform concentrations at Route 704 exceed the State geometric mean water-quality standard of 200 col/100 mL (fig. 19A). Based on the peak fecal coliform 30-day geometric mean concentration of 6,823 col/100 mL, roughly a 95-percent reduction of the current instream fecal coliform load is needed to meet the designated water-quality standard.

Most of the fecal coliform load (98.9 percent) entering Blacks Run is a result of nonpoint sources in the watershed (table 27). Thus, most of the fecal coliform bacteria are transported during stormflow periods. However, the incorporation of a geometric mean calculation and the need for compliance with the geometric mean water-quality standard places a greater emphasis on base-flow conditions that are dominated by point source contributions. The geometric mean calculation is used to identify an unbiased average in the presence of outliers, such as elevated concentrations of fecal coliform bacteria associated with stormflow events. In order to meet the State water-quality standard, reductions are needed in fecal coliform loads from both nonpoint sources and sources depositing directly in streams.

Scenarios for Fecal Coliform Load Reductions

Total instream fecal coliform load reductions of approximately 95 percent will reduce the observed fecal coliform concentrations below the State water-quality standard and designated 5-percent MOS (30-day geometric mean of 190 col/100 mL). Three source-load reduction scenarios for meeting the water-quality goals for Blacks Run were developed through discussions including DCR, DEQ, USGS (in a

Table 24. Final values of the total amount of feces produced daily and fecal coliform per gram of feces generated by the human, dog and cat populations in the residential hydrologic response unit represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces; POPN, population size; HAB, habitat area; –, not applicable]

Subwatershed	Fprod (grams)	FCden	POPN (number)		HAB (acres)	
			Residential impervious	Urban impervious	Residential impervious	Urban impervious
			Human			
1	150	4.66×10^8	107	–	131	–
2	150	4.66×10^8	143	–	165	–
3	150	4.66×10^8	175	–	288	–
4	150	4.66×10^8	0	–	37	–
			Dogs			
1	450	4.11×10^6	116	3,280	125	2,581
2	450	4.11×10^6	156	1,191	167	2,183
3	450	4.11×10^6	191	557	205	1,753
4	450	4.11×10^6	0	6	0	49
			Dogs-Impervious			
1	450	4.11×10^6	1	33	8	287
2	450	4.11×10^6	2	12	11	243
3	450	4.11×10^6	2	6	18	195
4	450	4.11×10^6	0	0	2	6
			Cats			
1	20	1.49×10^7	517	14,569	125	2,581
2	20	1.49×10^7	691	5,290	167	2,183
3	20	1.49×10^7	848	2,472	205	1,753
4	20	1.49×10^7	0	25	0	49

Table 25. Final values of the total amount of feces produced daily and fecal coliform per gram of feces generated by cattle, poultry, horses, and sheep represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces]

Source	Average daily Fprod (grams)	FCden
Dairy cattle	54,545	8.18×10^5
Beef cattle	20,909	1.87×10^6
Heifers	39,091	4.71×10^6
Poultry	231	1.83×10^9
Horse	23,182	2.22×10^6
Sheep	1,091	1.80×10^7

Table 26. Final values for population, total amount of feces produced per day and fecal coliform bacteria per gram of feces for deer, geese, duck, raccoon, and muskrat, represented in the fecal coliform model, Blacks Run, Rockingham County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces; POPN, population size; F, Forest; P, Pasture; U, Urban; R, Residential; H, Hayland; C, Cropland; B, Barren]

Wildlife source	Land-use type	Population density (number per acre)	POPN (number)	Fprod (grams)	FCden
Deer	F,P	0.040	64	772	4.48×10^8
Goose–Summer	U, R, P, H, C, B	.70	887	225	3.55×10^6
Goose–Winter	U, R, P, H, C, B	1.78	2,256	225	3.55×10^6
Duck–Summer	U, R, P, H, C, B	.20	253	150	4.90×10^7
Duck–Summer	F	.047	14	150	4.90×10^7
Duck–Winter	U, R, P, H, C, B	.375	475	150	4.90×10^7
Duck–Winter	F	.078	24	150	4.90×10^7
Raccoon	F	1.64	8,818	450	1.11×10^7
Raccoon	R, P, H, C, B	.70	3,764	450	1.11×10^7
Muskrat	U, R, P, H, C, F, B	.500	331	100	2.50×10^5

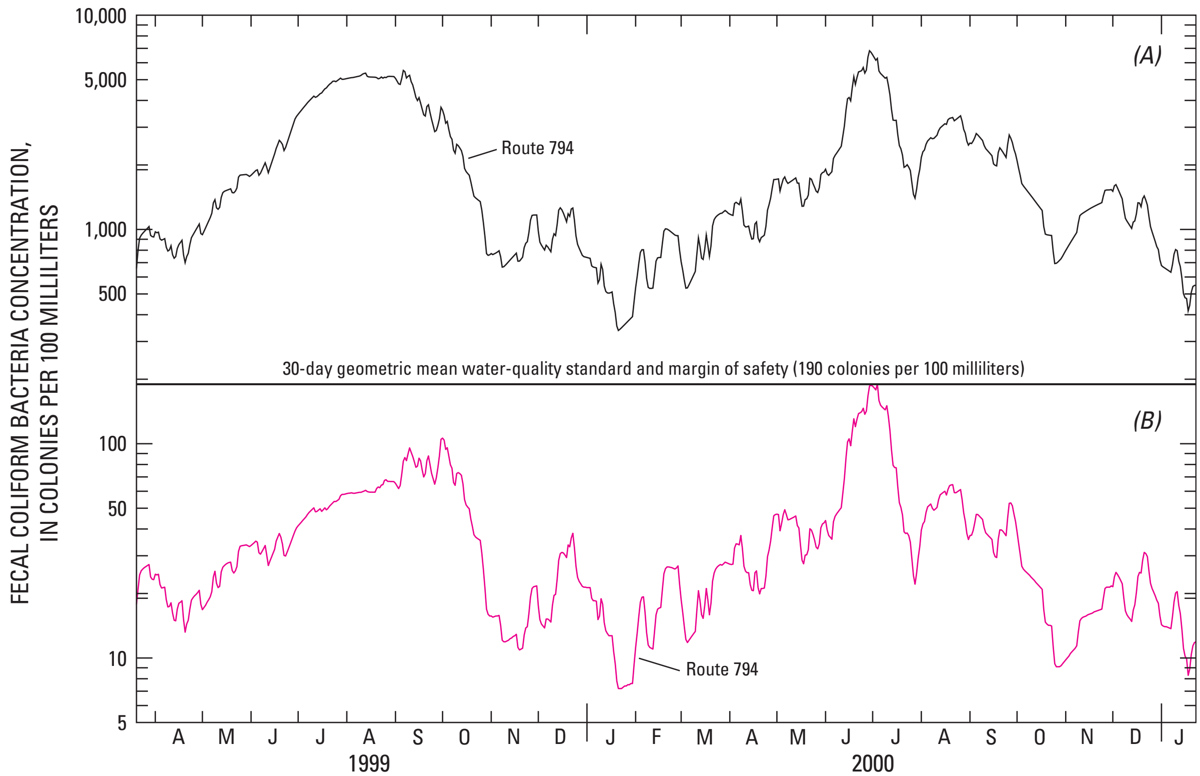


Figure 19. Simulated 30-day geometric mean fecal coliform concentrations before *(A)* and after *(B)* incorporation of the Total Maximum Daily Load (TMDL) allocation scenario, Blacks Run, Rockingham County, Virginia, February 20, 1999-January 23, 2001.

Table 27. Total annual load of fecal coliform bacteria delivered from the various land-use types, direct deposition by cattle and humans, and permitted discharges for present conditions in Blacks Run, Rockingham County, Virginia

Land-use types	Total annual load of fecal coliform bacteria for present conditions (colonies per year)	Contribution (percent)
Urban	3.88×10^{14}	14.47
Residential	4.18×10^{14}	15.59
Pasture	9.03×10^{14}	33.67
Hayland	7.51×10^{14}	28.00
Cropland	1.65×10^{14}	6.15
Forest	1.42×10^{13}	.53
Barren	1.82×10^{11}	.01
Urban impervious	1.18×10^{13}	.44
Residential impervious	1.06×10^{12}	.04
Point Sources		
Instream deposition from cattle	2.96×10^{13}	1.10
Permitted discharges	5.52×10^{9}	.00
Total	2.68×10^{15}	100.00

technical advisory role) and local stakeholders (table 28). These scenarios feature source-specific reductions in fecal coliform loads from nonpoint sources and direct deposition from cattle in streams. Scenario 1 requires a 100-percent reduction in the present fecal coliform loading from cattle, poultry, sheep, horses, humans, dogs, and cats (nonpoint sources), parking lots and roads, and cattle in streams (point sources) in order to ensure that the State water-quality standard is not exceeded. Scenarios 2 and 3 require greater reductions in fecal coliform loading from wildlife sources (50 and 90 percent, respectively) and parking lots and roads (90 and 98 percent, respectively), whereas lesser reductions are needed from the livestock and pet sources in order to ensure that the State water-quality standard is not exceeded. These three scenarios were discussed and evaluated in a public review process led by DCR and DEQ, and scenario 3 was chosen for the Blacks Run watershed.

After the source-load reduction strategies in scenario 3 were incorporated into the watershed model, simulated fecal coliform concentrations at Route 704 met the water-quality goals for Blacks Run (fig. 19B). Changes to the present fecal coliform load allocation following the incorporation of the source-specific load reductions specified in scenario 3 are shown in table 29. Average annual fecal coliform loading pre- and post-TMDL allocations are 2.68×10^{15} and 1.40×10^{14} col/year, respectively. The percent reductions in the fecal coliform load delivered from the various land types ranged from 90 to 98 percent as a result of the reduction scenario. The resulting percent reduction in contributions from cattle in streams is 99 percent. The resulting TMDL equation (see eq. 1) that meets the fecal coliform bacteria water-quality goals for Blacks Run is

$$1.47 \times 10^{14} \text{ col/yr } (\mathit{TMDL}) = 5.52 \times 10^{9} \text{ col/yr } (\sum \mathit{WLAs}) + 1.40 \times 10^{14} \text{ col/yr } (\sum \mathit{LAs}) + 7.00 \times 10^{12} \text{ col/yr } (\mathit{MOS}).$$

Attaining the designated water-quality goals for Blacks Run is a three-step process:

(1) Determination of the fecal coliform bacteria TMDL for Blacks Run.

(2) Development of a plan for reducing the current fecal coliform loading to Blacks Run.

(3) Implementation of the source-load reduction strategies and follow-up monitoring to ensure that the TMDL plan and implementation result in achievement of the water-quality goals for Blacks Run.

Table 28. Scenarios for reducing fecal coliform bacteria loads and associated percent reductions from nonpoint and point sources represented in the fecal coliform model for Blacks Run, Rockingham County, Virginia

Scenario number	Percent reduction in fecal coliform loading from present conditions															Average 30-day geometric mean concentration of fecal coliform bacteria (colonies per 100 milliliters)
	Nonpoint sources														Point sources	
	Cattle	Poultry	Sheep	Horse	Human	Dog	Cat	Goose	Duck	Deer	Raccoon	Muskrat	Parking lots and roads	Cattle in streams	Permitted discharges	
1	100	100	100	100	100	100	100	0	0	0	0	0	100	100	0	2
2	95	95	99	99	100	90	90	50	50	50	50	50	90	100	0	20
3	94	95	94	94	100	95	95	90	90	90	90	0	98	99	0	38

Table 29. Total annual loads of fecal coliform bacteria delivered from the land-use types, point sources, and permitted discharges for present conditions and after incorporation of total maximum daily load (TMDL) allocation in Blacks Run, Rockingham County, Virginia

[NC, no change]

Land-use types	Total annual load of fecal coliform bacteria for present conditions (colonies per year)	Total annual load after incorporation of TMDL (colonies per year)	Reduction (percent)
Urban	3.88×10^{14}	2.32×10^{13}	94.03
Residential	4.18×10^{14}	6.55×10^{12}	98.43
Pasture	9.03×10^{14}	5.60×10^{13}	93.80
Hayland	7.51×10^{14}	4.06×10^{13}	94.60
Cropland	1.65×10^{14}	1.17×10^{13}	92.94
Forest	1.42×10^{13}	1.39×10^{12}	90.21
Barren	1.82×10^{11}	1.14×10^{10}	93.77
Urban impervious	1.18×10^{13}	2.36×10^{11}	98.00
Residential impervious	1.06×10^{12}	2.13×10^{10}	98.00
Point Sources			
Instream deposition from cattle	2.96×10^{13}	2.95×10^{11}	99.00
Permitted discharges	5.52×10^{9}	5.52×10^{9}	NC
Total	2.68×10^{15}	1.40×10^{14}	94.78

DIRECTIONS FOR FUTURE RESEARCH

This study demonstrated the utility of incorporating both HSPF and BST data into the process of developing a TMDL for fecal coliform bacteria. This process would be enhanced by continued refinement of BST techniques and research in the following areas:

- The range of fecal coliform densities for various warm-blooded species and how this range varies temporally and spatially.
- The effect of sediment on the transport and storage of fecal coliform bacteria.
- The fate and transport of fecal coliform bacteria in the shallow subsurface (both the unsaturated zone and the shallow aquifer system) and potential contributions to the instream fecal coliform load.

SUMMARY

The U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Conservation and Recreation (DCR), began a 3-year study in 1999 to develop a total maximum daily load (TMDL) for fecal coliform bacteria in the Blacks Run watershed. The Virginia Department of Environmental Quality (DEQ) determined that Blacks Run is impaired by fecal coliform bacteria because of violations of the State water-quality standard (1,000 colonies/100 mL). This study demonstrates the utility of incorporating both watershed modeling using Hydrological Simulation Program–FORTRAN (HSPF) and bacterial source tracking (BST) as tools in the development of a fecal coliform bacteria TMDL. Attaining the designated water-quality goals for Blacks Run involves a three-step process, determined by DCR and DEQ, which is (1) determination of the fecal coliform TMDL, (2) development of a plan for reducing the current fecal coliform loading, and (3) implementation of

the source-load reduction strategies and follow-up water-quality monitoring. Specific objectives of this study were to (1) produce calibrated models of watershed streamflow and fecal coliform bacteria transport, (2) incorporate BST information into the fecal coliform model calibration process, (3) estimate fecal coliform source-load reductions required to meet the State water-quality standard, and (4) define the TMDL for fecal coliform bacteria for Blacks Run. The major findings and conclusions of the study are:

- The calibrated streamflow model simulated observed streamflow characteristics with respect to total annual runoff, seasonal runoff, average daily streamflow, and hourly stormflow.
- BST identified that the major contributors of fecal coliform bacteria to Blacks Run are cattle, poultry, humans, dogs, and cats.
- The calibrated fecal coliform model simulated the patterns and range of fecal coliform bacteria concentrations observed by DEQ (1991-2001) and USGS (1999-2000).
- The calibrated fecal coliform model simulated source-specific instream fecal coliform loads comparable to the source-specific percent contribution identified in Blacks Run by BST.
- Incorporation of BST data reduces uncertainty associated with determining source-specific fecal coliform loading in the watershed.
- A 95-percent reduction in the current fecal coliform load delivered to Blacks Run is required to meet the designated water-quality goals and associated TMDL.

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