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

Prepared in cooperation with:

Virginia Department of Conservation and Recreation

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

Water-Resources Investigations Report 03-4160

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Cover image of Accotink Creek watershed from Fairfax County, Virginia, Digital Orthophoto Quadrangle, MrSID mosaic.

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Richmond, Virginia
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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).

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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. Accotink Creek, in Fairfax 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 Accotink Creek. The Hydrological Simulation Program–FORTRAN (HSPF) was used to simulate streamflow, fecal coliform concentrations, and source-specific fecal coliform loading in Accotink Creek. Ribotyping, a bacterial source tracking technique, was used to identify the dominant sources of fecal coliform bacteria in the Accotink Creek watershed. Ribotyping also was used to determine the relative contributions of specific sources to the observed fecal coliform load in Accotink Creek. 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 Accotink Creek. 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 25 to 800 colonies per 100 milliliters, and peak concentrations during storm-flow periods ranged from 19,000 to 340,000 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, deer, dogs, ducks, geese, humans, muskrats, and raccoons. According to model results, an 89-percent reduction in the current fecal coliform load delivered from the watershed to Accotink Creek would result in compliance with the designated water-quality goals and associated TMDL.

INTRODUCTION

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 1,000 col/100 mL, or a geometric mean water-quality standard of 200 col/100 mL). Accotink Creek, in Fairfax 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

$$\text{TMDL} = \Sigma\text{WLAs} + \Sigma\text{LAs} + \text{MOS} \quad (1)$$

where ∑WLAs (waste-load allocations) represents the sum of all the point-source loadings, ∑ 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 animal 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 Accotink Creek watershed is ribotyping (Hyer and Moyer, 2003), which involves an analysis of the specific DNA (deoxyribonucleic acid) sequence that

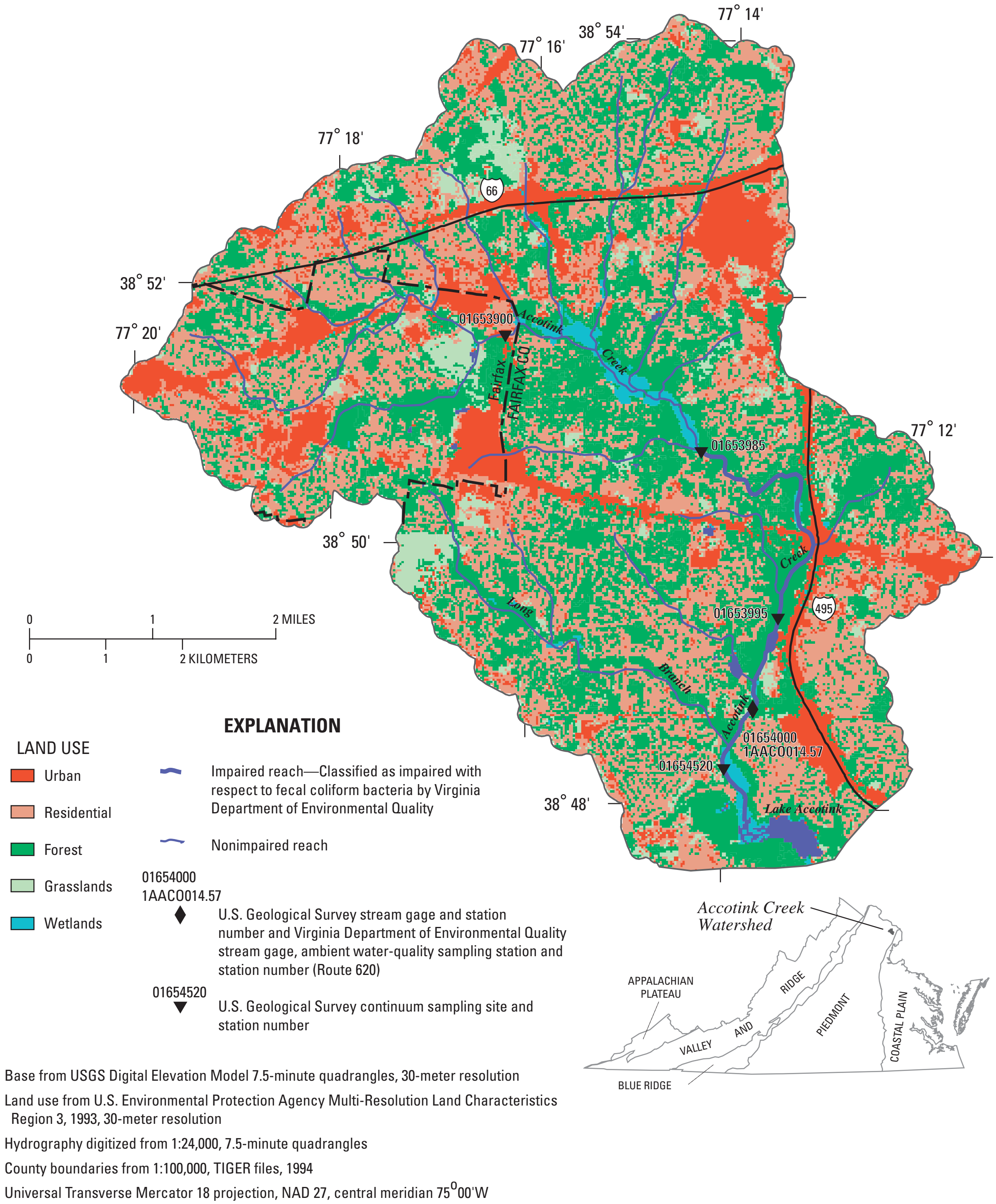


Figure 1. Land use, streams, stream-gaging station, and water-quality sampling stations in the Accotink Creek watershed, Fairfax City and County, Virginia.

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 Accotink Creek 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 Accotink Creek. These objectives ensure that the Accotink Creek 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 Accotink Creek 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 Accotink Creek watershed. The model simulation period is from October 1992 to December 1999. 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 Accotink Creek are presented as well as the load reductions needed to meet the designated TMDL and associated State water-quality standard.

Accotink Creek Watershed Characteristics

Accotink Creek originates in the city of Fairfax, Va., and flows for approximately 10.9 mi before draining into Lake Accotink in Fairfax County, Va. The impaired stream reach is a 4.5-mi-long section just upstream of Lake Accotink (Virginia Department of Environmental Quality, 1998). The portion of the Accotink Creek watershed under investigation has a drainage basin area of 25 mi^2 and a population of more than 110,000 (2000 Census). Approximately 600 ft upstream from the bridge at Route 620 (Braddock Road) is a stream gage that has been active since 1949 and that is jointly managed by USGS and DEQ (Accotink Creek near Annandale; USGS station number 01654000). DEQ has performed quarterly sampling of fecal coliform bacteria at this station since 1990.

The Accotink Creek watershed lies in the Piedmont physiographic province, and is underlain by crystalline igneous and metamorphic rocks (Froelich and Zenone, 1985). The geology of the watershed is composed of five geologic formations. The Wissahickon Formation dominates the watershed and is composed of quartz-mica schist, phyllite, and quartzite (Johnston, 1964). The Greenstone Contact Complex is present in certain headwater areas of the catchment and is composed of chlorite schist, sericite-chlorite schist, chlorite-quartz schist, talc schist and small amounts of quartzite (Johnston, 1962). Granitic rocks are distributed throughout the watershed; these rocks have variable composition including biotite granite, muscovite granite, biotite-muscovite granite, granodiorite, quartz monzonite, and quartz diorite (Johnston, 1964). A small portion of the watershed is underlain by the Sykesville Formation, which includes muscovite or sericite-biotite-quartz schist and gneiss, quartzite, epidote quartzite, and muscovite-biotite quartzite (Johnston, 1964). Alluvial material (composed of clay and sand, as well as quartz cobbles and pebbles) is also present along the channel and in the flood plain of Accotink Creek (Johnston, 1962).

The soils of the Accotink Creek watershed are present as three distinct soil associations, described by Porter and others (1963). The Glenelg-Elioak-Manor association has developed from the weathering of the crystalline bedrock of the Piedmont. These well-drained (and in some places excessively drained) silt-loam soils dominate the Accotink Creek watershed. The Fairfax-Beltsville-Glenelg association comprises a relatively small portion of the basin (limited to the headwater areas) and was formed from the residuum of Piedmont bedrock and fluvial Coastal Plain sediments. These soils are present as silt or sand loams, and range from poorly drained to well drained. The Chewacla-Wehadkee association is present only on a limited basis within the watershed, generally in the bottomland and floodplains along streams. These silt-loam soils range from moderately well-drained to poorly drained and have developed from alluvial material that was washed from the Piedmont uplands.

Although portions (39 percent) of the watershed remain forested (especially adjacent to the stream), urban and residential land uses dominate (55 percent) the rest of the watershed (fig. 1). Other minor land uses in the watershed are recreational grasslands (5 percent) and wetlands (1 percent). Potential sources of fecal contamination in this urban watershed are human-related (cross-pipes, leaking or overflowing sewer lines, and failing septic systems), domestic pets (dogs and cats), waterfowl (geese, ducks, and seagulls), and other wildlife (such as raccoons, opossum, rats, squirrels, and deer). There are no permitted point sources of fecal coliform bacteria within the watershed.

Modeling Approach

Streamflow and bacterial transport in the Accotink Creek 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), Fairfax County, and Fairfax City are 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 Accotink Creek 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 Accotink Creek 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 the hydrologic water budget (PWATER). PWATER includes parameters that represent storage (vegetative, surface, shallow subsurface, and deep subsurface) and

Table 1. Hydrologic parameters used in the simulation of streamflow in Accotink Creek, Fairfax 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

transport of precipitation along three flow paths: overland flow, interflow (shallow subsurface flow), and base flow (active ground-water discharge). Storage and transport para- meters 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 model is to determine the fraction of impervious area within urban and residential land types. This impervious fraction can be broken into two categories, “hydro

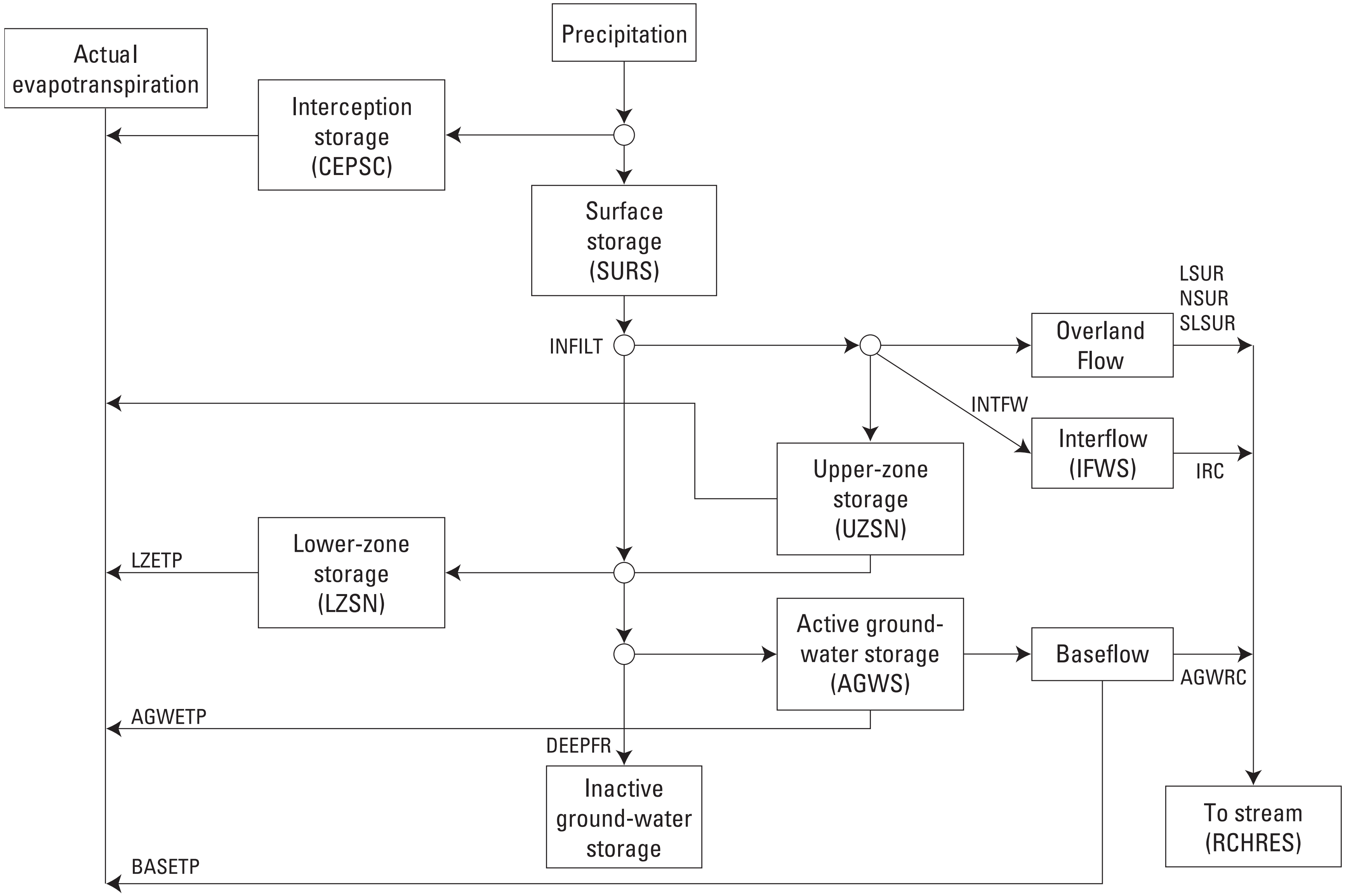


Figure 2. Rainfall-routing processes, associated with pervious land segments, represented by the Hydrological Simulation Program-FORTRAN for the simulation of streamflow in Accotink Creek, Fairfax County, Virginia. (See table 1 for definition of hydrologic parameters.)

logically 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 of urban and residential impervious fractions were based on USEPA Multi-Resolution Land Characteristics (MRLC) class information. Urban and residential land uses, as stated in the MRLC class definitions, contain no less than 80 percent and 30 percent constructed or impervious surfaces, respectively. Because these impervious values are based on total impervious area (hydrologically effective and ineffective), the initial model estimate of hydrologically effective impervious area is overestimated. 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).

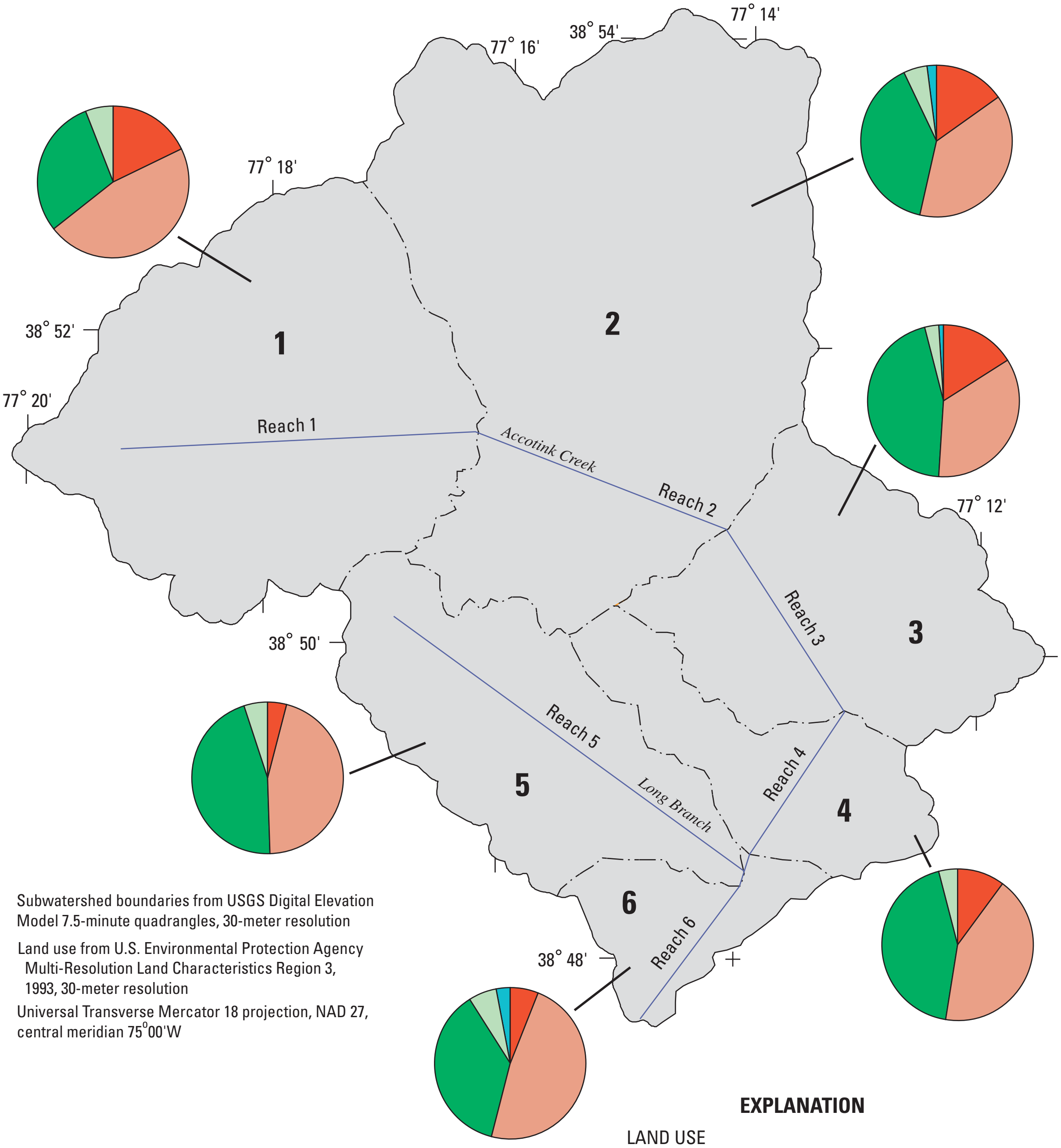
Subwatershed Delineation

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 Accotink Creek 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 Accotink Creek watershed.

Six subwatersheds were identified within the Accotink Creek watershed on the basis of variations in 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 Vienna, Fairfax, Falls Church, and Annandale 7.5-minute quadrangles. The DEM coverage has a cell size of 30 meters.

Land Use

Land-use data for the Accotink Creek watershed were derived from the MRLC Region 3 Classified Land Cover Geographic Information Systems (GIS) coverage. This land-use coverage represents land types in the basin as of 1993. The MRLC coverage consisted of 12 land-use categories, which were combined into 5 general types based on hydrological routing similarities: urban, residential, forest, grassland, and wetland (table 2). Each of these general land-use types represents the HRUs for each subwatershed.



Sub-watershed	Land use, in percent				
	Urban	Residential	Forest	Grassland	Wetland
1	18	47	30	6	0
2	15	38	39	5	2
3	16	35	45	3	1
4	10	42	43	4	0
5	4	45	45	5	0
6	6	48	37	6	3

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 Accotink Creek, Fairfax County, Virginia.

Table 2. Aggregated hydrologic response units used to develop the streamflow and fecal coliform models for Accotink Creek, Fairfax County, Virginia

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

Hydrologic Response Unit	Area	
	Acres	Percent of watershed
Urban[1]	2,698.4	13.9
Residential[2]	8,042.2	41.4
Forest[3]	7,545.6	38.9
Grassland[4]	897.6	4.6
Wetland[5]	233.1	1.2

[1] Includes urban impervious, commercial, industrial, transportation, and high density residential.
[2] Includes residential impervious, low density residential.
[3] Includes deciduous forest, evergreen forest, and mixed forest.
[4] Includes urban and recreational grasses, pasture, hay, row crops, and transitional.
[5] Includes emergent herbaceous wetlands and woody wetlands.

Channel Network

A single stream channel (reach) is represented in each of the six 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 FTABLE (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 620 (USGS station 01654000) was incorporated into the FTABLE for reach segment 4.

Six subwatersheds (1–6) represent the morphological features of the Accotink Creek watershed (fig. 3). Within each subwatershed there are 7 HRUs, including 5 pervious (urban, residential, forest, grassland, and wetland) and 2 impervious (urban and residential). Each subwatershed has a single reach that is governed by an FTABLE. Reaches 1, 2, 3, 4, and 6 represent Accotink Creek. Reach 5 represents Long Branch, a tributary to Accotink Creek.

Meteorological and Streamflow Data

Rainfall data were obtained from the Fairfax County Department of Public Works (table 3). These data are collected hourly at the Vienna Woods (M2028)

Table 3. Meteorological and streamflow data used in the streamflow model for Accotink Creek, Fairfax County, Virginia

[in., inches; °F, degrees Fahrenheit; FCDPW, Fairfax County Department of Public Works; 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.)	Vienna Woods	38°52′50″ 77°15′21″	FCDPW	hourly	8/11/92–9/4/00
Minimum air temperature (°F)	Ronald Reagan National Airport	38°51′01″ 77°02′35″	NCDC	daily	8/1/48–12/31/99
Maximum air temperature (°F)	Ronald Reagan National Airport	38°51′01″ 77°02′35″	NCDC	daily	8/1/48–12/31/99
Discharge (ft^3/sec)	Accotink Creek at Annandale (Route 620)	38°48′46″ 77°13′43″	USGS	hourly daily	10/1/90–7/1/00 3/1/47–9/30/00

rain gage that is in the northeastern portion of the Accotink Creek watershed, 4.9 mi northwest of the DEQ stream gage on Accotink Creek. This rain gage has been operational since August 4, 1992. Average annual rainfall measured between 1993 and 1999 was 40.9 in., with a maximum annual rainfall amount of 54.1 in. in 1996 and a minimum annual rainfall amount of 34.3 in. in 1995. The average rainfall observed at the Vienna Woods gage is consistent with the 30-year average rainfall amounts of 38.6 and 40.2 in. observed at nearby Ronald Reagan National Airport and Dulles International Airport, respectively (Climatological Data Annual Summary for Virginia, 1999).

Daily minimum and maximum temperatures were obtained from Ronald Reagan National Airport for the time period January 1, 1992, to December 31, 1999 (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 are higher than actual evapotranspiration (Kohler and others, 1959). Daily values of PET were disaggregated to hourly values using WDMUtil.

Streamflow data for Accotink Creek for the period October 1, 1990, to December 31, 1999, were collected by the USGS every 15 minutes at the Accotink Creek near Annandale stream gage (USGS station number 01654000) (table 3). Hourly streamflow values were used for the streamflow simulation. Average annual streamflow for the period October 1, 1992–September 30, 1999 (water years 1993–99) was 34.5 ft^3/s with a maximum average annual streamflow of 45.5 ft^3/s during water year 1996 and a minimum average annual streamflow of 18.8 ft^3/s during water year 1995.

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 written (simulated streamflow and fecal coliform bacteria) 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 Accotink Creek watershed. The 7-year simulation period extended from October 1, 1992, to December 31, 1999, and included a 5-year calibration and a 2-year verification period. Key steps in the development of the calibrated model of streamflow for the Accotink Creek watershed included collection of historical and current meteorological and streamflow data, determination of the effective impervious area, calibration of hydraulic parameters, and evaluation of the 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 Accotink Creek watershed (table 4).

Results from the streamflow model were evaluated for both the calibration and verification periods. The calibration period extended from October 1, 1992, to September 30, 1997. Results from the model calibration were evaluated based on 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.

The calibrated streamflow model was verified by simulating streamflow during the period from October 1, 1997, to December 31, 1999, using the adjusted hydraulic parameters obtained during model calibration. Model verification was performed once and was not used in the iterative calibration process. Results from model verification were evaluated following the same protocol as described for evaluation of the calibrated model results.

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 4. Initial streamflow model parameters and percent imperviousness in six subwatersheds represented in the streamflow model for Accotink Creek, Fairfax County, Virginia

[HRU, Hydrologic Response Unit; see table 1 for definitions of parameters; U, Urban; R, Residential; F, Forest; G, Grassland; W, Wetland; UI, Urban impervious; RI, Residential 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	0.95	0.00	0.20	0.03	1.00	0.95	0.00	0.40	6.00	0.50
R	–	.00	.95	.00	.20	.03	1.00	.95	.00	.40	6.00	.50
F	–	.00	.95	.00	.20	.03	1.00	.95	.00	.60	6.00	.50
G	–	.00	.95	.00	.20	.03	1.00	.95	.00	.40	6.00	.50
W	–	.00	.95	.00	.20	.03	1.00	.95	.00	.70	6.00	.50
UI	80	–	–	–	–	–	–	–	–	–	–	–
RI	30	–	–	–	–	–	–	–	–	–	–	–

Table 5. Parameters used in the simulation of the transport and storage of fecal coliform bacteria in Accotink Creek, Fairfax 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 ft^3
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

(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

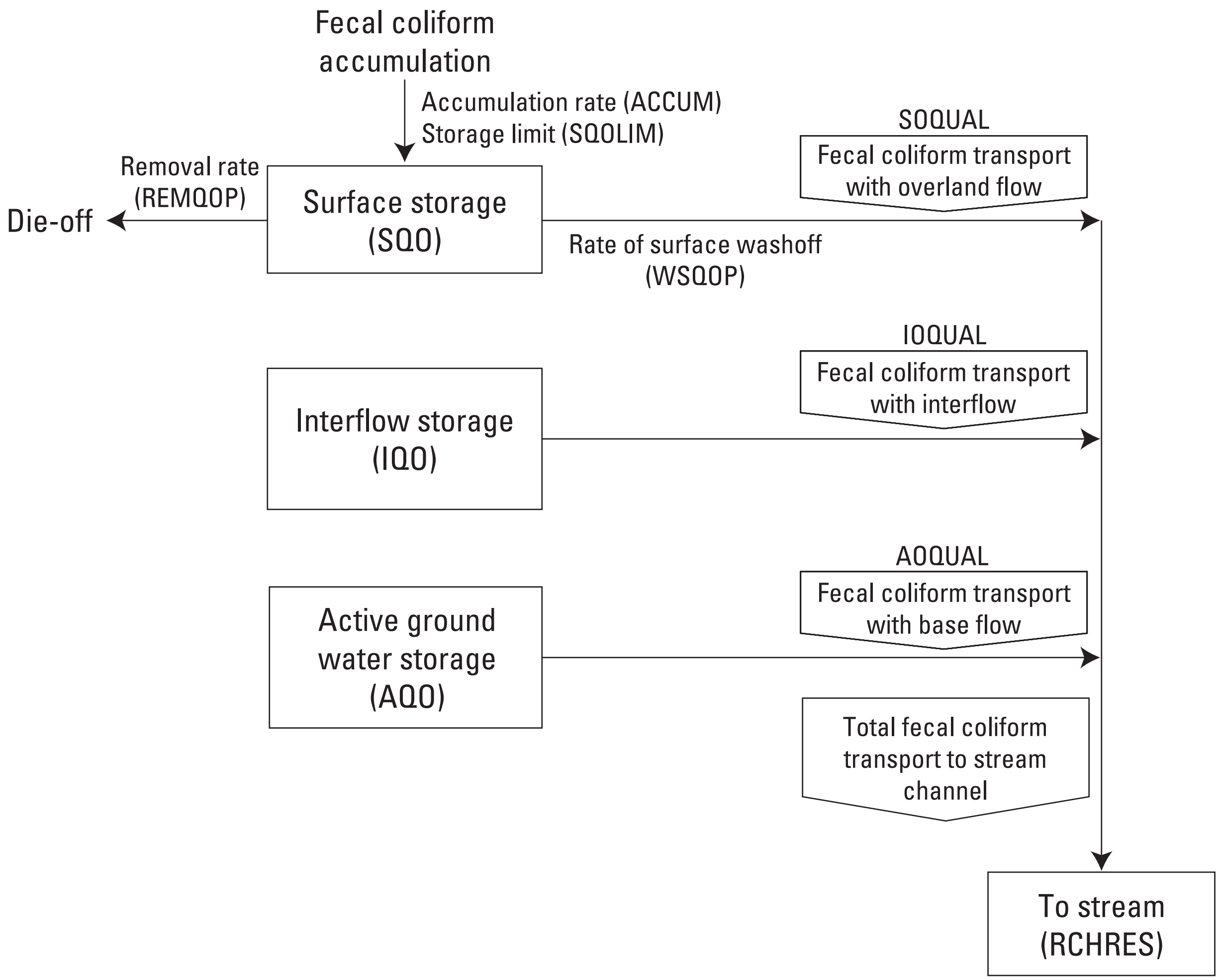


Figure 4. Routing processes represented by the Hydrological Simulation Program-FORTRAN for the simulation of fecal coliform bacteria transport in Accotink Creek, Fairfax County, Virginia. (See table 5 for definition of fecal coliform bacteria transport and storage parameters.)

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:

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

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

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),

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 for interval minus 20 (^oC).

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, and wildlife) within the Accotink Creek watershed.

There are no individual facilities that discharge directly to Accotink Creek; however, there are point discharges from the storm sewer system outfalls. These discharges are currently regulated by Fairfax County's municipal separate storm sewer system (MS4)/Virginia pollution discharge elimination system (VPDES) permit (Permit No. VA 0088587). While the MS4 was not represented directly in the fecal coliform model, the waste load allocation (WLA) for the MS4 was estimated based on the fecal coliform loading generated on the impervious land segments

Most of the fecal coliform bacteria in Accotink Creek are derived from and represented as nonpoint sources. These bacteria are deposited on the land surface by many different sources (people, pets, 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 potential fecal coliform sources in the Accotink Creek watershed, and eight sources were identified as potentially dominant and represented in the model. These eight sources are cats, deer, dogs, ducks, geese, humans, muskrats, and raccoons.   Second, the total daily amount of fecal coliform bacteria deposited on the land surface 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:

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

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),

HAB is the habitat area (acres), and

POPN is the population size, dimensionless.

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 Accotink Creek watershed is documented in the following section. The sources described in this section are humans, dogs, cats, 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 Accotink Creek watershed has a human population of approximately 110,000 (2000 Census). Within the watershed, many pathways can allow human-derived fecal coliform bacteria to enter Accotink Creek. 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 6. 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 the estimated septic-system failure rate of 1.62 percent for Fairfax County, Va. (Northern Virginia Planning District Commission, 1990). In the Accotink Creek watershed, 1,014 houses have septic systems. The average household occupancy rate for Fairfax County is 2.7 people (2000 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 6).

Fecal coliform bacteria derived from dogs were represented as a land application to both urban and residential land types. The accumulation rate for the bacteria was calculated using equation 6. Initial values used to calculate ACCUM are listed in table 7. On average, one dog generates 450 g of feces per day (Weiskel and others, 1996), and an estimated 4.11 x 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 eight people. This estimate was refined further to account for the approximately 30 percent of dog waste that is picked up and disposed of. Additionally, 10 percent of the waste generated by dogs was assumed to be deposited on impervious surfaces such as parking lots and roads. The POPN value in table 7 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 7. 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 x 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 deposit their feces outdoors. The POPN value in table 7 represents the effective number of cats that deposit 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.

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); Fairfax County Police Department Division of Animal Control; Arlington County Department of Parks, Recreation and Community Resources; GeesePeace; Virginia Polytechnic Institute and State University; 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 8). 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 (table 8). The amount of fecal coliform bacteria produced daily by each wildlife species (table 9) 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. Additionally, 5 percent of the waste generated by geese was assumed to be deposited on impervious surfaces such as parking lots and roads. 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 pet source in the model that is assumed to deposit feces on impervious surfaces. Ten 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 10). The fecal

Table 6. Initial values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by the human population in the residential hydrologic response unit represented in the fecal coliform model for Accotink Creek, Fairfax 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	4.66×10^8	8	1193
2	150	4.66×10^8	16	1511
3	150	4.66×10^8	9	530
4	150	4.66×10^8	3	337
5	150	4.66×10^8	5	639
6	150	4.66×10^8	0	214

[1]See figure 3 for location of subwatersheds.

Table 7. Initial values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by the dog and cat populations in the urban and residential hydrologic response units represented in the fecal coliform model for Accotink Creek, Fairfax 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	Urban	Residential	Urban
			Dogs			
1	450	4.11×10^6	1,141	760	1,193	630
2	450	4.11×10^6	2,143	1,429	1,511	829
3	450	4.11×10^6	984	656	530	336
4	450	4.11×10^6	519	346	337	114
5	450	4.11×10^6	776	517	639	80
6	450	4.11×10^6	278	186	214	36
			Cats			
1	20	1.49×10^7	2,599	1,733	1,193	630
2	20	1.49×10^7	4,884	3,256	1,511	829
3	20	1.49×10^7	2,243	1,495	530	336
4	20	1.49×10^7	1,183	789	337	114
5	20	1.49×10^7	1,768	1,178	639	80
6	20	1.49×10^7	635	423	214	36

[1]See figure 3 for location of subwatersheds.

Table 8. Initial population values of wildlife sources of fecal coliform bacteria in the fecal coliform model for Accotink Creek, Fairfax County, Virginia

[POPN, population size; F, Forest; G, Grassland; U, Urban; R, Residential; W, Wetland; UI, Urban impervious]

Wildlife source	Land-use type	Habitat[1]	Population density[2] (number per acre)	POPN (number)
Deer	F	Entire Watershed	0.12	884
Deer	G		.039	35
Goose–Summer	U, R, G, W	Within 300 feet of streams and ponds	2.34	3,770
Goose–Winter	U, R, G, W	Within 300 feet of streams and ponds	2.50	4,028
Goose–Summer	UI, R	Within 300 feet of streams and ponds	2.34	198
Goose–Winter	UI, R	Within 300 feet of streams and ponds	2.50	212
Duck–Summer	U, R, G, W	Within 300 feet of streams and ponds	.23	390
Duck–Summer	F	Within 300 feet of streams and ponds	.06	94
Duck–Winter	U, R, G, W	Within 300 feet of streams and ponds	.366	621
Duck–Winter	F	Within 300 feet of streams and ponds	.078	122
Raccoon	R, F, W	Within 2,640 feet of streams and ponds	.31	4,374
Muskrat	R, G, F, W	Within 60 feet of streams and ponds	.23	181

[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]Deer–Dan Lovelace, Virginia Department of Game and Inland Fisheries, oral commun., 2000; Geese, David Field, GeesePeace, oral commun., 2000; Duck, Earl Hodnett, Animal Control Division, Fairfax County Police Department, oral commun., 2000; Raccoon; Francois Elvinger, Virginia Polytechnic Institute and State University, oral commun., 2000; Muskrat, Randy Farrar, Virginia Department of Game and Inland Fisheries, oral commun., 2000.

Table 9. Initial values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by deer, goose, duck, raccoon, and muskrat represented in the fecal coliform model for Accotink Creek, Fairfax County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of 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 10. Initial values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by the dog population in the urban and residential impervious hydrologic response units represented in the fecal coliform model for Accotink Creek, Fairfax 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
1	450	4.11×10^6	127	84	976	210
2	450	4.11×10^6	238	159	1,236	276
3	450	4.11×10^6	109	73	434	112
4	450	4.11×10^6	58	38	275	38
5	450	4.11×10^6	86	57	523	27
6	450	4.11×10^6	31	21	175	12

[1]See figure 3 for location of subwatersheds

coliform bacteria from the feces directly deposited on the impervious surfaces are modeled as a nonpoint source. The fecal coliform accumulation rate is calculated using equation 6 and is based on fecal production from 10 percent of the dog population.

Canada geese are the only wildlife source in the model that is assumed to deposit feces on impervious surfaces. Five percent of the total waste generated by Canada geese is assumed to fall directly on the impervious potions of the residential and urban land-use types. The bacteria from the Canada geese feces directly deposited to the impervious surfaces are modeled as a nonpoint source. The fecal coliform accumulation rate is calculated using equation 6 and is based on fecal production from 5 percent of the Canada geese population. Monthly values of ACCUM are calculated for Canada geese to account for seasonal migration patterns.

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 Accotink Creek (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 Accotink Creek. 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 identified by Hyer and Moyer (2003). These sources are dogs, ducks, geese, and humans.

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 pet and other nonpoint sources were present in base-flow samples from Accotink Creek. 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 dogs, ducks, geese, and humans 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 a lower detection limit of 100 col/100 mL (established in 1993) and an upper detection limit of 16,000 col/100 mL for enumeration of fecal coliform bacteria. Therefore, reported fecal coliform bacteria concentrations of 100 and 16,000 col/100 mL have an actual concentration of 0–100 col/100 mL or greater than or equal to 16,000 col/100 mL, respectively. DEQ generally collects water-quality samples quarterly to monthly under low-flow or post stormflow conditions; peak stormflow water-quality samples are not collected routinely.

Fairfax County Health Department (FCHD) monitors water quality in streams throughout Fairfax County; fecal coliform bacteria is one constituent of interest and is analyzed using membrane filtration. These samples are collected to determine if the streams in Fairfax County are in compliance with the State water-quality standard for fecal coliform bacteria. FCHD established a lower detection limit of 99 col/100 mL and an upper detection limit of 6,001 col/100 mL for enumeration of fecal coliform bacteria. Therefore, measured fecal coliform bacteria concentrations reported by FCHD of 99 and 6,001 col/100 mL have an actual concentration of 0–99col/100 mL or greater than or equal to 6,001 col/100 mL, respectively. FCHD generally collects water-quality samples under low-flow or post stormflow conditions; peak stormflow water-quality samples are not collected routinely.

DEQ collects quarterly water-quality samples at the Route 620 long-term monitoring station on Accotink Creek (station number 1AACO014.57; fig. 1; table 11). Results of monitoring by DEQ during 1991-99 show that fecal coliform bacteria concentrations were greater than the State instantaneous water-quality standard in 23.1 percent of samples taken (fig. 5). FCHD collects biweekly water-quality samples at the Route 620 water-quality monitoring station (station number 16-08; table 11). Results of monitoring by FCHD during 1986-99 show that 42.5 percent of the samples taken had fecal coliform bacteria concentrations greater than the State water-quality standard (fig. 6). Seasonal patterns also were identified in the FCHD data (fig. 7). Generally, fecal coliform concentrations are higher during the warmer months (April–September) and lower during the cooler months (October–March). Similar seasonal patterns have been observed in other studies of fecal coliform concentrations and loads

Table 11. Fecal coliform bacteria concentrations for water-quality samples collected by the Virginia Department of Environmental Quality (DEQ) and Fairfax County Health Department (FCHD) on Accotink Creek, Fairfax County, Virginia

Data-collection agency	Station number[1]	Station name	Latitude Longitude	Period of record	Fecal coliform bacteria concentration, in colonies per 100 milliliters			
					Minimum	Maximum	Mean	Median
DEQ	1AACO014.57	Route 620	38°48′40″ 77°13′50″	1991–99	45	16,000	1,671	300
FCHD	16-08	Route 620	38°48′40″ 77°13′50″	1986–99	99	6,001	1,687	800

[1]See figure 1 for location of station.

(Christensen and others, 2001; Baxter-Potter and Gilliland, 1988).

The USGS collected water-quality data for this study at five sites in Accotink Creek 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 12).

Low-flow samples were collected every 6 weeks at Route 620. 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 samples 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 17.6 percent of the low-flow samples exceeded the State fecal coliform bacteria standard (fig. 8). All of the violations were observed during recession-flow periods. These fecal coliform data also exhibited a seasonal pattern; higher concentrations were observed during the warmer months (April–September) than during the cooler months (October–March). This seasonal pattern for concentra-

Table 12. Fecal coliform bacteria concentrations for water-quality samples collected by the U. S. Geological Survey during low-flow and stormflow conditions at Route 620 (01654000) and at five other sites along the continuum of Accotink Creek, Fairfax 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							
01654000	Route 620	38°48′46″ 77°13′43″	108	25	41,000	1,419	311
Stormflow samples							
01654000	Route 620	38°48′46″ 77°13′43″	54	625	337,000	72,821	51,000
Continuum samples							
01653900	Route 237	38°51′39″ 77°16′17″	4	190	38,000	12,878	6,660
01653985	Route 846	38°50′46″ 77°14′16″	4	25	18,000	8,306	7,660
01653995	Woodlark Drive	38°49′32″ 77°13′29″	4	50	23,000	10,026	8,527
01654000	Route 620	38°48′46″ 77°13′43″	4	37	13,000	6,528	6,537
01654520	Lonsdale Drive	38°48′10″ 77°13′52″	3	42	9,300	3,135	64

[1]See figure 1 for location of stations.

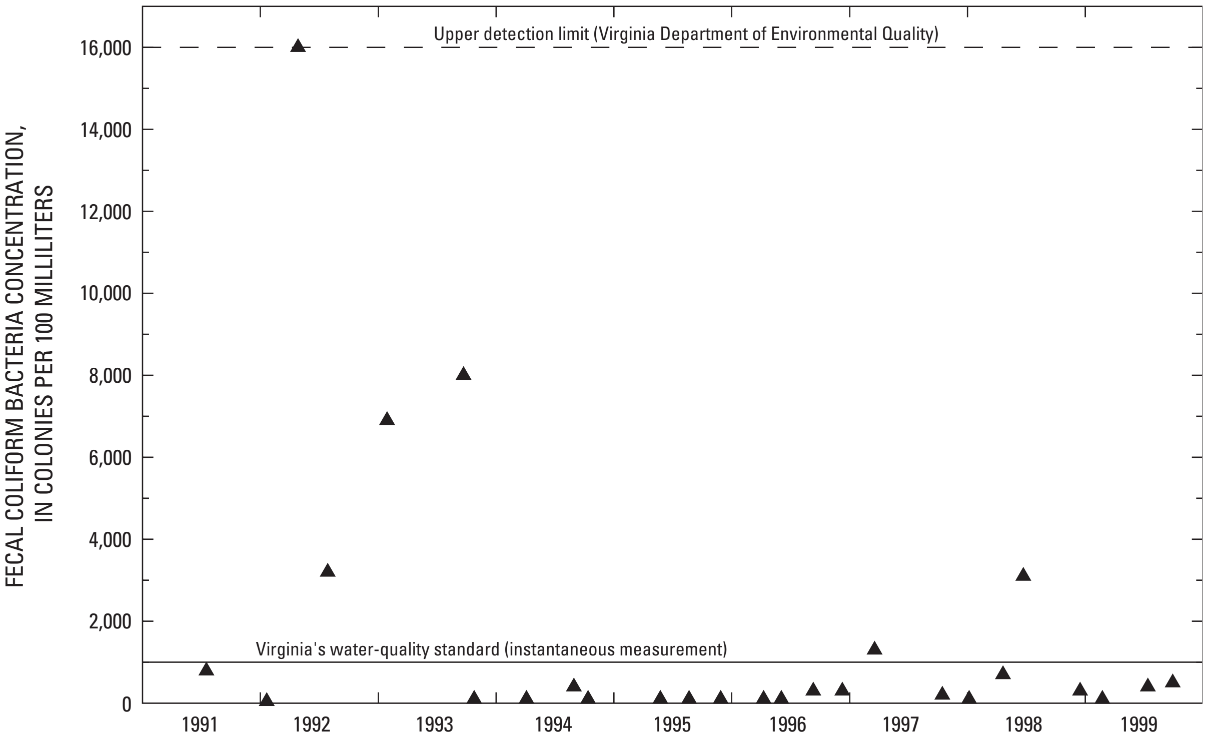


Figure 5. Observed fecal coliform bacteria concentrations for Accotink Creek at Route 620, Fairfax County, Virginia, 1991-99. (Data from Joan C. Crowther, Virginia Department of Environmental Quality, written commun., 1999.)

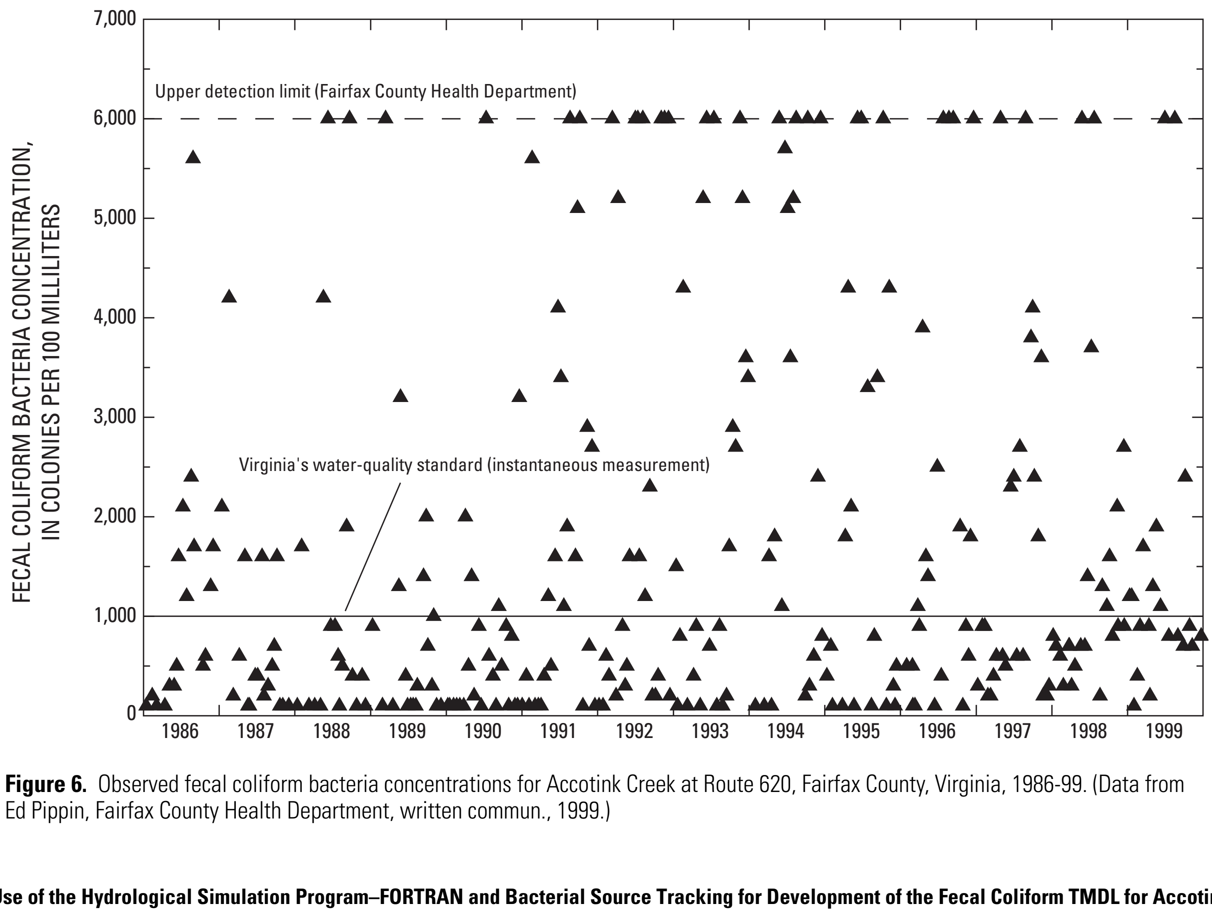


Figure 6. Observed fecal coliform bacteria concentrations for Accotink Creek at Route 620, Fairfax County, Virginia, 1986-99. (Data from Ed Pippin, Fairfax County Health Department, written commun., 1999.)

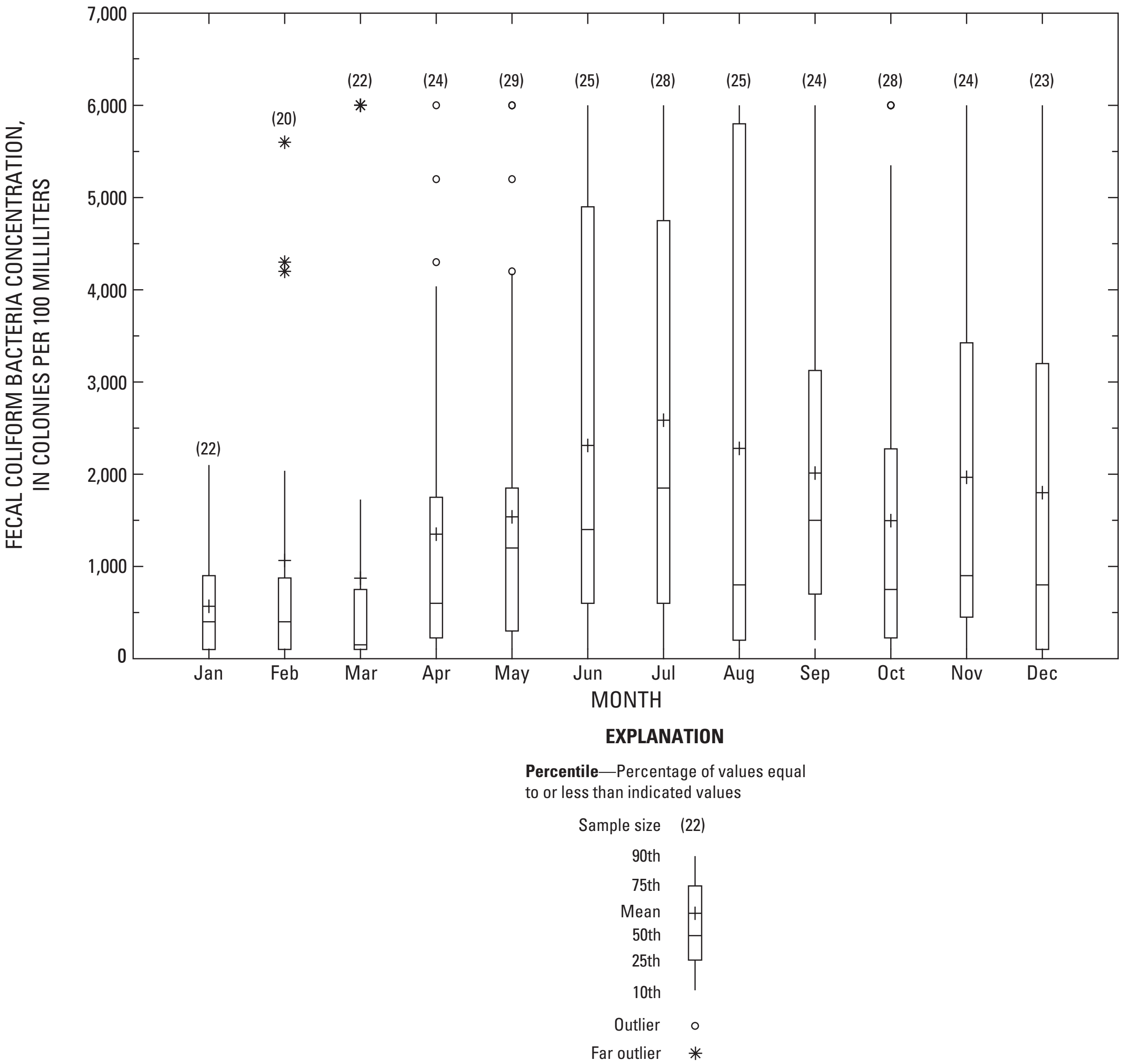


Figure 7. Relation between observed fecal coliform bacteria concentrations for Accotink Creek at Route 620, Fairfax County, Virginia, 1986-99. (Data from Ed Pippin, Fairfax County Health Department, written commun., 1999.)

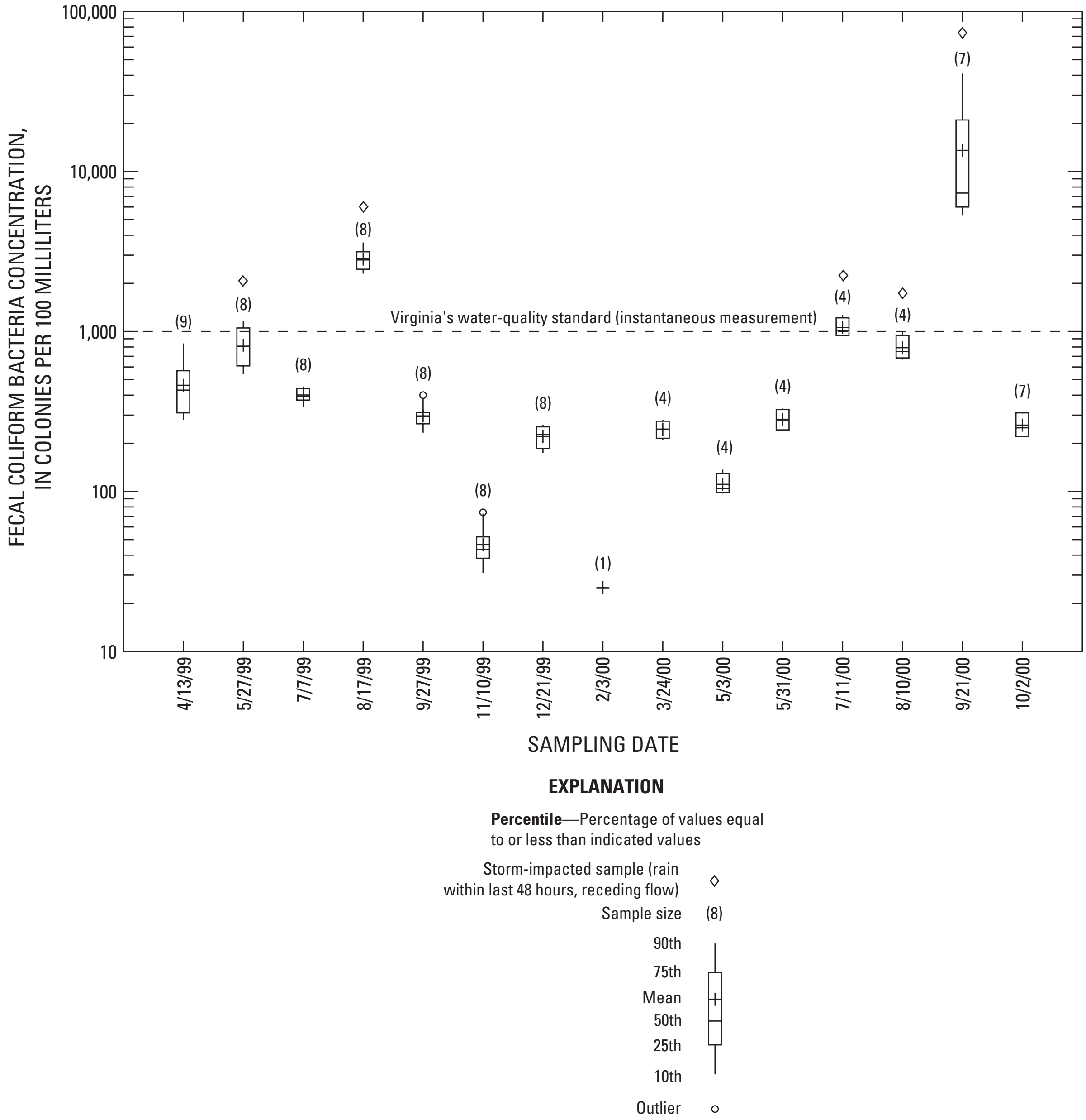


Figure 8. Observed fecal coliform bacteria concentrations from stream-water samples for Accotink Creek at Route 620, Fairfax County, Virginia, during low-flow periods.

tions of fecal coliform bacteria is consistent with the pattern identified in the historical data.

Stormflow samples were collected during five storm events (May 24, 1999; August 14, 1999; September 9, 1999; September 16, 1999; and June 5, 2000) at Route 620. 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. 9) 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 19,000 to 340,000 col/100 mL. Of the samples collected during stormflow periods, 94.8 percent have fecal coliform bacteria concentrations that exceeded the State water-quality standard. Elevated fecal coliform concentrations during storm events have been observed in previous studies (Christensen and others, 2001; Bolstad and Swank, 1997). In general, these ele

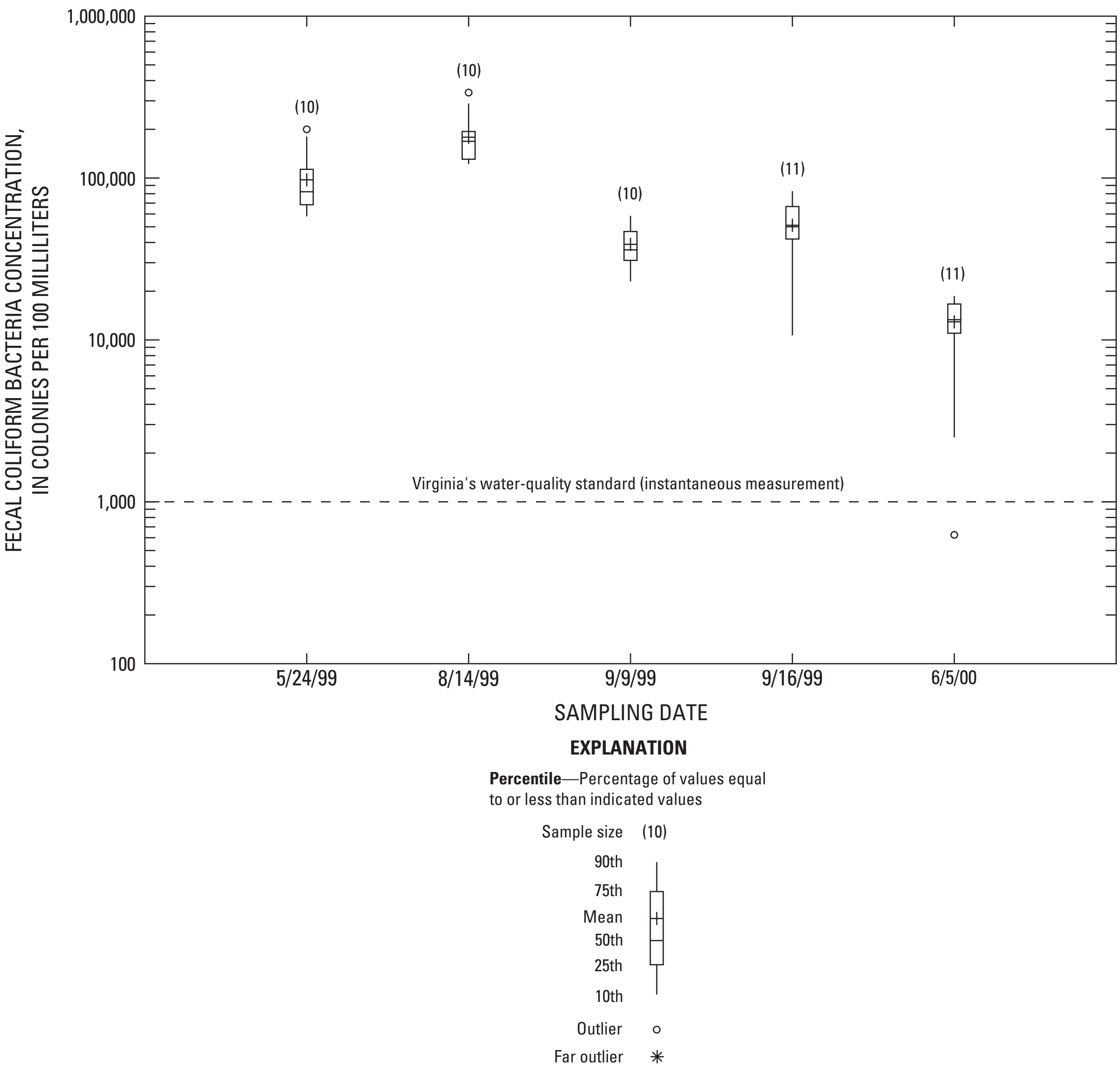


Figure 9. Observed fecal coliform bacteria concentrations from stream-water samples collected for Accotink Creek at Route 620 during stormflow periods, Fairfax County, Virginia.

vated 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).

Four continuum sampling sites in addition to Route 620 were established along Accotink Creek (fig. 1; table 12). These five sites were sampled four times (March 18, 1999; August 11, 1999; June 6, 2000; and August 8, 2000) to examine how well the intensive sampling at Route 620 represented the entire watershed. These samples were collected as a single, depth-integrated sample from the approximate center of the stream channel. Two of the continuum samples were collected during low-flow periods while the remaining two were collected during stormflow/recession-flow periods. Data from these continuum sites also provided information on the spatial variability observed in fecal coliform bacteria (table 12).

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 Accotink Creek (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 Accotink Creek.

The results from the BST study indicate that a diverse collection of organisms contributes to the impairment of Accotink Creek (Hyer and Moyer, 2003). Hyer and Moyer (2003) identified 22 different sources of fecal coliform bacteria; the top 10 contributors identified by ribotyping include goose, human, dog, duck, cat, sea gull, and raccoon, with rodent, cattle, and deer considered minor sources, making up less than 5 percent of the total contributors (fig. 10).

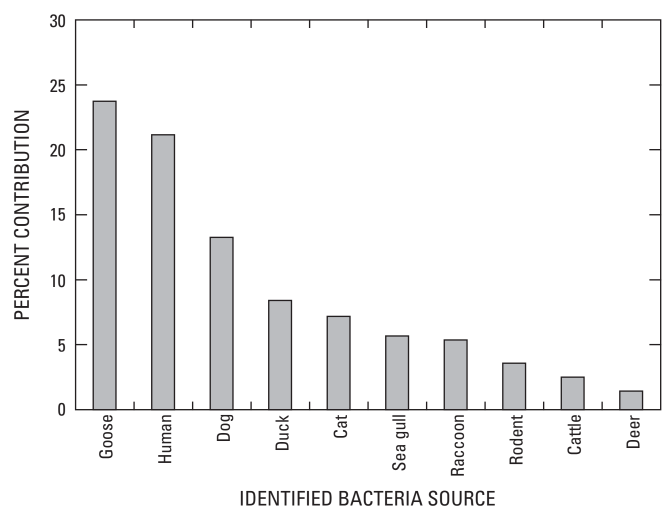


Figure 10. Distribution of the top ten contributors of fecal coliform bacteria identified by bacterial source tracking in the Accotink Creek watershed, Fairfax County, Virginia.

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 Accotink Creek watershed. The simulations cover approximately a 7-year period from October 1, 1992, to December 31, 1999.

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 Accotink Creek 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, FCHD, and USGS during low-flow periods. The primary source represented in the model which contributes fecal coliform bacteria during low-flow periods is active ground-water discharge (AQO). Thus, the low-flow periods represented in the model were calibrated by adjusting the fecal coliform inputs from 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 13). 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.

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 Accotink Creek 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 13.1 percent of the *E. coli* isolates identified. However, 86.9 percent of the *E. coli* isolates identified by means of BST (including geese, humans, dogs, ducks, cats, sea gulls, raccoons, and deer) were represented explicitly in the model with one exception, sea gulls. Sea gulls are included with geese 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.

Table 13. Initial values of WSQOP used for the various land-use types represented in the fecal coliform model for Accotink Creek, Fairfax County, Virginia

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

Land-use type	WSQOP (inches per hour)
Urban	0.5
Residential	.5
Grassland	.5
Forest	.7
Wetland	.5
Urban impervious	.3
Residential impervious	.3

The calibration of the fecal coliform model was evaluated through graphical comparisons and comparison 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

$$GM = [(a_1)...(a_n)]^{1/n} \quad (7)$$

where *GM* is the geometric mean,

$[(a_1)...(a_n)]^{1/n}...$

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 biweekly samples collected by FCHD. 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 and FCHD. These limitations include (1) censoring of the data by upper and lower detection limits, and (2) lack of data during peak stormflow periods. DEQ and FCHD collect 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 and FCHD collect 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 Accotink Creek 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 Accotink Creek, 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 Accotink Creek 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 Accotink Creek. 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 Accotink Creek. Each load-reduction scenario was simulated over the time period used for model calibration (1992–99). 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 Accotink Creek.

Reductions from Point and Nonpoint Sources

Fecal coliform load reduction from the MS4 outfalls is achieved through reductions from impervious land surfaces. Impervious land-surface fecal coliform loadings affect water quality primarily during stormflow and recession flow periods. The fecal coliform load associated with surface runoff is reduced through source-specific reductions from dogs and geese.

Fecal coliform loads were reduced from nonpoint sources through reductions from the land surface. Land-surface loadings of fecal coliform bacteria affect water quality primarily during stormflow and recession flow periods. The fecal coliform load associated with surface runoff was reduced through source-specific reductions from the eight 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 14). Observed and

Table 14. Observed and simulated runoff values for Route 620, for Accotink Creek, Fairfax County, Virginia, water years 1993-97

Runoff category	Observed (inches)	Simulated (inches)	Difference (percent)[1]	Criterion (percent)
Total annual runoff	95.47	95.39	-0.08	10
Highest 10-percent flow[2]	57.69	56.91	-1.35	10
Lowest 50-percent flow[3]	9.23	8.63	-6.50	15
Winter runoff	33.22	34.82	4.82	15
Spring runoff	20.36	21.12	3.73	15
Summer runoff	17.99	15.05	-16.34	15
Fall runoff	23.91	24.41	2.09	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).

simulated total annual runoff for water years 1993–97 was 95.47 and 95.39 in., respectively. The percent difference of –0.08 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), spring (April, May, and June), and fall (October, November, and December) runoff were 4.82 percent, 3.73 percent, and 2.09 percent greater than the respective observed season runoff. Simulated total summer (July, August, and September) runoff was 2.94 in. (-16.34 percent) less than the observed summer runoff.

The observed and simulated annual runoff for the calibration period ranged from 10.12 to 24.58 and from 9.21 to 23.44 in., respectively (table 15). The percent difference between the simulated and observed annual runoff ranged from –9.11 to 11.67 percent. The long-term average annual runoff for Accotink Creek for water years 1948–2000 is 16.41 in. (White and others, 2001). Based on this long-term average, the streamflow model accurately simulated runoff over a range of hydrologic extremes from very dry (1995) to very wet (1996).

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 16). Between 28.54 percent and 31.87 percent of the annual runoff for water years 1993–97 was derived from base flow (ground-water inputs). Rutledge and Mesko (1996) calculated a base-flow index of 38.50 percent for Accotink Creek from streamflow data at Accotink Creek near Annandale, Va., for the period 1981–90. Base-flow contribution to streamflow in Accotink Creek varies seasonally from 38.50 percent in the spring to 17.67 percent in the summer, and contributions from surface runoff during spring and summer range from 47.63 to 70.63 percent, respectively (table 16).

Table 15. Observed and simulated annual runoff, Accotink Creek, Fairfax County, Virginia, water years 1993-97

Water year	Observed (inches)	Simulated (inches)	Difference (percent)[1]
1993	19.19	21.43	11.67
1994	22.51	20.46	-9.11
1995	10.12	9.21	-8.99
1996	24.58	23.44	-4.64
1997	19.07	20.85	9.33
Total	95.47	95.39	-0.08

[1]Value calculated as simulated minus observed divided by observed times 100.

Table 16. Simulated total annual and seasonal runoff, interflow and base flow for calibration period, Accotink Creek, Fairfax County, Virginia, water years, 1993-97

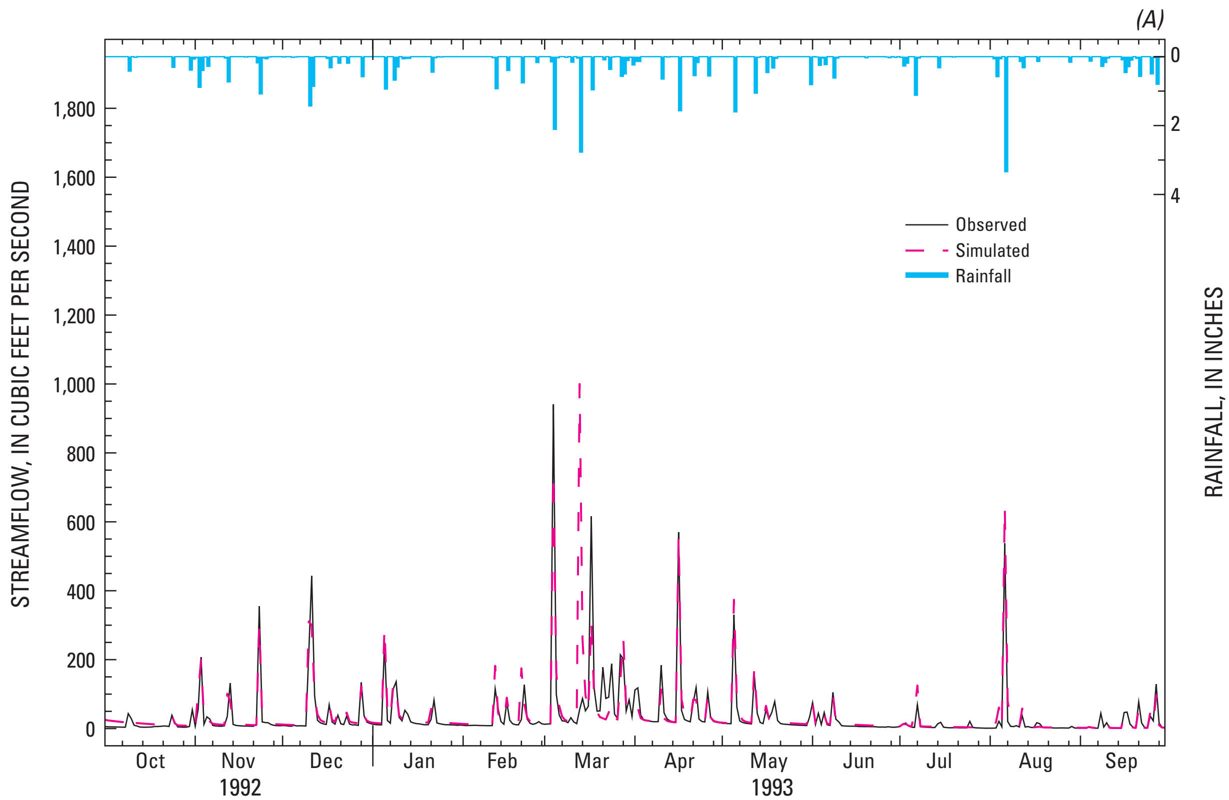
Water Year	Annual runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
1993	21.43	10.36	4.05	6.83	31.87
1994	20.46	10.99	4.15	5.12	25.02
1995	9.21	5.20	1.02	2.85	30.94
1996	23.44	12.20	4.21	6.84	29.18
1997	20.85	10.38	4.31	5.95	28.54
Total[1]	95.39	49.13	17.74	27.59	28.92

Water years 1993-97	Total runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
Winter	34.82	15.49	8.35	10.75	30.87
Spring	21.12	10.06	2.73	8.13	38.50
Summer	15.05	10.63	1.55	2.66	17.67
Fall	24.41	12.94	5.12	6.05	24.79
Total[1]	95.40	49.14	17.74	27.59	28.92

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

Various graphical comparisons provided information on the quality of the calibrated streamflow model. The hydrographs for water years 1993–97 show the simulated and observed streamflow response to individual precipitation events (fig. 11). 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 71 percent of the variability in observed streamflow is explained by simulated streamflow (fig. 12). Residual plots display the measured difference between simulated and observed; no difference will generate a residual equal to zero. Residuals between simulated and observed streamflow in Accotink Creek for water years 1993-97 are distributed uniformly around zero, indicating no bias in the model simulation (fig. 13). 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 Accotink Creek are similar over the majority of flow conditions except for the extreme low (less than 1 ft^3/s) and extreme high (greater than 700 ft^3/s) flows (fig. 14).

Graphical comparisons also were used to further evaluate the observed and simulated seasonal hydrologic response in Accotink Creek. 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. 15). The observed summer streamflow has the greatest amount of variability because Accotink Creek nearly ran dry during the summer of 1995. In addition, simulated flow-duration curves for winter, spring, and fall closely approximate the respective seasonal observed flow-duration curves (fig. 16). The simulated and observed summer flow-duration curves are similar over the majority of the flow conditions and variability increases only during the extreme high and low flows.



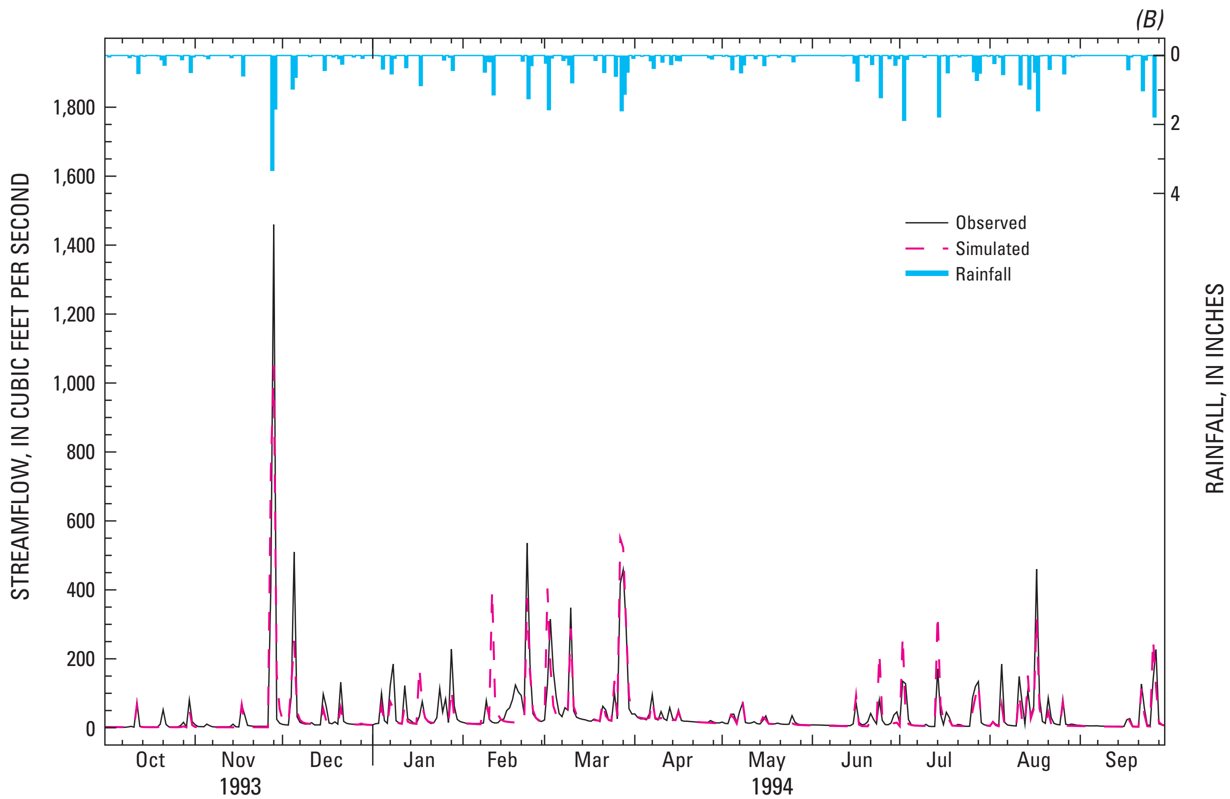


Figure 11. Daily rainfall and observed and simulated daily mean streamflows for water years 1993 *(A)*, 1994 *(B)*, 1995 *(C)*, 1996 *(D)*, and 1997 *(E)*, Accotink Creek, Fairfax County, Virginia.

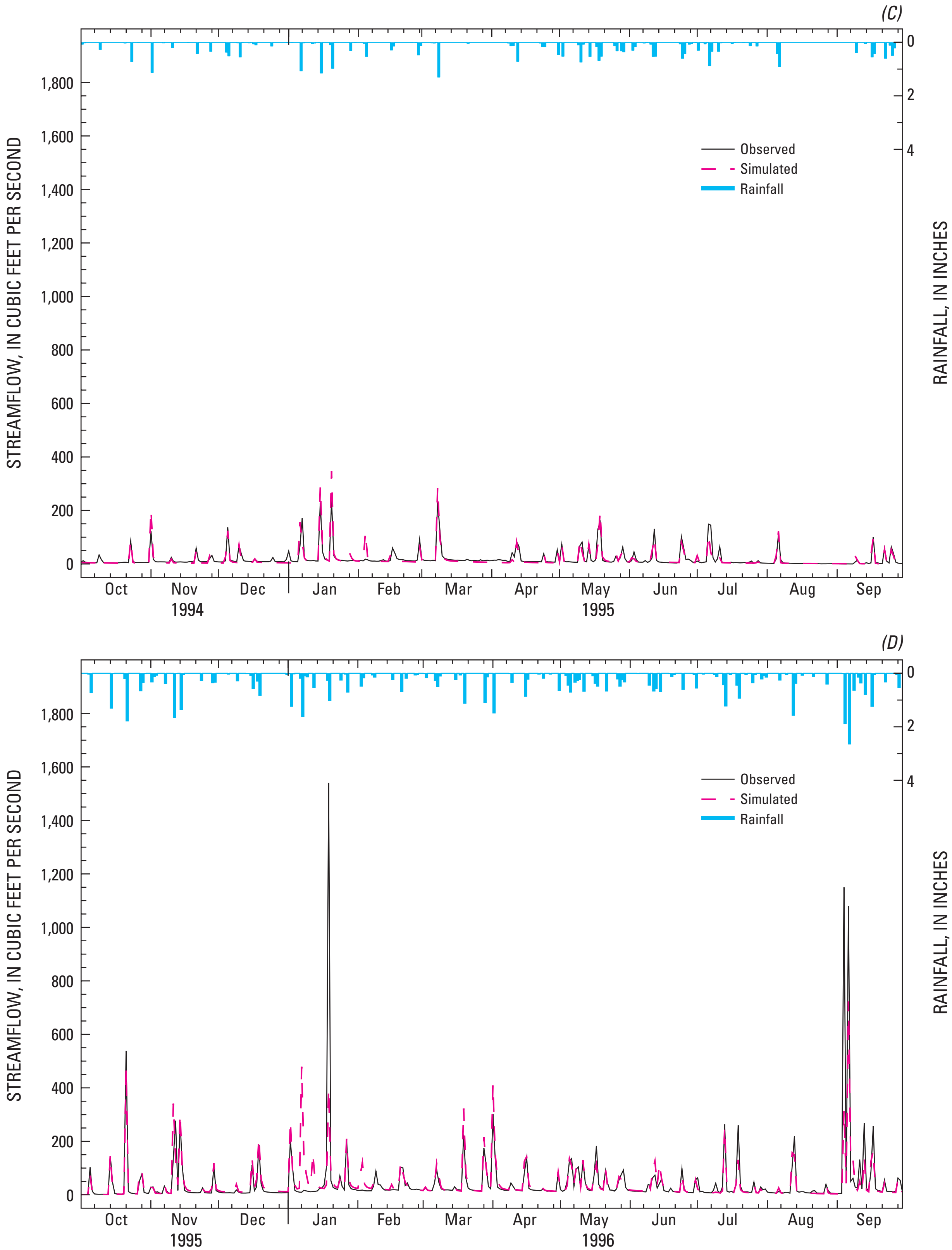


Figure 11. Daily rainfall and observed and simulated daily mean streamflows for water years 1993 *(A)*, 1994 *(B)*, 1995 *(C)*, 1996 *(D)*, and 1997 *(E)*, Accotink Creek, Fairfax County, Virginia—Continued.

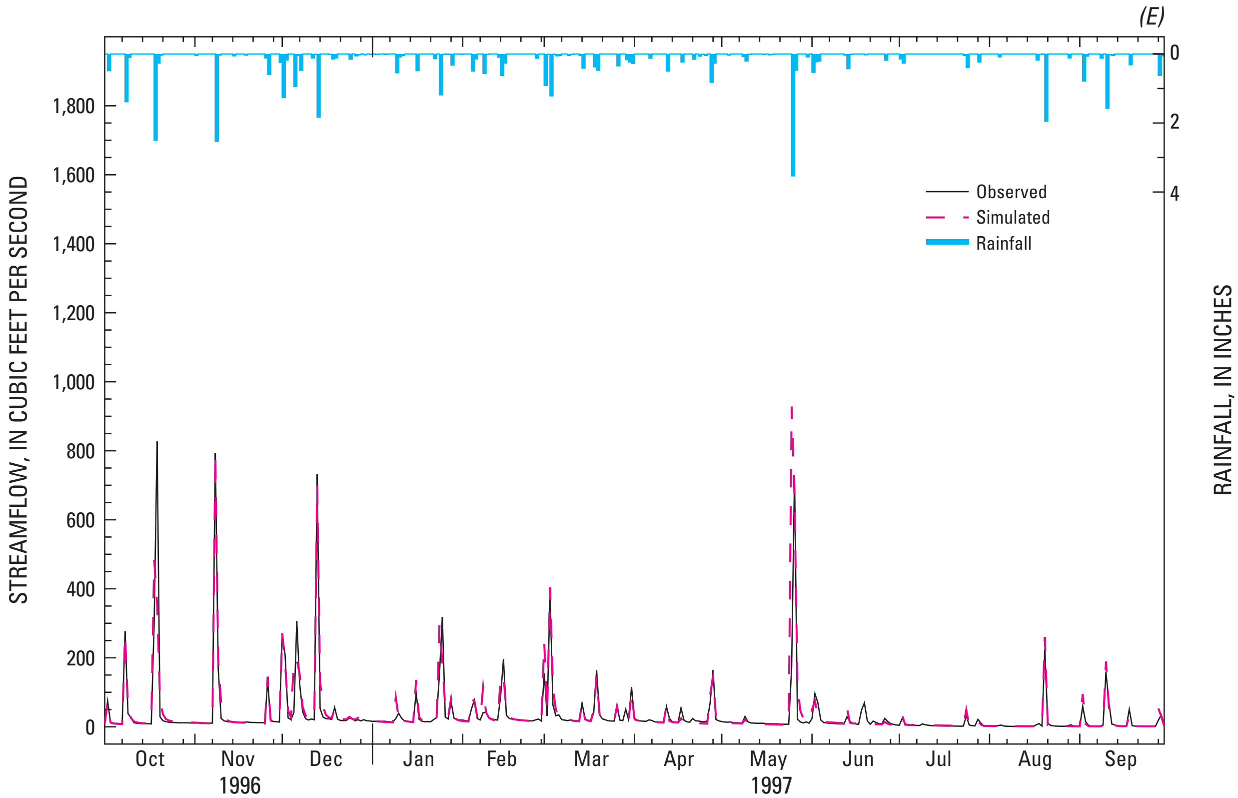


Figure 11. Daily rainfall and observed and simulated daily mean streamflows for water years 1993 *(A)*, 1994 *(B)*, 1995 *(C)*, 1996 *(D)*, and 1997 *(E)*, Accotink Creek, Fairfax County, Virginia—Continued.

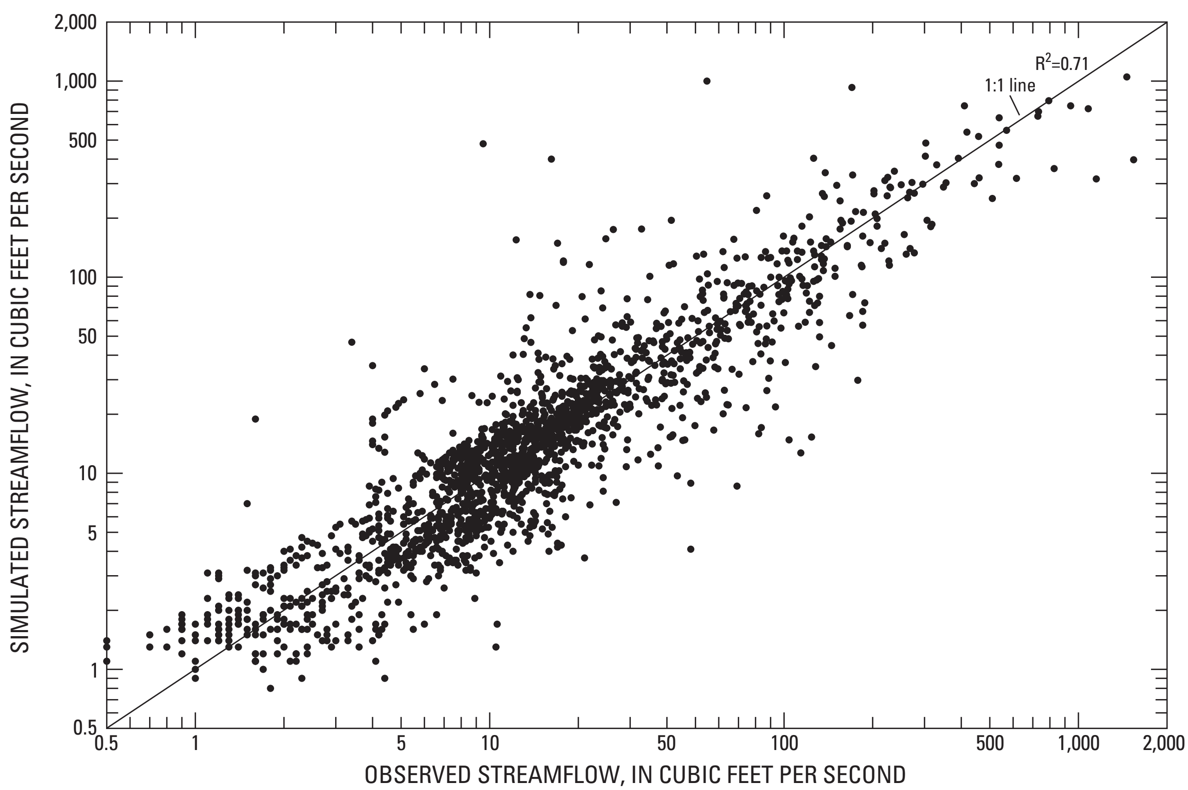


Figure 12. Simulated daily streamflow in relation to observed daily streamflow, Accotink Creek, Fairfax County, Virginia, water years 1993-97.

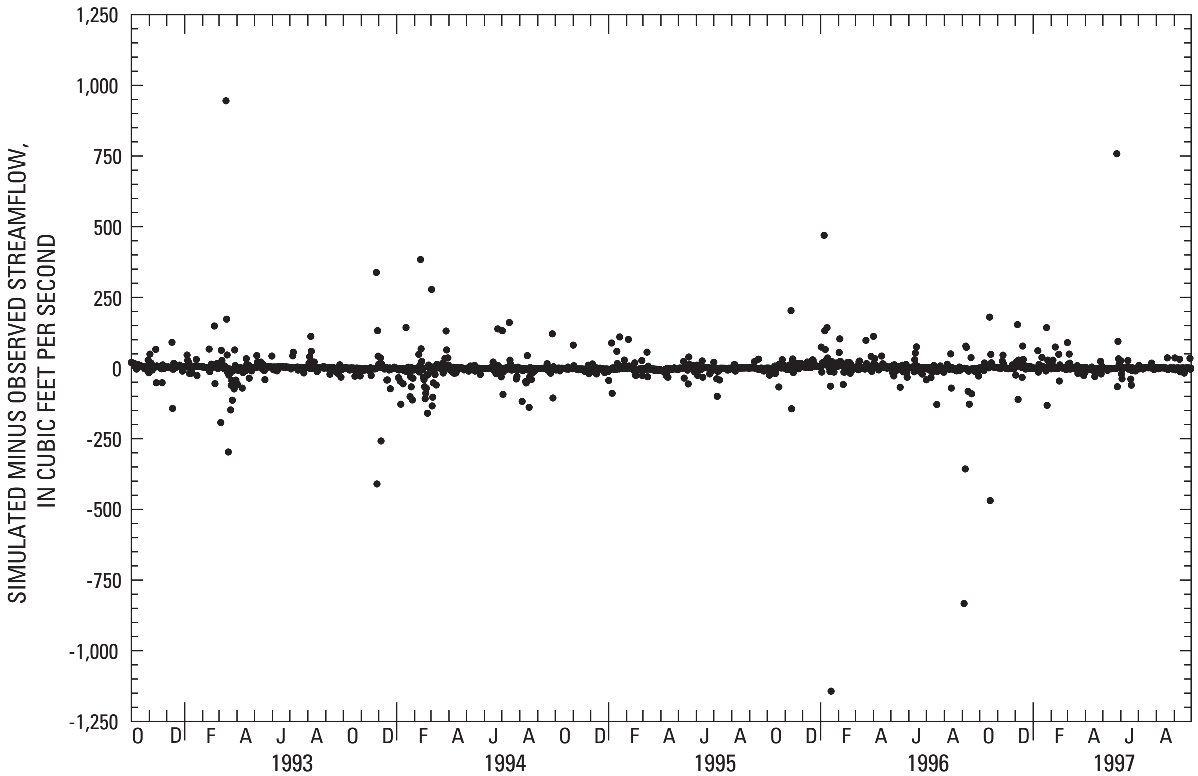


Figure 13. Residuals for simulated minus observed daily streamflow, Accotink Creek, Fairfax County, Virginia, water years 1993-97.

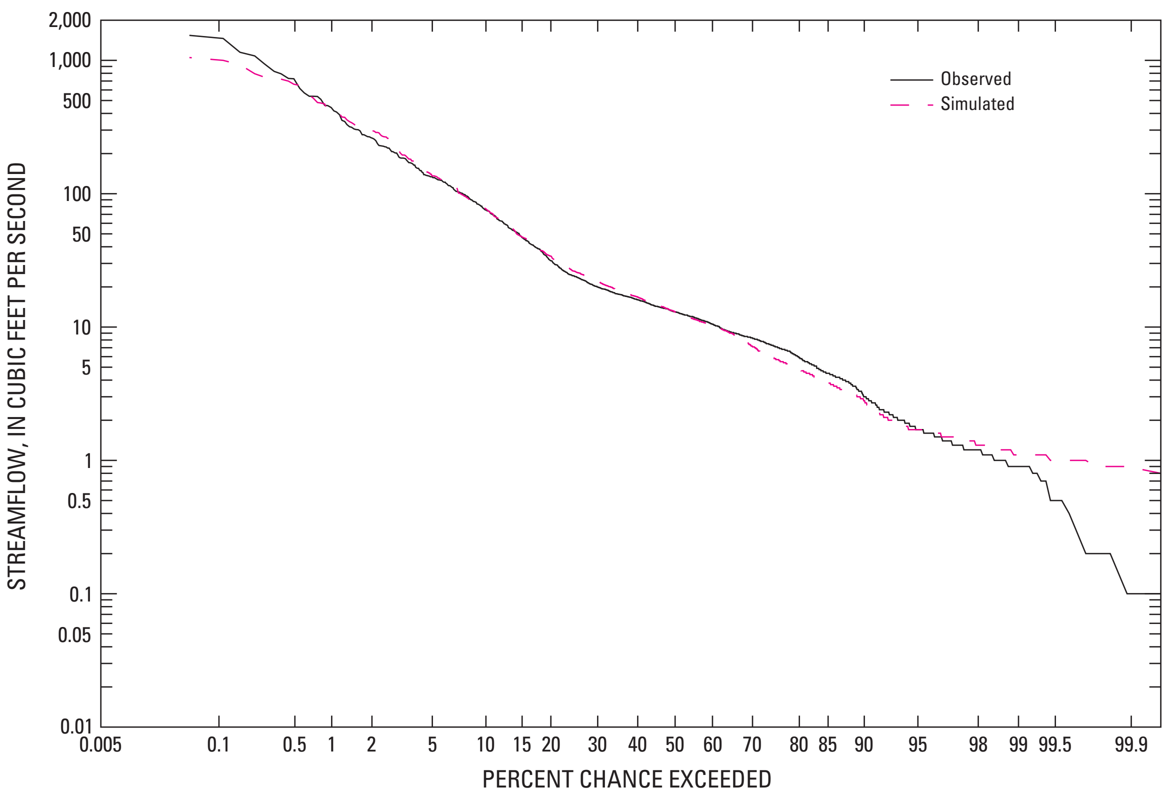


Figure 14. Flow-duration curves for observed and simulated daily mean streamflow, Accotink Creek, Fairfax County, Virginia, water years 1993-97.

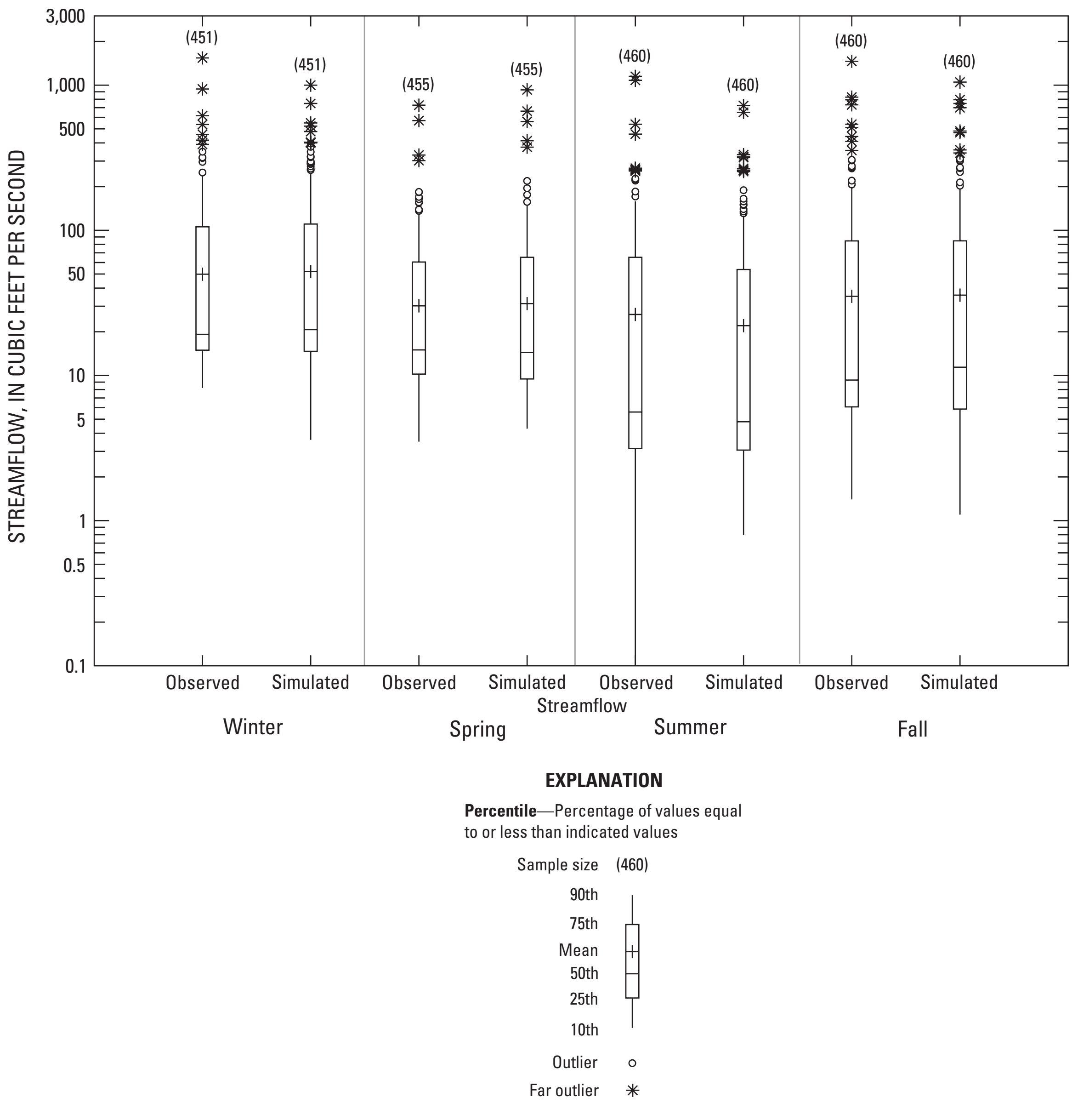
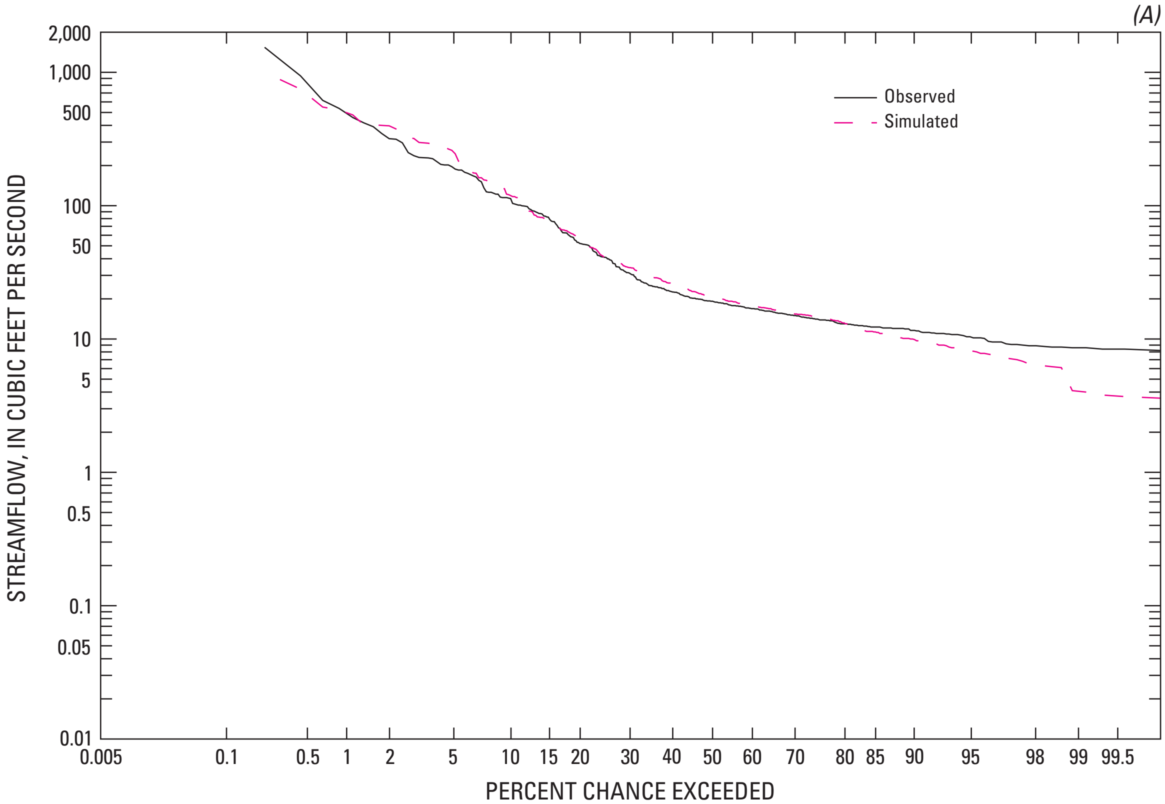


Figure 15. Observed and simulated daily streamflow (Winter, January-March; Spring, April-June; Summer, July-September; Fall, October-December), Accotink Creek, Fairfax County, Virginia, water years 1993-97.



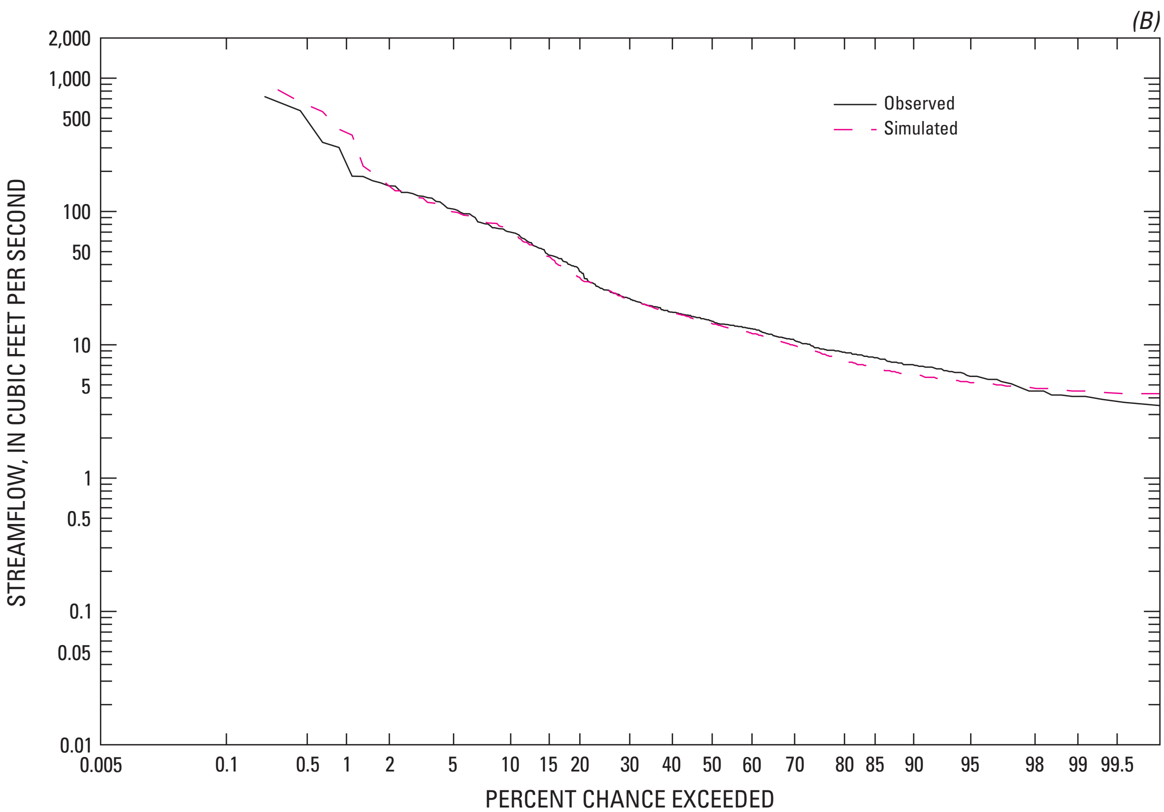
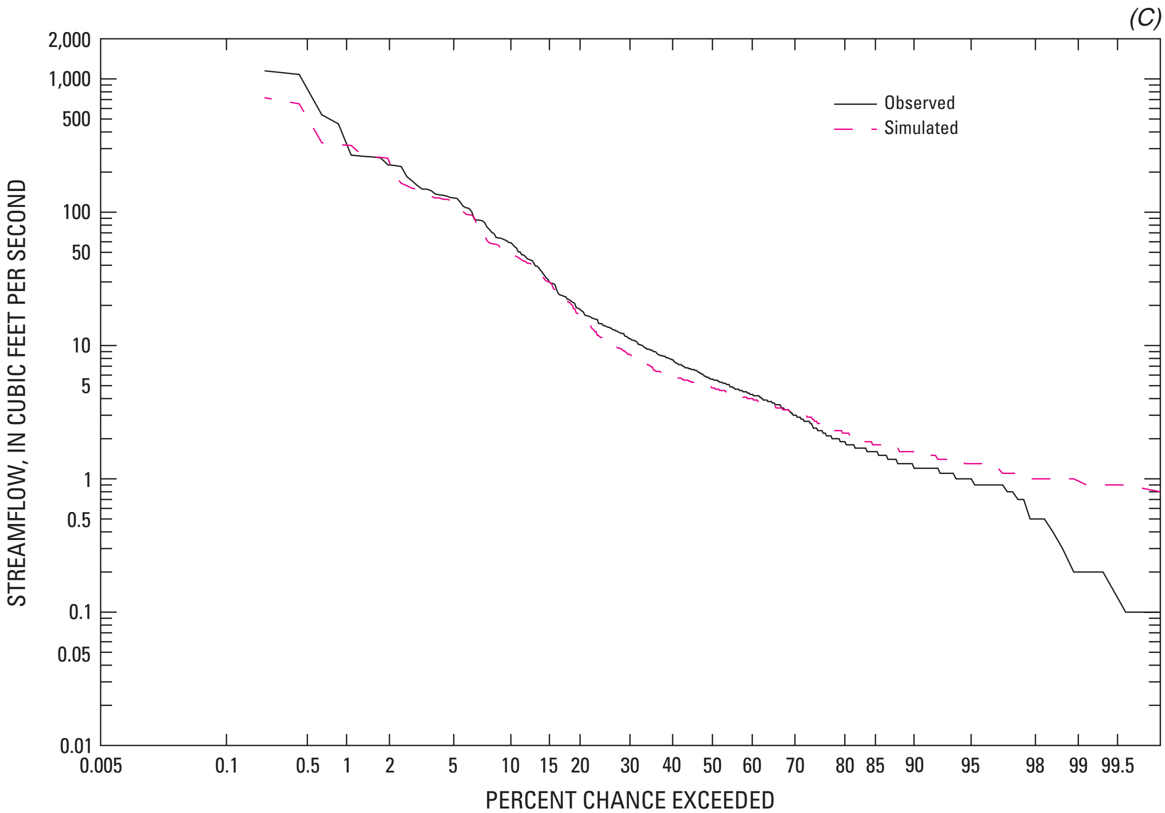


Figure 16. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Accotink Creek, Fairfax County, Virginia, water years 1993-97.



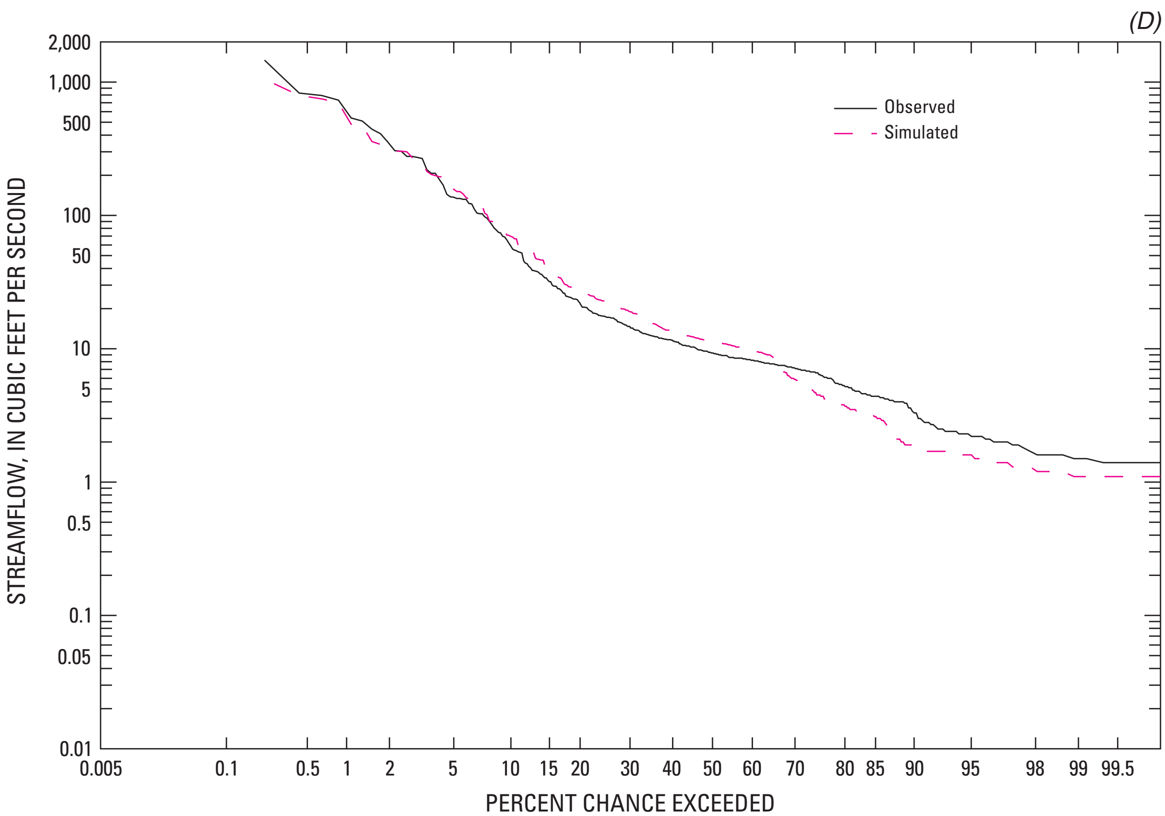


Figure 16. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Accotink Creek, Fairfax County, Virginia, water years 1993-97—Continued.

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 storm events during March 14–20, 1997, simulated and observed stormflow characteristics are similar except for stormflow timing (fig. 17A). The simulated stormflow response occurs approximately 3 hours before the observed response. This time lag is present because the Vienna Woods rainfall gage is 4.9 mi northwest of the streamflow gage on Accotink Creek. Storm movement for the northern Virginia area generally is from the northwest to the southeast; therefore, rain falls at the rain gage before falling over the rest of the watershed. For a large storm event during November 8–9, 1996 (fig. 17B), simulated and observed streamflow are similar with respect to storm peaks, volume, and recession, although an approximate 4-hour lag results.

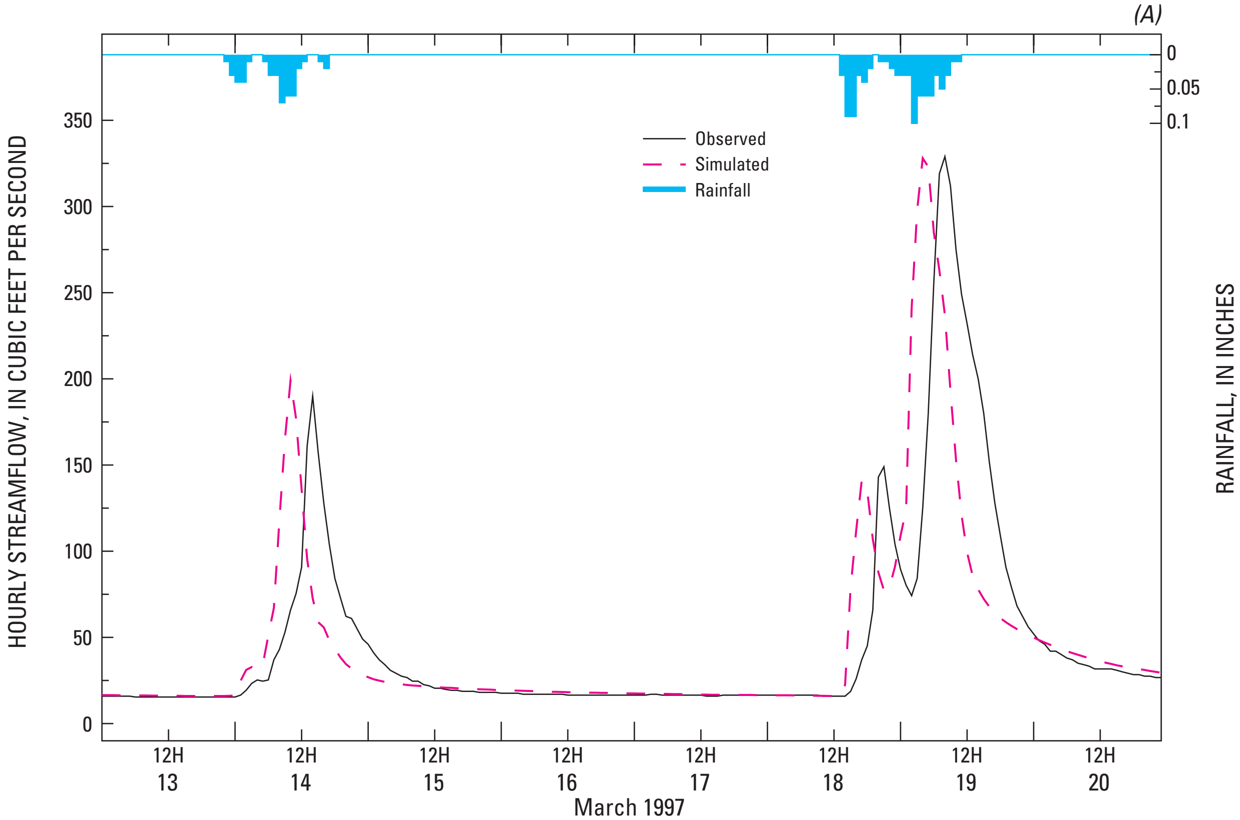
An example of a storm event for which the stormflow response was not well simulated occured during January 18–20, 1996 (fig. 17C). On January 19th, approximately 0.8 in. of rain fell on 9 in. of snow. The hydrologic model only accounted for the volume of water in the 0.8 in. of rain and not the 9 in. of snow. Consequently, the simulated and observed stormflow characteristics differ with respect to stormflow peaks and volume.

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.

The most important input dataset to the streamflow model is rainfall. Because of the spatial and temporal 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, on September 4, 1996, the observed measured daily rainfall at the Vienna Woods gage was 1.88 in. (fig. 11D). The simulated daily mean streamflow on September 4th was 317 ft^3/s, whereas the observed daily mean streamflow was 1,150 ft^3/s. The amount of rainfall recorded at Vienna Woods on this date was compared with rainfall measurements of 3.14, 1.29, and 1.83 in. at nearby Vienna Dunn Loring, Washington Dulles Airport, and Ronald Reagan National Airport rain gages (operated by the National Oceanic and Atmospheric Administration), respectively. Because the data from Vienna Woods fell within the range of rainfall data from surrounding gages, the data value from Vienna Woods was used during the simulation. However, the observed streamflow indicate that greater than 1.88 in. of rain fell within the Accotink Creek watershed. This result is one example of model error that occurred because of input rainfall data. When large errors between simulated and observed streamflow resulted, the measured rainfall data from Vienna Woods were evaluated with data collected at nearby rain gages. There were no occasions where results of rainfall analysis from nearby rain gages warranted changes to the Vienna Woods rainfall dataset.

Snowfall on the watershed also caused differences between simulated and observed streamflow. Snow accumulation and melt was not included in the streamflow model for Accotink Creek 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 snow accumulation on the land surface. The extended period of undersimulated storms occurs because the additional volume of water stored in the snow on the ground 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 13–24, 1993; February 11–23, 1994; and January 6–20, 1996 (fig. 11).



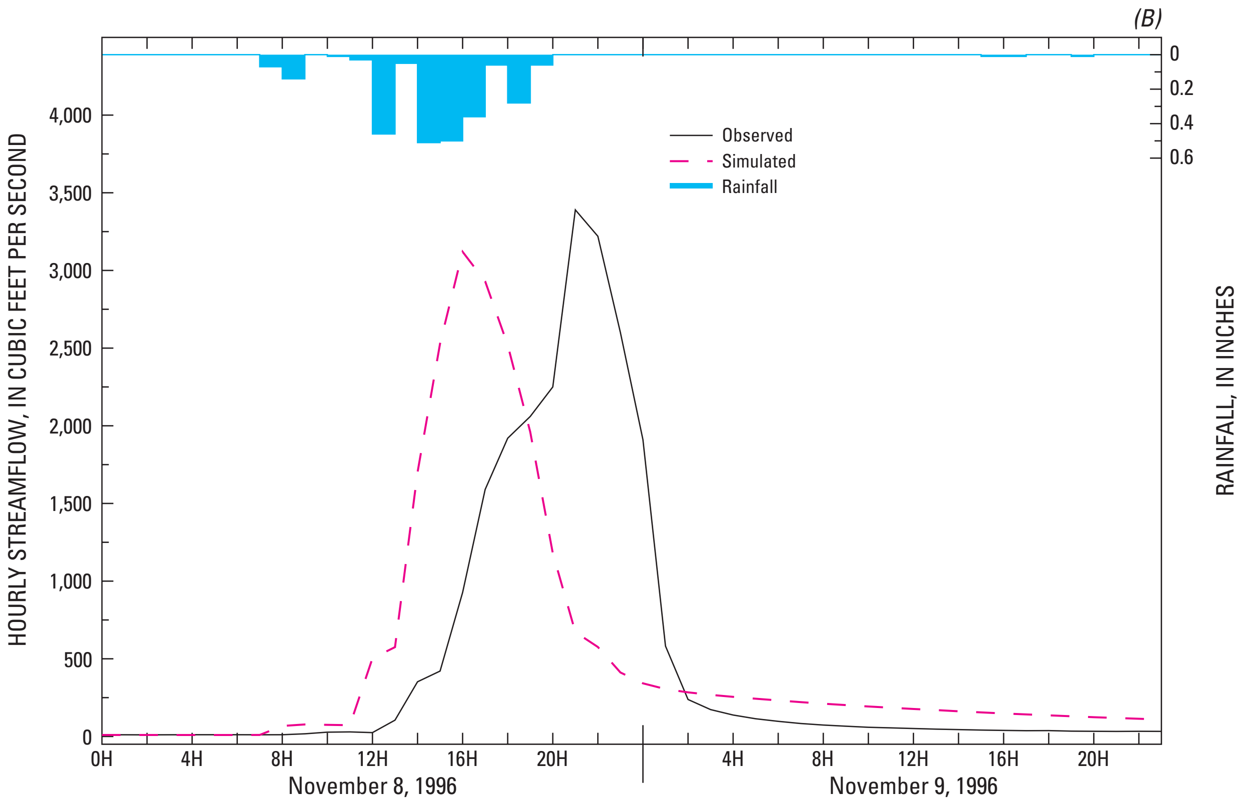


Figure 17. Hourly rainfall and observed and simulated daily mean streamflow, March 13-20, 1997 (A), November 8-9, 1996 (B), and January 18-20, 1996 (C), Accotink Creek, Fairfax County, Virginia.

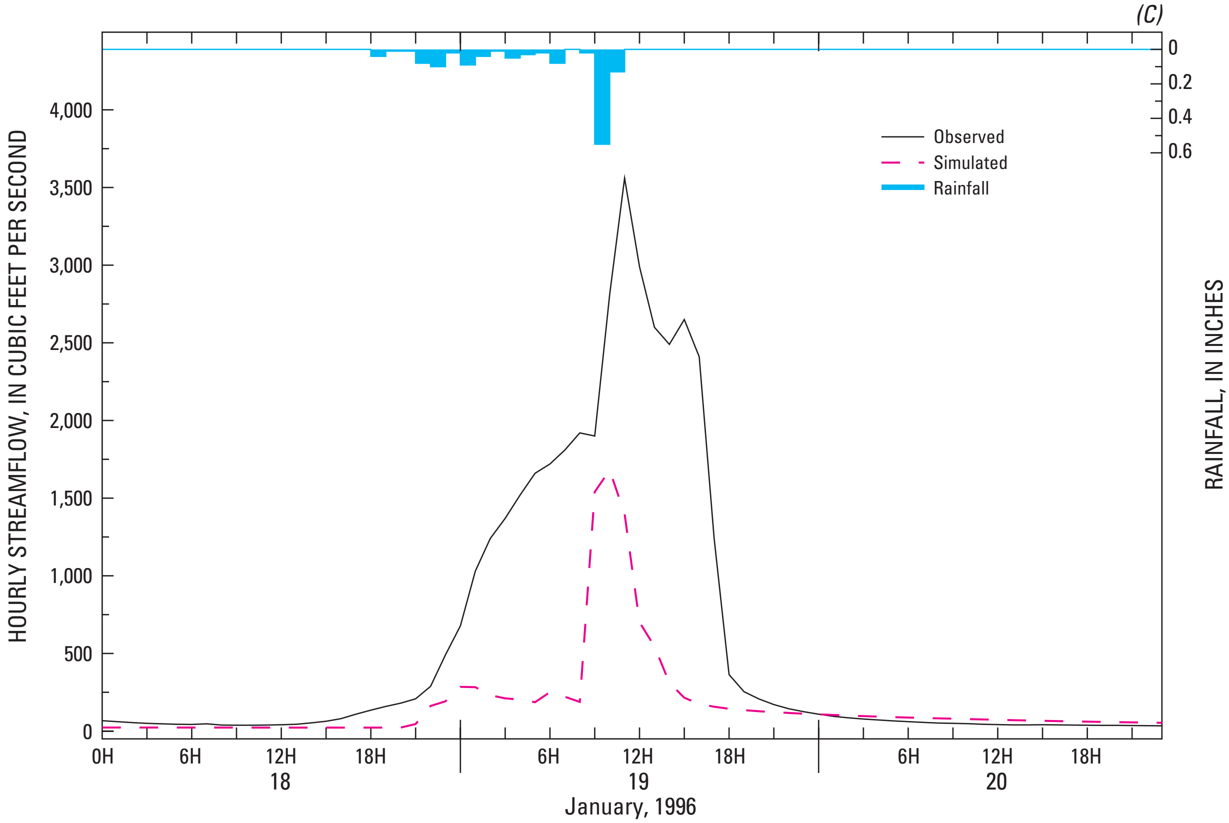


Figure 17. Hourly rainfall and observed and simulated daily mean streamflow, March 13-20, 1997 (A), November 8-9, 1996 (B), and January 18-20, 1996 (C), Accotink Creek, Fairfax County, Virginia—Continued.

Streamflow Model Verification Results

The verification process tests the capacity of the calibrated streamflow model to simulate streamflow during a time period that was not used for model calibration and, thus, is the best test of model reliability.

Streamflow model verification results first were assessed by comparing simulated and observed streamflow from the Route 620 stream gage for water years 1998-99 (table 17). Observed and simulated total annual runoff for water years 1998–99 was 35.03 and 37.67 in., respectively. The 7.54 percent difference is within the designated 10-percent criterion and indicates that the simulated water budget closely approximates the observed water budget. The percent difference between the total of the highest 10-percent flows was –1.84 percent. The total of the lowest 50-percent flows was 1.77 and 2.12 in. for observed and simulated flows, respectively, with a 19.77 percent difference. This percent difference can be explained by the drought of the summer of 1999, where Accotink Creek was reduced to a series of disconnected pools while simulated flow during this period did not change. Simulated winter (January, February, and March), spring (April, May, and June), and summer (July, August, and September) runoff were 10.42, 3.40, and 9.98 percent greater than the respective observed season runoff. Simulated total fall (October, November, and December) runoff was 0.23 percent less than the observed fall runoff.

The observed and simulated annual runoff for water years 1998-99 were 22.80 and 23.94 in., and 12.23 and 13.73 in., respectively (table 18). The percent difference between the simulated and observed annual runoff for water years 1998-99 was 5.00 percent and 12.26 percent, respectively. The long-term average annual runoff for Accotink Creek for water years 1948–2000 is 16.41 in. (White and others, 2001). Based on this long-term average, the verification of the calibrated streamflow model included an unusually dry (1998) and wet (1996) year. Total simulated runoff was derived from surface runoff, interflow, and base flow (table 19). A total of 26.60 percent of the total annual

Table 17. Observed and simulated runoff values for Route 620, for Accotink Creek, Fairfax County, Virginia, water years 1998-99

Runoff category	Observed (inches)	Simulated (inches)	Difference (percent)[1]	Criterion (percent)
Total annual runoff	35.03	37.67	7.54	10
Highest 10-percent flow[2]	23.94	23.50	-1.84	10
Lowest 50-percent flow[3]	1.77	2.12	19.77	15
Winter runoff	16.69	18.43	10.42	15
Spring runoff	7.92	8.19	3.40	15
Summer runoff	6.14	6.76	9.98	15
Fall runoff	4.30	4.29	-0.23	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).

runoff for water years 1998-99 was derived from base flow (ground-water inputs), which is consistent with the findings from Rutledge and Mesko (1996) that 31.6 percent of the total annual runoff for Accotink Creek (1981–90) was derived from base flow. Base-flow contribution to streamflow in Accotink Creek varied seasonally from 39.90 percent in the spring to 15.51 percent in the summer, whereas contributions from surface runoff ranged from 46.76 percent in the spring to 68.64 percent in the summer (table 19).

Table 18. Observed and simulated annual runoff, Accotink Creek, Fairfax County, Virginia, water years 1998-99

Water year	Observed (inches)	Simulated (inches)	Difference (percent)[1]
1998	22.80	23.94	5.00
1999	12.23	13.73	12.26
Total	35.03	37.67	7.54

[1]Value calculated as simulated minus observed divided by observed times 100.

Various graphical comparisons also were used to evaluate the results of the streamflow model verification. Graphical representation included data from water years 1998 and 1999, and from October 1 to December 31, 1999. Hydrographs for the verification period generally show good agreement between simulated and observed daily mean values for streamflow during individual rainfall events (fig. 18). A strong correlation was observed between simulated and observed streamflow where 79 percent of the variability in observed streamflow is explained by simulated streamflow (fig. 19). Residuals between simulated and observed streamflow in Accotink Creek vary normally around zero, indicating a lack of bias in the model simulation (fig. 20). Flow-duration curves for simulated and observed daily flows are similar over the majority of flows except for the extreme low (less than 1 ft^3/s) and extreme high (greater than 500 ft^3/s) flows (fig. 21).

Additional graphical comparisons were used to further evaluate the observed and simulated seasonal hydrologic response in Accotink Creek. 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. 22). Observed summer streamflow has the greatest amount of variability because Accotink Creek ran dry during the 1999 drought. Flow-duration curves also illustrate how closely the model simulates the observed seasonal hydrologic response (fig. 23). Simulated flow-duration curves for winter and spring closely approximate the observed flow-duration curves. The simulated and observed flow-duration curves for summer and fall indicate the greatest separation for flows less than 5 ft^3/s.

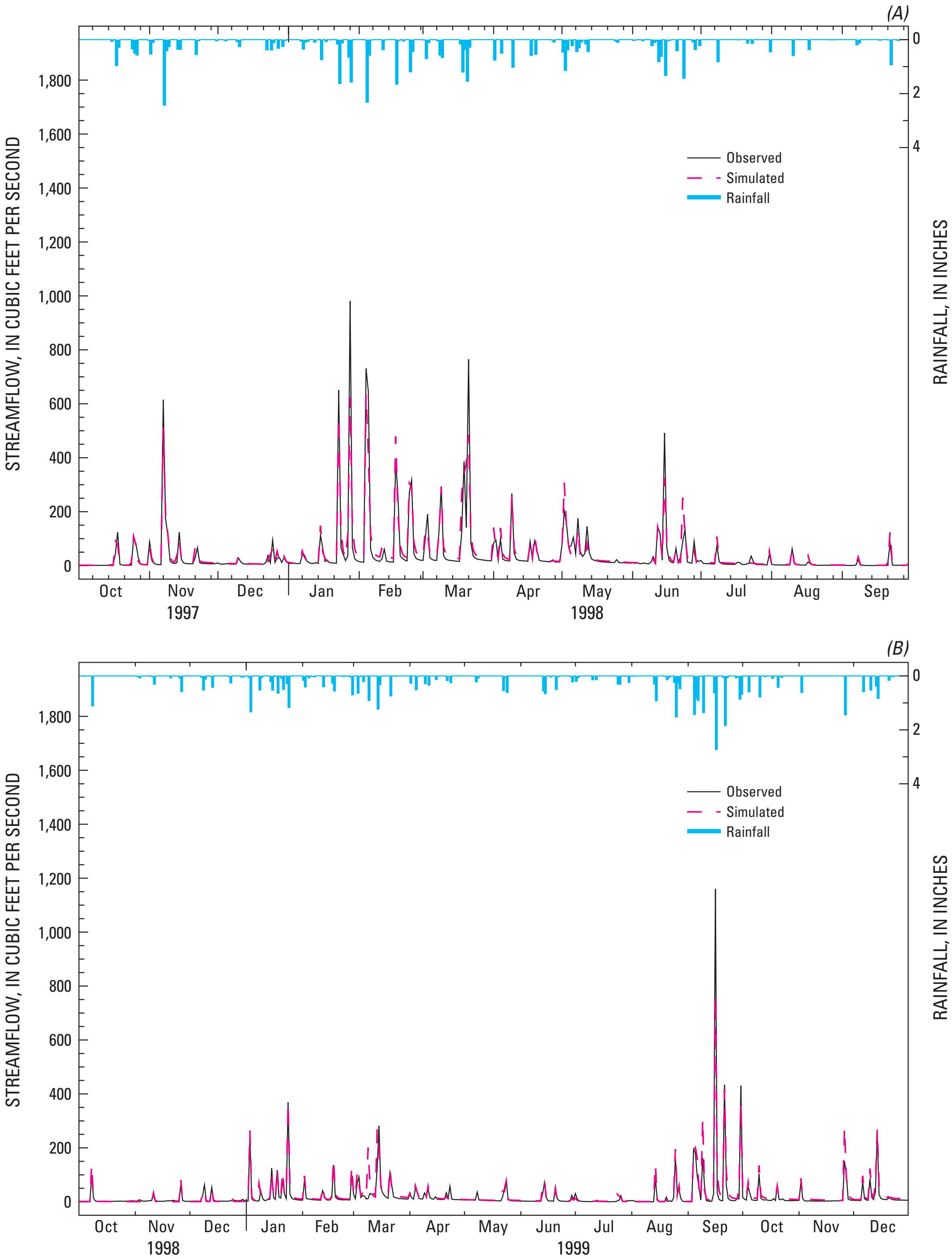


Figure 18. Daily rainfall and observed and simulated daily mean streamflow for October 1, 1997-September 30, 1998 (A) and October 1, 1998-December 31, 1999 (B), Accotink Creek, Fairfax County, Virginia.

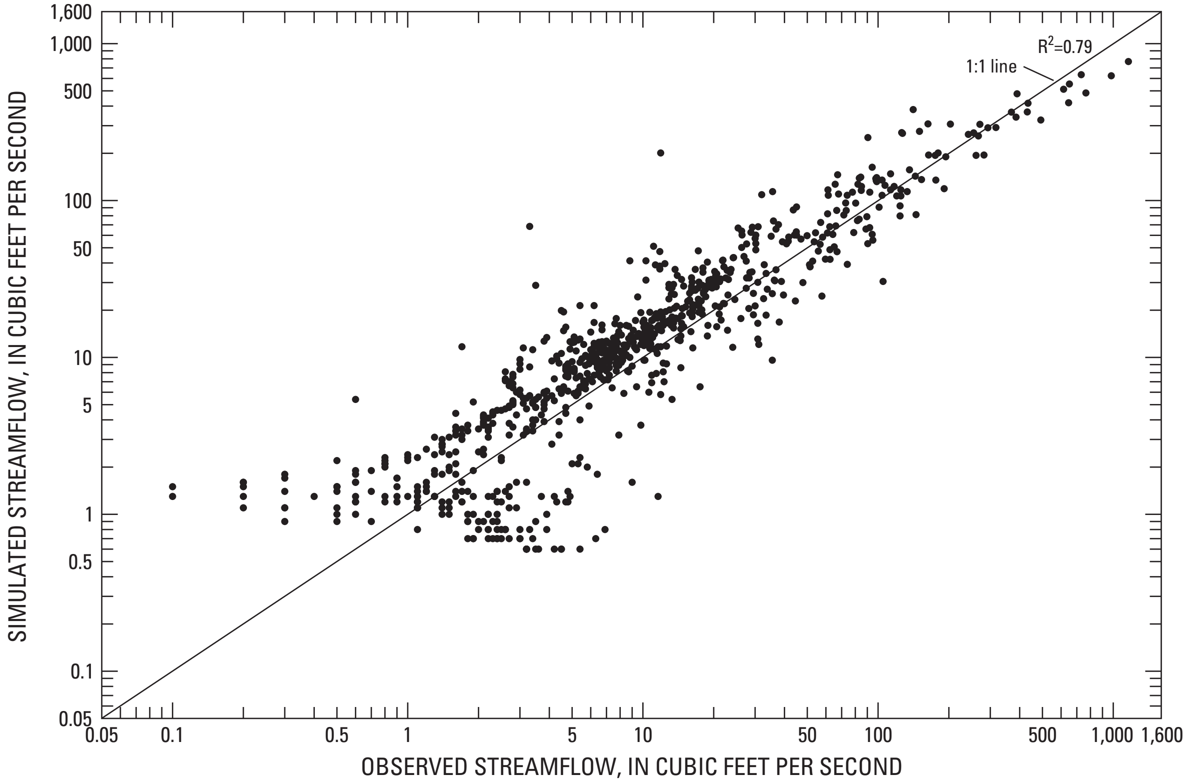


Figure 19. Simulated daily streamflow in relation to observed daily streamflow, Accotink Creek, Fairfax County, Virginia, October 1, 1997-December 31, 1999.

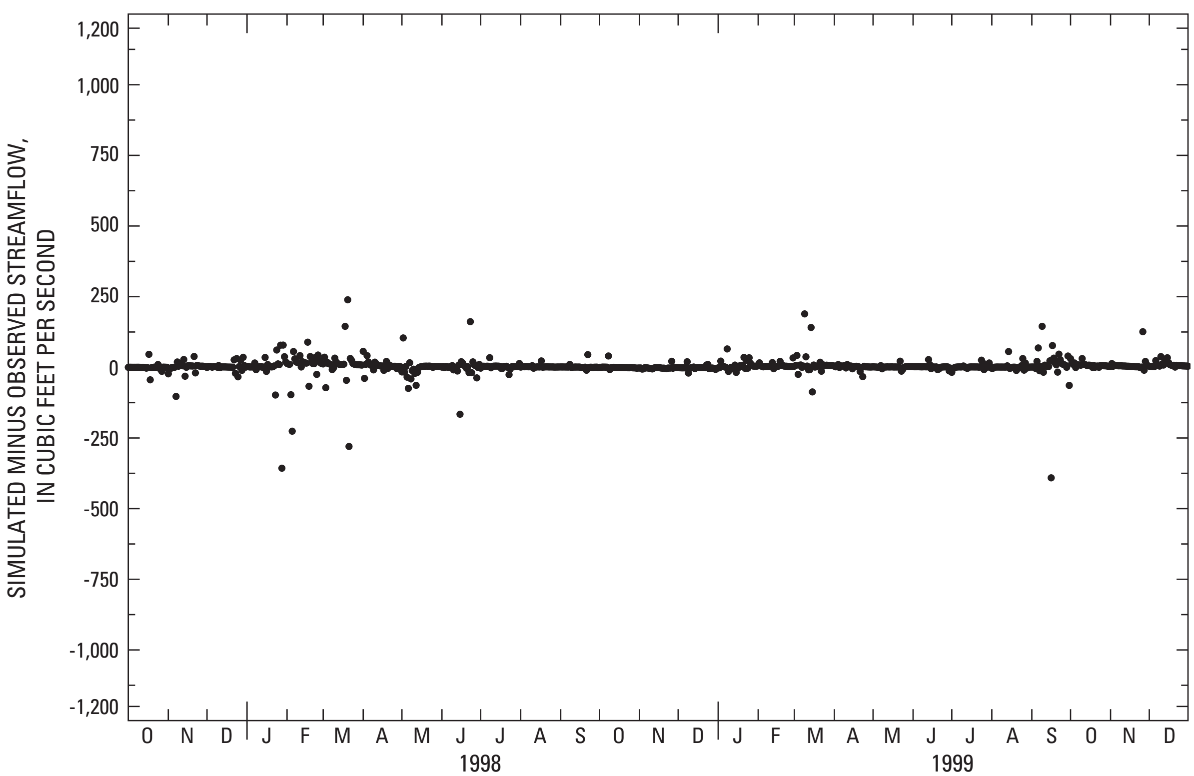


Figure 20. Residuals for simulated minus observed daily streamflow, Accotink Creek, Fairfax County, Virginia, October 1, 1997-December 31, 1999.

Table 19. Simulated total annual and seasonal runoff, surface runoff, interflow and base flow for verification period, Accotink Creek, Fairfax County, Virginia, water years 1998-99

Water year	Annual runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
1998	23.94	11.48	5.27	7.00	29.24
1999	13.73	8.35	2.21	3.02	22.00
Total[1]	37.67	19.83	7.48	10.02	26.60

Water years 1998-1999	Total runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
Winter	18.43	8.67	4.90	4.75	25.74
Spring	8.19	3.83	1.02	3.27	39.90
Summer	6.76	4.64	1.00	1.05	15.51
Fall	4.29	2.69	.56	.96	22.45
Total[1]	37.67	19.83	7.48	10.02	26.60

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

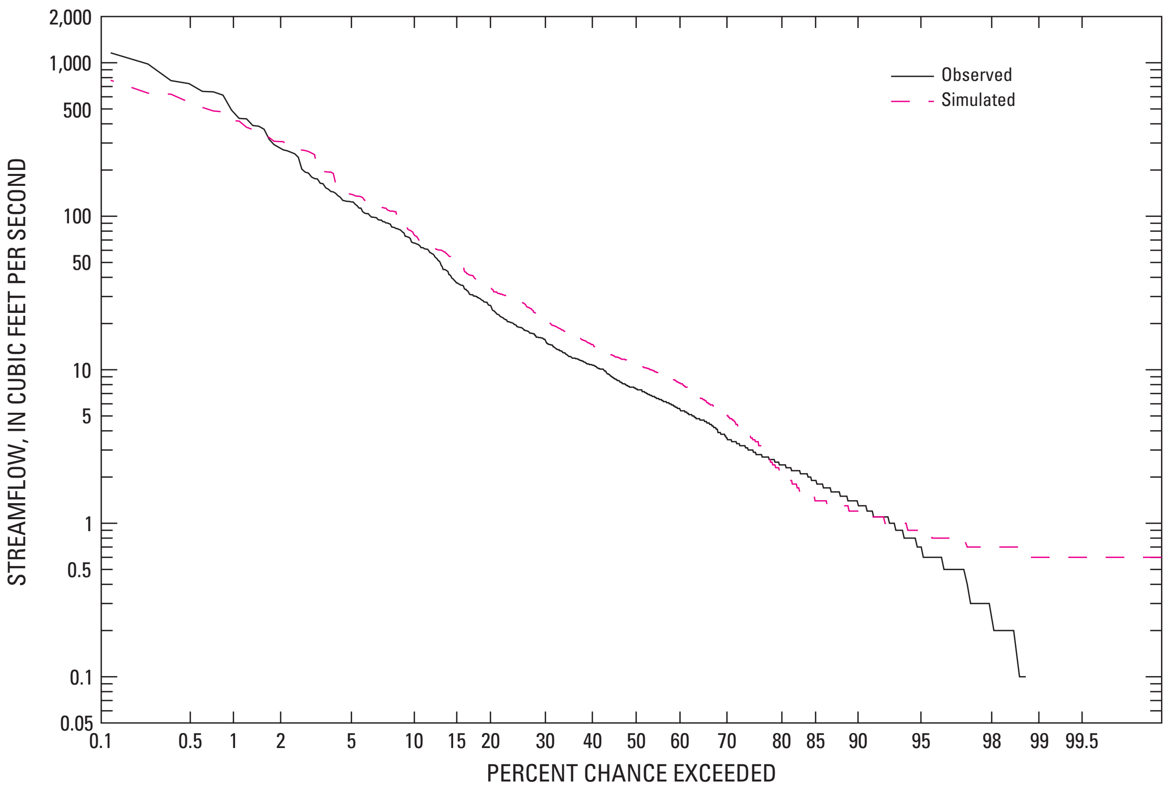


Figure 21. Flow-duration curves for observed and simulated daily mean streamflow, Accotink Creek, Fairfax County, Virginia,

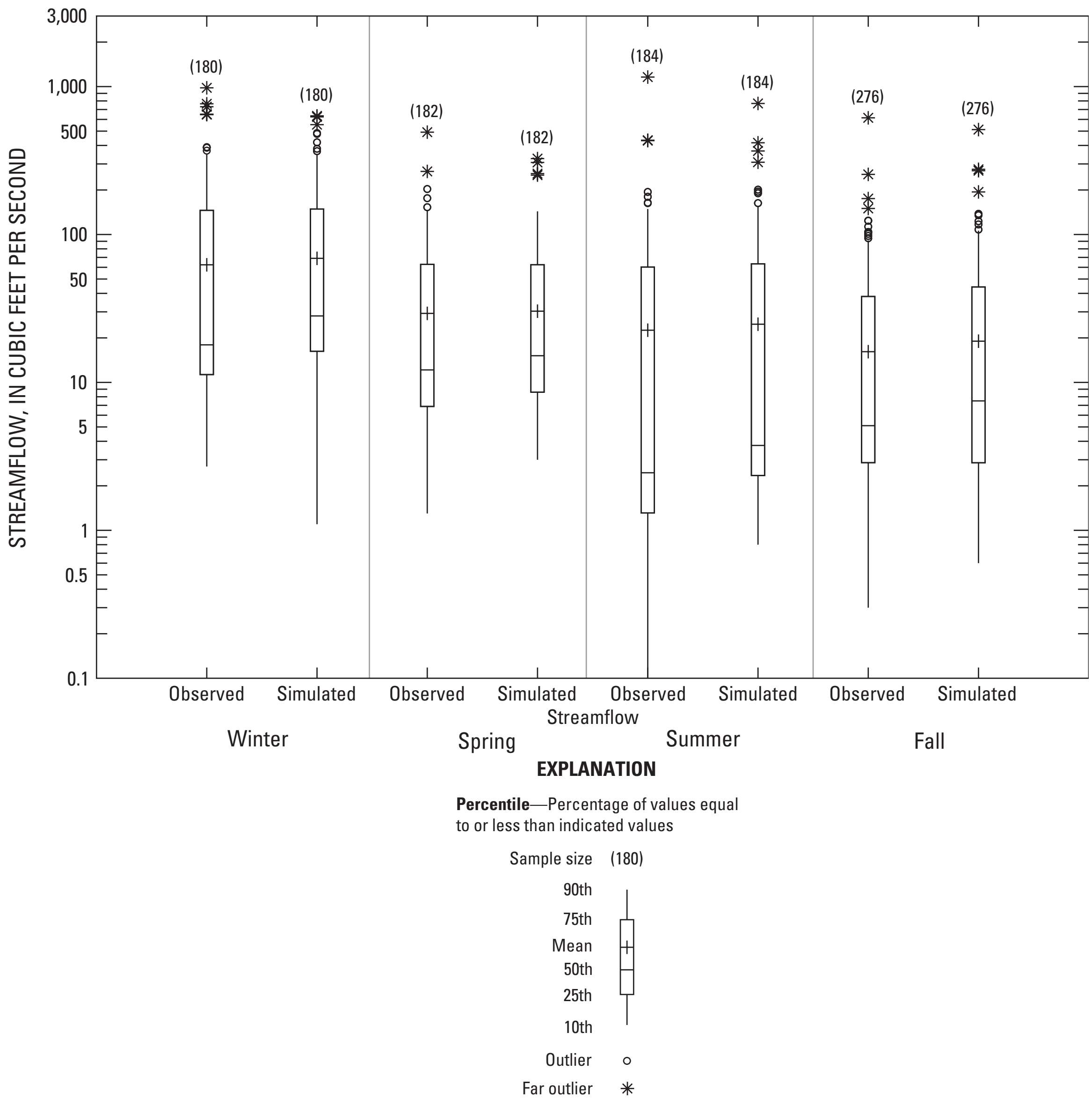


Figure 22. Observed and simulated daily streamflow (Winter, January-March; Spring, April-June; Summer, July-September; Fall, October-December), Accotink Creek, Fairfax County, Virginia, October 1, 1997-December 31, 1999.October 1, 1997-December 31, 1999.

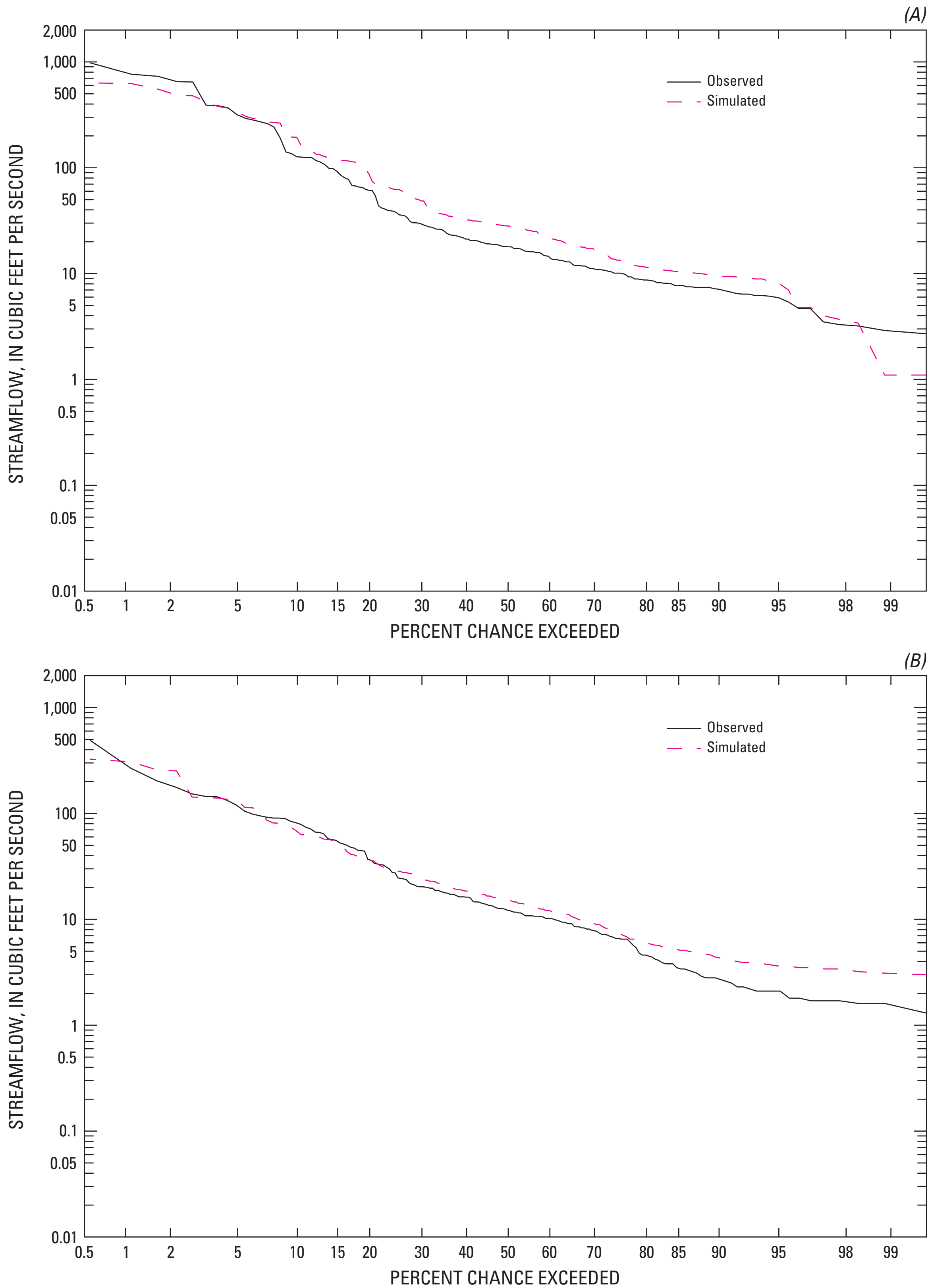
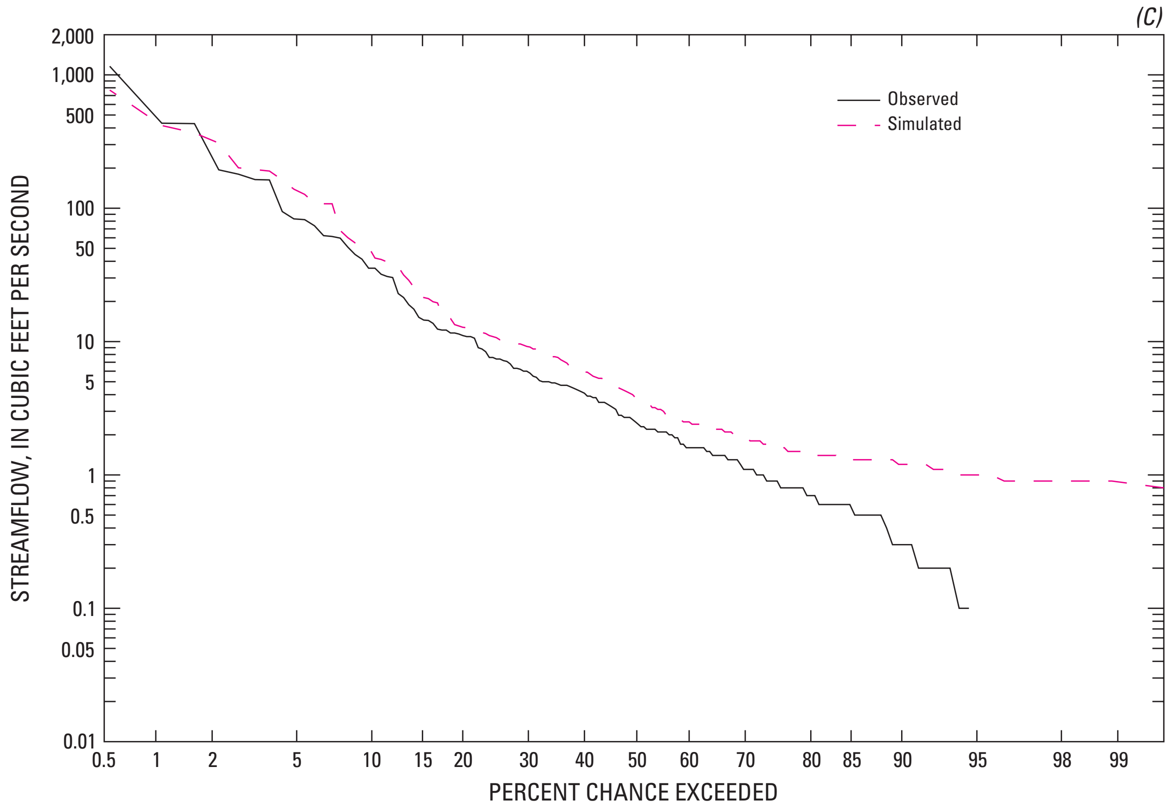


Figure 23. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Accotink Creek, Fairfax County, Virginia, October 1, 1997-December 31, 1999.



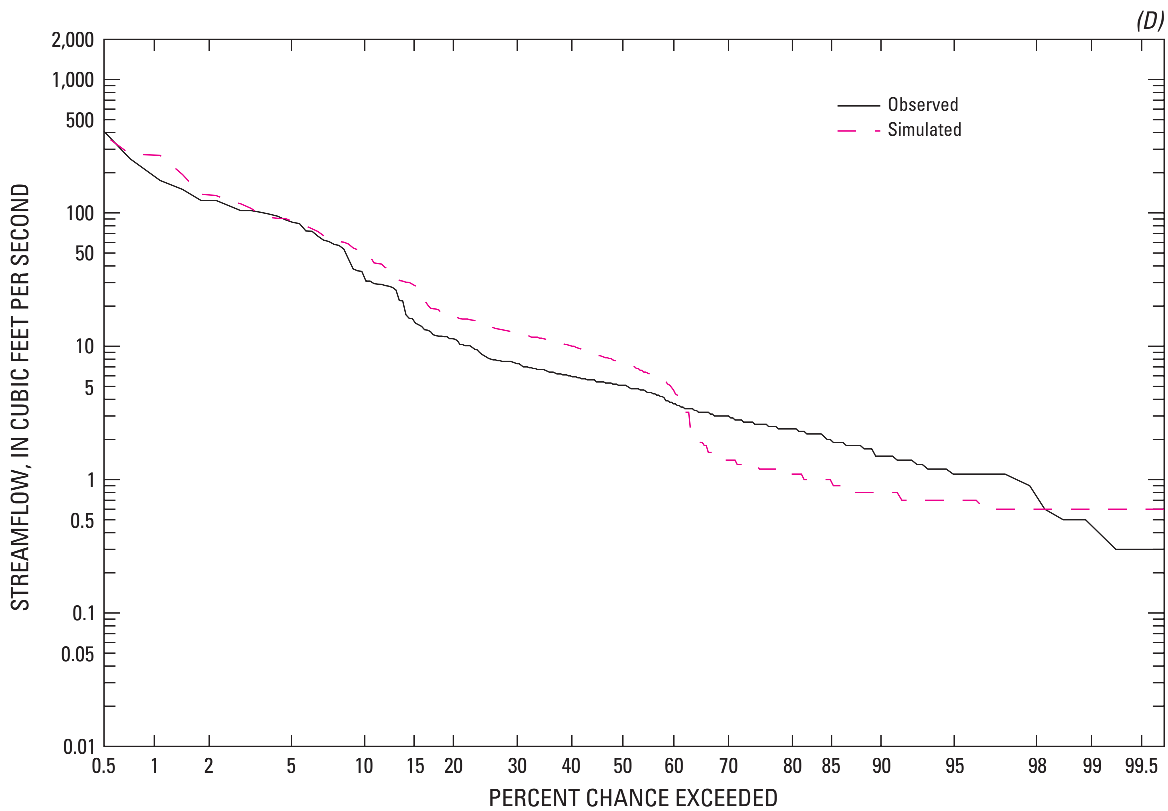


Figure 23. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Accotink Creek, Fairfax County, Virginia, October 1, 1997-December 31, 1999—Continued.

The streamflow model verification also was evaluated on an hourly time step. The simulated and observed stormflow characteristics for the October 17-18, 1997, storm event are similar except for stormflow timing (fig. 24A). In the Accotink Creek watershed, rain generally falls at the Vienna Woods rain gage before falling over the rest of the watershed. The observed and simulated streamflow responses for the large April 9-10, 1998, storm were similar with respect to storm volume and recession, whereas the storm peaks and timing are slightly askew (fig. 24B). The simulated and observed stormflow responses did not match closely for the September 15-17, 1999, event (fig. 24C). Rainfall during this event was associated with Hurricane Floyd. The discrepancies in the simulated and observed stormflow responses are attributed to rainfall data and/or model calibration. Measured rainfall at Vienna Woods during Hurricane Floyd was 3.36 in. while 3.12, 2.40, 2.47, and 4.57 in. of rainfall was measured at nearby Vienna Dunn Loring, Sterling RCS (Reference Climatological Station), Washington Dulles Airport, and Ronald Reagan National Airport rain gages, respectively. The undersimulated storm peak and volume indicate that greater than 3.36 in. of rain fell in the Accotink Creek watershed during Hurricane Floyd. Another possible explanation is that the model is not calibrated to represent such a large storm event.

Final Streamflow Model Parameters

The results of the streamflow model calibration demonstrate its effectiveness for simulating streamflow response in Accotink Creek. 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 20).

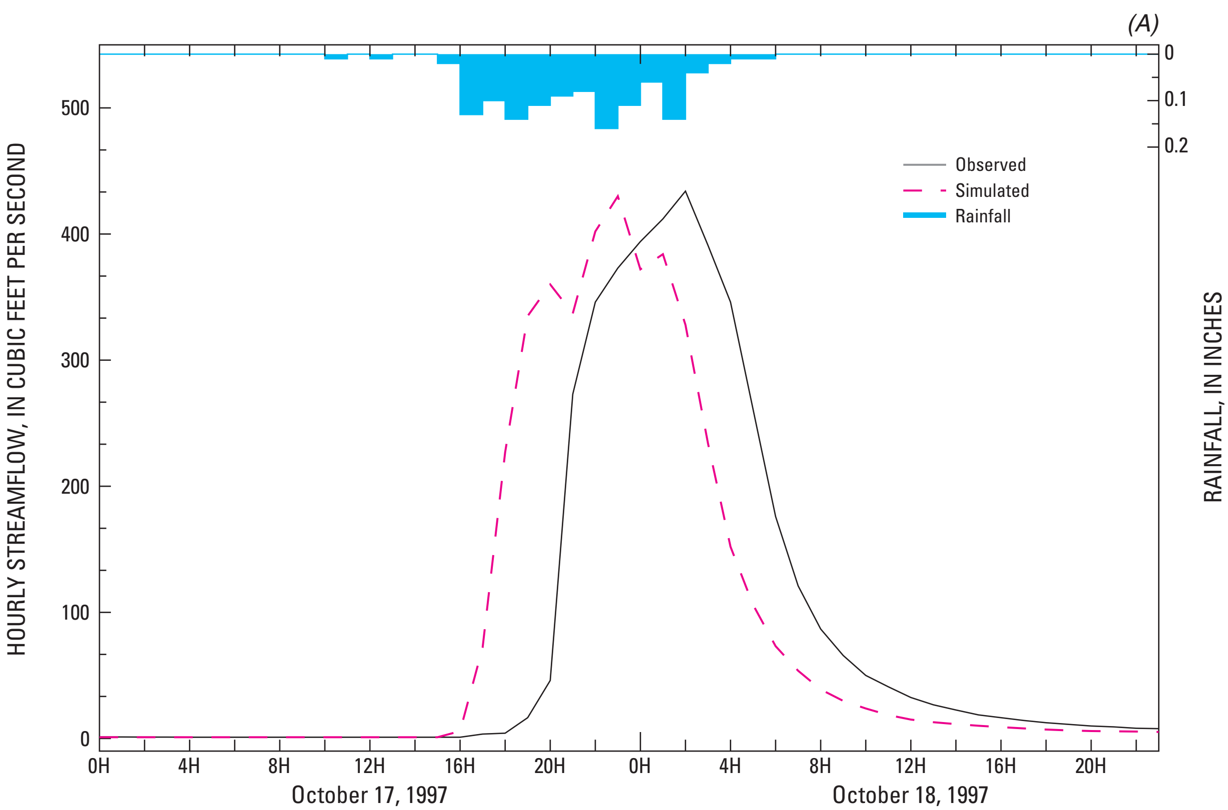


Figure 24. Hourly rainfall and observed and simulated daily mean streamflow, October 17-18, 1997 *(A)*, April 9-10, 1998 *(B)*, and September 15-17, 1999 *(C)*, Accotink Creek, Fairfax County, Virginia.

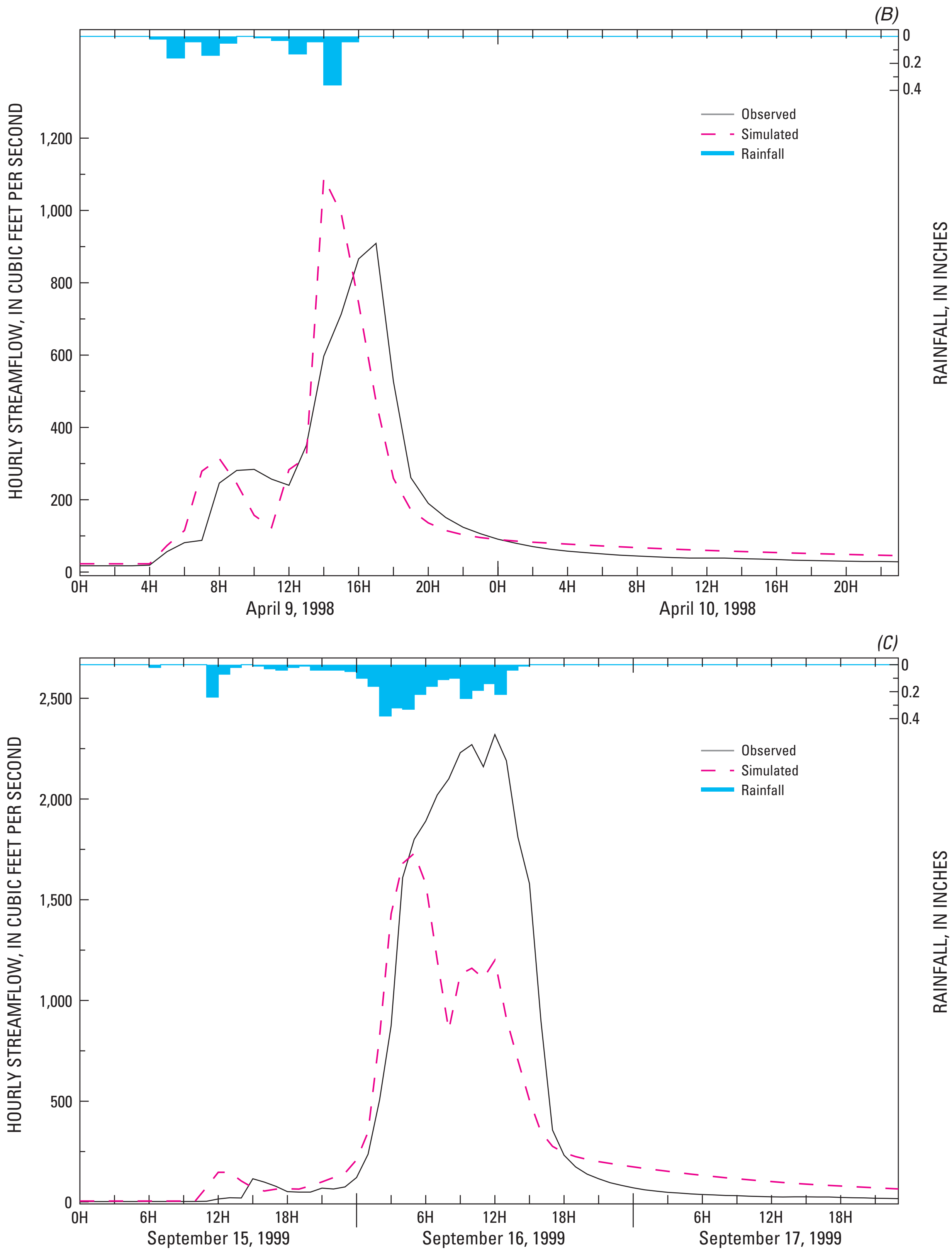


Figure 24. Hourly rainfall and observed and simulated daily mean streamflow, October 17-18, 1997 *(A)*, April 9-10, 1998 *(B)*, and September 15-17, 1999 *(C)*, Accotink Creek, Fairfax County, Virginia—Continued.

Table 20. Final parameters and percent imperviousness in each of six subwatersheds represented in the streamflow model for Accotink Creek, Fairfax County, Virginia

[HRU, Hydrologic Response Unit; see table 1 for definition of parameters; U, Urban; R, Residential; F, Forest; G, Grassland; W, Wetland UI, Urban impervious; RI, Residential 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	0.94	0.00	0.10	0.02	2.00	0.30	0.00	–	7.00	0.20
R	–	.00	.94	.00	.10	.02	2.00	.30	.00	–	7.00	.20
F	–	.00	.97	.00	.10	.12	3.00	.30	.00	–	8.00	.20
G	–	.00	.97	.00	.10	.08	2.50	.30	.00	–	7.00	.20
W	–	.00	.97	.00	.10	.12	2.50	.30	.00	–	8.00	.20
UI	45	–	–	–	–	–	–	–	–	–	–	–
RI	25	–	–	–	–	–	–	–	–	–	–	–

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 Accotink Creek 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 620 (fig. 25). 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 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. 25). In general, these conditions were well represented in the model. Simulated maximum fecal coliform concentrations during storm events generally ranged from 20,000 to 400,000 col/100 mL. Observed maximum fecal coliform concentrations in water samples collected by the USGS at Route 620 during 1999–2000 storm events ranged from 16,000 to 340,000 col/100 mL (Hyer and Moyer, 2003). The simulated recession of fecal coliform concentrations following a storm event ranged from 1 to 4 days (fig. 25). This range is consistent with the findings from Hyer and Moyer (2003) that elevated fecal coliform concentrations are maintained for 1–5 days following a storm event.

The calibrated fecal coliform model also was evaluated by comparing simulated with observed BST data collected at Route 620. These data describe the percent contribution of fecal coliform bacteria from various sources to Accotink Creek 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 dogs and cats were overestimated, whereas the simulated contributions from geese, humans, ducks, and raccoons were underestimated (fig. 26A). 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. 26B).

The calibrated fecal coliform model also was evaluated by comparison of the 30-day geometric mean for the simulated fecal coliform bacteria concentrations with the geometric mean of observed concentrations from FCHD (1986-99). This comparison was a final

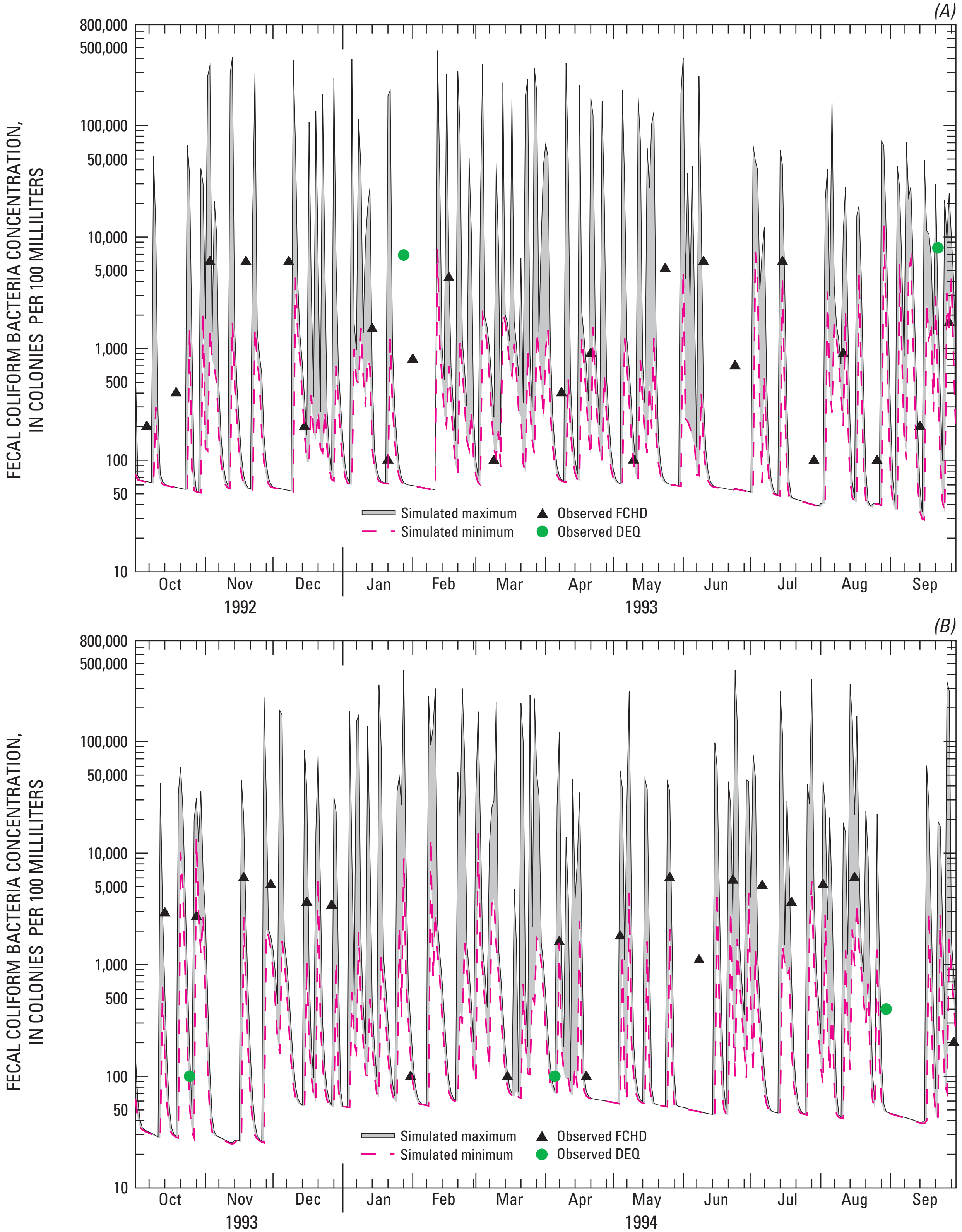


Figure 25. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 620, October 1, 1992-September 30, 1993 *(A)*, October 1, 1993-September 30, 1994 *(B)*, October 1, 1994-September 30, 1995 *(C)*, October 1, 1995-September 30, 1996 *(D)*, October 1, 1996-September 30, 1997 *(E)*, October 1, 1997-September 30, 1998 *(F)*, October 1, 1998-December 31, 1999 *(G)*, Accotink Creek, Fairfax County, Virginia. (Data from Joan C. Crowther, Virginia Department of Environmental Quality (DEQ), written commun., 1999, and Ed Pippin, Fairfax County Health Department (FCHD), written commun., 1999)

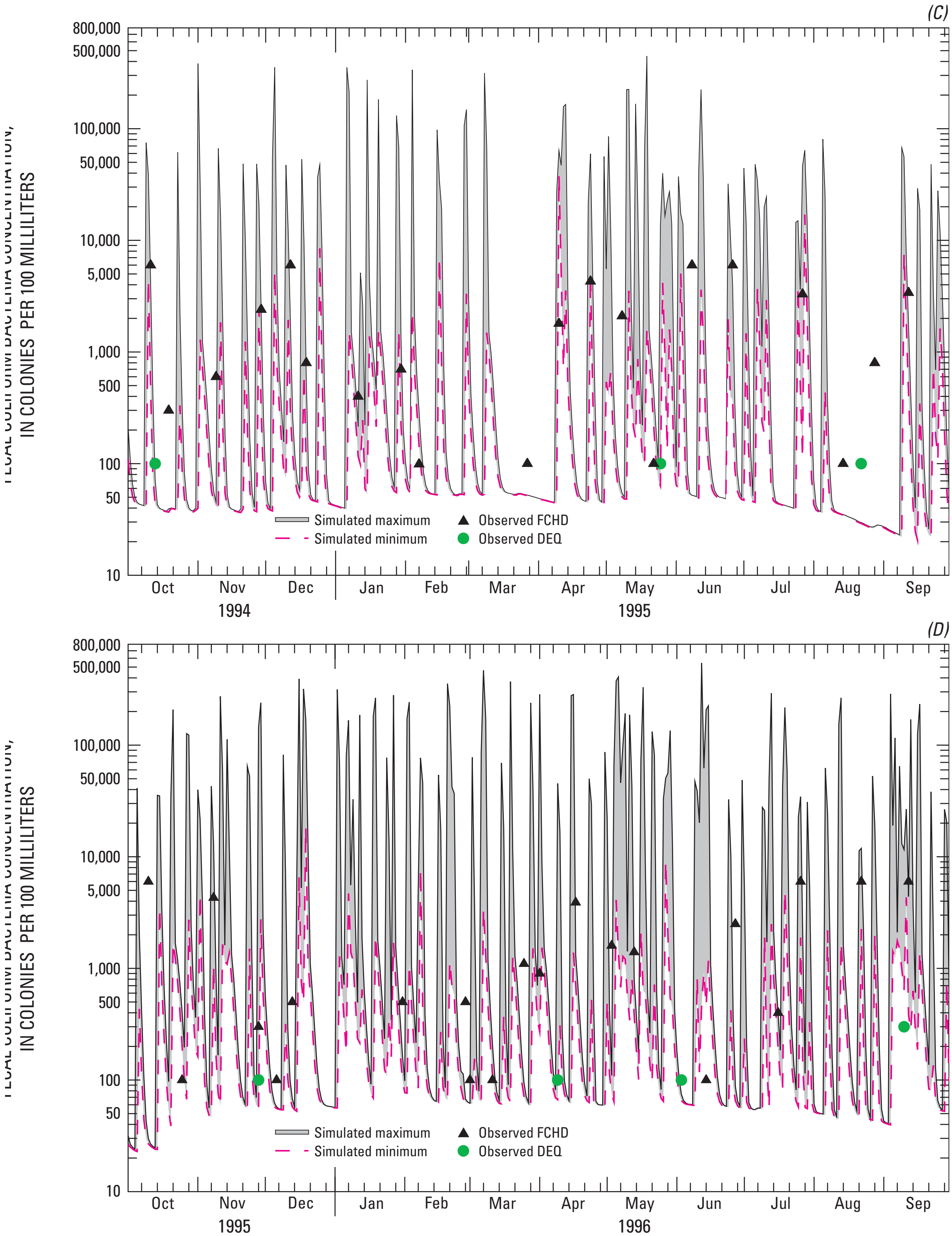
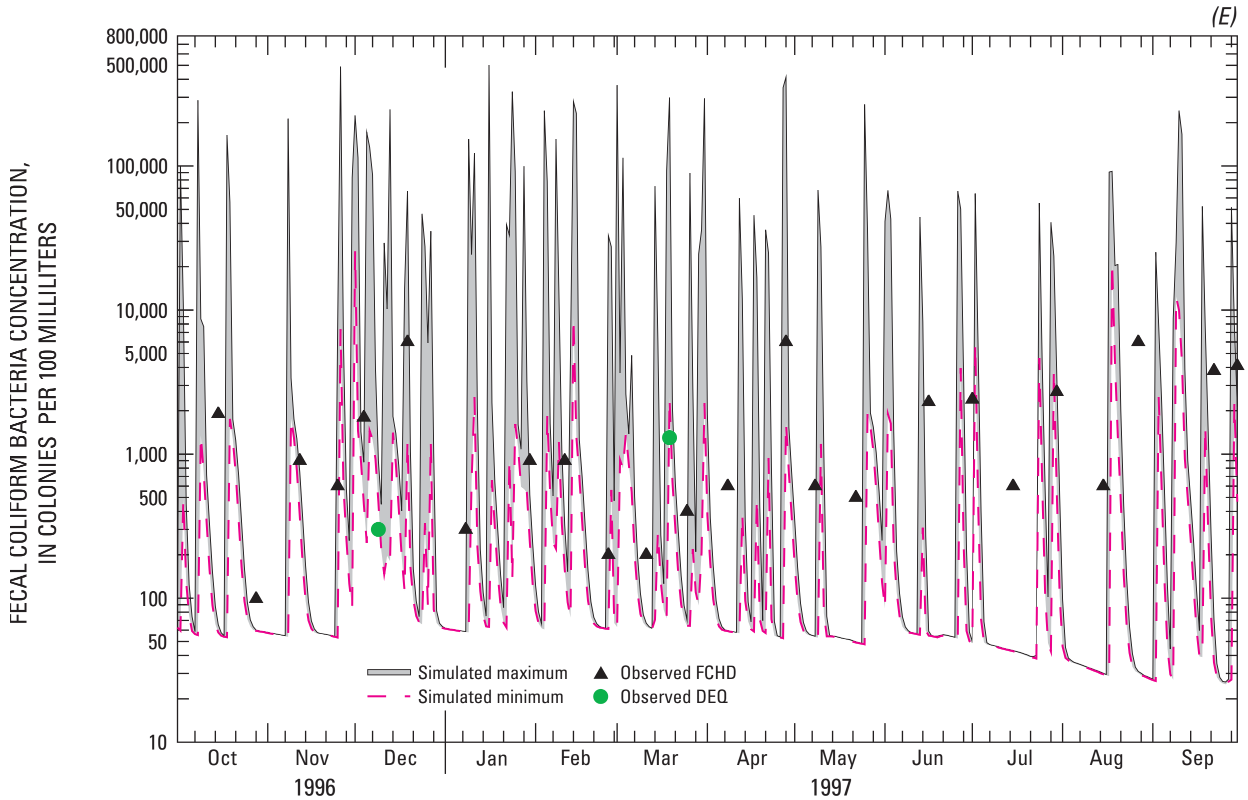


Figure 25. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 620, October 1, 1992-September 30, 1993 *(A)*, October 1, 1993-September 30, 1994 *(B)*, October 1, 1994-September 30, 1995 *(C)*, October 1, 1995-September 30, 1996 *(D)*, October 1, 1996-September 30, 1997 *(E)*, October 1, 1997-September 30, 1998 *(F)*, October 1, 1998-December 31, 1999 *(G)*, Accotink Creek, Fairfax County, Virginia. (Data from Joan C. Crowther, Virginia Department of Environmental Quality (DEQ), written commun., 1999, and Ed Pippin, Fairfax County Health Department (FCHD), written commun., 1999)—Continued.



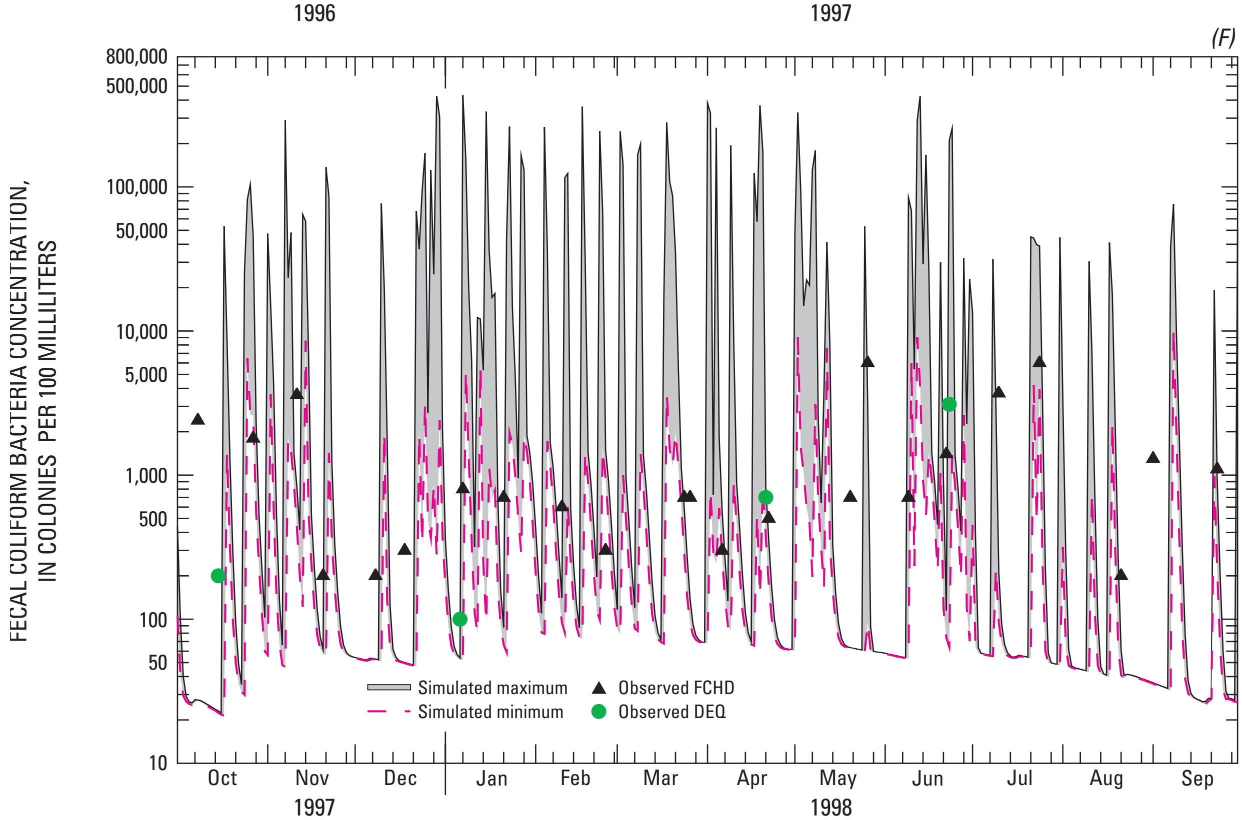


Figure 25. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 620, October 1, 1992-September 30, 1993 *(A)*, October 1, 1993-September 30, 1994 *(B)*, October 1, 1994-September 30, 1995 *(C)*, October 1, 1995-September 30, 1996 *(D)*, October 1, 1996-September 30, 1997 *(E)*, October 1, 1997-September 30, 1998 *(F)*, October 1, 1998-December 31, 1999 *(G)*, Accotink Creek, Fairfax County, Virginia. (Data from Joan C. Crowther, Virginia Department of Environmental Quality (DEQ), written commun., 1999, and Ed Pippin, Fairfax County Health Department (FCHD), written commun., 1999)—Continued.

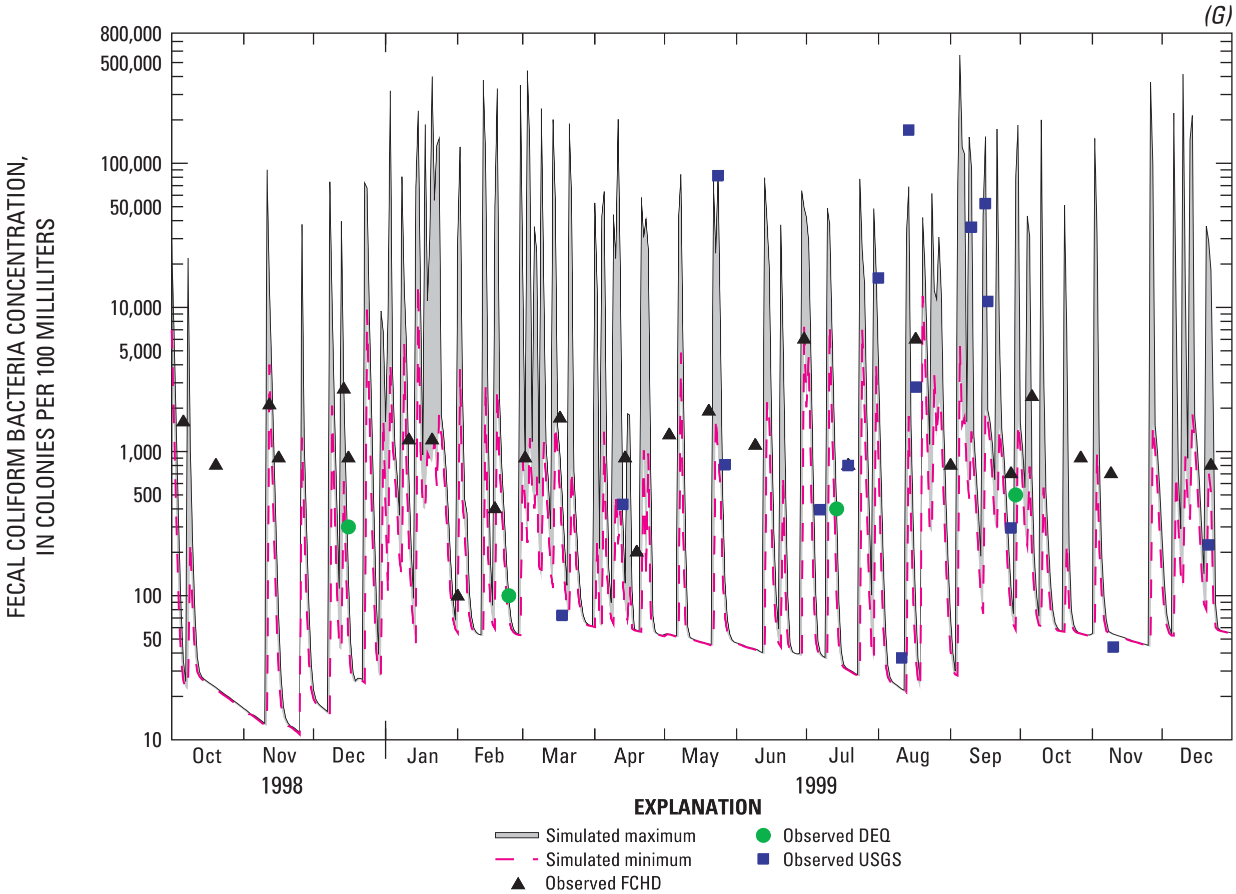


Figure 25. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 620, October 1, 1992-September 30, 1993 *(A)*, October 1, 1993-September 30, 1994 *(B)*, October 1, 1994-September 30, 1995 *(C)*, October 1, 1995-September 30, 1996 *(D)*, October 1, 1996-September 30, 1997 *(E)*, October 1, 1997-September 30, 1998 *(F)*, October 1, 1998-December 31, 1999 *(G)*, Accotink Creek, Fairfax County, Virginia. (Data from Joan C. Crowther, Virginia Department of Environmental Quality (DEQ), written commun., 1999, and Ed Pippin, Fairfax County Health Department (FCHD), written commun., 1999)—Continued.

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 data at Route 620 are 794 and 634 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 Accotink Creek 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 0.5 in. per hour (table 21).

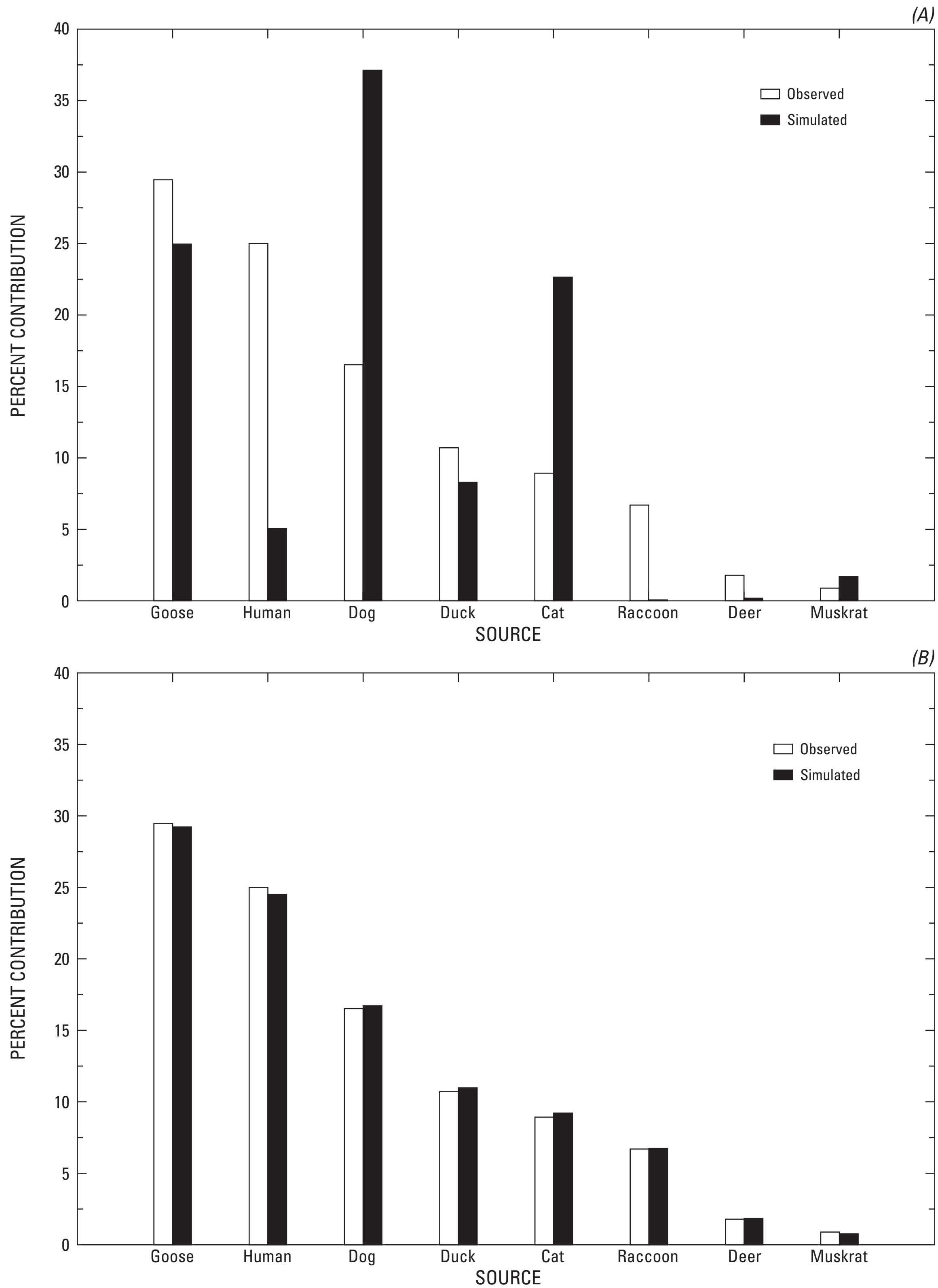


Figure 26. Observed and simulated percent contribution from the simulated sources in the watershed to the total instream fecal coliform bacteria load at Route 620, initial calibration *(A)*, and final calibration *(B)*, Accotink Creek, Fairfax County, Virginia.

Table 21. Final values of WSQOP used for the land-use types represented in the fecal coliform model for Accotink Creek, Fairfax 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	0.3
Residential	.3
Grassland	.4
Forest	.5
Wetland	.4
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) (table 22). The percentage of dogs depositing their feces on impervious areas was decreased from 10 percent to 1 percent. ACCUM values for deer and muskrat were calibrated by adjusting FCden, whereas ACCUM values for geese, ducks, and raccoons were calibrated through adjustments to POPN (table 23). 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.

FECAL COLIFORM TMDL

Present Conditions

The simulated fecal coliform bacteria concentrations in Accotink Creek, water years 1993-99, were converted to 30-day geometric mean concentrations. The 30-day geometric mean concentrations indicate that approximately 80 percent of the mean concentrations exceed the State geometric mean water-quality standard of 200 col/100 mL (fig. 27A). Based on the peak fecal coliform 30-day geometric mean concentration of 3,724 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 entering Accotink Creek is a result of nonpoint sources in the watershed (table 24). 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 and diffuse ground-water 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 for both stormflow and base-flow periods.

Scenarios for Fecal Coliform Load Reductions

Total instream fecal coliform load reductions of approximately 89 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 Accotink Creek were developed through discussions including DCR, DEQ, Fairfax County, Fairfax City, USGS (in a technical advisory role), and local stakeholders (table 25). These scenarios feature source-specific reductions in fecal coliform

Table 22. Final values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by the human, dog and cat populations in the urban and residential hydrologic response units represented in the fecal coliform model, Accotink Creek, Fairfax County, Virginia

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

Subwatershed[1]	Fprod (grams)	FCden	POPN (number)		HAB (acres)	
			Residential	Urban	Residential	Urban
			Human			
1	150	4.66×10^8	194	–	1,193	–
2	150	4.66×10^8	386	–	1,511	–
3	150	4.66×10^8	207	–	530	–
4	150	4.66×10^8	77	–	337	–
5	150	4.66×10^8	121	–	639	–
6	150	4.66×10^8	2	–	214	–
			Dog			
1	450	4.11×10^6	2,698	1,799	1,193	630
2	450	4.11×10^6	5,070	3,380	1,511	829
3	450	4.11×10^6	2,328	1,552	530	336
4	450	4.11×10^6	1,228	819	337	114
5	450	4.11×10^6	1,835	1,223	639	80
6	450	4.11×10^6	659	439	214	36
			Dog Impervious			
1	450	4.11×10^6	300	200	976	210
2	450	4.11×10^6	563	376	1,236	276
3	450	4.11×10^6	259	172	434	112
4	450	4.11×10^6	136	91	275	38
5	450	4.11×10^6	204	136	523	27
6	450	4.11×10^6	73	49	175	12
			Cat			
1	20	1.49×10^7	10,917	7,278	1,193	630
2	20	1.49×10^7	20,511	13,674	1,511	829
3	20	1.49×10^7	9,421	6,280	530	336
4	20	1.49×10^7	4,968	3,312	337	114
5	20	1.49×10^7	7,424	4,949	639	80
6	20	1.49×10^7	2,666	1,777	214	36

[1]See figure 3 for location of subwatersheds.

Table 23. Final values for wildlife sources of fecal coliform bacteria in the fecal coliform model, Accotink Creek, Fairfax County, Virginia

[Fprod, feces produced per day; FCden, fecal coliform bacteria per gram of feces; POPN, population size; U, Urban; R, Residential; G, Grassland; W, Wetland; F, Forest; UI, Urban impervious]

Wildlife source	Land-use type	Population density (number per acre habitat)	POPN (number)	Fprod (grams)	FCden
Deer	F	0.15	1,120	772	4.66×10^{7}
Deer	G	.08	70	772	4.66×10^{7}
Goose–Summer	U, R, G, W	70.31	113,271	225	3.55×10^{6}
Goose–Winter	U, R, G, W	75.00	120,827	225	3.55×10^{6}
Goose–Summer	UI, R	3.52	5,961	225	3.55×10^{6}
Goose–Winter	UI, R	3.75	6,359	225	3.55×10^{6}
Duck–Summer	U, R, G, W	2.95	5,003	150	4.90×10^{7}
Duck–Summer	F	.13	203	150	4.90×10^{7}
Duck–Winter	U, R, G, W	3.28	5,562	150	4.90×10^{7}
Duck–Winter	F	.16	250	150	4.90×10^{7}
Raccoon	R, F, W	.59	8,258	450	1.11×10^{7}
Muskrat	R, G, F, W	.23	181	100	3.75×10^{8}

Table 24. Total annual load of fecal coliform bacteria load delivered from the various land-use types for present conditions in Accotink Creek, Fairfax County, Virginia

Land-use type	Total annual load of fecal coliform bacteria for present conditions (colonies per year)	Contribution (percent)
Residential	1.95×10^{16}	69.96
Urban	5.12×10^{15}	18.37
Forest	7.91×10^{14}	2.84
Grassland	6.16×10^{14}	2.21
Wetland	2.88×10^{14}	1.03
Point Sources		
Residential impervious	1.05×10^{15}	3.77
Urban impervious	5.08×10^{14}	1.82
Total	2.79×10^{16}	100.00

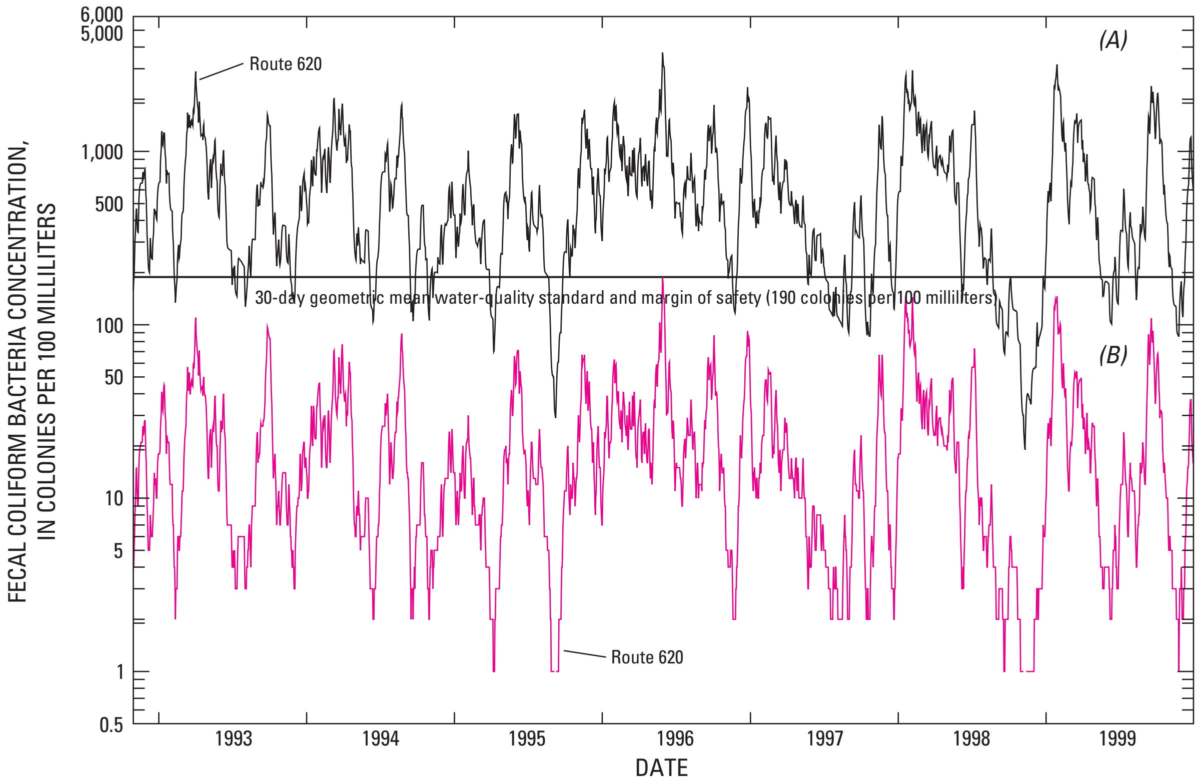


Figure 27. Simulated 30-day geometric mean fecal coliform concentrations before *(A)* and after *(B)* incorporation of the Total Maximum Daily Load (TMDL) allocation scenario at Route 620 for Accotink Creek, Fairfax County, Virginia, October 1, 1992-December 31, 1999.

Table 25. Scenarios for reducing fecal coliform bacteria loads and associated percent reductions from nonpoint sources represented in the fecal coliform model for Accotink Creek, Fairfax County, Virginia

Percent reduction in fecal coliform loading from present conditions										Average 30-day geometric mean concentration of fecal coliform bacteria (colonies per 100 milliliters)
Scenario number	Human	Dog	Cat	Goose	Duck	Deer	Raccoon	Muskrat	Parking lots and roads	
1	99	99	99	98	98	0	0	0	93	22
2	99	95	95	93	93	75	75	0	97	28
3	99	94	94	92	92	85	85	0	99	28

loads from nonpoint sources. Scenario 1 requires a 99-percent reduction from human and pet loadings, 98-percent reduction from waterfowl loadings, and 93-percent reduction from the load on parking lots and roads in order to ensure that the State water-standard is not exceeded. Scenarios 2 and 3 require lesser load reductions from the pets (95 and 94 percent, respectively) and waterfowl (93 and 92 percent, respectively) sources, but greater load reductions from deer (75 and 85 percent), raccoon (75 and 85 percent), and parking lots and roads (97 and 99 percent) in order to ensure the State water-quality standard is not exceeded. These three scenarios were discussed and evaluated in a public review process led by DEQ and DCR, and scenario 1 was chosen for the Accotink Creek watershed.

After the source-load reduction strategies in scenario 1 were incorporated into the watershed model, simulated fecal coliform concentrations at Route 620 met the water-quality goals for Accotink Creek (fig. 27B). Changes to the present fecal coliform load allocation following the incorporation of the source-specific load reductions specified in scenario 1 are shown in table 26. Average annual fecal coliform loading pre- and post-TMDL allocations are 2.79×10^{16} and 3.04×10^{15} col/year, respectively. The percent reductions in the fecal coliform load delivered from the various land types ranged from 18 to 99 percent as a result of the reduction scenario.

The resulting TMDL equation (see eq. 1) that meets the fecal coliform bacteria water-quality goals for Accotink Creek is

$$3.19 \times 10^{15} \text{ col/yr } (TMDL) = 1.30 \times 10^{14} \text{ col/yr } (\sum WLAs) + 2.91 \times 10^{15} \text{ col/yr } (\sum LAs) + 1.52 \times 10^{14} \text{ col/yr } (MOS).$$

Attaining the designated water-quality goals for Accotink Creek is a three-step process:

(1) Determination of the fecal coliform bacteria TMDL for Accotink Creek.

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

(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 Accotink Creek.

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.

Table 26. Total annual loads of fecal coliform bacteria delivered from the land-use types for present conditions and after incorporation of total maximum daily load (TMDL) allocation in Accotink Creek, Fairfax County, Virginia

Land use	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)
Residential	1.95×10^{16}	2.04×10^{15}	89.57
Urban	5.12×10^{15}	7.51×10^{13}	98.53
Forest	7.91×10^{14}	6.49×10^{14}	17.96
Grassland	6.16×10^{14}	1.02×10^{14}	83.37
Wetland	2.88×10^{14}	4.06×10^{13}	85.88
Residential impervious	1.05×10^{15}	8.64×10^{13}	91.79
Urban impervious	5.08×10^{14}	4.40×10^{13}	91.34
Total	2.79×10^{16}	3.04×10^{15}	89.10

- 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 Accotink Creek watershed. The Virginia Department of Environmental Quality (DEQ) determined that Accotink Creek 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 Accotink Creek 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 Accotink Creek. 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 Accotink Creek are geese, humans, dogs, cats, sea gulls, and raccoons.
- The calibrated fecal coliform model simulated the patterns and range of fecal coliform bacteria concentrations observed by DEQ, Fairfax County Health Department, and USGS.
- The calibrated fecal coliform model simulated source-specific instream fecal coliform loads comparable to the source-specific percent contribution identified in Accotink Creek by BST.
- Incorporating BST data reduces uncertainty associated with determining source-specific fecal coliform loading in the watershed.
- An 89-percent reduction in the current fecal coliform load delivered to Accotink Creek is required to meet the designated water-quality goals and associated TMDL.

REFERENCES CITED

Arcement, G.J., Jr., and Schneider, V.R., 1989, Guide for selecting Manning's roughness coefficients for natural channels and flood plains: U.S. Geological Survey Water-Supply Paper 2339, 38 p.

Barnes, H.H., Jr., 1967, Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1849, 213 p.

Baxter-Potter, W.R., and Gilliland, M.W., 1988, Bacterial pollution in runoff from agricultural lands: Journal of Environmental Quality, v. 17, no. 1, p. 27-34.

Berris, S.N., 1996, Daily flow-routing simulations for the Truckee River, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 96-4097, 79 p.

Bicknell, B.R., Donigian, A.S., Jr., and Barnwell, T.A., 1985, Modeling water quality and the effects of agricultural best management practices in the Iowa River basin: Journal of Water Science Technology, v. 17, p. 1141-1153.

Bicknell, B.R., Imhoffl, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C., 1997, Hydrological Simulation Program-FORTRAN, User's manual for Version 11: Athens, Ga., U.S. Environmental Protection Agency Report No. EPA/600/R-97/080, 775 p.

Bolstad, P.V., and Swank, W.T., 1997, Cumulative impacts of land use on water quality in a Southern Appalachian watershed: Journal of the American Water Resources Association, v. 33, p. 519-533.

Burton, G.A., Jr., Gunnison, D., and Lanza, G.R., 1987, Survival of pathogenic bacteria in various freshwater sediments: Applied and Environmental Microbiology, v. 53, no. 4, p. 633-638.

Carson, C.A., Shear, B.L., Ellersieck, M.R., and Asfaw, A., 2001, Identification of fecal *Escherichia coli* from humans and animals by ribotyping: Applied and Environmental Microbiology, v. 67, p. 1503-1507.

Chen, Y.D., McCutcheon, S.C., Norton, D.J., and Nutter, W.L., 1998, Stream temperature simulation of forested riparian areas: II Model Application: Journal of Environmental Engineering, April 1998, p. 316-328.

Christensen, V.G., Rasmussen, P.P., Ziegler, A.C., and Jian, X., 2001, Continuous monitoring and regression analysis to estimate bacteria loads: Water Environment Federation, TMDL Science Issues Conference, St. Louis, Mo., March 4-7, 2001, Onsite Program, p. 405-411.

Climatological Data Annual Summary for Virginia, 1999: National Oceanic and Atmospheric Administration, v. 109, no. 13, ISSN 0364-5630, 19 p.

Coon, W.F., 1998, Estimation of roughness coefficients for natural stream channels with vegetated banks: U.S. Geological Survey Water-Supply Paper 2441,133 p.

Davidian, Jacob, 1984, Computation of water-surface profiles in open channels: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A15, 48 p.

Dinicola, R.S., 1997, Estimates of recharge from runoff at the Hanford site, Washington: U.S. Geological Survey Water-Resources Investigations Report 97-4038, 172 p.

Donigian, A.S., 1986, Integration of runoff and receiving water models for comprehensive watershed simulation and analysis of agricultural management alternatives: Agricultural Nonpoint Source Pollution: Model Selection and Application, Amsterdam, Netherlands, p. 265-275.

Donigian, A.S., Bicknell, B.R., and Imhoff, J.C., 1995, Hydrological Simulation Program-FORTRAN (HSPF): *in* chap. 12 of Singh, V.P., ed. Computer models of watershed hydrology, p. 395-442.

Farag, A.M., Goldstein, J.N., Woodward, D.F., and Samadpour, M., 2001, Water quality in three creeks in the backcountry of Grand Teton National Park, USA: Journal of Freshwater Ecology, v. 16, no. 1, p. 135-143.

Felton, G.K., 1996, Agricultural chemicals at the outlet of a shallow carbonate aquifer: Transactions of the ASAE, v. 39, p. 873-882.

Fontaine, T.A., and Jacomino, V.M.F., 1997, Sensitivity analysis of simulated contaminated sediment transport: Journal of the American Water Resources Association, v. 33, no. 2, p. 313-326.

Froelich, A.J., and Zenone, C., 1985, The relation of water quality to geology and land use changes in Fairfax County and vicinity, Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I-1561, scale 1:48,000.

Geldreich, E.E., Bordner, R.H., Huff, C.B., Clark, H.F., and Kabler, P.W., 1962, Type distribution of coliform bacteria in the feces of warm-blooded animals: Journal of Water Pollution Control Federation, v. 34, no. 3, p. 295-301.

Goyal, S.M., Gerba, C.P., and Melnick, J.L., 1977, Occurrence and distribution of bacterial indicators and pathogens in canal communities along the Texas coast: Applied and Environmental Microbiology, v. 34, no. 2, p. 139-149.

Hagedorn, C., Robinson, S.L., Filtz, J.R., Grubbs, S.M., Angier, T.A., and Reneau, R.B., 1999, Determining sources of fecal pollution in a rural Virginia watershed with antibiotic resistance patterns in fecal streptococci: Applied and Environmental Microbiology, v. 65, p. 5,522-5,531.

Hamon, R.W., 1961, Estimating potential evapotranspiration, proceedings of the American Society of Civil Engineers: Journal of the Hydraulic Division, v. 87, no. HY3, p. 107-120.

Herrera Environmental Consultants, Inc., 1993, Pipers Creek: Bacteriological source tracking investigation: Consultants report prepared for Seattle Engineering Department, Drainage and Wastewater Utility, 40 p.

Howell, J.M., Coyne, M.S., and Cornelius, P., 1995, Fecal bacteria in agricultural waters of the bluegrass region of Kentucky: Journal of Environmental Quality, v. 24, no. 3, p. 411 – 419.

Hunter, C., McDonald, A., and Beven, K., 1992, Input of fecal coliform bacteria to an upland stream channel in the Yorkshire Dales: Water Resources Research, v. 28, no. 7, p. 1869-1876.

Hussong, D., Damare, J.M., Limpert, R.J., Sladen, W.J., Weiner, R.M., and Colwell, R.R., 1979, Microbial impact of Canada geese (*Branta canadensis*) and whistling swans (*Cygnus columbianus columbianus*) on aquatic ecosystems: Applied Environmental Microbiology, v. 37, no. 1, p. 14-20.

Hyer, K.E., and Moyer, D.L., 2003, Patterns and sources of fecal coliform bacteria in three streams in Virginia, 1999-2000: U.S. Geological Survey Water-Resources Investigations Report 03-4115, 76 p.

Johnston, P.M., 1962, Geology and ground-water resources of the Fairfax quadrangle, Virginia: U.S. Geological Survey Water-Supply Paper 1539-L, 61 p.

Johnston, P.M., 1964, Geology and ground-water resources of Washington D.C., and vicinity: U.S. Geological Survey Water-Supply Paper 1776, 97 p.

Kohler, M.A., Nordenson, T.J., and Baker, D.R., 1959, Evaporation maps for the United States: U.S. Department of Commerce, Weather Bureau Technical Paper No. 37, 13 p.

LaLiberte, P. and Grimes, D.J., 1982, Survival of *Escherichia coli* in lake bottom sediment: Applied and Environmental Microbiology, v. 43, no. 3, p. 623-628.

Laroche, A.M., Gallichand, J., Lagace, R., and Pesant, A., 1996, Simulating atrazine transport with HSPF in an agricultural watershed: Journal of Environmental Engineering, v. 122, no. 7, p. 622-630.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system: User's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p.

Linker, L.C., Stigall, C.G., Chang, C.H., and Donigian, A.S., 1996, Aquatic accounting: Chesapeake Bay Watershed Model quantifies nutrient loads: Water Environment and Technology, v. 8, no. 1, p. 48-52.

Lumb, A.M., McCammon, R.B., and Little, J.L., Jr., 1994, Users manual for an expert system (HSPEXP) for calibration of the Hydrological Simulation Program-FORTRAN: U.S. Geological Survey Water-Resources Investigations Report 94-4168, 102 p.

Makino, S., Asakura, H., Shirahata, T., Ikeda, T., Takeshi, K., Arai, K., Nagasawa, M., Abe, T., and Sadamoto, T., 1999, Molecular epidemiological study of a mass outbreak caused by enteropathogenic *Escherichia coli* O157:H45: Microbiology and Immunology, v. 43, p. 381-384.

Mara, D.D., and Oragui, J.I., 1981, Occurrence of *Rodococcus coprophilus* and associated actinomycetes in feces, sewage, and freshwater: Applied and Environmental Microbiology, v. 42, no. 6, p. 1,037-1,042.

Marino, R.P., and Gannon, J.J., 1991, Survival of fecal coliforms and fecal streptococci in storm drain sediment: Water Resources, v. 25, p. 1,089-1,098.

Martin, J.L, and McCutcheon, S.C., 1999, Hydrodynamics and transport for water quality modeling: Boca Raton, Fla., Lewis Publishers, 794 p.

McDonald, A., and Kay, D., 1981, Enteric bacterial concentrations in reservoir feeder streams: Base flow characteristics and response to hydrograph events: Water Research, v. 15, p. 961-968.

McMurry, S.W., Coyne, M.S, and Perfect, E., 1998, Fecal coliform transport through intact soil blocks amended with poultry litter: Journal of Environmental Quality, v. 27, p. 86-92.

Miller, F.D., Moravcik, P.S., Siren, N., and Williams, S., 1991, Bacterial contamination of water resources on Moen, Truk Islands, Federated States of Micronesia: Available from National Technical Information Service, Springfield, Va., 22161, as PB93-190650, Technical Memorandum Report No. 83.

Moore, L.W., Matheny, H., Tyree, T., Sabatini, D., and Klain, S., 1988, Agricultural runoff modeling in a small west Tennessee watershed: Journal of the Water Pollution Control Federation, v. 60, no. 2, p. 242-249.

Myers, D.N., and Sylvester, M.A., 1997, Fecal indicator bacteria: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A7.1, 38 p.

Ng, H.Y.F., and Marsalek, J., 1989, Simulation of the effects of urbanization on basin streamflow: Water Resources Bulletin, v. 25, no. 1, p. 117-124.

Northern Virginia Planning District Commission, 1990, Occoquan watershed septic system assessment, Final report submitted to the Virginia State Water Control Board: NVPDC, Annandale, Virginia.

Ongerth, J.E., and Samadpour, Mansour, 1994, A practical method for differentiating between fecal coliforms of human and of animal origin in shellfish and shellfish waters: Water Microbiology for the 21st Century, Seattle, March 23-24, 1994 [Proceedings].

Pasquarell, G.C. and Boyer, D.G., 1995, Agricultural impacts on bacterial water quality in karst groundwater: Journal of Environmental Quality, v. 24, p. 959-969.

Porter, H.C., Derting, J.F., Elder, J.h., Henry, E.F., and Pendleton, R.F., 1963, Soil survey of Fairfax County, Virginia: U.S. Department of Agriculture, 103 p.

Rahe, T.M., Hagedorn, C., McCoy, E.L., and Kling, G.F., 1978, Transport of antibiotic-resistance *Escherichia coli* through western Oregon hillslope soils under conditions of saturated flow: Journal of Environmental Quality, v. 7, p. 487-494.

Regan, R.S., and Schaffranek, R.W., 1985, A computer program for analyzing channel geometry: U.S. Geological Survey Water-Resources Investigations Report 85-4335, 49 p.

Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.

Samadpour, M., and Chechowitz, N., 1995, Little Soos Creek microbial source tracking: Prepared for the King County Department of Public Works, Surface Water Management Division, 36 p.

Sams, J.I., III, and Witt, E.C., III, 1995, Simulation of streamflow and sediment transport in two surface-coal-mined basins in Fayette County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 92-4093, 43 p.

Searcy, J.K., 1959, Flow duration curves, manual of hydrology: part 2, low flow techniques: U.S. Geological Survey Water-Supply Paper 1542-A, 33 p.

Sherer, B.M., Miner, J.R., Moore, J.A., and Buckhouse, J.C., 1988, Resuspending organisms from a rangeland stream bottom: American Society of Agricultural Engineers, v. 31, no. 4, p. 1217-1222.

Simmons, G.M., Herbein, S.A., and James, C.M., 1995, Managing nonpoint fecal coliform sources to tidal inlets: Water Resources Update, Universities Council on Water Resources, no. 100, p. 64-74.

Smith, H.W., 1961, The development of the bacteria flora of the faeces of animals and man: the changes that occur during ageing: Journal of Applied Bacteriology, v. 24, no. 3, p. 235-241.

Srinivasan, M.S., Hamlett, J.M., Day, R.L., Sams, J.I., and Petersen, G.W., 1998, Hydrologic modeling of two glaciated watersheds in northeast Pennsylvania: Journal of the American Water Resources Association, v. 34, no. 4, p. 963-978.

U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 2000: accessed January15, 2000 at http://www.fs.fed.us/database/feis/

U.S. Environmental Protection Agency, 1985, Rates, constants, and kinetics formulations in surface water quality modeling (2nd ed.): EPA 600/3-85/040. U.S. Environmental Protection Agency, Environmental Research Labatory, Athens, Ga.

U.S. Environmental Protection Agency, 1986, Ambient water quality criteria for bacteria: EPA 440/5-84-002. Washington, D.C.

U.S. Environmental Protection Agency, 2000, Basins Case Study 1: Cottonwood Creek Watershed, Idaho County, Idaho, Report No. EPA 823-R-00-024, 12 p.

U.S. Environmental Protection Agency, 2001, WDMUtil Version 2.0 (BETA): A tool for managing watershed modeling time-series data, user's manual (Draft), 157 p.

Weiskel, P.A., Howes, B.L., and Heufelder, G.R., 1996, Coliform contamination of a coastal embayment: sources and transport pathways: Environmental Science & Technology, v. 30, p. 1872-1881.

Wheater, D.W.F., Mara, D.D., and Oragui, J., 1979, Indicator systems to distinguish sewage from stormwater run-off and human from animal faecal material, *in* James and Evison, eds., Biological indicators of water quality, p. 21-27.

White, R.K., Hayes, D.C., Eckenwiler, M.R., and Herman, P.E., 2001, Water resources data for Virginia water year 2000, Volume 1. Surface-water discharge and surface-water quality records: U.S. Geological Survey Water-Data Report VA-00-1, 547 p.

Wiggins, B.A., 1996, Discriminant analysis of antibiotic resistance patterns in fecal streptococci, a method to differentiate human and animal sources of fecal pollution in natural waters: Applied and Environmental Microbiology, v. 62, p. 3997-4002.

Wright, W.G., 1990, Ground-water hydrology and quality in the Valley and Ridge and Blue Ridge physiographic provinces of Clarke County, Virginia: U.S. Geological Survey Water-Resources Investigations Report 90-4134, 61 p.

Zarriello, P.J., 1999, A precipitation-runoff model for part of the Ninemile Creek watershed near Camillus, Onondaga County, New York: U.S. Geological Survey Water-Resources Investigations Report 98-4201, 60 p.