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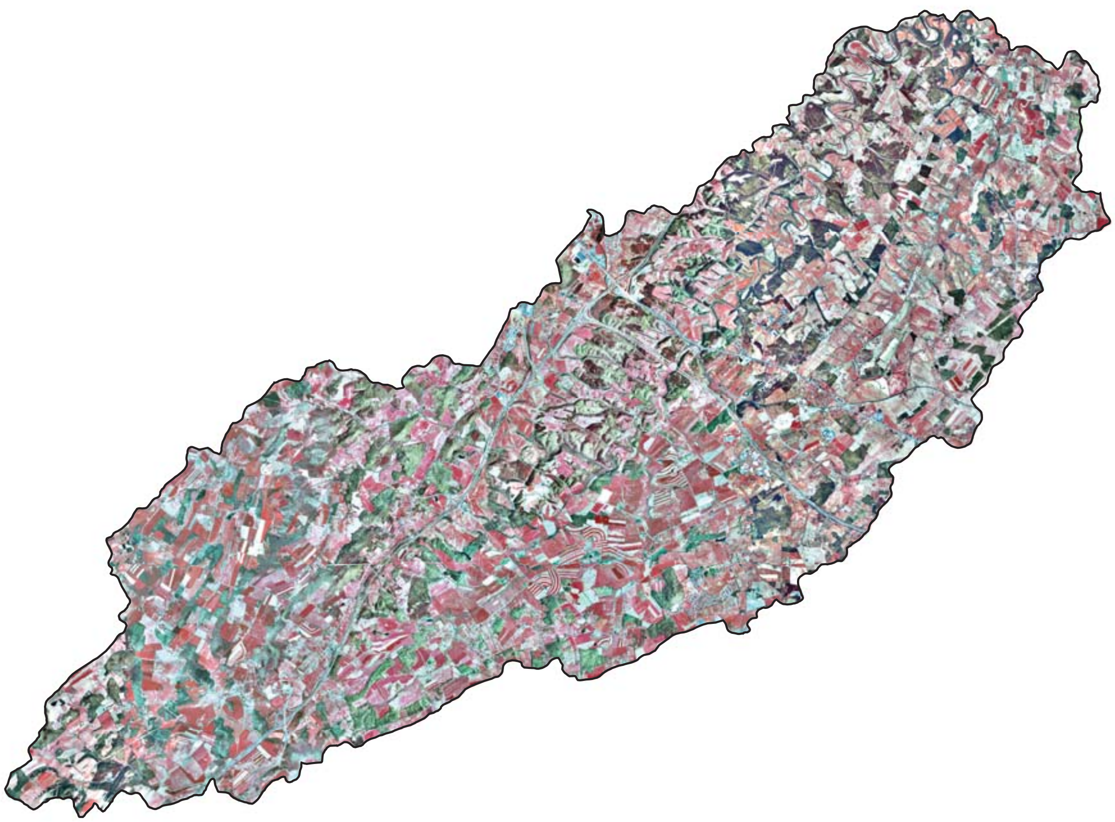
Prepared in cooperation with:

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 Christians Creek, Augusta County, Virginia

Water-Resources Investigations Report 03-4162



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

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By Douglas L. Moyer and Kenneth E. Hyer

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Richmond, Virginia
2003

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CONVERSION FACTORS, DATUM, AND ABBREVIATED WATER-QUALITY UNITS

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

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

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

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

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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. Christians Creek, in Augusta 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 bac- teria TMDL for Christians Creek. The Hydrological Simulation Program–FORTRAN (HSPF) was used to simulate streamflow, fecal coliform concentrations, and source-specific fecal coliform loading in Christians Creek. Ribotyping, a bacterial source tracking technique, was used to identify the dominant sources of fecal coliform bacteria in the Christians Creek watershed. Ribotyping also was used to determine the relative contributions of specific sources to the observed fecal coliform load in Christians 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 Christians 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 40 to 2,000 colonies per 100 milliliters, and peak concentrations during stormflow periods ranged from 23,000 to 730,000 colonies per 100 milliliters. Additionally, fecal coliform bacteria concentrations were generally higher upstream and lower downstream. Simulated source-specific contributions of fecal coliform bacteria to instream load were matched to the observed contributions from the dominant sources, which were beaver, cats, cattle, deer, dogs, ducks, geese, horses, humans, muskrats, poultry, raccoons, and sheep. According to model results, a 96-percent reduction in the current fecal coliform load delivered from the watershed to Christians 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). Christians Creek, in Augusta County, Virginia (fig. 1), is one of these impaired streams. Fecal coliform bacteria concentrations that are elevated above the State water-quality standard indicate an increased risk to human health when these waters are contacted through swimming or other recreational activities.

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

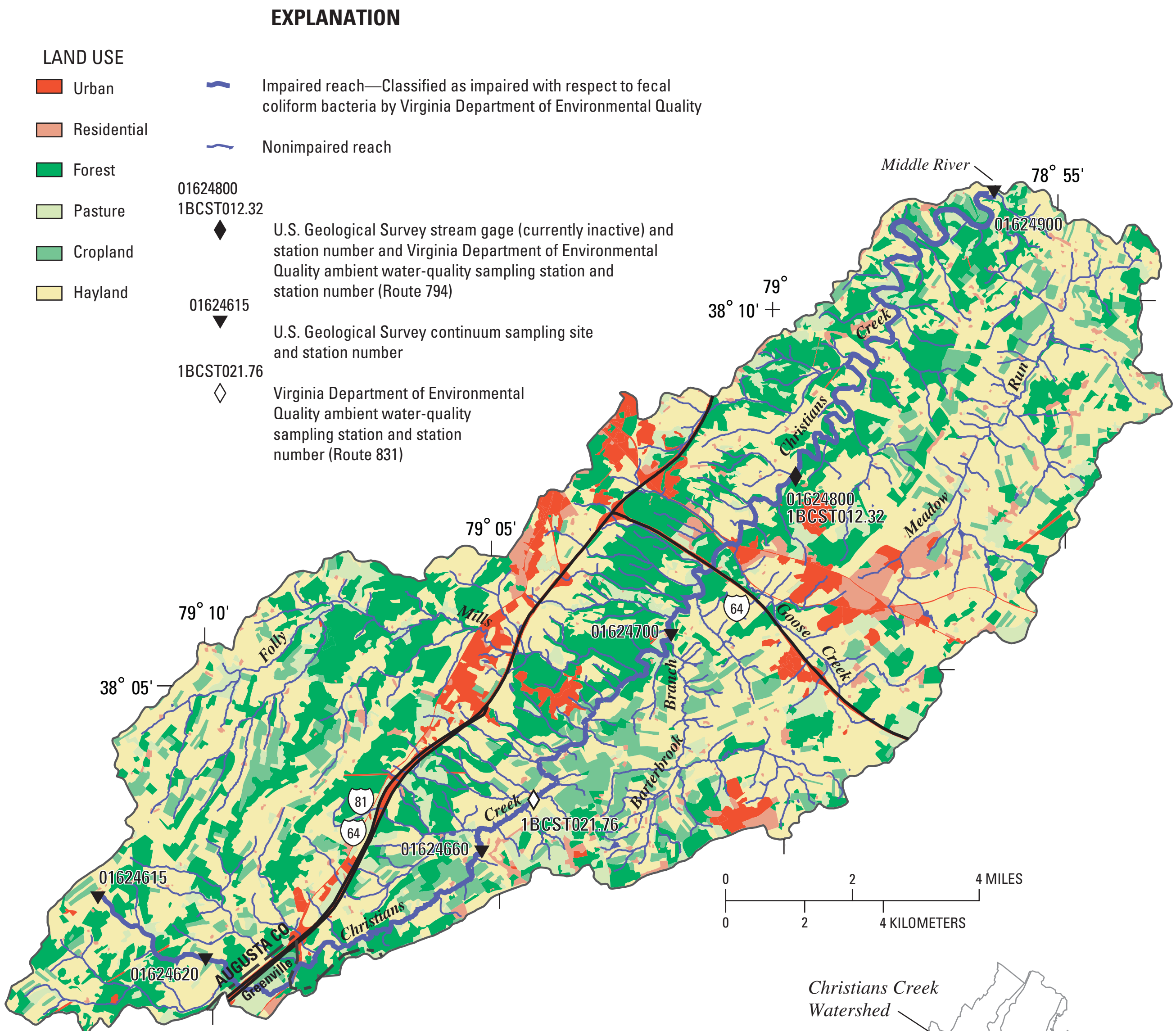
$$TMDL = \Sigma WLAs + \Sigma LAs + MOS \qquad (1)$$

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

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

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

Bacterial source tracking (BST) is a recently developed tool for identifying the sources of fecal coliform bacteria 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



Base from USGS Digital Elevation Model 7.5-minute quadrangles, 30-meter resolution

Land use from Virginia Department of Conservation and Recreation, Carterra imagery 1996, 1997, and 1998, 5-meter resolution panchromatic Indian Remote Sensing fused with 1997 Landsat, 30-meter resolution

Hydrography digitized from 1:24,000, 7.5-minute quadrangles

County boundaries from 1:100,000, TIGER files, 1994

Universal Transverse Mercator 17 projection, NAD 27, central meridian 81°00'W

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

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 Christians Creek watershed is ribotyping (Hyer and Moyer, 2003), which involves an analysis of the specific DNA (deoxyribonucleic acid) sequence that codes for the production of ribosomal RNA (ribonucleic acid). Ribotyping identifies bacteria sources with a degree of precision that makes it well suited for use in the development of a fecal coliform TMDL.

In 1999, the U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Conservation and Recreation (DCR), began a 3-year study to develop a fecal coliform bacteria TMDL for the Christians 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 Christians Creek. These objectives ensure that the Christians 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 Christians 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 Christians Creek watershed. The model simulation period is from October 1991 to September 1997. 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 Christians Creek are presented as well as the load reductions needed to meet the designated TMDL and associated State water-quality standard.

Christians Creek Watershed Characteristics

Christians Creek, located in Augusta County, Va., originates northwest of Greenville, Va., and extends to the confluence with the Middle River. The entire 31.5-mi-long reach is classified as impaired with respect to fecal coliform bacteria (Virginia Department of Environmental Quality, 1998). The basin has a drainage area of 107 mi^2, and an estimated population of 12,000 (1990 Census). A recently deactivated USGS stream gage (station number 01624800; fig. 1), still operational for instantaneous stage determinations, is at Route 794 (Sangers Lane), and has a period of record from 1967 to 1997. DEQ has performed monthly sampling of fecal coliform bacteria at Route 794 and also at Route 831 (Old White Hill Road) (DEQ station number 1BCST021.76; fig. 1) since 1991. Route 794 was the primary sampling site for this study.

The Christians Creek watershed lies in the Valley and Ridge physiographic province. Underlying the watershed are 10 geologic formations dominated by limestone and dolomite; information about each formation is summarized from the work of Rader (1967). The Martinsburg Formation (calcareous shale and sandstone) is the dominant formation within the basin. Other formations in the watershed include the Edinburg Formation (argillaceous limestone and shale), Lincolnshire Formation (cherty limestone), New Market Limestone (limestone with dolomite beds near the base), Beekmantown Formation (dolomite and limestone), Chepultepec Formation (limestone and dolomite), Conococheague Formation (limestone, dolomite, and sandstone), and Elbrook Formation (limestone and dolomite). Karst features, such as sinkholes and caves, are evident in portions of the watershed. Alluvial material (composed of sand and clay) is present in portions of the floodplain adjacent to Christians Creek. Small amounts of fault breccia (large blocks of dolomite and limestone with crush conglomerate) also occur in the basin.

The soils of the Christians Creek watershed have been described thoroughly (Hockman and others, 1979) and are best classified as a product of their parent material. Much of the soil in the watershed has formed from the residuum of interbedded limestone, dolomite, and calcareous shale. Three soil assemblages have been identified in this category. The Frederick-Christian-Rock outcrop assemblage consists of deep, well-drained, silt loam or fine sandy loam soils with limestone outcrop areas. The Frederick-Bookwood-Christian assemblage consists of deep to moderately deep, well-drained, silt loam or fine sandy loam soils; scattered sinkholes or rock outcrops also may occur. The Chilhowie-Edom assemblage consists of deep to moderately deep, well drained, silt loam or silty clay loam soils with occasional bedrock outcrops. Considerable soil has also formed from the residuum of shale and thin interbedded sandstone and limestone. These soils are part of the Berks-Weikert-Sequoia assemblage, which consists of shallow to deep, well-drained, silt loam or shaly silt loam soils. On flood plains and terraces, soils have formed in the alluvial or colluvial material. Although not extensive within the watershed, these soils are part of the Buchanan-Wheeling-Buckton assemblage, which consists of deep, somewhat poorly drained to well-drained soils. These are generally silt loam, loam, or fine sandy loam soils, although some areas are gravelly or cobbly.

Land use in the watershed is dominated by agricultural practices that are potential sources of fecal coliform bacteria in the watershed. Major components of the animal husbandry in this watershed include the production of beef cattle, dairy cattle, heifers, broilers, and turkeys. Other potential sources of fecal coliform bacteria within the watershed are human-related (failing septic systems, leaking or overflowing sewer lines, cross-pipes, and straight pipes), domestic animals (dogs and cats), waterfowl (geese, ducks, and sea gulls), and other wildlife (such as deer, raccoons, opossum, rabbits, muskrats, ground hogs, foxes, and beaver).

Modeling Approach

Streamflow and bacterial transport in the Christians 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) is acknowledged for their technical support and assistance. The authors also would like to thank Tom Jobes (Aqua Terra Consultants) for his help with the development of the model. Michael J. Gearheart, Trisha L. Baldwin, and Robert R. Lotspeich provided outstanding technical support on this project. Allison A Shipp and Michael E. Lewis are acknowledged for providing technical reviews of this report. Lastly, we are indebted to the residents of and stakeholders in the Christians 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 Christians 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 transport (evaporation, transpiration, inflow, and outflow) components of the hydrologic cycle (table 1). PWATER simulates the storage and transport of precipitation along three flow paths: overland flow, interflow (shallow subsurface flow), and base flow (active ground-water discharge). Storage and transport parameters are refined to simulate the hydrologic routing through each HRU, generating a simulated watershed response between and during precipitation events.

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

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

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

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

The routing of precipitation in IWATER is similar to the surface runoff routing in the PERLND module. Precipitation that falls on the watershed is first intercepted by impervious surfaces (building tops, urban vegetation, and asphalt wetting) that extend above the land surface (impervious retention storage – RETS). Most of the precipitation is passed to the land surface because the storage capacity of the intercepting surfaces is relatively small compared to the volume of incoming precipitation. The water that remains in

Table 1. Hydrologic parameters used in the simulation of streamflow in Christians Creek, Augusta 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

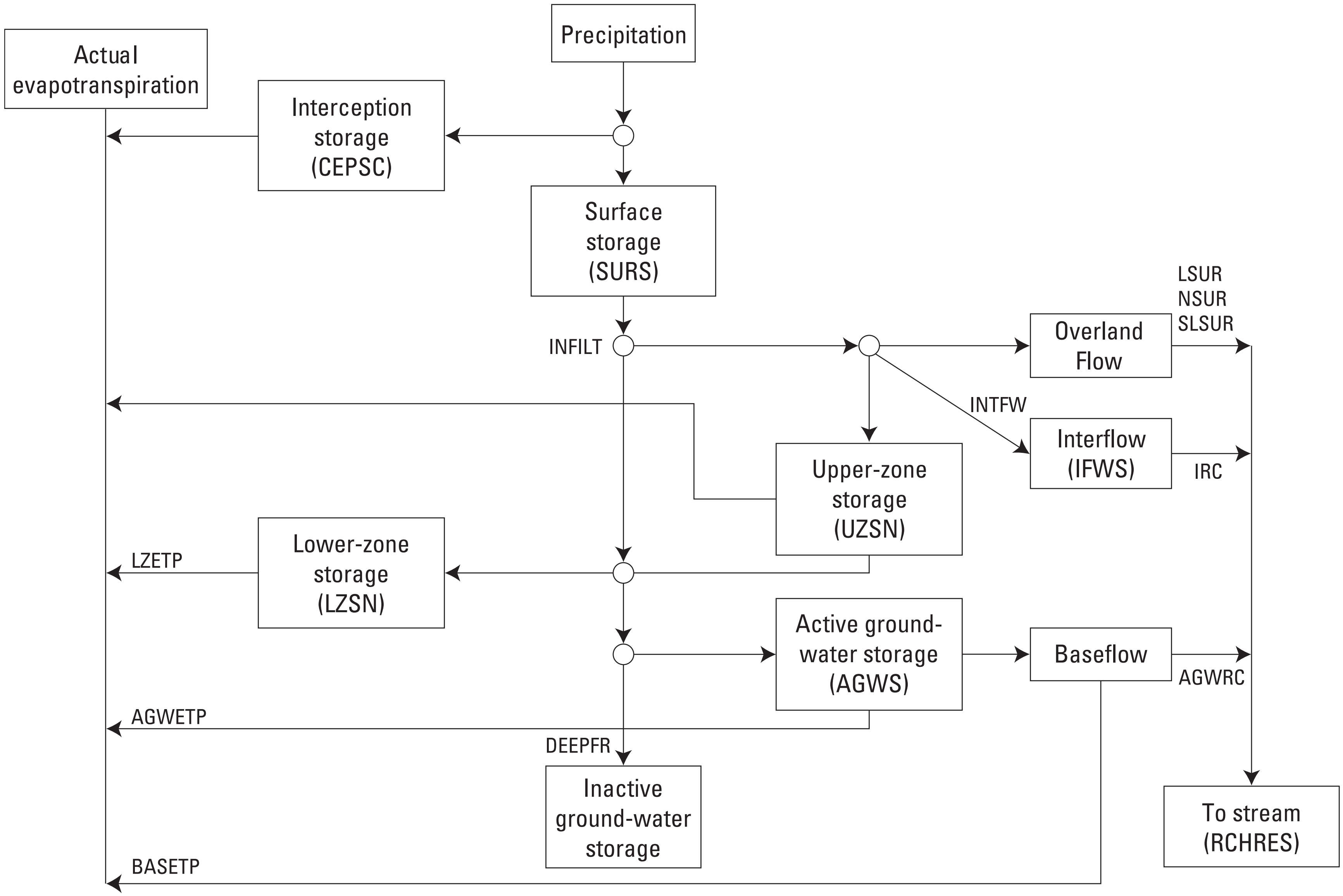


Figure 2. Rainfall-routing processes, associated with pervious land segments, represented by the Hydrological Simulation Program-FORTRAN for the simulation of streamflow in Christians Creek, Augusta County, Virginia. (See table 1 for definition of hydrologic parameters.)

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 pasture (primarily loafing lots or heavily grazed areas adjacent to the stream channel) 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 the urban and pasture land types. This impervious fraction can be broken into two categories, "hydrologically effective" or "hydrologically ineffective" (Zarriello, 1999). Hydrologically effective areas drain directly to stream channels and are represented by the IMPLND module. Hydrologically ineffective areas drain onto pervious land types, such as grassland or forest, and are better represented by the PERLND module. For example, rain that falls on a rooftop, and then is transported to a grassy lawn, would be considered hydrologically ineffective. Initial estimates were that urban land use contains between 18- and 50-percent and pasture contains 1-percent effective impervious (Northern Virginia Planning District Commission, 1980). This initial estimate was refined during model calibration of stormflow timing and magnitude. For instance, overestimating the impervious area will cause a greater volume of water to be routed directly to the stream through surface runoff (in contrast to the delayed response associated with pervious land segments) during a storm event; thus, the simulated storm response will be earlier and of greater magnitude than the observed storm response.

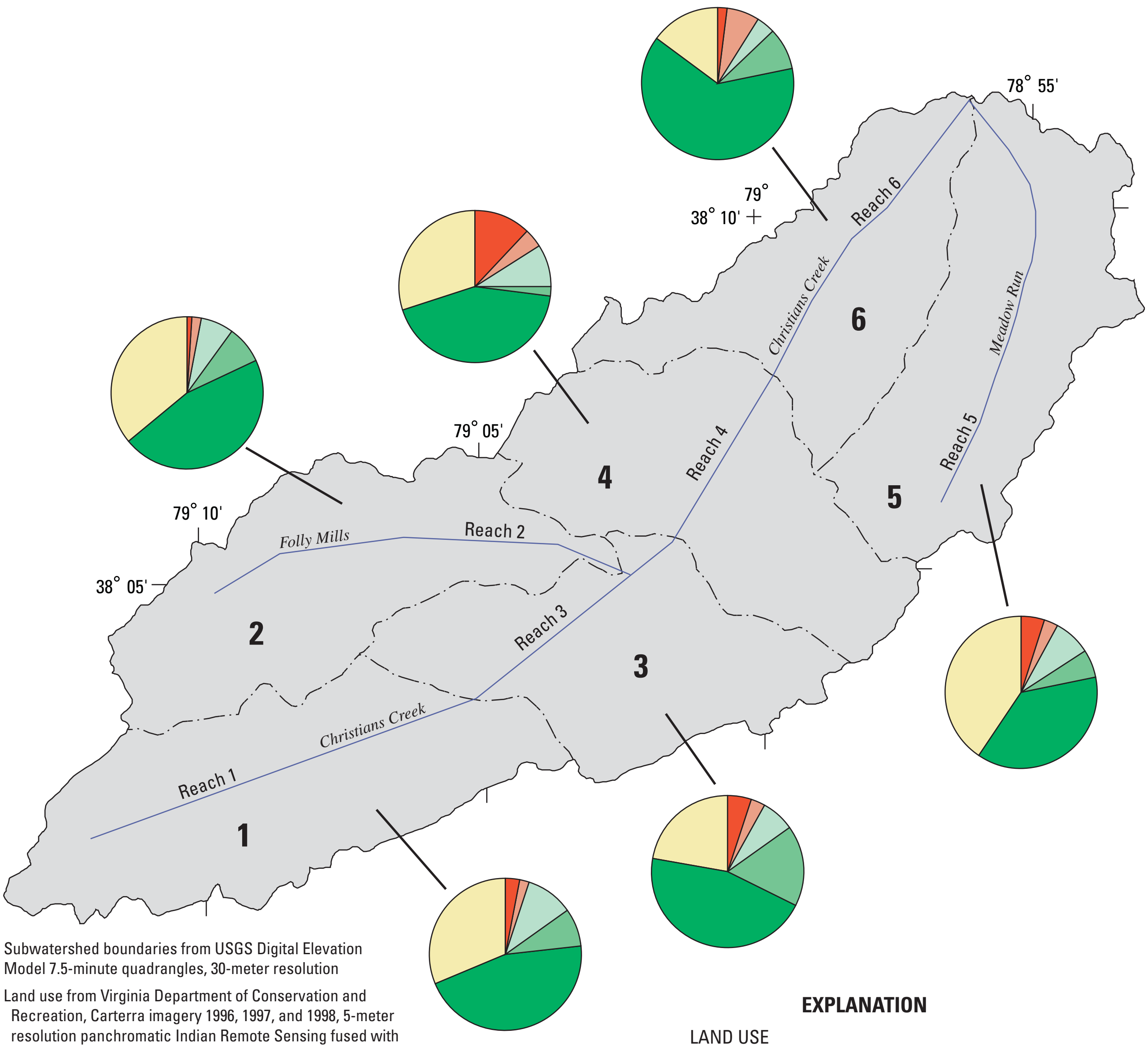
Stream Channels

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

Subwatershed Delineation

A critical step in the simulation of streamflow and bacterial transport within a watershed is characterization of the watershed morphology. The morphology consists of watershed characteristics such as topography (slope, aspect, and elevation), soil types, and land use. Within the watershed boundary, each of these characteristics typically is highly variable. For example, the southern portion of the Christians Creek watershed has a higher elevation and steeper slopes than the northern 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 Christians Creek watershed.

Six subwatersheds were identified within the Christians 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 Greenville, Stuarts Draft, Staunton, Waynesboro West, and Fort Defiance 7.5-minute quadrangles. The DEM coverage has a cell size of 30 meters.



Subwatershed boundaries from USGS Digital Elevation Model 7.5-minute quadrangles, 30-meter resolution

Land use from Virginia Department of Conservation and Recreation, Carterra imagery 1996, 1997, and 1998, 5-meter resolution panchromatic Indian Remote Sensing fused with 1997 Landsat, 30-meter resolution

Universal Transverse Mercator 17 projection, NAD 27, central meridian 81°00'W

Sub-watershed	Land use, in percent					
	Urban	Residential	Pasture	Cropland	Hayland	Forest
1	3	2	10	8	45	31
2	1	2	7	8	46	36
3	5	3	7	17	45	22
4	12	4	9	2	43	30
5	5	3	8	6	38	41
6	2	7	4	9	64	15

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

EXPLANATION

LAND USE
- Urban
- Residential
- Pasture
- Cropland
- Forest
- Hayland

—·— Subwatershed boundary

Figure 3. Hydrologic subwatersheds, land use, and reaches as represented in the streamflow and fecal coliform models for Christians Creek, Augusta County, Virginia.

Land Use

DCR provided land-use data in the form of a Geographic Information System (GIS) coverage for the Christians Creek Watershed. The GIS coverage provides land-use/land-cover information. The land-use coverage identifies 19 possible land-use types, which were combined into 6 general types based on hydrological routing similarities: urban, residential, cropland, hayland, pasture, and forest (table 2). Each of these general land-use types represents the HRUs for each subwatershed.

Table 2. Aggregated hydrologic response units used to develop the watershed model for Christians Creek, Augusta County, Virginia

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

Hydrologic Response Unit	Area	
	Acres	Percent of watershed
Urban[1]	3,208	4.7
Residential[2]	2,357	3.4
Cropland	5,379	8.3
Hayland[3]	32,523	47.3
Pasture[4]	5,066	7.4
Forested[5]	19,896	28.9

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

[2] Includes residential impervious, low-density residential, mobile home park, wooded residential, poultry operations, and farmstead.

[3] Includes improved pasture and permanent hay.

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

[5] Includes harvested forest land.

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 794 (USGS station 01624800) was incorporated into the FTABLE for reach segment 4.

Six subwatersheds (1–6) represent the morphological features of the Christians Creek watershed (fig. 3). Within each subwatershed there are 8 HRUs, including 6 pervious (urban, residential, cropland, hayland, pasture, and forest) and 2 impervious areas (urban and pasture). Each subwatershed has a single reach that is governed by an FTABLE. Reaches 1, 3, 4, and 6 represent Christians Creek. Reaches 2 and 5 represent the Folly Mills and Meadow Run tributaries, respectively.

Meteorological and Streamflow Data

Rainfall data were obtained from the National Climatic Data Center. These data are collected hourly at the Staunton Sewage Treatment Plant (SSTP) rain gage that is approximately 6 mi west of the USGS stream gage on Christians Creek. This rain gage has been operational since August 1, 1948. Average annual rainfall measured between 1991 and 1997 was 40.2 in., with a maximum annual rainfall amount of 52.0 in. in 1996 and a minimum annual rainfall amount of 35.1 in. in 1991. The 30-year average rainfall at the SSTP gage is 41.1 in. (Climatological Data Annual Summary for Virginia, 1999). Missing data in the hourly rainfall record were supplemented with data from the Sherando, Spottswood, Middlebrook, and Stoney Creek

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

[in., inches; °F, degrees Fahrenheit; NCDC, National Climatic Data Center; NWS, National Weather Service; ft^3/sec, cubic feet per second]

Type of data	Location of data collection	Latitude Longitude	Source	Recording frequency	Period of record
Rainfall (in.)	Staunton Sewage Treatment Plant	38°10′52″ 79°05′25″	NCDC	hourly daily	1/1/73–12/31/99 8/1/48–12/31/99
Rainfall (in.)	Sherando	37°59′45″ 78°59′30″	NWS	hourly	4/1/91–12/31/99
Rainfall (in.)	Spottswood	37°57′42″ 79°12′44″	NWS	hourly	4/1/91–12/31/99
Rainfall (in.)	Middlebrook	38°02′54″ 79°13′45″	NWS	hourly	4/1/91– 12/31/99
Rainfall (in.)	Stoney Creek	37°59′24″ 79°07′22″	NWS	hourly	10/1/93–12/31/99
Minimum air temperature (°F)	Staunton Sewage Treatment Plant	38°10′52″ 79°05′25″	NCDC	daily	8/1/48–12/31/99
Maximum air temperature (°F)	Staunton Sewage Treatment Plant	38°10′52″ 79°05′25″	NCDC	daily	8/1/48 – 12/31/99
Minimum air temperature (°F)	Dale Enterprise Weather Station	38°27′19″ 78°56′07″	NCDC	daily	8/1/48– 2/31/99
Maximum air temperature (°F)	Dale Enterprise Weather Station	38°27′19″ 78°56′07″	NCDC	daily	8/1/48– 2/31/99
Cloud cover (percent)	Lynchburg Regional Airport	37°20′15″ 79°12′24″	NCDC	hourly	8/1/48–6/30/96
Cloud cover (percent)	Quantico Marine Corp Air Station (MCAS)	38°30′00″ 77°18′00″	NCDC	hourly	4/1/45–5/31/98
Dew point temperature (°F)	Lynchburg Regional Airport	37°20′15″ 79°12′24″	NCDC	hourly	1/1/48–6/30/96
Wind speed (360° and knots)	Elkins-Randolph Airport, Elkins, W.Va.	38°53′07″ 79°51′10″	NCDC	hourly	1/1/64–12/31/99
Streamflow (ft^3/sec)	Christians Creek at Fishersville (Route 794)	38°07′42″ 78°59′41″	USGS	hourly daily	10/1/90–9/30/97 10/1/67–9/30/97

rain gages in and around the Christians Creek watershed (table 3). These gages are part of the National Weather Service's Automated Flood Warning System for Augusta County, Va. Data gaps were filled primarily with data from the Middlebrook rain gage, which is nearest to the SSTP. For the 1991–94 time period, data from Spottswood were used when rainfall data from both SSTP and Middlebrook were missing. For 1995–97, average rainfall data from Spottswood, Sherando, and Stoney Creek (activated in 1995) rain gages generally were used when data from both SSTP and Middlebrook were missing.

Daily minimum temperature, daily maximum temperature, percent cloud cover, dew-point temperature, and wind-speed data were collected for the purpose of calculating potential evapotranspiration (PET) for the Christians Creek watershed (table 3). Daily minimum and maximum temperature data were collected from SSTP. Missing temperature data were supplemented with temperature data collected at the Dale Enterprise weather station. Dew-point temperature and percent cloud-cover data were collected from the Lynchburg Regional Airport. Collection of percent cloud-cover data at the airport ended June 1996, so percent cloud-cover data for the period July 1996–December 1997 were obtained from Quantico Marine Corp Air Station. Wind-speed data required for calculating PET were collected from Elkins–Randolph Airport, Elkins, W.Va. 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, in the model, 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 Christians Creek, for the period October 1, 1990–September 30, 1999, were collected by the USGS every 15 minutes at the Christians Creek at Fishersville stream gage (USGS station number 01624800) (fig. 1; table 3). Hourly streamflow values were used for the streamflow simulation. Average annual streamflow for the period October 1, 1990–September 30, 1997 (water years 1991-97), was 75.4 ft^3/s with a maximum average annual streamflow of 113.2 ft^3/s during water year 1996 and a minimum average annual streamflow of 41.5 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 (simulated streamflow and fecal coliform bacteria) written to the WDM file.

Calibration Approach

The objective of the streamflow modeling effort was to simulate the observed water budget and hydrologic response in the Christians Creek watershed. The 6-year simulation period extended from April 1, 1991, to September 30, 1997, and included a 4-year calibration and a 2-year verification period. Key steps in the development of the calibrated model of streamflow for the Christians Creek watershed included collection of historical 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

Table 4. Initial streamflow model parameters and percent imperviousness in six subwatersheds represented in the streamflow model for Christians Creek, Augusta County, Virginia

[HRU, Hydrologic Response Unit; see table 1 for definitions of parameters; U, Urban; R, Residential; P, Pasture; H, Hayland; C, Cropland; F, Forest; UI, Urban impervious; PI, Pastureland 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	0.985	0.00	0.50	0.02	0.40	0.60	0.00	0.20	7.00	0.50
R	–	.00	.985	.00	.50	.02	.40	.60	.00	.20	7.00	.50
P	–	.00	.985	.00	.50	.02	1.00	.60	.00	.20	10.00	.80
H	–	.00	.985	.00	.50	.03	.80	.60	.00	.20	8.50	.60
C	–	.00	.985	.00	.50	.03	.80	.60	.00	.20	8.50	.60
F	–	.00	.985	.00	.50	.09	1.00	.65	.00	.20	9.50	.70
UI	38	–	–	–	–	–	–	–	–	–	–	–
PI	1	–	–	–	–	–	–	–	–	–	–	–

parameter is adjusted/calibrated until simulated streamflow closely represents observed streamflow. Eleven parameters were adjusted to obtain a calibrated model of streamflow for the Christians Creek watershed (table 4).

Results from the streamflow model were evaluated for both the calibration and verification periods. The period from October 1, 1993, to September 30, 1997 (water years 1994-97), was selected for calibration because of the observed variability in average annual streamflow. The largest (113.2 ft^3/s) and smallest (41.5 ft^3/s) amount of average annual streamflow occurred during this period. Calibration over this period ensures that the streamflow model will account for this increased hydrologic variability. Results from the model calibration were evaluated on the basis of comparisons between simulated and observed streamflow with respect to water budget (total runoff volume), high-flow and low-flow distribution (comparison of low-flow and high-flow periods), stormflow (comparison of stormflow volume, peak, and recession), and season (seasonal runoff volume). These comparisons were performed using Expert System for the Calibration of the Hydrological Simulation Program–FORTRAN (HSPEXP) (Lumb and others, 1994). Seven calibration criteria, expressed as a percent difference, were established in HSPEXP to aid in the evaluation of simulated and observed runoff:

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

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

The calibrated streamflow model was verified by simulating streamflow during the period from April 4, 1991, to September 30, 1993, using the adjusted hydrologic 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 (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:

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

$$WSFAC = \frac{2.30}{WSQOP} \tag{3}$$

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

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

SURO is the total amount of surface runoff (in/interval),

WSFAC is susceptibility of fecal coliform bacteria to washoff (per inch), and

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

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

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

Table 5. Parameters used in the simulation of the transport and storage of fecal coliform bacteria in Christians Creek, Augusta County, Virginia

[ft^3, cubic feet]

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

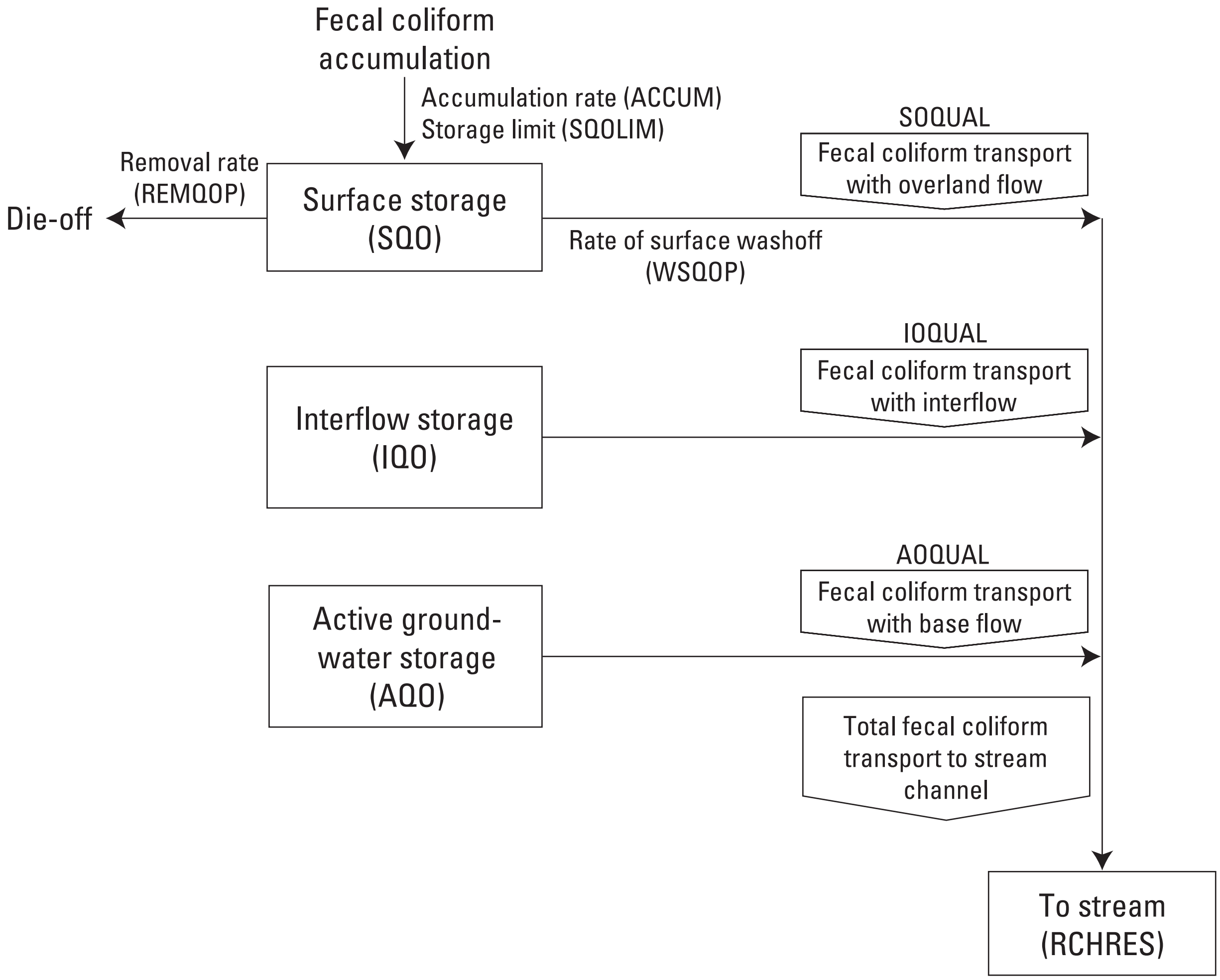


Figure 4. Routing processes represented by the Hydrological Simulation Program-FORTRAN for the simulation of fecal coliform bacteria transport in Christians Creek, Augusta County, Virginia. (See table 5 for definition of fecal coliform bacteria transport and storage parameters.)

Stream Channels

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

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

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

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

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

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

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

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

THGEN is the temperature correction parameter, dimensionless, and

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

Limitations of the Fecal Coliform Model

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

Point and Nonpoint Source Representation

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

There are six permitted point source dischargers of fecal coliform bacteria in the Christians Creek watershed (table 6). Three are STPs, each of which is permitted by DEQ to release treated wastewater to Christians Creek or associated tributaries. According to the permit, this wastewater may not contain fecal coliform bacteria concentrations that exceed 200 col/100 mL. The maximum permitted discharge rate and fecal coliform concentration were used to represent each of these STPs in the Christians Creek watershed model. These STPs were represented as a continuous and direct supply of water and bacteria to the respective simulated stream channel. The combined total annual load from the STPs is 2.33×10^{12}col/year. There also are 12 private permitted dischargers, including 9 residences and 3 small businesses, in the watershed (table 7). Combined, these private dischargers contribute 3.32×10^{10}col/year to Christians Creek.

Most of the fecal coliform bacteria in Christians Creek are derived from and represented as nonpoint sources. These bacteria are deposited on the land surface by many different sources (people, pets, livestock, and wildlife) and subsequently are transported to the stream network with rainfall runoff. Two critical pieces of information must be obtained to simulate the transport of fecal coliform bacteria derived from nonpoint sources using HSPF. First, the dominant sources of fecal coliform bacteria in the watershed must be identified. A survey was conducted of fecal coliform sources in the Christians Creek watershed, and 13 sources were identified as potentially dominant and represented in the model. These 13 sources are beavers, cats, cattle, deer, dogs, ducks, geese, horses, humans, muskrats, poultry, raccoons, and sheep. Second, the total daily amount of fecal coliform bacteria deposited on the land surface or directly in streams (straight pipes, cattle in streams, and beaver) by each of the identified sources must be determined for both pervious and impervious land segments.

General Quantification of Fecal Coliform Bacteria

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

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

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

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

Table 6. Permitted point-source dischargers of fecal coliform bacteria in Christians Creek, Augusta County, Virginia, 1992-97

Permit number	Owner	Facility	Discharge rate (million gallons per day)	Fecal coliform limit (number of colonies per 100 milliliters)	Annual fecal coliform load (number of colonies per year)
VA0025291	Augusta County Service Authority	Fishersville Sewage Treatment Plant	0.7	200	1.94×10^{12}
VA0022306	Augusta County Service Authority	Staunton Plaza Sewage Treatment Plant	.09	200	2.49×10^{11}
VA0022292	Augusta County Service Authority	Brookwood Interchange	.03	200	8.32×10^{10}
VA0020427	Augusta County School Board	Rivershead High School	.014	200	3.88×10^{10}
VA0089061	Woodlawn Village L.L. Corp.	Woodlawn Village Mobile Home Park	.007	200	1.94×10^{10}
VA0086738	Southern States Coop, Inc.	Southern States Coop	0	200	0
Total					2.33×10^{12}

Table 7. Private permitted point-source dischargers of fecal coliform bacteria in Christians Creek, Augusta County, Virginia

Permit number	Discharge rate (gallons per day)	Fecal coliform limit (number of colonies per 100 milliliters)	Annual fecal coliform load (number of colonies per year)
VAG401655	1,000	200	2.76×10^{9}
VAG401967	1,000	200	2.76×10^{9}
VAG401968	1,000	200	2.76×10^{9}
VAG401082	1,000	200	2.76×10^{9}
VAG401138	1,000	200	2.76×10^{9}
VAG401159	1,000	200	2.76×10^{9}
VAG401195	1,000	200	2.76×10^{9}
VAG401203	1,000	200	2.76×10^{9}
VAG401443	1,000	200	2.76×10^{9}
VAG401449	1,000	200	2.76×10^{9}
VAG401896	1,000	200	2.76×10^{9}
VAG401969	1,000	200	2.76×10^{9}
Total			3.32×10^{10}

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

POPN is the population size, dimensionless, and

HAB is the habitat area (acres).

The calculation of ACCUM is based on values of Fprod, FCden, HAB, and POPN that are source specific, and selection of these values is challenging. Information on Fprod and HAB generally is well documented for individual species. Therefore, single values of Fprod and HAB are used and held constant throughout the entire modeling effort. Values of FCden and POPN, however, generally are more variable and poorly documented compared to values of Fprod and HAB. For example, dog, cat, and human feces have measured FCden ranges of 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 Christians Creek watershed is documented in the following section. The sources described in this section are humans, dogs, cats, beef cattle, dairy cattle, heifers, broilers, turkeys, horses, sheep, deer, geese, ducks, raccoons, muskrats, and beavers. These sources are described with respect to their contribution to the pervious and impervious land segments within the basin.

Pervious Land Segments

The Christians Creek watershed has a human population of approximately 12,000 (1990 Census). Within the watershed, many pathways can allow human-derived fecal coliform bacteria to enter Christians Creek. These pathways include failing septic systems, overflowing sewer lines, leaking sewer lines, and straight pipes (direct discharge of untreated sewage from private residences), 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 8. On average, one person generates approximately 150 g of feces per day (Geldreich and others, 1962) and an estimated 4.66×10^8 col/g of human feces (Mara and Oragui, 1981). The initial population value (POPN) used was based on an estimated septic-system failure rate of 15 percent, which is consistent with failure rates determined for nearby communities (Virginia Polytechnic Institute and State University, 2000). In the Christians Creek watershed, 2,950 houses have septic systems. The average household occupancy rate for Augusta County is 2.69 people (1990 Census). POPN is the most uncertain value in equation 6 and, therefore, is adjusted during the model calibration process. These bacteria then are distributed over the residential land type (HAB) (table 8).

Straight pipes were represented as point sources in HSPF. Three factors were used to estimate the number of straight pipes in each subwatershed: the number of houses in each subwatershed, the age of each house, and the proximity of each house to the nearest stream. The number of houses was identified by using the emergency-911 database for Augusta County, Va., which was provided as a GIS coverage by the county. These houses were placed in three possible age categories (pre-1964, 1964-84, and post-1984). The selection of the age categories was based on two versions of USGS 7.5-minute topographic maps. The first series of topographic maps were derived from 1964 aerial photography and were photo-revised in 1984. Therefore, houses represented on the 1984 maps would have been built between 1964 and 1984. The proximity of each house to the nearest stream was identified using the emergency-911 coverage. The total number of houses within 150 ft of a stream was identified. Ten percent and 2 percent of the houses identified to be within 150 ft of a stream, in the pre-1964 and 1964-84 age categories, respectively, were assumed to have a straight pipe (Virginia Polytechnic Institute and State University, 2000). Based on the outlined methodology, there are an estimated number of four straight pipes within the Christians Creek watershed (table 8). The estimated number of fecal coliform bacteria discharged from each straight pipe is based on the occupancy for a single-family residence of 2.69 people and the daily per capita fecal coliform production rate of 6.99×10^{10} col/day (table 8).

Fecal coliform bacteria derived from dogs were represented as a land application to both urban and residential land types. The accumulation rate for these bacteria was calculated using equation 6. Initial values used to calculate ACCUM are listed in table 9. On average, one dog generates 450 g of feces per day (Weiskel and others, 1996), and an estimated 4.11×10^{6} col/g of feces (Mara and Oragui, 1981). The initial value for the total number of dogs in the watershed was based on the estimate of one dog per three people. This estimate was refined further to account for the approximately 20 percent of dog waste that is picked up and disposed of. Additionally, 10 percent of the dog waste was assumed to be deposited on impervious surfaces such as parking lots and roads. The POPN value in table 9 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 9. On average, one cat generates 20 g of feces per day (Jutta Schneider, Virginia Department of Conservation and Recreation, written commun., 2000), and an estimated 1.49×10^{7} col/g of feces (Mara and Oragui, 1981). The initial value for the total number of cats in the watershed was based on an estimate of two cats per three people. It was assumed that 70 percent of the estimated number of cats deposits their feces outdoors. The POPN value in table 9 represents the initial estimated number of cats that deposit their feces outdoors. Because the actual number of cats that deposit their feces outdoors is unknown, POPN is treated as a fitted value during the model-calibration process.

There are approximately 10,000 beef cattle, 1,650 dairy cattle, and 2,100 heifers in the Christians Creek Watershed. Each of these cattle types has different estimated daily fecal production rates (American Society of Agricultural Engineers, 1998) and associated fecal coliform densities (Mara and Oragui, 1981) (table 10). The fecal coliform bacteria derived from cattle feces can be transported to Christians Creek along three possible pathways: (1) Feces generated while cattle are confined are stored and later distributed over the various croplands in the watershed, and then transported to the stream network with surface runoff. (2) Feces are deposited directly on the pastureland by grazing cattle, and then transported to the stream network through surface runoff. (3) Feces are deposited directly in Christians Creek and associated tributaries by cattle standing in these streams. Each of these three pathways is represented in HSPF.

Table 8. 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, Christians Creek, Augusta 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 of humans)	HAB (acres)
		Human–land applied		
1	150	4.66×10^8	209	289
2	150	4.66×10^8	135	206
3	150	4.66×10^8	260	309
4	150	4.66×10^8	172	485
5	150	4.66×10^8	253	808
6	150	4.66×10^8	161	261
		Human–straight pipes		
1	150	4.66×10^8	3	–
2	150	4.66×10^8	3	–
3	–	–	–	–
4	150	4.66×10^8	3	–
5	–	–	–	–
6	150	4.66×10^8	3	–

[1]See figure 3 for location of subwatersheds.

Table 9. 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, Christians Creek, Augusta 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	368	199	289	414
2	450	4.11×10^6	238	129	206	153
3	450	4.11×10^6	458	248	309	495
4	450	4.11×10^6	303	164	485	1,244
5	450	4.11×10^6	446	242	808	196
6	450	4.11×10^6	283	153	261	429
			Cats			
1	20	1.49×10^7	654	393	289	414
2	20	1.49×10^7	423	254	206	153
3	20	1.49×10^7	814	490	309	495
4	20	1.49×10^7	537	324	485	1,244
5	20	1.49×10^7	792	477	808	196
6	20	1.49×10^7	502	302	261	429

[1]See figure 3 for location of subwatersheds.

Table 10. Initial values of the total amount of feces produced daily and fecal coliform per gram of feces generated by dairy cattle, beef cattle, and heifers represented in the fecal coliform model, Christians Creek, Augusta County, Virginia

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

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

Dairy cattle are confined in or around milking parlors between 7.2 and 18.0 hr/day during the summer and winter months, respectively (table 11). The feces generated by confined dairy cattle are collected and stored in anaerobic lagoons. Fecal coliform bacteria stored in anaerobic lagoons are subject to die-off; the die-off rate was simulated using the equation

$$C_t = C_o e^{-Kt} \tag{7}$$

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

C_o is the initial fecal coliform bacteria load,

t is the time in days, and

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

C_o was set to the number of fecal coliform bacteria produced annually by dairy cattle in confinement. The time (t) these bacteria were stored was set to 100 days, which represents the average storage capacity of dairy lagoons in the Christians Creek watershed. A decay rate (K) of 0.375 day^{-1} was used to represent the decay rate observed in an anaerobic lagoon (Crane and Moore, 1986). The amount of fecal coliform bacteria remaining after the 100 days of storage (C_t), which then is available for manual application to croplands, is incorporated into equation 6 to determine the accumulation rate per acre of cropland. Because the number of dairy cattle in the watershed is known, FCden is adjusted during the model-calibration process. The percentage of stored dairy waste applied to cropland varies from month to month (table 12); the monthly field application rate and the number of cattle in confinement were represented by means of monthly ACCUM values. The fecal coliform bacteria from the dairy waste applied to cropland are treated as a nonpoint source in the model simulation.

Beef cattle and heifers spend an average of 9.6 hours per day in confinement during the months of December, January, and February (table 13). During these months, the cattle are confined in a small area but are housed in barns where they deposit feces and associated fecal coliform bacteria. The accumulating manure is removed routinely and stored until it can be applied to cropland. Fecal coliform bacteria are subject to die-off during the manure storage phase. Equation 7 was used to determine the total amount of bacteria removed from the stored manure through die-off. C_o was set to the total number of fecal coliform bacteria produced yearly by beef cattle and heifers in confinement. The total time (t) these bacteria were stored was set to 30 days. A decay rate (K) of 0.066 day^{-1} was used to represent the decay rate in an uncovered manure pile (Crane and Moore, 1986). The amount of fecal coliform bacteria remaining after the 30 days of storage (C_t), which then is available for manual application to croplands is incorporated into equation 6 to determine the accumulation rate per acre of cropland. Because the number of beef cattle and heifers in the watershed is known, FCden is treated as an adjusted value during the model-calibration process. The percentage of stored manure applied to cropland varies from month to month (table 14); the monthly field application rate and number of cattle in confinement were represented in the model by means of monthly ACCUM values. The bacteria from the manure applied to cropland are treated as a nonpoint source in the model simulation.

Dairy cattle spend between 5.5 and 15.8 hours per day in the pasture (table 11) while beef cattle and heifers spend between 13.9 and 23.0 hours per day in the pasture (table 13). In the model, pasture is represented by both pasture and hayland, with 80 percent of the cattle distributed on pasture and 20 percent distributed on hayland. These cattle deposit feces with associated fecal coliform bacteria directly onto the pasture. The daily total number of bacteria deposited on the pasture is determined by the time cattle spend in the pasture and the daily fecal coliform production rate. Monthly values of ACCUM were used to represent the monthly

Table 11. Initial values of the total hours per day dairy cattle spend in a given month in the pasture, in confinement, and with access to a stream in the Christians Creek watershed, Augusta County, Virginia

Month	Time (hours)		
	Pasture	Access to stream	Confinement
January	5.5	0.5	18.0
February	5.5	.5	18.0
March	13.4	1.0	9.6
April	15.8	1.0	7.2
May	15.8	1.0	7.2
June	13.8	3.0	7.2
July	13.8	3.0	7.2
August	13.8	3.0	7.2
September	15.8	1.0	7.2
October	15.8	1.0	7.2
November	13.4	1.0	9.6
December	5.5	.0	18.0

Table 12. Percentage of the total stored liquid dairy cattle waste applied to cropland in the Christians Creek watershed, Augusta County, Virginia

Month	Application amount[1] (percent)
January	0.0
February	5.0
March	25.0
April	20.0
May	5.0
June	7.5
July	2.5
August	5.0
September	12.5
October	7.5
November	10.0
December	.0

[1]From Virginia Department of Conservation and Recreation

Table 13. Total hours per day beef cattle and heifers spend in a given month in the pasture, with access to a stream, and in confinement in the Christians Creek watershed, Augusta County, Virginia

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

Table 14. Percentage of stored beef cattle and heifer manure and poultry litter applied to cropland in the Christians Creek watershed, Augusta County, Virginia

Month	Application amount[1] (percent)
January	0.0
February	5.0
March	25.0
April	20.0
May	5.0
June	5.0
July	5.0
August	5.0
September	10.0
October	10.0
November	10.0
December	.0

[1]From Virginia Department of Conservation and Recreation

varying number of cattle in the pastures, and the bacteria from the feces deposited directly to the pasture are treated as a nonpoint source in the model simulation.

When stream access is provided, cattle spend an average of 0.5 hr/day during cold months to 3.5 hr/day during warm months (table 13) in and near streams. In order to determine and simulate the total amount of feces that is deposited directly to the stream, the number of cattle with direct access to a stream must be identified. This number is estimated by first identifying the total number of pasture and hayland land segments (pastures) that are bordered by Christians Creek or its major tributaries, Folly Mills Creek, Barterbrook Branch, Goose Creek, and Meadow Run (fig. 1). GIS coverages for land use and stream networks in the Christians Creek watershed revealed that 35 percent of all pastures are bordered by a major stream. The number of cattle in the major streams is determined by the equation

$$Cattle_{Instream} = (Cattle_{Total}(0.35))\left[\frac{T_{Access}}{24}\right] \qquad (8)$$

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

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

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

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

There are 10,000 broilers and 172,000 turkeys in the Christians Creek watershed. In addition, 3,000 tons of poultry litter are imported annually. The imported litter and the resident broiler and turkey population was represented in the model as combined poultry. A fecal production rate for turkey of 231 g/day (American Society of Agricultural Engineers, 1998) and an estimated fecal coliform density of 1.82 x 10^9 col/g (Mara and Oragui, 1981) were used to determine the total number of fecal coliform bacteria produced per day. Because the entire poultry population is confined to poultry houses, the generated poultry litter is stored and later applied to cropland. The extent of fecal coliform bacteria die-off during poultry litter storage was determined using equation 7. C_o was set to the total number of fecal coliform bacteria produced yearly by poultry. The time (t) these bacteria were stored was set to 90 days, which is the average poultry litter storage time. A decay rate (K) of 0.08 day^{-1} was used to represent the decay rate observed for poultry litter applied to the soil surface (Giddens and others, 1973). The amount of fecal coliform bacteria remaining (C_t) after the 90 days of storage is incorporated into equation 6 to determine ACCUM. The percentage of stored poultry litter applied to cropland varies from month to month (table 14); the monthly field application rate was represented in the model by means of monthly ACCUM values. Because the number of poultry in the watershed is known, FCden is adjusted during the model-calibration process. The fecal coliform bacteria from the poultry litter applied to cropland are treated as a nonpoint source in the model simulation.

There are 600 horses and 1,100 sheep in the Christians Creek watershed. The average fecal production rate for horses and sheep is 23,182 g/day and 1,091 g/day, respectively (American Society of Agricultural Engineers, 1998). The fecal coliform density assumed for horse feces is 1.81 x 10^5 col/g (American Society of Agricultural Engineers, 1998) and 1.80 x 10^5 col/g for sheep (Mara and Oragui, 1981). ACCUM values for horses and sheep are adjusted during the calibration process, as needed, through the FCden parameter. Horses and sheep deposit their waste directly onto pasture. The bacteria applied to pasture are treated as a nonpoint source in the model simulation.

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

The wildlife sources represented in the model are deer, geese, ducks, raccoons, muskrats, and beavers. These sources were selected on the basis of information from the Virginia Department of Game and Inland Fisheries (VDGIF) and watershed surveys performed by the USGS as part of this study. The population of each of these wildlife species was estimated on the basis of habitat area, species density within the habitat area, and seasonal migration (table 15). GIS coverages for animal habitat and land use were used to determine the size of each animal's habitat. For example, Canada geese prefer to be within 300 ft of streams on all land segments except forested; therefore, the total acres of Canada geese habitat is equal to the sum of the acres of all land segments within 300 ft of a stream, except forested, in the habitat area. The population density for geese and ducks increases during the winter months (December, January, and February) because of migration. The amount of fecal coliform bacteria produced daily by each wildlife species (table 16) is used in equation 6 to identify ACCUM for each wildlife species represented in the model. POPN for all wildlife species except deer, and FCden for deer, are adjusted during the model-calibration process. Monthly values of ACCUM are adjusted for geese and ducks in order to account for migration. The feces of all wildlife species except beaver are deposited directly to the land segments in their habitat; therefore, these sources of fecal coliform bacteria are represented in the model as nonpoint sources. Beaver feces are deposited directly in streams and, therefore, are represented as a point source.

Impervious Land Segments

Dogs are the only source in the model that is assumed to deposit feces on impervious surfaces (table 17). Ten percent of the total waste generated by dogs is assumed to fall directly on the impervious portions of the urban land-use type. The bacteria from the feces directly deposited on impervious surfaces are modeled as a nonpoint source. The fecal coliform accumulation rate is calculated using equation 6 and is based on fecal production from 10 percent of the dog population.

Fecal Coliform Bacteria in the Subsurface

The decision to represent fecal coliform bacteria in the subsurface was based primarily on results from intensive monitoring of fecal coliform bacteria during stormflow and base-flow conditions in Christians 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 Christians 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 cattle, dogs, humans, and poultry.

Base flow, which represents the portion of ground water that enters the stream, is the dominant component of the stream hydrograph during periods of extended dry weather. Fecal coliform bacteria observed during these base flow periods typically are transported through diffuse ground-water input or pathways that mimic this diffuse input, such as resuspension of fecal coliforms from streambed sediments by animals walking in the stream, sloughing of fecal coliforms from the surface of streambed sediments, and advective trans-

Table 15. Initial population values of wildlife sources of fecal coliform bacteria in the fecal coliform model, Christians Creek, Augusta County, Virginia

[POPN, population size; F, Forest; P, Pasture; U, Urban; R, Residential; H, Hayland; C, Cropland]

Wildlife source	Land-use type	Habitat[1]	Population density[2] (number per acre)	POPN (number)
Deer	F, P	Entire watershed	0.040	975
Goose–Summer	U, R, P, H, C	Within 300 feet of streams and ponds	.078	373
Goose–Winter	U, R, P, H, C	Within 300 feet of streams and ponds	.11	526
Duck–Summer	U, R, P, H, C	Within 300 feet of streams and ponds	.047	225
Duck–Summer	F	Within 300 feet of streams and ponds	.016	35
Duck–Winter	U, R, P, H, C	Within 300 feet of streams and ponds	.063	301
Duck–Winter	F	Within 300 feet of streams and ponds	.031	67
Raccoon	F	Within 2,640 feet of streams and ponds	.055	1,083
Raccoon	R, P, H, C	Within 2,640 feet of streams and ponds	.023	1,042
Muskrat	U, R, P, H, C, F	Within 60 feet of streams and ponds	.500	479
Beaver	F	Within 60 feet of streams and ponds	.016	5
Beaver	U, R, P, H, C	Within 60 feet of streams and ponds	.008	5

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

Table 16. Initial values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by deer, goose, duck, raccoon, muskrat, and beaver represented in the fecal coliform model, Christians Creek, Augusta 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
Beaver	200	1.00×10^3

Table 17. 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 impervious hydrologic response unit represented in the fecal coliform model, Christians Creek, Augusta 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	450	4.11×10^6	22	26
2	450	4.11×10^6	14	10
3	450	4.11×10^6	28	32
4	450	4.11×10^6	18	170
5	450	4.11×10^6	27	13
6	450	4.11×10^6	17	27

[1]See figure 3 for location of watersheds.

port of fecal coliforms from the streambed sediment by ground-water inputs. Results from Hyer and Moyer (2003) indicate that bacteria linked to poultry, pet, and other nonpoint sources were present in base-flow samples from Christians 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 cattle, dogs, humans, and poultry identified by Hyer and Moyer (2003).

Water-Quality Data

DEQ monitors water quality in streams and rivers across the State. One constituent monitored is fecal coliform bacteria, which are derived from the intestinal tract of warm-blooded animals. These bacteria are used as an indicator organism for identifying the presence of fecal contamination and associated pathogens such as *Salmonella* and *Shigella*. The predominant form of fecal coliform bacteria is *Escherichia coli (E. coli).* DEQ collects and analyzes water samples to determine if a particular stream or river is in compliance with the State water-quality standard for fecal coliform bacteria, which is an instantaneous concentration of 1,000 col/100 mL. Sites with fecal coliform bacteria concentrations greater than 1,000 col/100 mL pose a risk to individuals who are in direct contact with the contaminated water because of the increased likelihood of encountering a pathogen (U.S. Environmental Protection Agency, 1986). DEQ has established a lower detection limit of 100 col/100 mL and an upper detection limit of 8,000 col/100 mL for enumeration of fecal coliform bacteria. Therefore, fecal coliform bacteria concentrations reported by DEQ of 100 and 8,000 col/100 mL have an actual concentration of 0–100 col/100 mL or greater than or equal to 8,000 col/100 mL, respectively. DEQ generally collects water-quality samples monthly under low-flow or post stormflow conditions; peak stormflow water-quality samples are not collected routinely.

DEQ collects monthly water-quality samples at two long-term monitoring stations on Christians Creek (fig. 1; table 18). Samples are analyzed for fecal coliform bacteria using the membrane filtration technique. Results of monitoring during 1991-97 show that fecal coliform bacteria concentrations were higher than the State instantaneous water-quality standard in 64.4 percent of the samples taken at the upstream site (Route 831) (fig. 5) and in 33.8 percent of the samples taken at the downstream site (Route 794) (fig. 6). Comparison of the fecal coliform bacteria data from the Route 831 and Route 794 monitoring stations (fig. 7), by means of a two-sided Wilcoxon rank sum test, indicates significantly higher concentrations at the Route 831 station relative to those at the Route 794 station ($p = 0.0004$). Seasonal patterns also were identified in the data (figs. 8-9). Generally, fecal coliform concentrations are higher during the warmer months (April–October) and lower during the cooler months (November–March). This seasonal pattern was more pronounced at the Route 831 station than the Route 794 station and is consistent with the animal practices in the

Table 18. Fecal coliform bacteria concentrations for water-quality samples collected by the Virginia Department of Environmental Quality at two water-quality monitoring stations on Christians Creek, Augusta County, Virginia

Station number[1]	Station name	Latitude Longitude	Period of record	Fecal coliform bacteria concentration, in colonies per 100 milliliters			
				Minimum	Maximum	Mean	Median
1BCST021.76	Route 831	38°03′22″ 79°04′18″	1991-2001	100	8,000	2,526	1,500
1BCST012.32	Route 794	38°07′43″ 78°59′41″	1979-2001	100	8,000	1,205	600

[1]See figure 1 for location of stations.

watershed (increased animal density and activity around the streams during the hot summer months) and possible seasonal differences in bacteria survivorship. Similar seasonal patterns have been observed in other studies of fecal coliform concentrations and loads (Christensen and others, 2001; Baxter-Potter and Gilliland, 1988).

The USGS collected water-quality data for this study at six sites in Christians 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 the complete range of hydrologic conditions (table 19).

Low-flow samples were collected every 6 weeks at Route 794. 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 50 percent of the low-flow samples exceeded the State fecal coliform bacteria standard (fig. 10). Recession-flow samples generally had fecal coliform concentrations that were elevated relative to the low-flow samples. The fecal coliform data also exhibited a strong seasonal pattern; higher concentrations were observed during the warmer months (June–September) than during the cooler months (October–May). This seasonal pattern for concentrations of fecal coliform bacteria is consistent with the pattern identified in the historical data.

Stormflow samples were collected during five storm events (September 9, 1999; November 11, 1999; March 20, 2000; April 25, 2000; and June 28, 2000) at Route 794. 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. 11) 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 23,000 to 730,000 col/100 mL. Elevated fecal coliform concentrations during storm events have been observed in previous studies (Christensen and others, 2001; Bolstad and Swank, 1997). In general, these elevated stormflow concentrations are interpreted as resulting from a combination of a flushing response (whereby fecal coliform bacteria that have been deposited near the stream are washed off the land surface and into the stream) and a resuspension of streambed sediments containing fecal coliform bacteria (Hunter and others, 1992; McDonald and Kay, 1981).

Five continuum sampling sites in addition to Route 794 were established along Christians Creek (fig. 1; table 19). These six sites were sampled three times (March 25, 1999; July 27, 1999; and August 1, 1999) to examine how well the intensive sampling at Route 794 represented the entire watershed. These samples were collected as a single, depth-integrated sample from the approximate center of the stream channel. Additionally, data from these continuum sites provided information on the spatial variability observed in concentrations of fecal coliform bacteria (table 19). These data are con

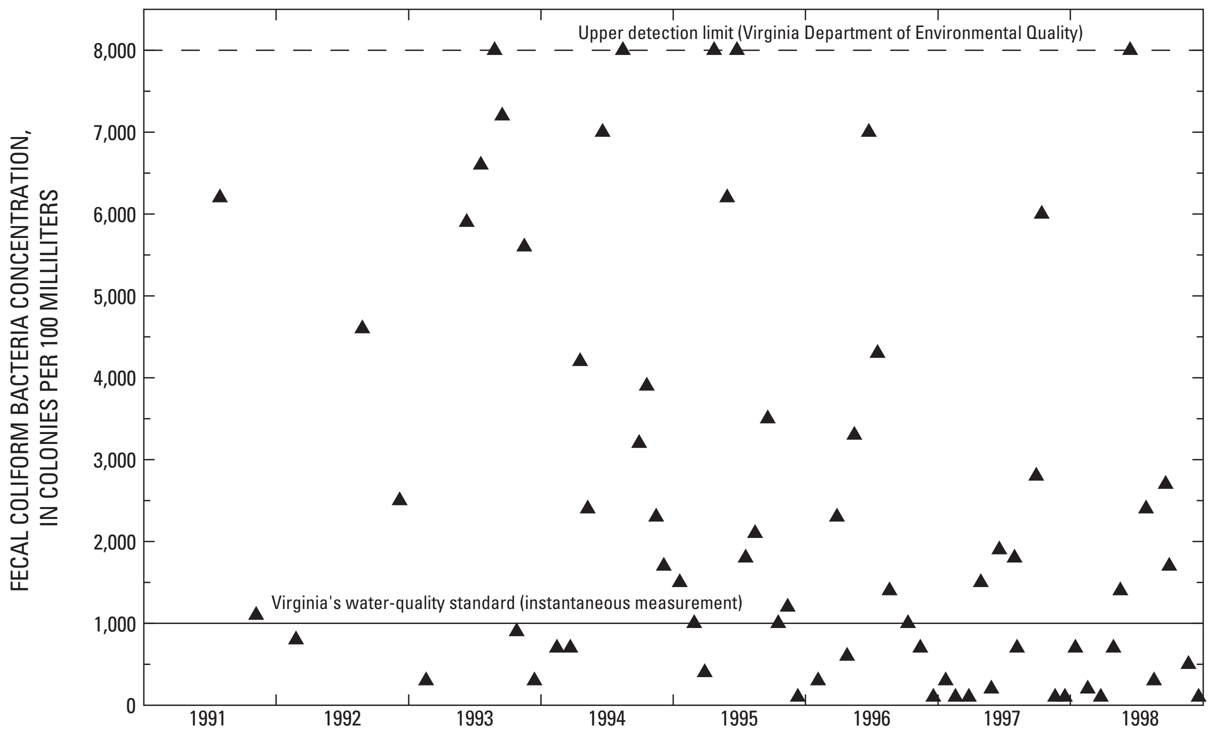


Figure 5. Observed fecal coliform bacteria concentrations for Christians Creek at Route 831, Augusta County, Virginia, from 1991-98. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

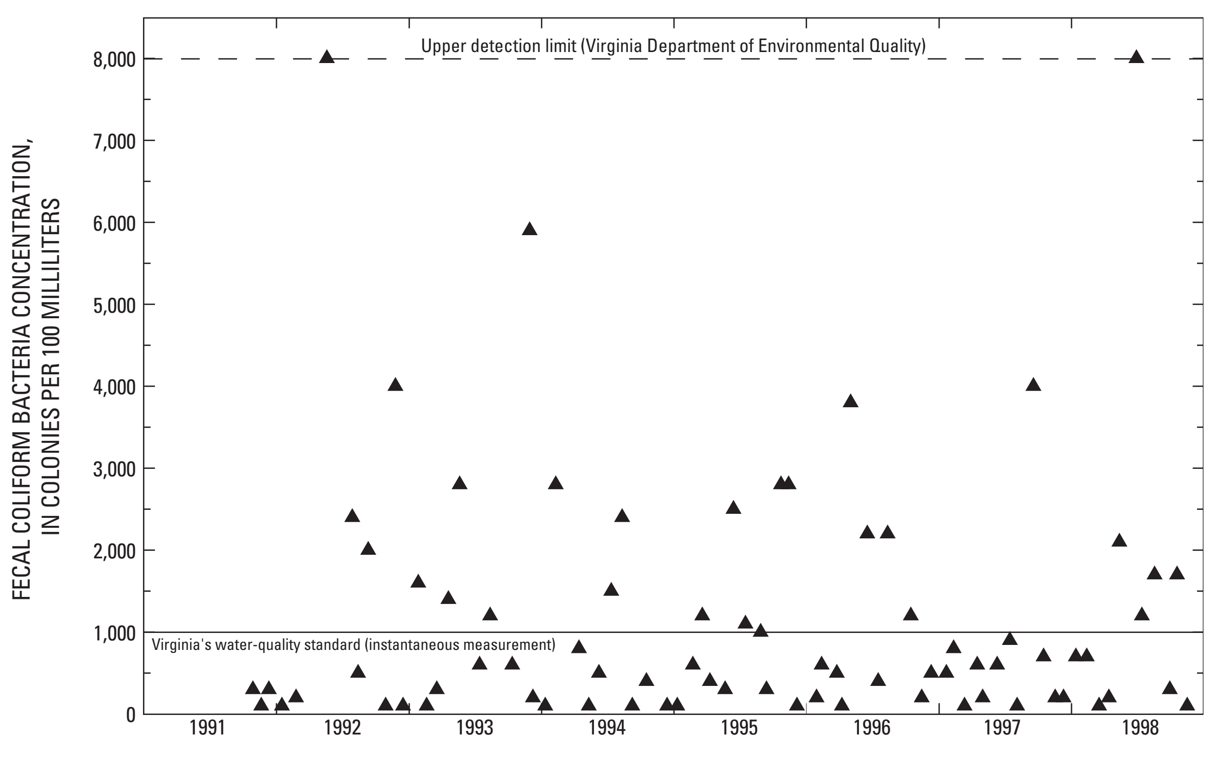


Figure 6. Observed fecal coliform bacteria concentrations for Christians Creek at Route 794, Augusta County, Virginia, from 1991-98. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

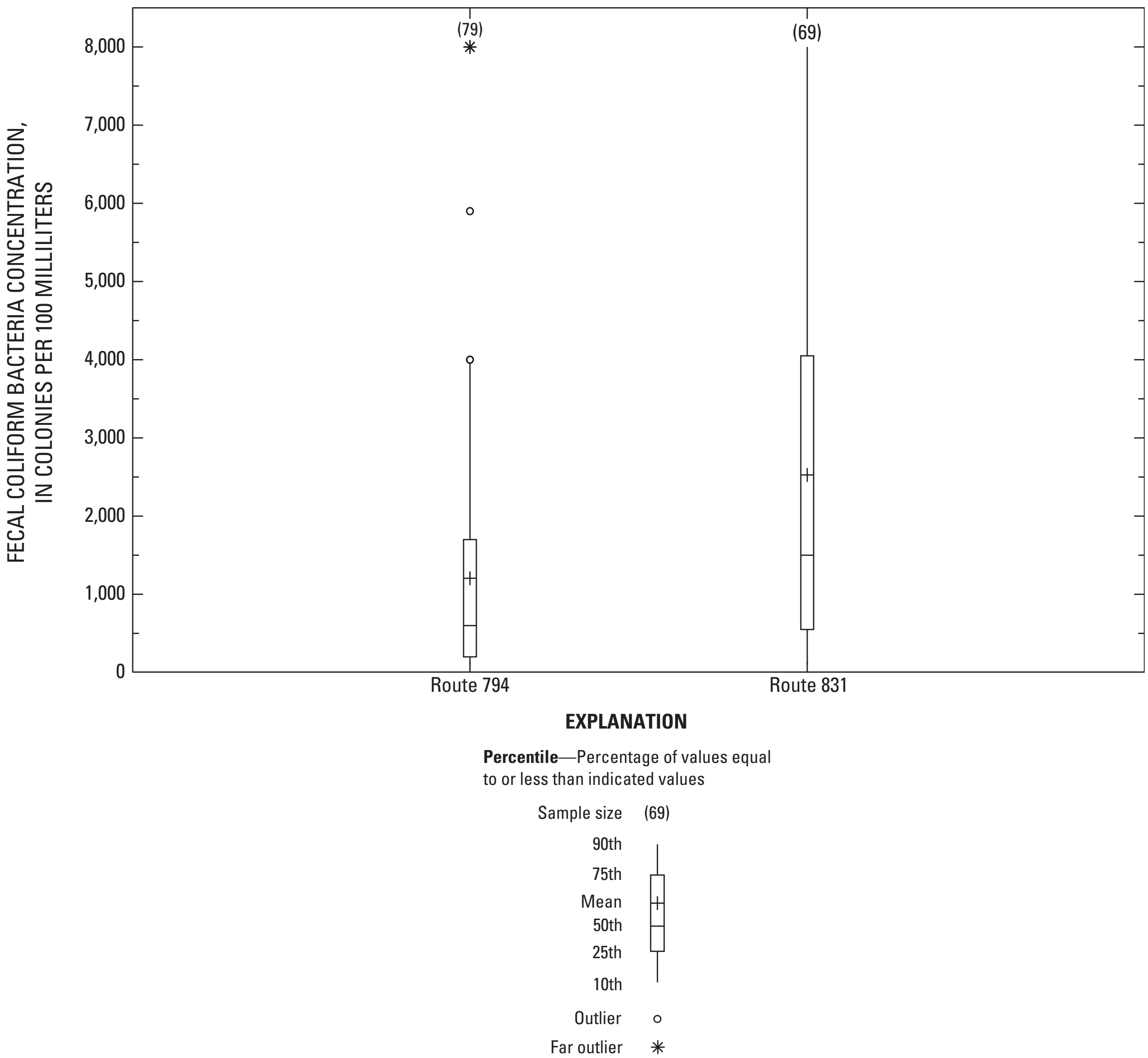


Figure 7. Relation between observed fecal coliform bacteria concentrations for Christians Creek at Route 831 and Route 794, Augusta County, Virginia, 1991-97. (Observed data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

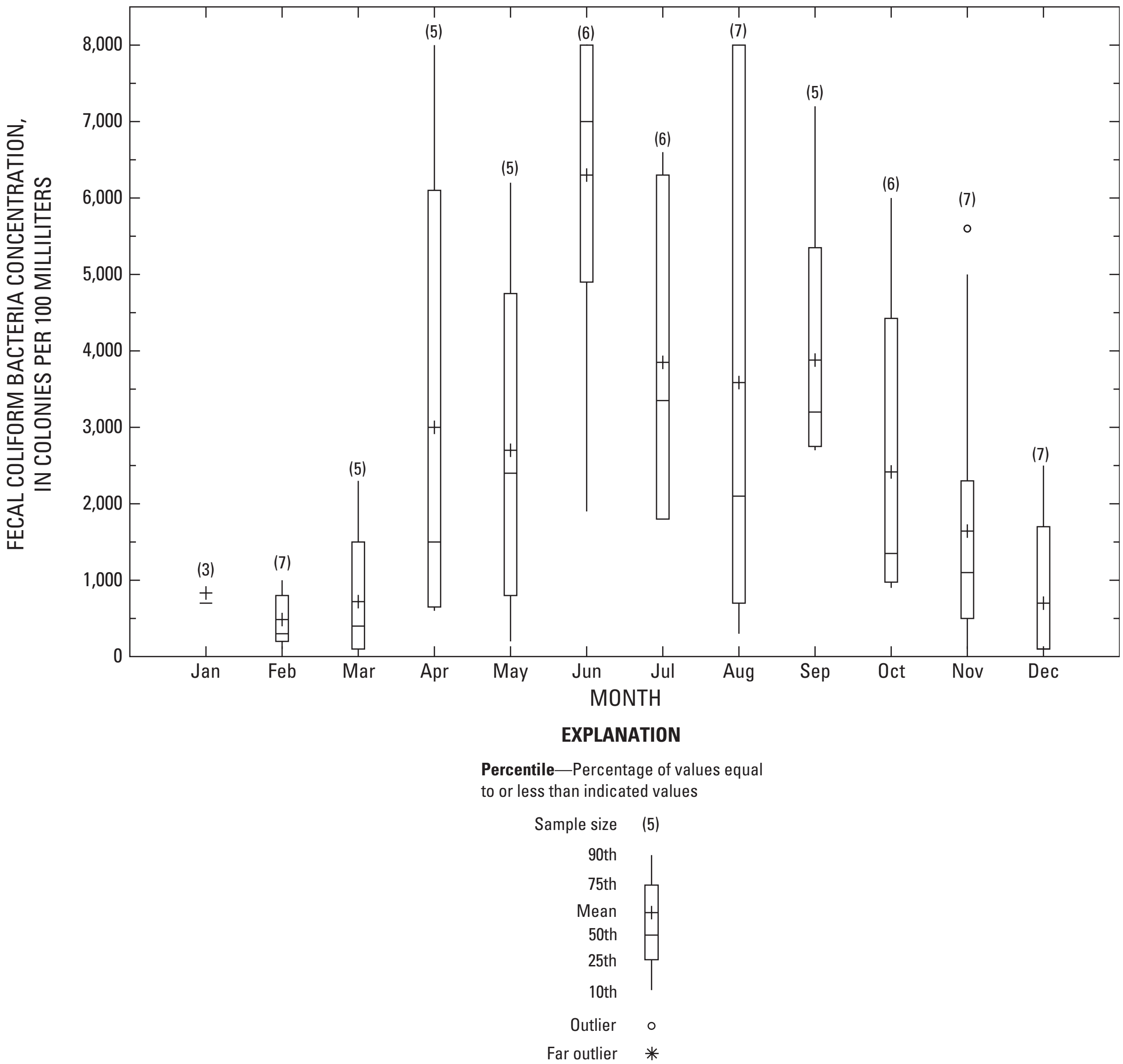


Figure 8. Monthly distribution of observed fecal coliform bacteria concentrations for Christians Creek at Route 831, Augusta County, Virginia,1991-97. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

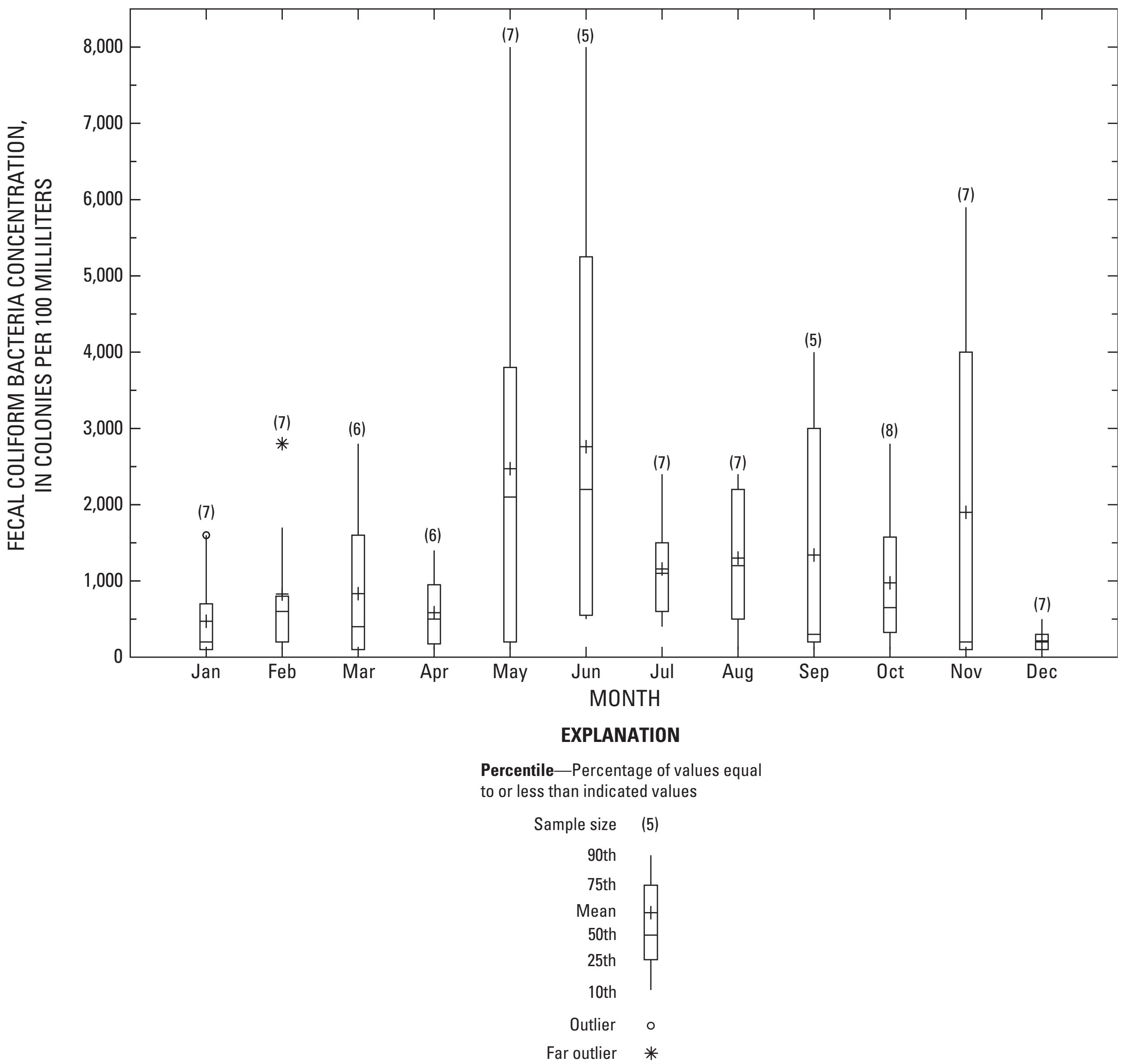


Figure 9. Monthly distribution of observed fecal coliform bacteria concentrations for Christians Creek at Route 794, Augusta County, Virginia1991-97. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)

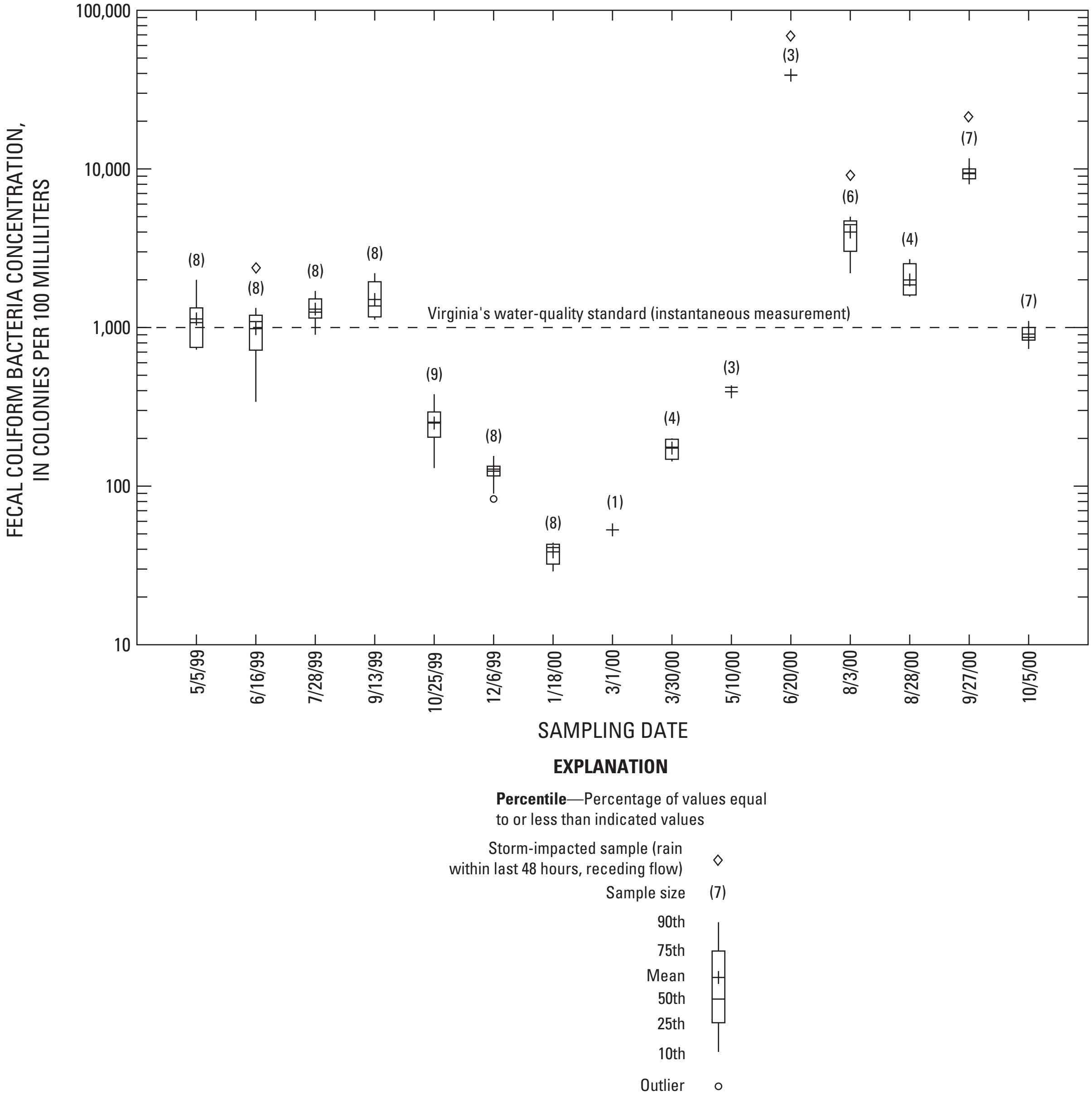


Figure 10. Observed fecal coliform bacteria concentrations from stream-water samples for Christians Creek at Route 794 during low-flow periods, Augusta County, Virginia.

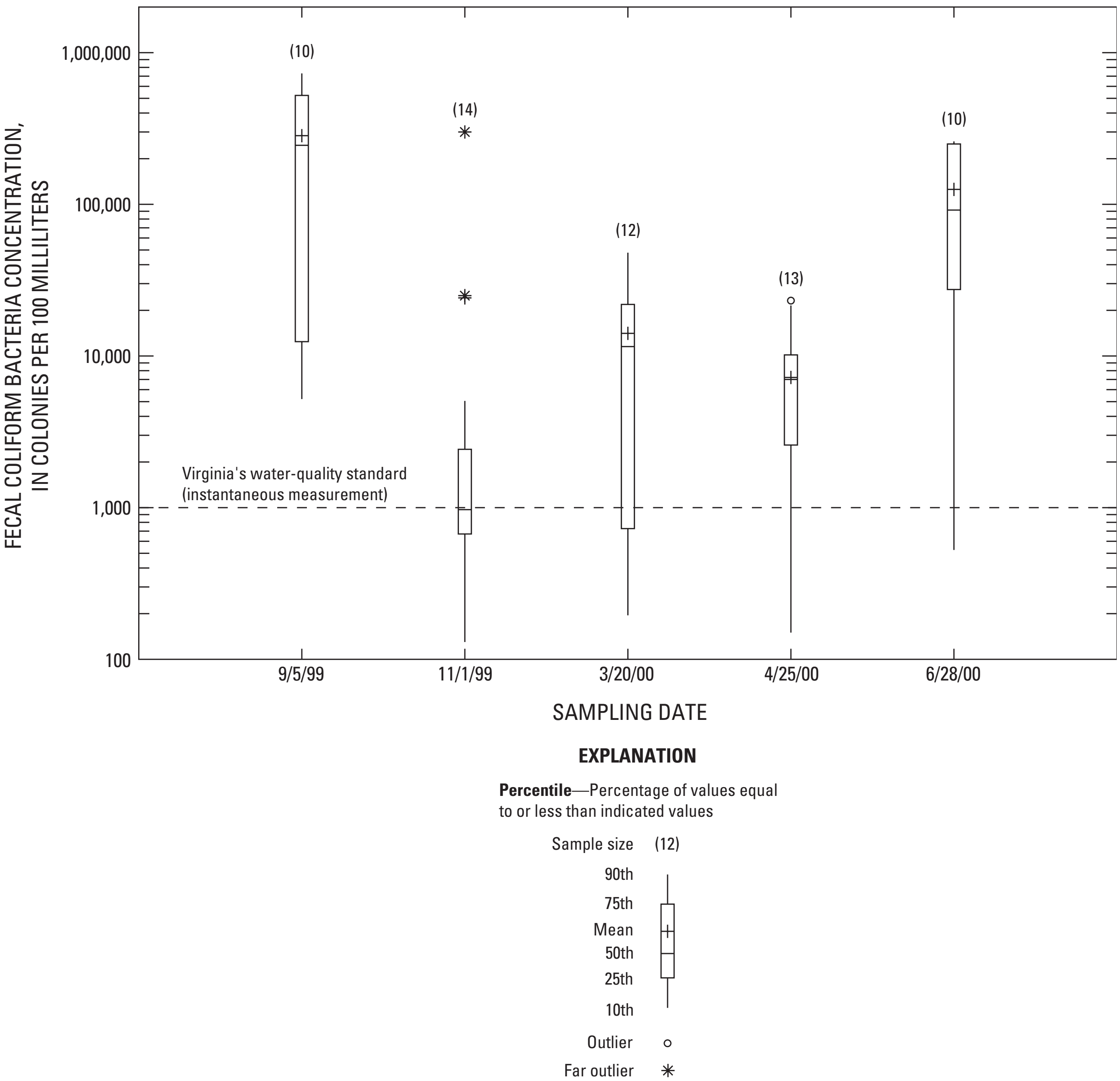


Figure 11. Observed fecal coliform bacteria concentrations from stream-water samples for Christians Creek at Route 794 during low-flow periods, Augusta County, Virginia.

Table 19. Fecal coliform bacteria concentrations for water-quality samples collected by the U. S. Geological Survey during low-flow and stormflow conditions at Route 794 (01624800) and at five other sites along the continuum of Christians Creek, Augusta 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							
01624800	Route 794	38°07′42″ 78°59′41″	104	29	43,000	3,190	1,010
Stormflow samples							
01624800	Route 794	38°07′42″ 78°59′41″	66	130	730,000	78,216	7,611
Continuum samples							
01624615	Route 693	38°02′08″ 79°11′56″	3	5	71	28	7
01624620	Route 604	38°01′08″ 79°10′05″	3	87	1,500	629	300
01624660	Route 340	38°02′38″ 79°05′17″	3	230	3,800	2,010	2,000
01624700	Route 635	38°05′35″ 79°01′54″	3	23	6,400	2,774	1,900
01624800	Route 794	38°07′42″ 78°59′41″	3	15	1,800	868	790
01624900	Route 612	38°11′35″ 78°56′07″	3	9	830	326	140

[1]See figure 1 for location of stations

sistent with patterns observed in the fecal coliform bacteria collected by DEQ at Route 831 and Route 794; fecal coliform concentrations generally are higher upstream and lower downstream.

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 rely 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 Christians 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 Christians Creek.

The results from the BST study indicate that a diverse collection of organisms contribute to the impairment of Christians Creek (Hyer and Moyer, 2003). Hyer and Moyer (2003) identified 22 different sources of fecal coliform bacteria; the top 10 contributors identified by the ribotyping analysis are poultry, cattle, human, dog, horse, and deer, with cat, duck, goose, and raccoon considered minor sources, making up less than 5 percent of the total contributors (fig. 12).

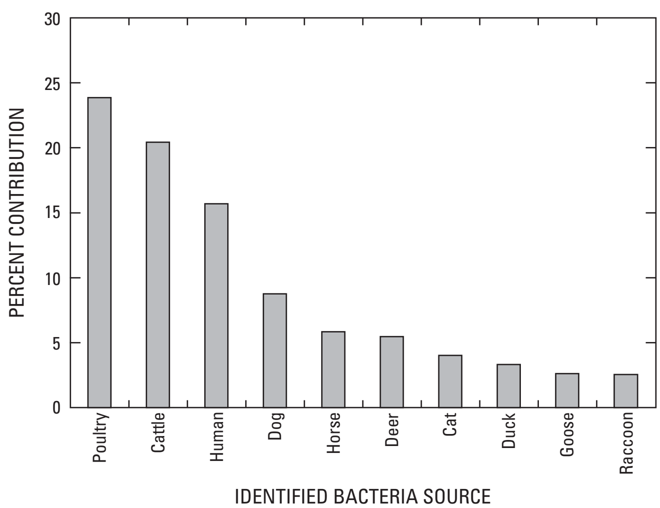


Figure 12. Distribution of the top ten contributors of fecal coliform bacteria identified by bacterial source tracking in the Christians Creek watershed, Augusta County, Virginia.

The poultry category (fig. 12) was adjusted to improve the data interpretation. The poultry category represents a combination of chicken, turkey, and other poultry sources. The ribotyping technique sometimes can be used to distinguish chickens from turkeys (and, in these cases, the two are identified separately), whereas, in other cases, an unknown isolate can be identified only as either a chicken or a turkey isolate (in this case, the isolate is labeled as poultry). Additionally, a general avian category was identified by the ribotyping analysis. The avian category represents strains of fecal coliform bacteria that can occur in multiple bird species. Whereas the poultry category was specific to chickens and turkeys, the avian category is more extensive, encompassing all birds, including chickens and turkeys. For data interpretation and watershed modeling purposes, this avian category was distributed among all the observed bird species.

Quantitatively, the avian category was assumed to be distributed proportionally, according to the occurrence of each individual bird species. For example, the poultry contribution to Christians Creek is 71 percent of all the bird species that are identified uniquely; therefore, 71 percent of the avian category was attributed to poultry. A detailed description of the manipulation of the avian category is in Hyer and Moyer (2003).

Calibration Approach

The calibrated fecal coliform model can be used to accurately simulate the range of observed fecal coliform concentration data as well as observed BST data from the Christians Creek Watershed. The simulations cover approximately a 7-year period from April 1, 1991, to September 30, 1997.

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 Christians 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 collected by DEQ from 1991 through 1997, (2) the range of stormflow fecal coliform concentrations collected by USGS from 1999 through 2000, and (3) BST data collected by Hyer and Moyer (2003).

The fecal coliform model first was calibrated to the data collected 1991 through 1997 by DEQ during low-flow periods. The primary sources represented in the model that contribute fecal coliform bacteria during low-flow periods are direct deposition by instream cattle, permitted point source dischargers, nonpermitted point source dischargers (straight pipes), and active ground-water discharge (AQO). The low-flow periods represented in the model were calibrated by adjusting the inputs from instream cattle and active ground-water discharge.

Next, the fecal coliform model was calibrated to data collected 1999 through 2000 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 20). 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 1999 through 2000 (Hyer and Moyer, 2003). These data provide information on the sources of fecal coliform bacteria to Christians Creek and also 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 2.6 percent of the *E. coli* isolates identified. However, 98.4 percent of the *E. coli* isolates identified by means of BST (including poultry, cattle, humans, dogs, horses, deer, cats, ducks, geese, raccoons, beaver, sheep, and muskrats) were represented in the model. Source-specific instream fecal coliform loads are determined by simulating each source independently. Each source-specific instream fecal coliform load is a product of bacteria transported through surface runoff, interflow, base flow, and various point sources. The sum of the source-specific fecal coliform contributions is equal to the total fecal coliform contribution used to calibrate the model to observed concentration data. The fecal coliform accumulation rate (ACCUM) is adjusted for each source represented in the model in order to calibrate the simulated source-specific instream load to observed BST data. This calibration step helps to reduce the inherent error in the calculated ACCUM value for each source. As a result, the dominant contributing sources in the watershed identified by means of BST are represented in the model.

Table 20. Initial values of WSQOP used for the various land-use types represented in the fecal coliform model for Christians Creek, Augusta County, Virginia

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

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

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

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

where *GM* is the geometric mean,

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

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

Data Limitations

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

The model-construction and -calibration process also was limited by the uncertainty associated with the fecal coliform accumulation rate (ACCUM) for each source. This uncertainty is linked to the four parameters used to calculate ACCUM: feces produced per day (Fprod), number of fecal coliform bacteria per gram of feces produced (FCden), population size (POPN), and habitat area (HAB). Most of this uncertainty is associated with FCden and POPN. The range of observed FCden values in previous studies (Hussong and others, 1979; Smith, 1961; Wheater and others, 1979) commonly extends over 2–5 orders of magnitude. For example, Mara and Oragui (1981) found FCden for dogs, cats, and humans ranges from 4.1 x 10^6 col/g to 4.3 x 10^9 col/g; 8.9 x 10^4 col/g to 2.6 x 10^9 col/g; and 1.3 x 10^5 col/g to 9.0 x 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 fecal coliform 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 Christians 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 Christians 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 Christians 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 Christians 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 Christians Creek. Each load-reduction scenario was simulated over the time period used for model calibration (1991–97). 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 Christians Creek.

Reductions from Point and Nonpoint Sources

Representation of permitted point source discharges in the Christians Creek model was modified during the fecal coliform load allocation assessment to reflect the current (post-2001) or proposed discharge rates for the various facilities in the watershed (table 21). Major modifications to the permitted point-source discharges used for model calibration were (1) discharge rate proposed for Fishersville sewage treatment plant (STP) (VA0025291) was increased from 0.7 mgd to 4.0 mgd, and (2) the Greenville STP (VA0090417) was added. The increased discharge rate from the Fishersville STP is a result of service-area expansion to include areas once serviced by the Staunton Plaza STP (VA0022306) and Brookwood Interchange STP (VA0022292), which were removed from service in July and August 2001. The Greenville STP was scheduled to begin discharging to Christians Creek by the end of 2002. Fecal coliform load reductions from permitted and general point sources are not required by DEQ as part of the TMDL development for Christians Creek because the dischargers are required to operate at or below the geometric mean water-quality standard of 200 col/100 mL.

Fecal coliform loads were reduced from nonpoint sources, including direct instream deposition and land surface runoff, which impact water quality during low-flow and stormflow periods. Direct instream deposition was reduced through source-specific reductions from instream cattle and straight pipes. The fecal coliform load associated with surface runoff was

Table 21. Current (post-2001) permitted point-source dischargers of fecal coliform bacteria in Christians Creek, Augusta County, Virginia

Permit number	Owner	Facility	Discharge rate (million gallons per day)	Fecal coliform permit limit (number of colonies per 100 milliliters)	Annual fecal coliform load (number of colonies per year)
VA0025291	Augusta County Service Authority	Fishersville Sewage-Treatment Plant	4.0	200	1.10×10^{13}
VA0090417	Augusta County Service Authority	Greenville Sewage-Treatment Plant	0.25	200	6.90×10^{11}
VA0020427	Augusta County School Board	Rivershead High School	0.016	200	4.41×10^{10}
VA0089061	Woodlawn Village L.L. Corp.	Woodlawn Village Mobile Home Park	0.015	200	4.16×10^{10}
VA0086738	Southern States Coop, Inc.	Southern States Coop	0	200	0
Total					1.18×10^{13}

reduced through source-specific reductions from the 13 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 at Route 794 against predefined criteria (table 22). Observed and simulated total annual runoff for water years 1994–97 was 57.87 and 58.25 in., respectively. The percent difference of 0.66 percent is within the designated 10-percent criterion and indicates that the simulated water budget closely approximates the observed water budget. The range of observed and simulated flows during the calibration period was evaluated by comparing the total of the highest 10-percent flows and the lowest 50-percent flows. The highest 10-percent flows category is representative of major storm events, whereas the lowest 50-percent is representative of base-flow conditions. The percent difference between the total of the highest 10-percent and lowest 50 percent simulated and observed flows was within the designated criteria of 10- and 15-percent difference. Additionally, the seasonality inherent in the observed and simulated seasonal flows was compared. Simulated total winter (January, February, and March) and spring (April, May, and June) runoff was –7.99 percent and –5.63 percent less, respectively, than the observed seasonal runoff. Simulated total summer (July, August, and September) and fall (October, November, and December) runoff were 1.61 (15.30 percent) and 1.47 in. (15.30 percent) greater than the observed summer and fall runoff, respectively.

The observed and simulated annual runoff for the calibration period ranged from 7.72 to 21.37 and 9.77 to 20.88 in., respectively (table 23). The percent difference between the simulated and observed annual runoff ranged from –15.82 to 26.55 percent. The long-term average annual runoff for Christians Creek for water years 1968–97 is 14.07 in. (White and others, 1998). Based on this long-term average, the streamflow model simulated runoff over a range of hydrologic extremes from dry (1995) to wet (1996).

Table 22. Observed and simulated runoff values for Route 794 for Christians Creek, Augusta County, Virginia, water years 1994-97

Runoff category	Observed (inches)	Simulated (inches)	Difference (percent)[1]	Criterion (percent)
Total annual runoff	57.87	58.25	0.66	10
Highest 10-percent flow[2]	24.90	24.26	-2.55	10
Lowest 50-percent flow[3]	10.08	10.94	8.48	15
Winter runoff	25.16	23.15	-7.99	15
Spring runoff	12.60	11.89	-5.63	15
Summer runoff	10.52	12.13	15.30	15
Fall runoff	9.61	11.08	15.30	15

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

Table 23. Observed and simulated annual runoff, Christians Creek, Augusta County, Virginia, water years 1994-97

Water year	Observed (inches)	Simulated (inches)	Difference (percent)[1]
1994	14.76	15.79	6.98
1995	7.72	9.77	26.55
1996	21.37	20.88	-2.29
1997	14.03	11.81	-15.82
Total	57.87	58.25	0.66

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

Similar to total amount of runoff simulated, the pathways by which the streamflow model routes incoming precipitation is important. Total simulated runoff was derived from surface runoff, interflow, and base flow (table 24). Between 50.19 and 73.16 percent of the annual runoff for water years 1994–97 was derived from base flow (ground-water inputs). Rutledge and Mesko (1996) calculated a base-flow index of 72.2 percent for an adjacent watershed from streamflow data at South River near Dooms, Va. (station number 01626850), for the period 1981–90. Base-flow contribution to streamflow in Christians Creek varies seasonally from 72.92 percent in the spring to 50.95 percent in the summer and contributions from surface runoff during spring and summer range from 12.53 to 31.90 percent, respectively (table 24).

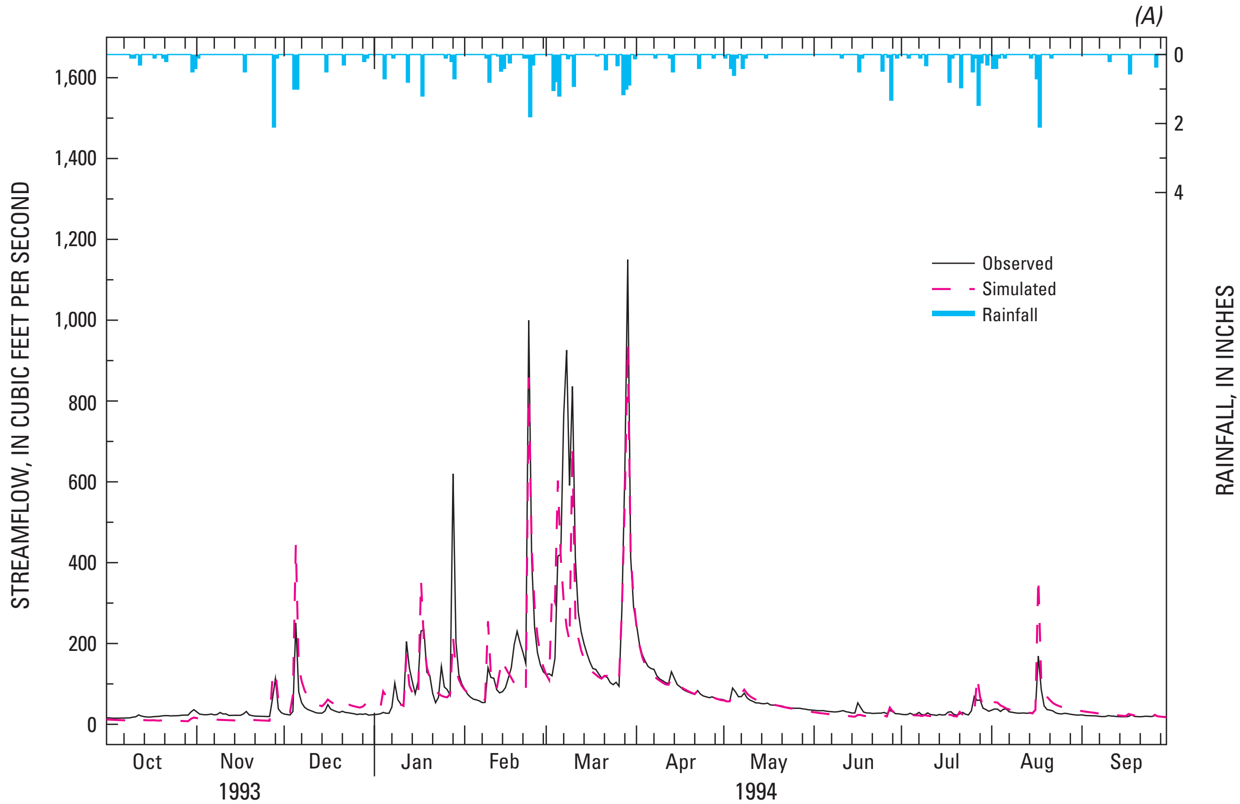
Various graphical comparisons provided information on the quality of the calibrated streamflow model. The hydrographs for water years 1994–97 show the simulated and observed streamflow response to individual precipitation events (fig. 13). These hydrographs show generally good agreement between simulated and observed daily mean streamflow values. A strong correlation was observed between simulated and observed streamflow where 89 percent of the variability in observed streamflow is explained by simulated streamflow (fig. 14). Residual plots display the measured difference between simulated and observed streamflow; no difference will generate a residual equal to zero. Residuals between simulated and observed streamflow in Christians Creek for water years 1994-97 are distributed uniformly around zero, indicating no bias in the model simulation (fig. 15). 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 Christians Creek are similar over the majority of flow conditions except for the extreme low (less than 20 ft^3/s) flows (fig. 16).

Table 24. Simulated total annual and seasonal runoff, interflow and base flow for calibration period, Christians Creek, Augusta County, Virginia, water years 1994-97

Water year	Annual runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
1994	15.79	2.58	3.60	9.35	59.21
1995	9.77	1.51	1.44	6.57	67.25
1996	20.88	6.15	3.95	10.48	50.19
1997	11.81	1.08	1.83	8.64	73.16
Total[1]	58.25	11.32	10.82	35.04	60.15

Water years 1994-1997	Total runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
Winter	23.15	4.49	5.64	12.75	55.08
Spring	11.89	1.49	1.47	8.67	72.92
Summer	12.13	3.87	1.80	6.18	50.95
Fall	11.08	1.47	1.91	7.44	67.15
Total[1]	58.25	11.32	10.82	35.04	60.15

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



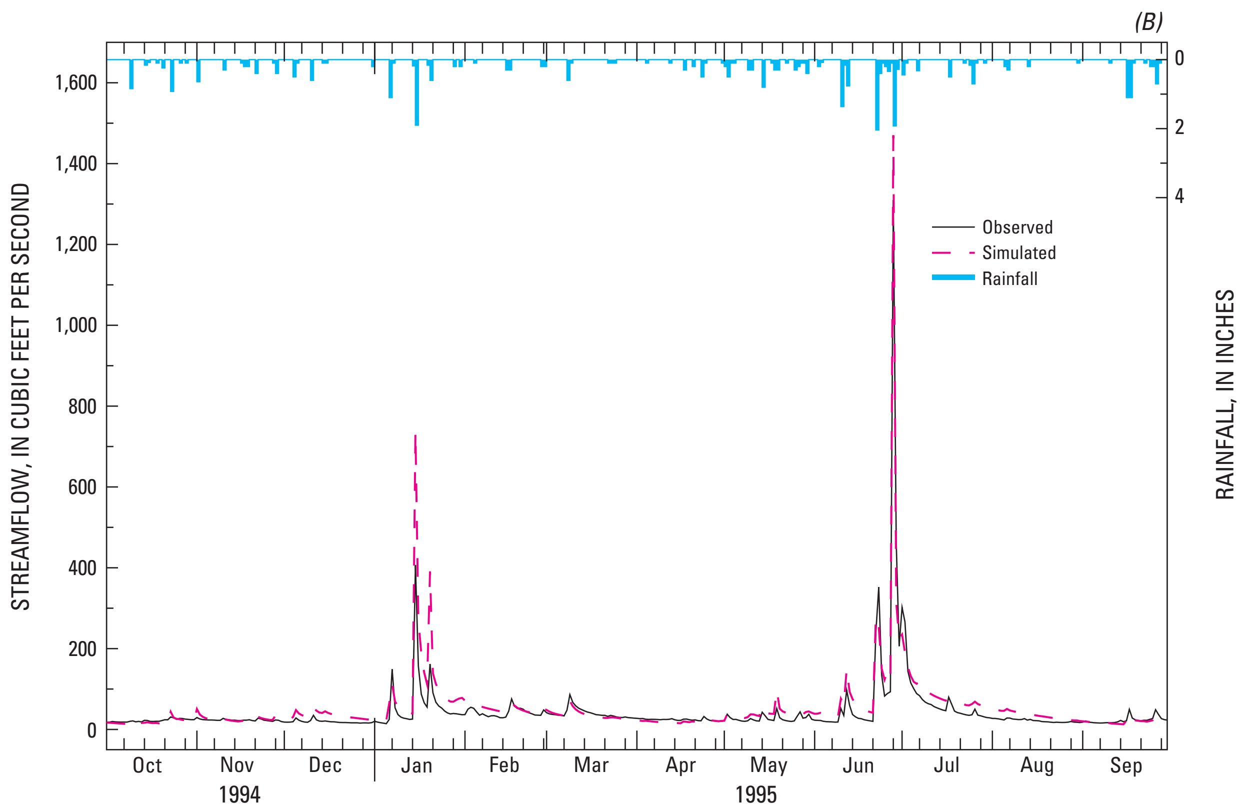


Figure 13. Daily rainfall and observed and simulated daily mean streamflows for water years 1994 *(A)*, 1995 *(B)*, 1996 *(C)*, and 1997 *(D)*, Christians Creek, Augusta County, Virginia.

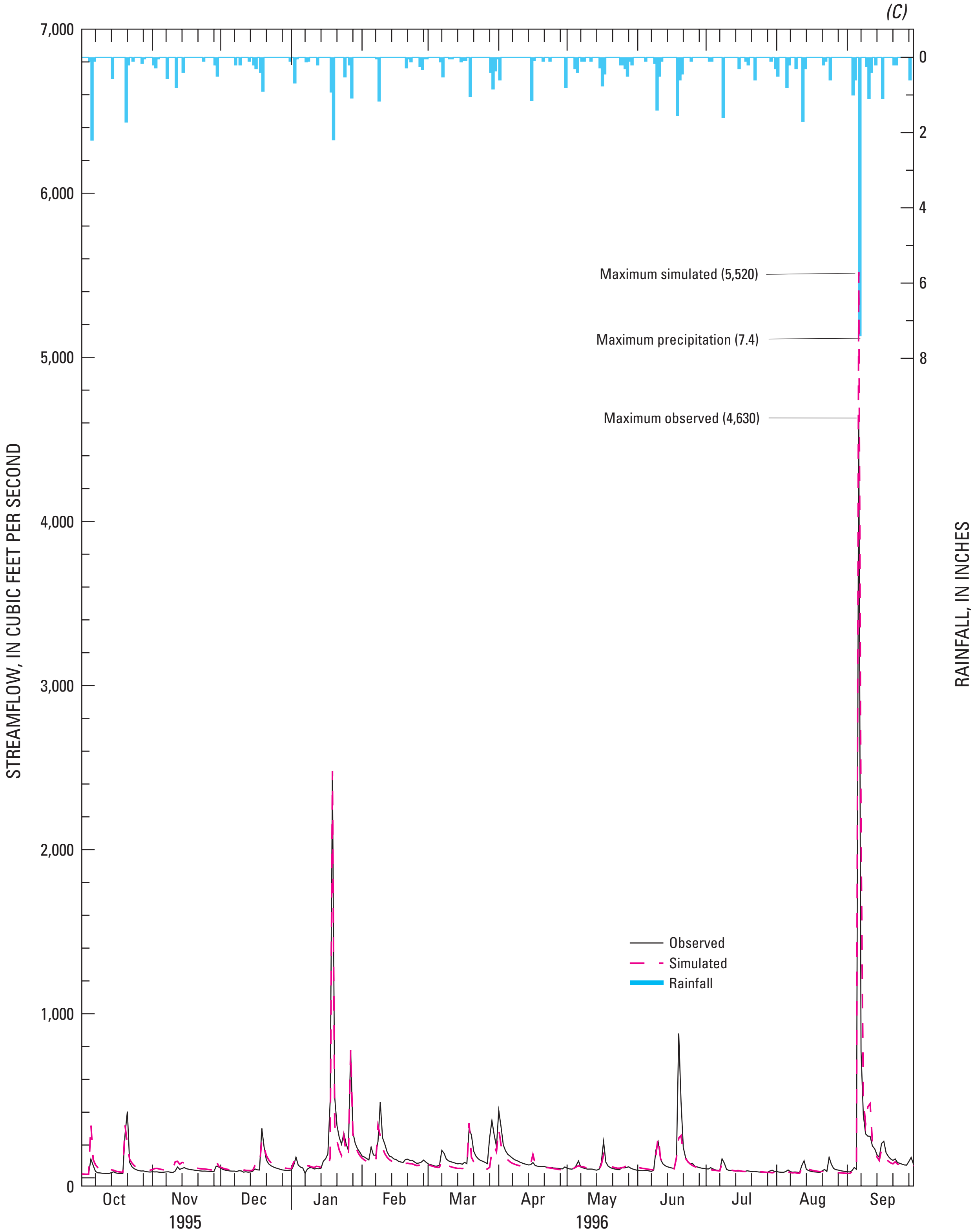


Figure 13. Daily rainfall and observed and simulated daily mean streamflows for water years 1994 *(A)*, 1995 *(B)*, 1996 *(C)*, and 1997 *(D)*, Christians Creek, Augusta County, Virginia—Continued.

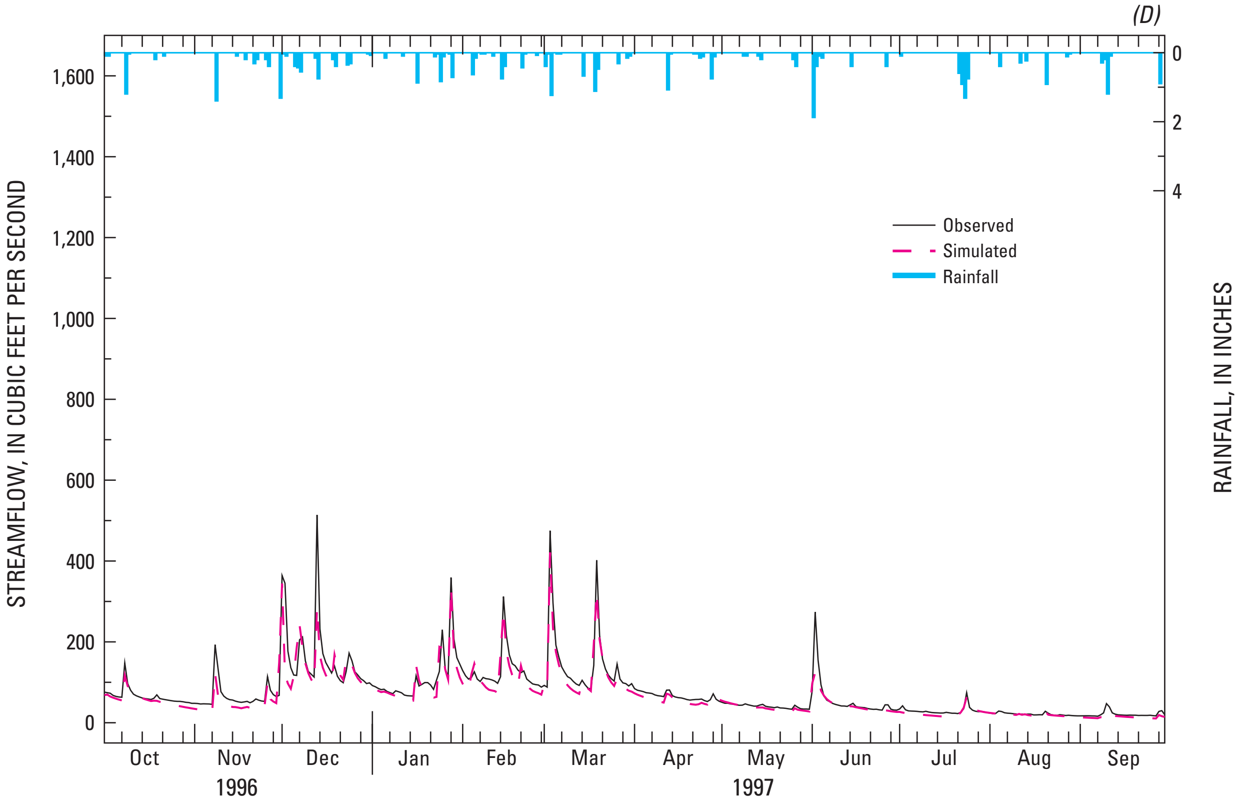


Figure 13. Daily rainfall and observed and simulated daily mean streamflows for water years 1994 *(A)*, 1995 *(B)*, 1996 *(C)*, and 1997 *(D)*, Christians Creek, Augusta County, Virginia—Continued.

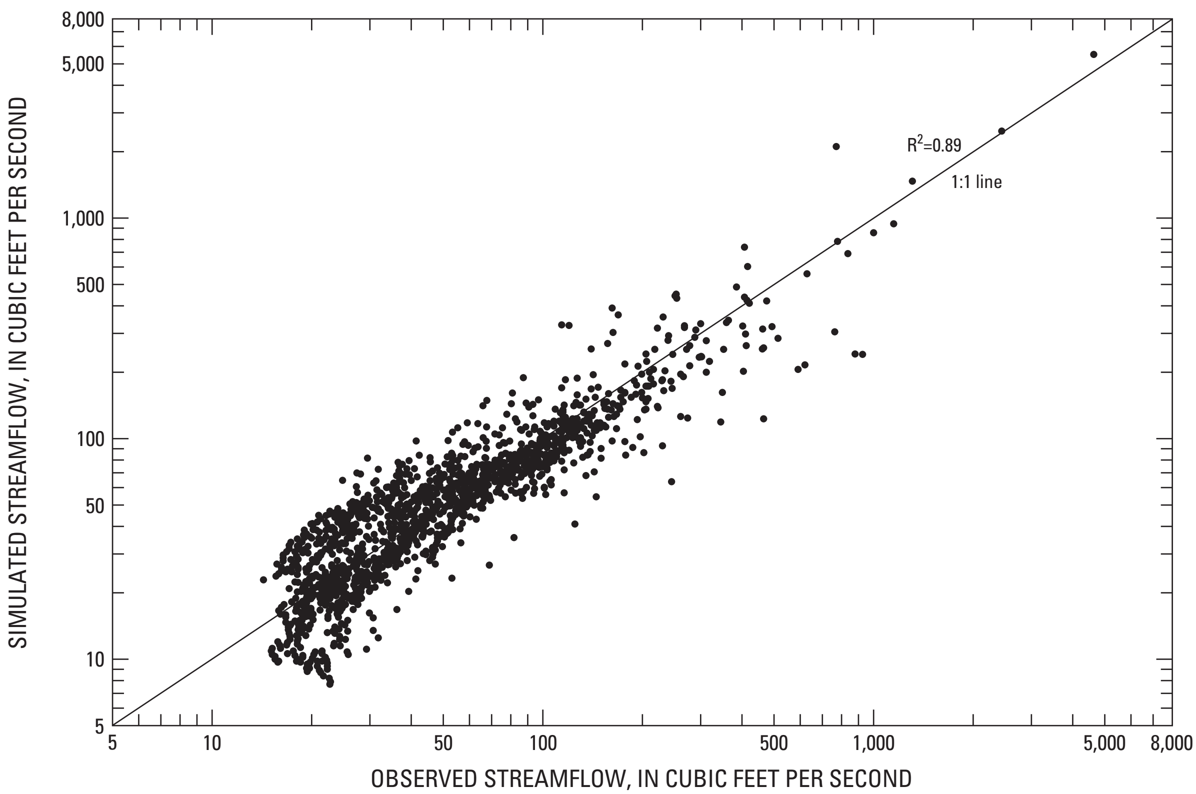


Figure 14. Simulated daily streamflow in relation to observed daily streamflow, at Christians Creek, Augusta County, Virginia, water years 1994-97.

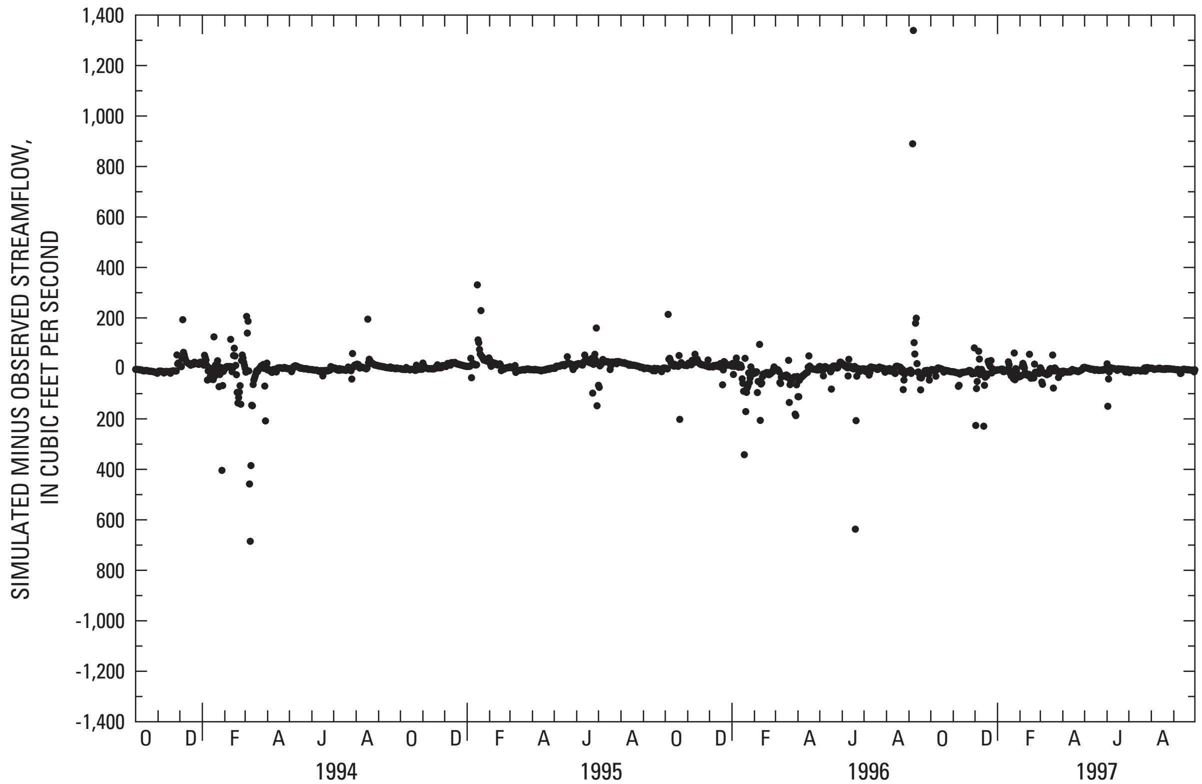


Figure 15. Residuals for simulated minus observed daily streamflow, Christians Creek, Augusta County, Virginia, water years 1994-97.

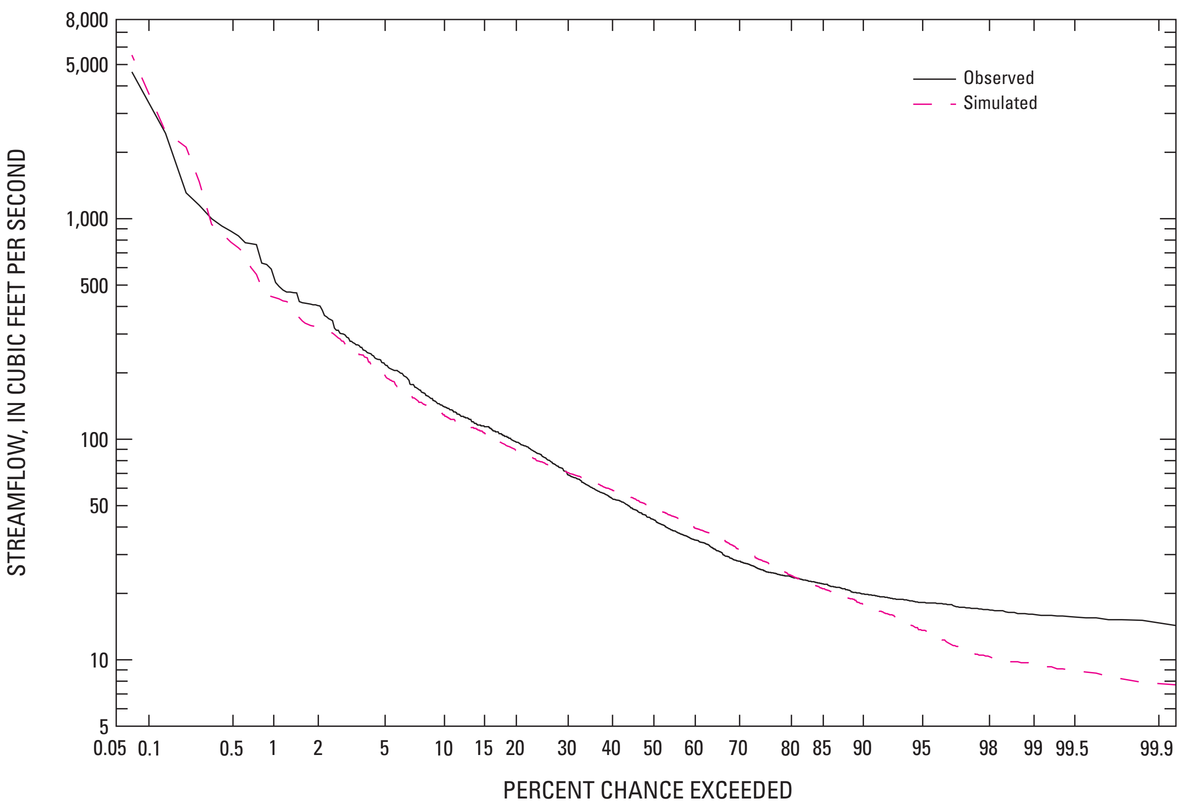


Figure 16. Flow-duration curves for observed and simulated daily mean streamflow, Christians Creek, Augusta County, Virginia, water years 1994-97

Graphical comparisons also were used to further evaluate the observed and simulated seasonal hydrologic response in Christians 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. 17). In addition, simulated flow-duration curves for winter, spring, and summer closely approximate the observed seasonal flow-duration curves (fig. 18). The simulated and observed fall flow-duration curves are similar over the majority of the flow conditions and variability increases only during the low-flow periods.

The streamflow model calibration also was evaluated using hourly simulated and observed streamflow data. This shortened time step allows for detailed evaluation of stormflow characteristics such as timing, peak flows, volume, and flow recession. For a storm event during February 23–24, 1994, simulated and observed stormflow characteristics are similar except for stormflow timing (fig. 19A). The simulated stormflow response occurs approximately 2 hours before the observed response. This time lag is present primarily because the Staunton sewage-treatment plant (SSTP) rainfall gage is approximately 6 mi. west of the streamflow gage on Christians Creek. Storm movement in the Shenandoah Valley generally is from the southwest to the northeast; therefore, rain falls at the rain gage before falling over the rest of the watershed. The simulated streamflow peak on February 24th is a result of measured rainfall occurring at the SSTP rain gage and not over the rest of the watershed.

An example of a storm event for which the stormflow response was not well simulated resulted during September 6–7, 1996 (fig. 19B). On September 6th, approximately 7.40 in. of rain fell in association with Hurricane Fran. The discrepancies in the simulated and observed stormflow characteristics can be linked to rainfall volume and intensity data and/or model calibration. Measured rainfall at the SSTP rain gage during Hurricane Fran was 7.40 in. while 2.28, 6.84, and 7.86 in. of rainfall was measured at the nearby Todd Lake, Dale Enterprise, and Sherando rain gages (operated by the National Oceanic and Atmospheric Administration), respectively. The simulated storm hydrograph is more jagged and undersimulates runoff compared to the observed hydrograph, indicating that the rainfall volume and intensity measured at SSTP is not representative of what fell in the watershed. Another explanation is that the model is not well calibrated to simulate a storm event of this magnitude.

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. Additionally, 33 percent of the rainfall data at the SSTP rain gage were missing for the period 1990–97. Rainfall data from nearby gages were used to fill these missing data. 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 August 17, 1994, the measured daily rainfall at SSTP was 2.10 in. (fig. 13A). The simulated daily mean streamflow on August 17th was 387 ft^3/s, whereas the observed daily mean streamflow was 169 ft^3/s (fig. 13A). The amount of rainfall recorded at SSTP on this date was compared with rainfall measurements of 1.24, 1.90, 2.72, 3.68, and 4.72 in. at nearby Craigsville, Dale Enterprise, Middlebrook, and Spottswood rain gages (operated by the National Oceanic and Atmospheric Administration), respectively. Because the data recorded at SSTP fell within the range of rainfall data from surrounding gages, the data value from SSTP was used during the simulation. However, the observed streamflow data indicate that less than 2.10 in. of rain fell within the Christians Creek watershed. This result is one example of model error that occurred because of input rainfall data.

Snowfall on the watershed also caused differences between simulated and observed streamflow. Snow accumulation and melt were not included in the streamflow model for Christians 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. During a snowfall event, the volume of water in the

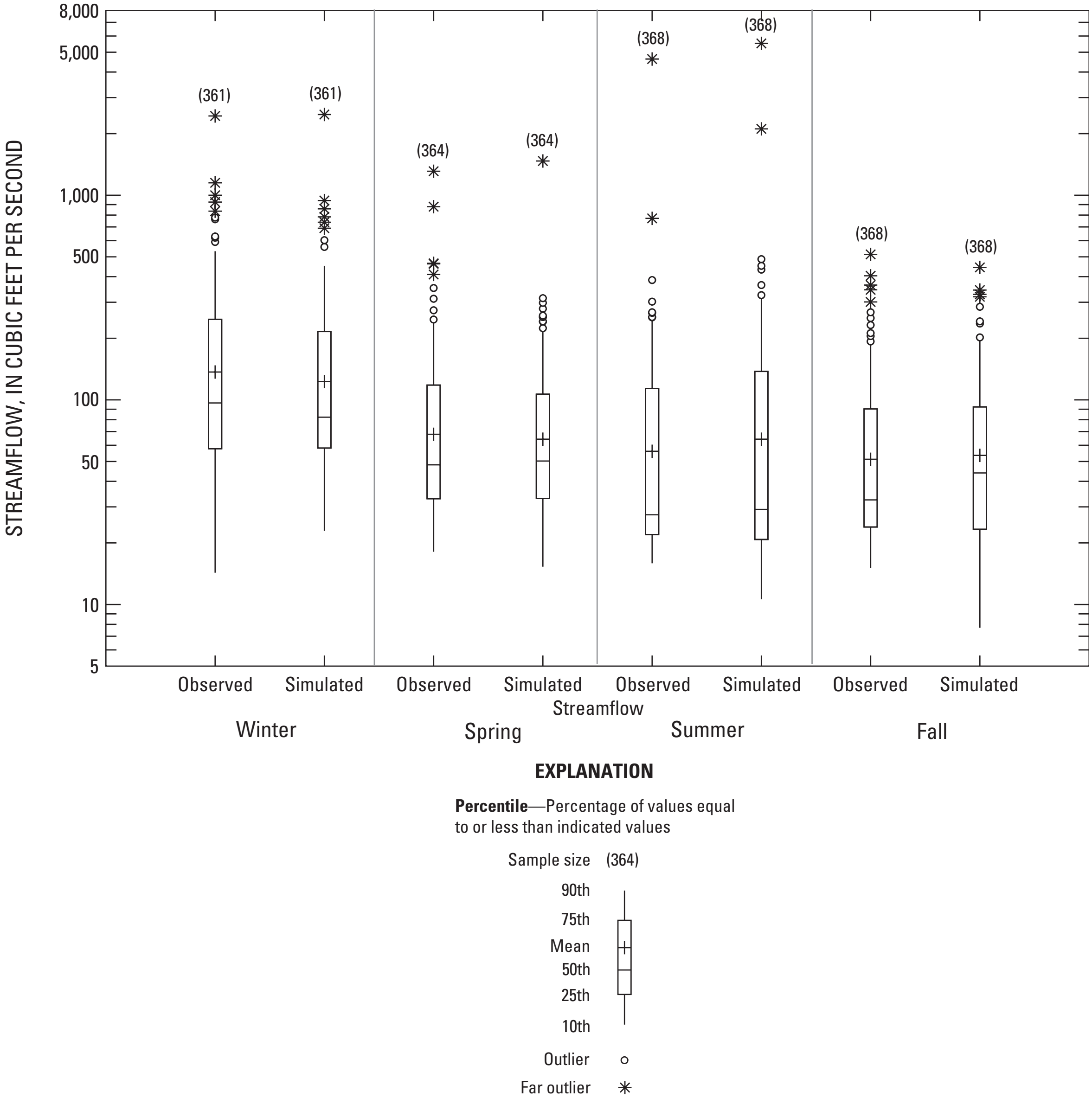


Figure 17. Observed and simulated daily streamflow (Winter, January-March; Spring, April-June; Summer, July-September; Fall, October-December), Christians Creek, Augusta County, Virginia, water years 1994-97.

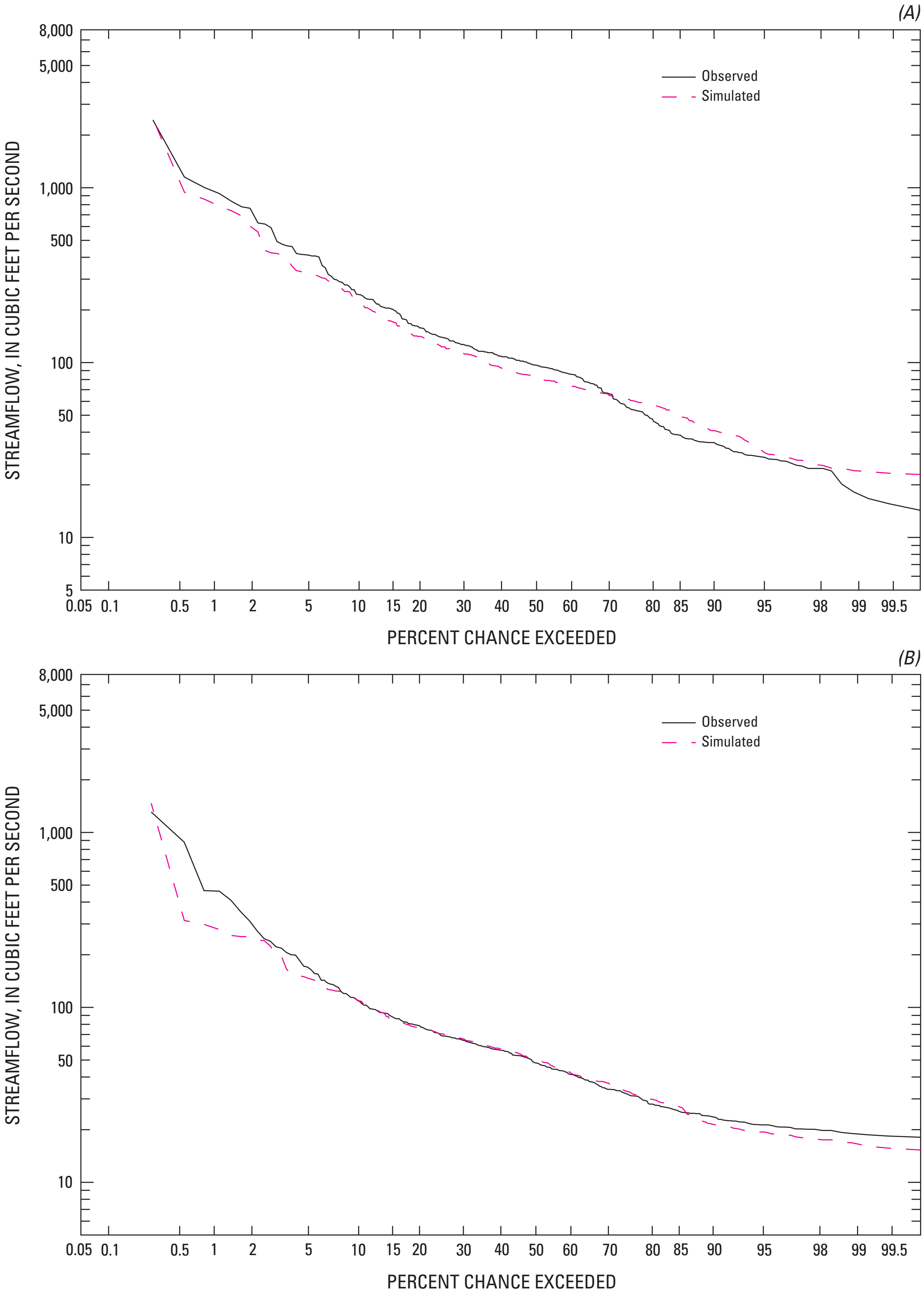
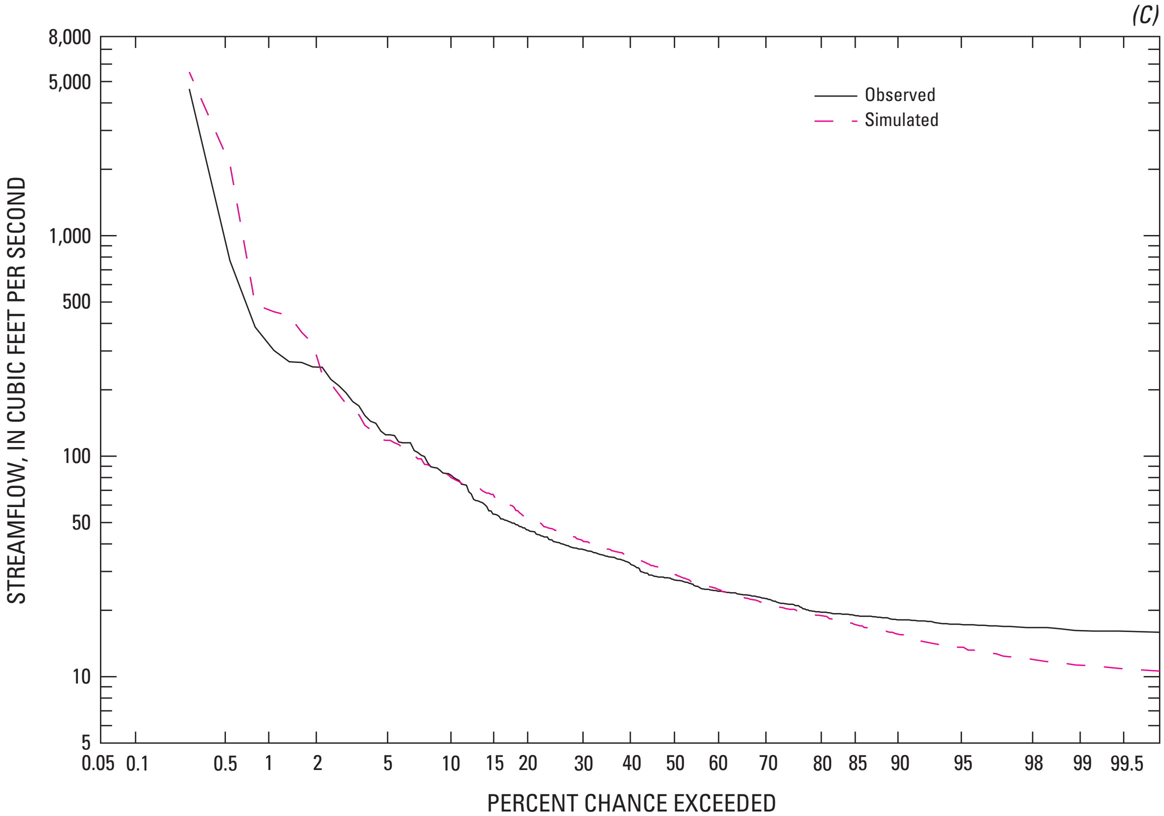


Figure 18. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Christians Creek, Augusta County, Virginia, water years 1994-97.



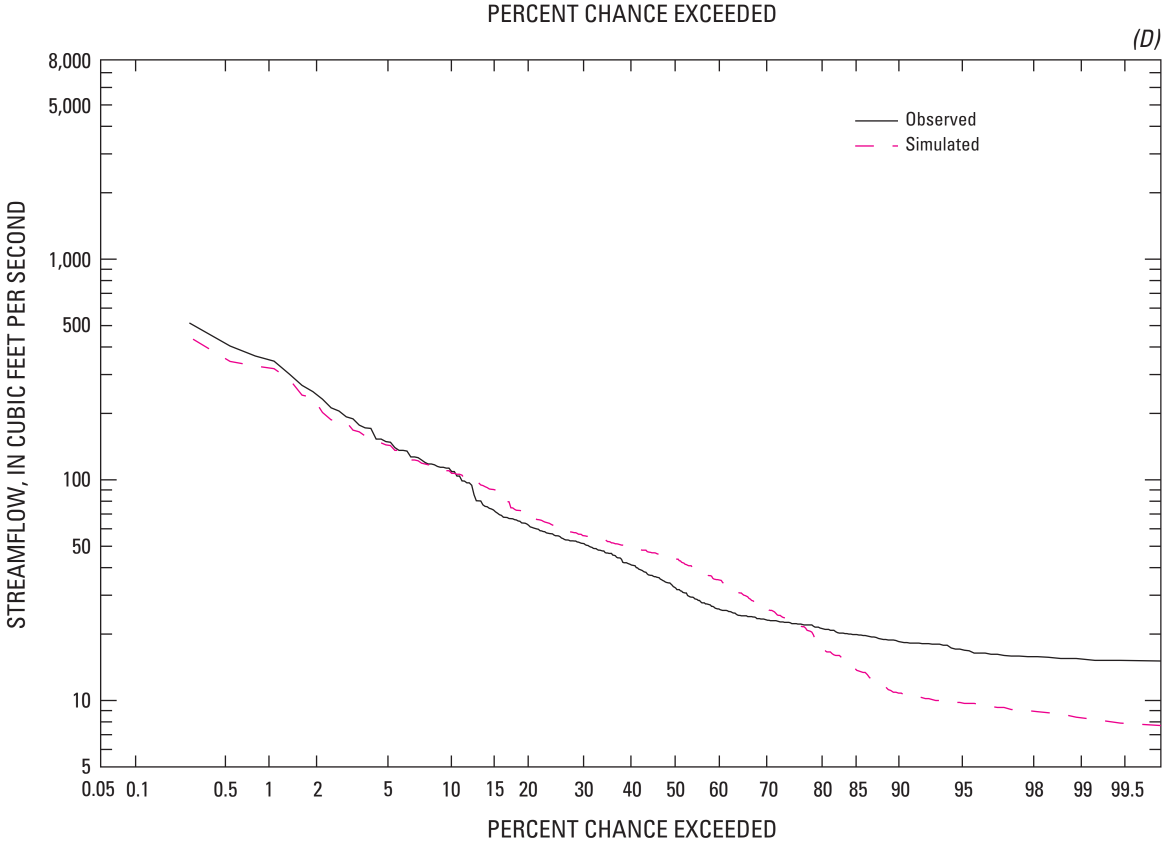


Figure 18. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Christians Creek, Augusta County, Virginia, water years 1994-97—Continued.

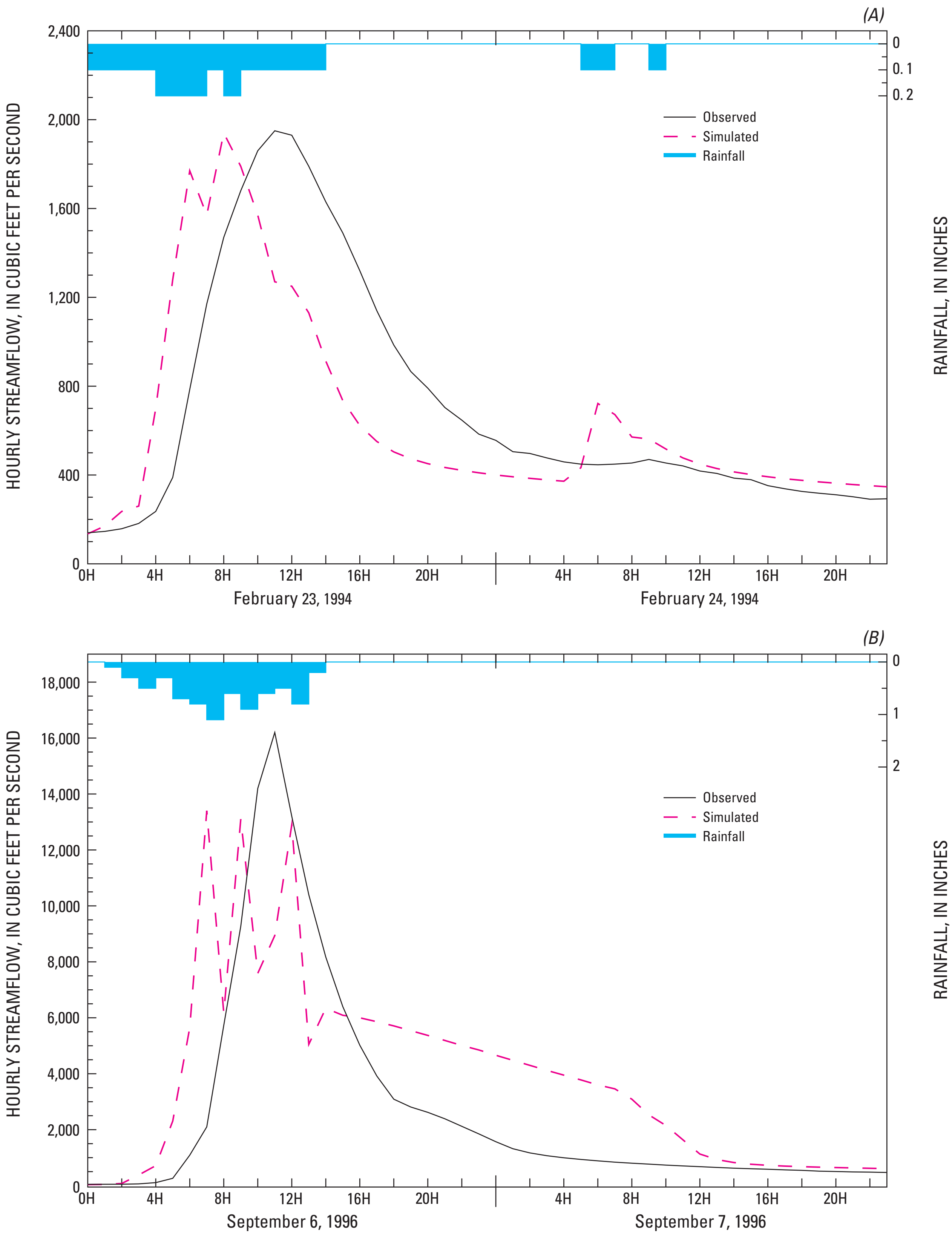


Figure 19. Hourly rainfall and observed and simulated daily mean streamflow, February 23-24, 1994 *(A)* and September 6-7, 1996 *(B)*, Christians Creek, Augusta County, Virginia.

snow typically is recorded at the rainfall gage. This recorded volume is treated as a volume of rain and used in the streamflow model. The resulting simulated streamflow response is an initial oversimulated peak followed by an extended period of undersimulated storms. The initial oversimulation is caused by the recorded volume of snow being treated like rainfall instead of the snow accumulating on the land surface. The extended period of undersimulated storms occurs because of the additional volume of water stored in the snow on the ground that is not accounted for by the model. Therefore, greater amounts of runoff per volume of incoming rain are observed than are simulated. These discrepancies resulted during the following time periods: January 14–28, 1994; March 2–15, 1994; and December 5–20, 1996 (fig. 13).

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.

Hydrologic model verification results were first assessed by comparing simulated and observed streamflow from the Route 794 stream gage for water years 1992-93 (table 25). Observed and simulated total annual runoff for water years 1992-93 was 25.96 and 25.53 in., respectively. The –1.66 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 –8.24 percent. The total of the lowest 50-percent flows was 4.67 and 4.72 in. for observed and simulated flows, respectively. Simulated and observed winter (January, February, and March), spring (April, May, and June), and summer (July, August, and September) runoff were well within the designated criterion. Simulated total fall (October, November, and December) runoff was 0.68 in. (17.96 percent) greater than the observed fall runoff.

The observed and simulated annual runoff for water years 1992-93 were 10.36 and 15.60, and 10.35 and 15.18 in., respectively (table 26) which yielded –0.10 and –2.69 percent differences. The long-term average annual runoff for Christians Creek for water years 1968-97 is 14.07 in. (White and others, 1998). Based on this long-term average, the verification of the calibrated streamflow model included a dry (1992) and an average (1993) year. Total simulated runoff was derived from surface runoff, interflow, and base flow (table 27). A total of 63.18 percent of the total annual runoff for water years 1992-93 was derived from base flow (ground-water inputs), which is consistent with the findings from Rutledge and Mesko (1996) for an adjacent watershed to Christians Creek, calculated from streamflow data at South River near Dooms, Va. (station number 01626850), where the base-flow index for the period 1981–90 was 72.2 percent. Base-flow contribution to streamflow in Christians Creek varied

Table 25. Observed and simulated runoff values for Route 794, Christians Creek, Augusta County, Virginia, water years 1992-93

Runoff category	Observed (inches)	Simulated (inches)	Difference (percent)[1]	Criterion (percent)
Total annual runoff	25.96	25.53	-1.66	10
Highest 10-percent flow[2]	11.17	10.25	-8.24	10
Lowest 50-percent flow[3]	4.67	4.72	1.07	15
Winter runoff	11.33	10.76	-5.03	15
Spring runoff	9.14	8.56	-6.35	15
Summer runoff	2.24	2.38	6.25	15
Fall runoff	3.23	3.81	17.96	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).

seasonally from 86.75 percent in the summer to 50.65 percent in the winter, whereas contributions from surface runoff ranged from 4.62 percent during the summer to 21.38 percent during the winter (table 27).

Table 26. Observed and simulated annual runoff, Christians Creek, Augusta County, Virginia, water years 1992-93

Water year	Observed (inches)	Simulated (inches)	Difference (percent)[1]
1992	10.36	10.35	-0.10
1993	15.60	15.18	-2.69
Total	25.96	25.53	-1.66

[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. Hydrographs for the verification period generally show good agreement between simulated and observed daily mean values for streamflow during individual rainfall events (fig. 20). A strong correlation was observed between simulated and observed streamflow where 87 percent of the variability in observed streamflow is explained by simulated streamflow (fig. 21). This plot also shows an area where the model is underpredicting streamflow during low-flow periods, which primarily occurred in the first two months of the verification period. The residuals between simulated and observed streamflow in Christians Creek for water years 1992-1993 vary normally around zero, indicating a lack of bias in the model simulation (fig. 22). Flow duration curves for simulated and observed daily flows are similar for flows greater than 20 cfs (80 percent chance exceeded) (fig. 23). Increased separation between simulated and observed results for flows less than 20 ft^3/s. This separation can be explained by the undersimulation during the October–November 1992 time period.

Additional graphical comparisons were made to further evaluate the observed and simulated seasonal hydrologic response in Christians 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 and medians (fig. 24). Simulated and observed streamflows for the winter and spring months exhibit nearly identical variation while simulated summer and fall streamflows had greater variability than the observed flows. Simulated and observed fall streamflows show increased variability for low flows that can be linked to the October–November 1992 time period. Flow-duration curves also illustrate how closely the model simulates the observed seasonal hydrologic response (fig. 25). 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 exhibit the greatest separation for flows less than 20 ft^3/s.

Table 27. Simulated total annual and seasonal runoff, surface runoff, interflow and base flow for verification period, Christians Creek, Augusta County, Virginia, water years 1992-93

Water year	Annual runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
1992	10.35	1.62	1.64	6.83	65.99
1993	15.18	2.43	3.19	9.30	61.26
Total[1]	25.53	4.05	4.83	16.13	63.18

Water years 1992-1993	Total runoff (inches)	Surface runoff (inches)	Interflow (inches)	Base flow (inches)	Base-flow index (percent)
Winter	10.76	2.30	2.88	5.45	50.65
Spring	8.56	1.24	1.35	5.83	68.15
Summer	2.38	.11	.09	2.06	86.75
Fall	3.81	.40	.50	2.78	72.99
Total[1]	25.51	4.05	4.83	16.12	63.19

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

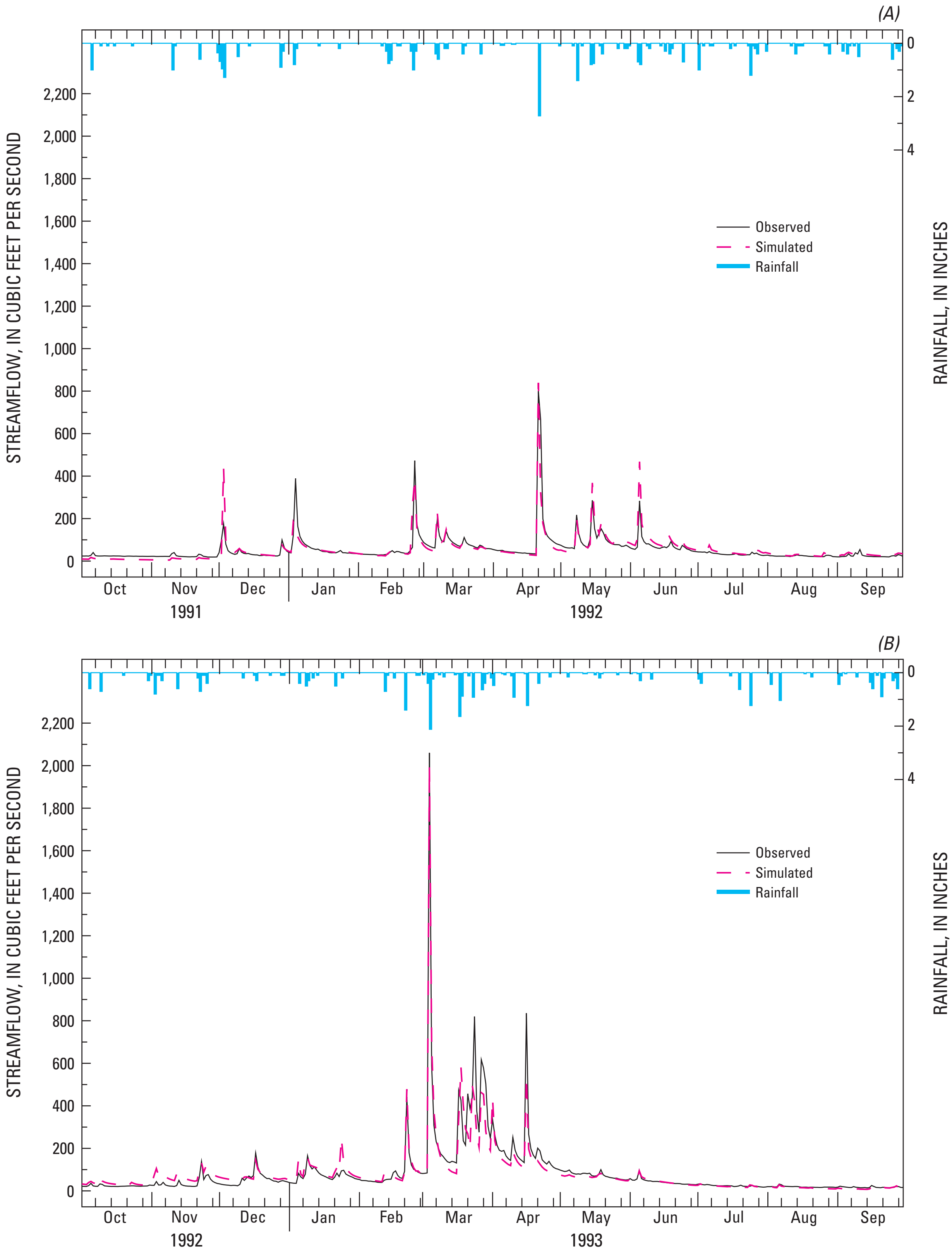


Figure 20. Daily rainfall and observed and simulated daily mean streamflow for water years 1992 *(A)*, 1993 *(B)* Christians Creek, Augusta County, Virginia.

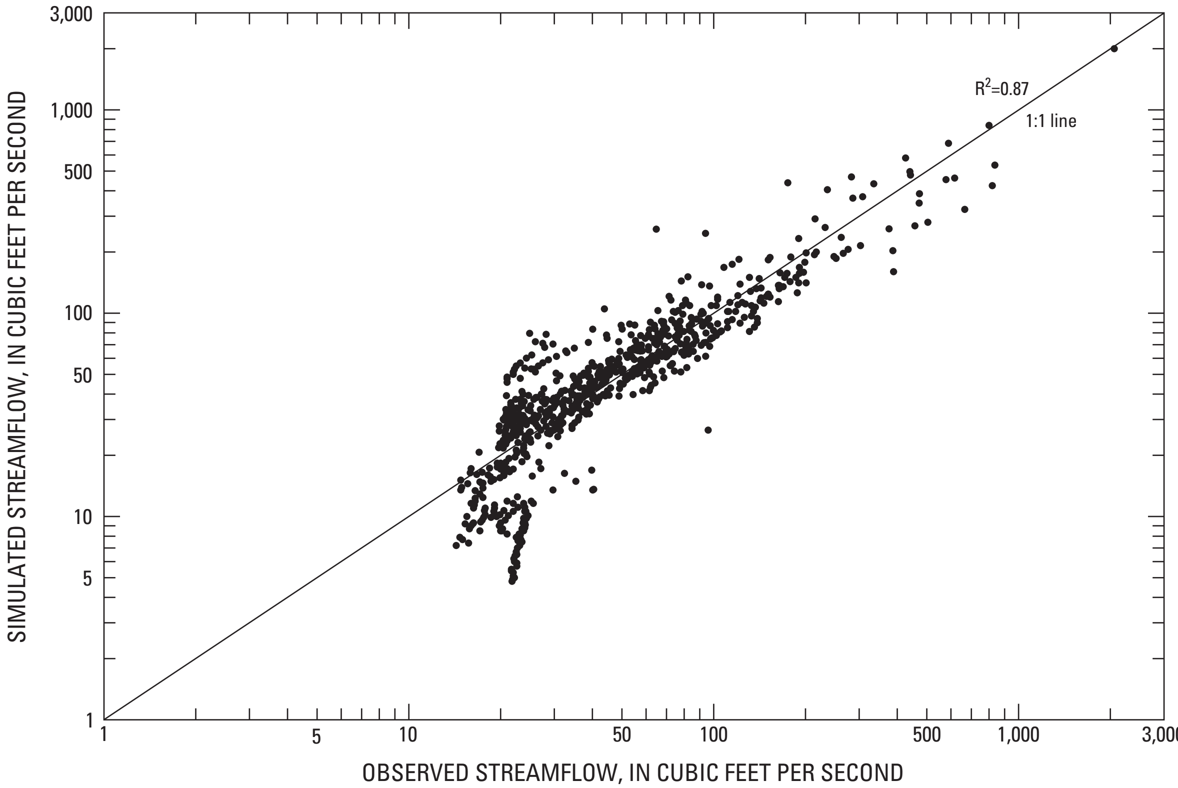


Figure 21. Simulated daily streamflow in relation to observed daily streamflow, at Christians Creek, Augusta County, Virginia, water years 1992-93.

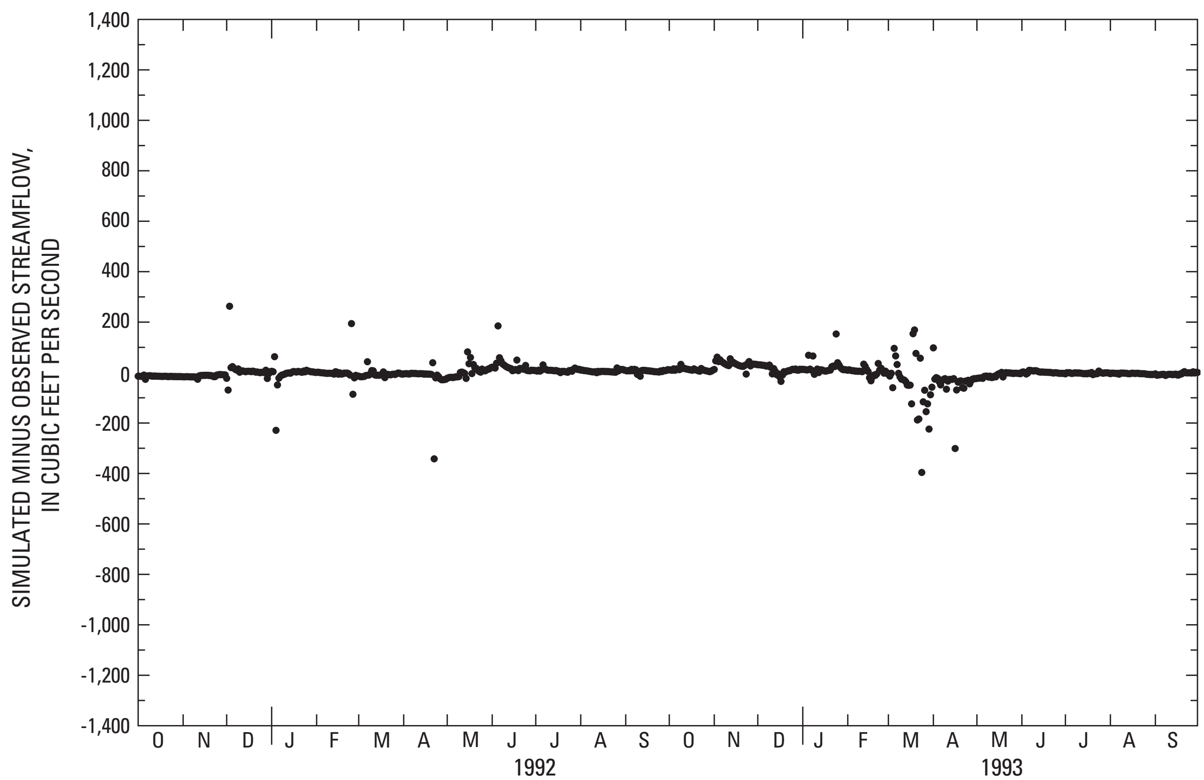


Figure 22. Residuals for simulated minus observed daily streamflow, Christians Creek, Augusta County, Virginia, water years 1992-93.

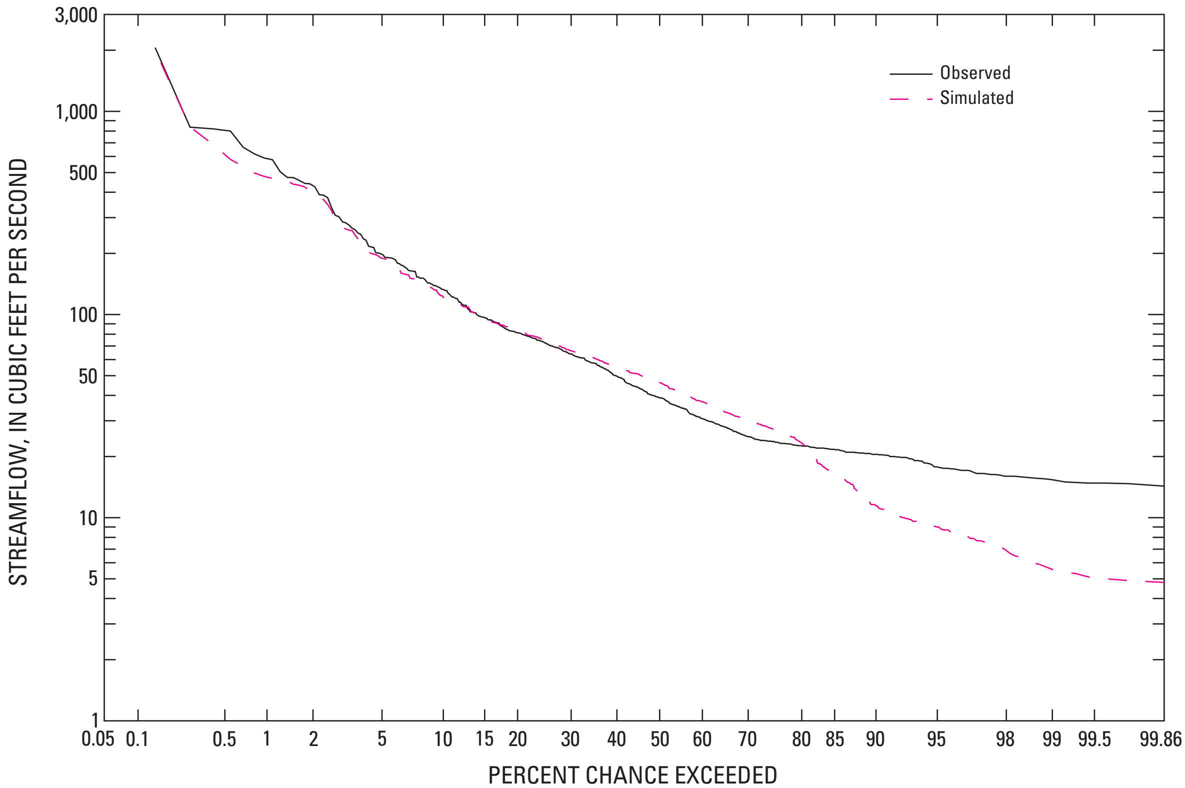


Figure 23. Flow-duration curves for observed and simulated daily mean streamflow, water years 1992-1993, Christians Creek, Augusta County, Virginia.

The streamflow model verification also was evaluated on an hourly time step. The simulated and observed stormflow responses for the April 21-22, 1992, storm event are similar with respect to storm timing, peaks, volume, and recession (fig. 26A). The simulated and observed stormflow responses did not match closely for the March 17-19, 1996, event (fig. 26B). On March 17, 1.64 in. of rain fell on top of a pre-existing 18 in. of snow and the streamflow model accounted only for the volume of rainwater, not the 18 in. of snow already on the ground. Consequently, the simulated and observed stormflow responses are different with respect to stormflow peaks and volume. The storm peak that occurred on March 18th is a result of 0.88 in. of rainfall at SSTP while a lesser amount fell over the Christians Creek watershed.

Final Streamflow Model Parameters

The results of the streamflow model calibration demonstrate its effectiveness for simulating the streamflow response in Christians Creek. Final values for the 11 hydraulic parameters used to calibrate the streamflow model and the urban effective impervious area are used in the fecal coliform model simulation (table 28).

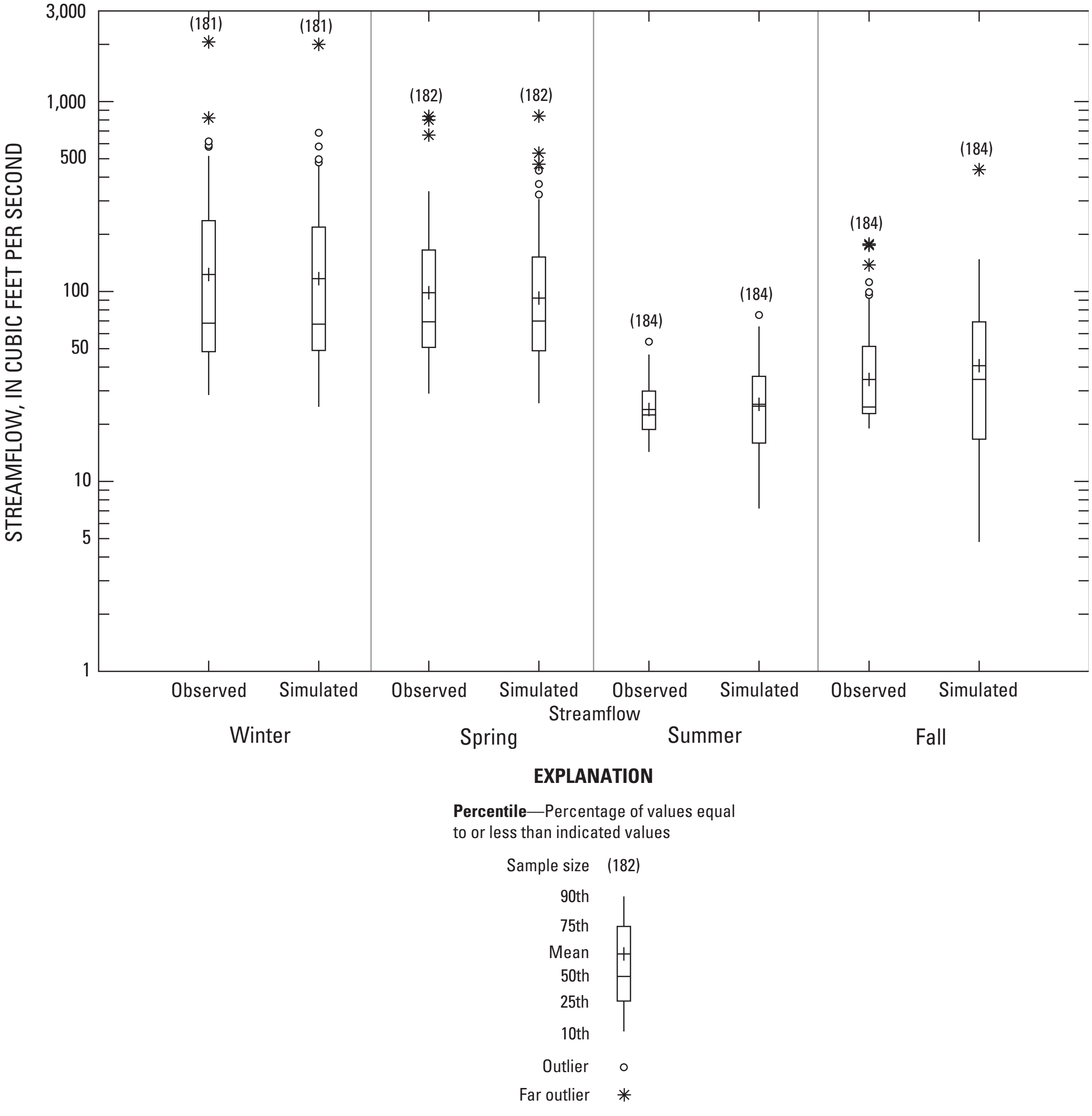
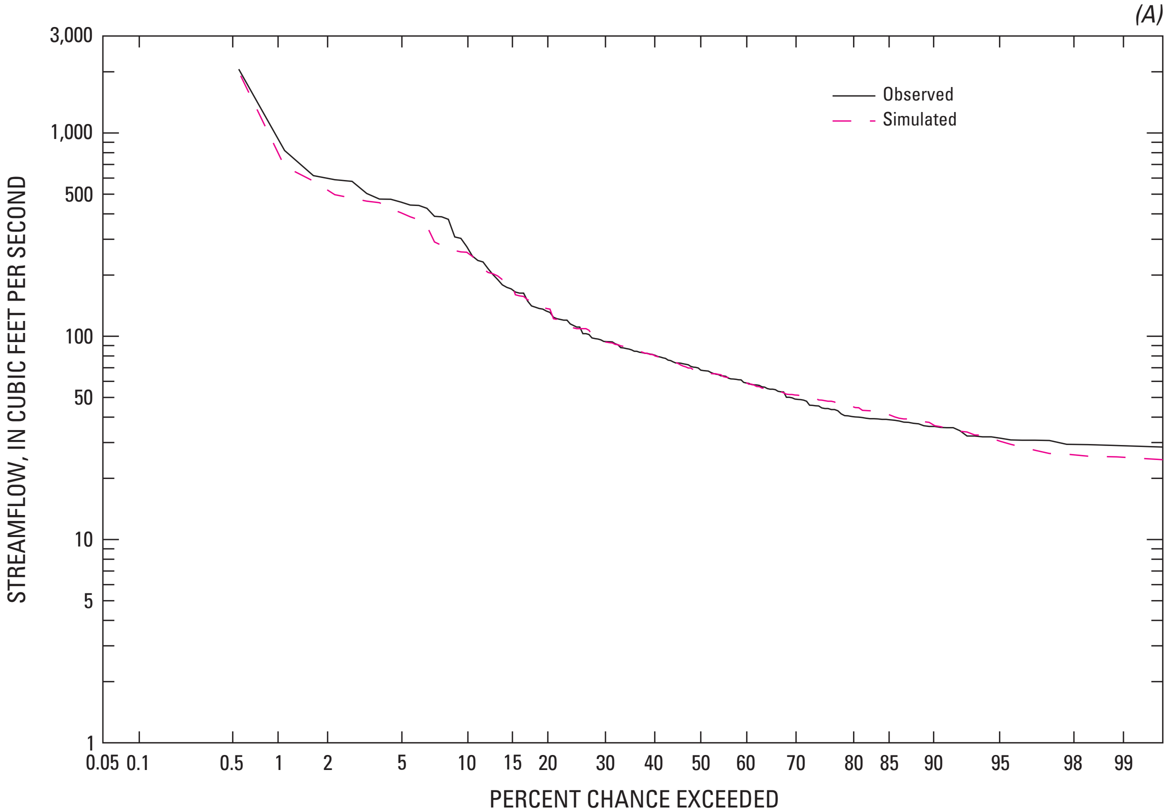


Figure 24. Observed and simulated daily streamflow (Winter, January-March; Spring, April-June; Summer, July-September; Fall, October-December), Christians Creek, Augusta County, Virginia, water years 1992-93.



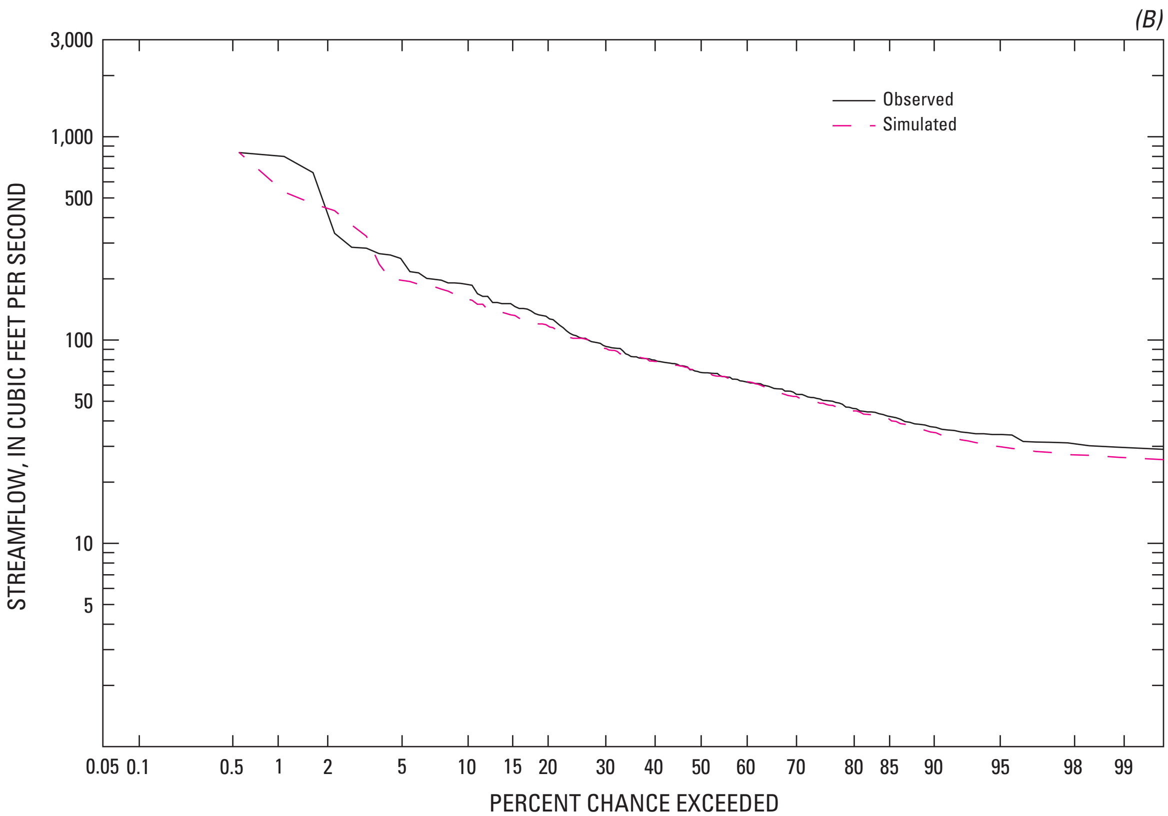


Figure 25. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Christians Creek, Augusta County, Virginia, water years 1992-93.

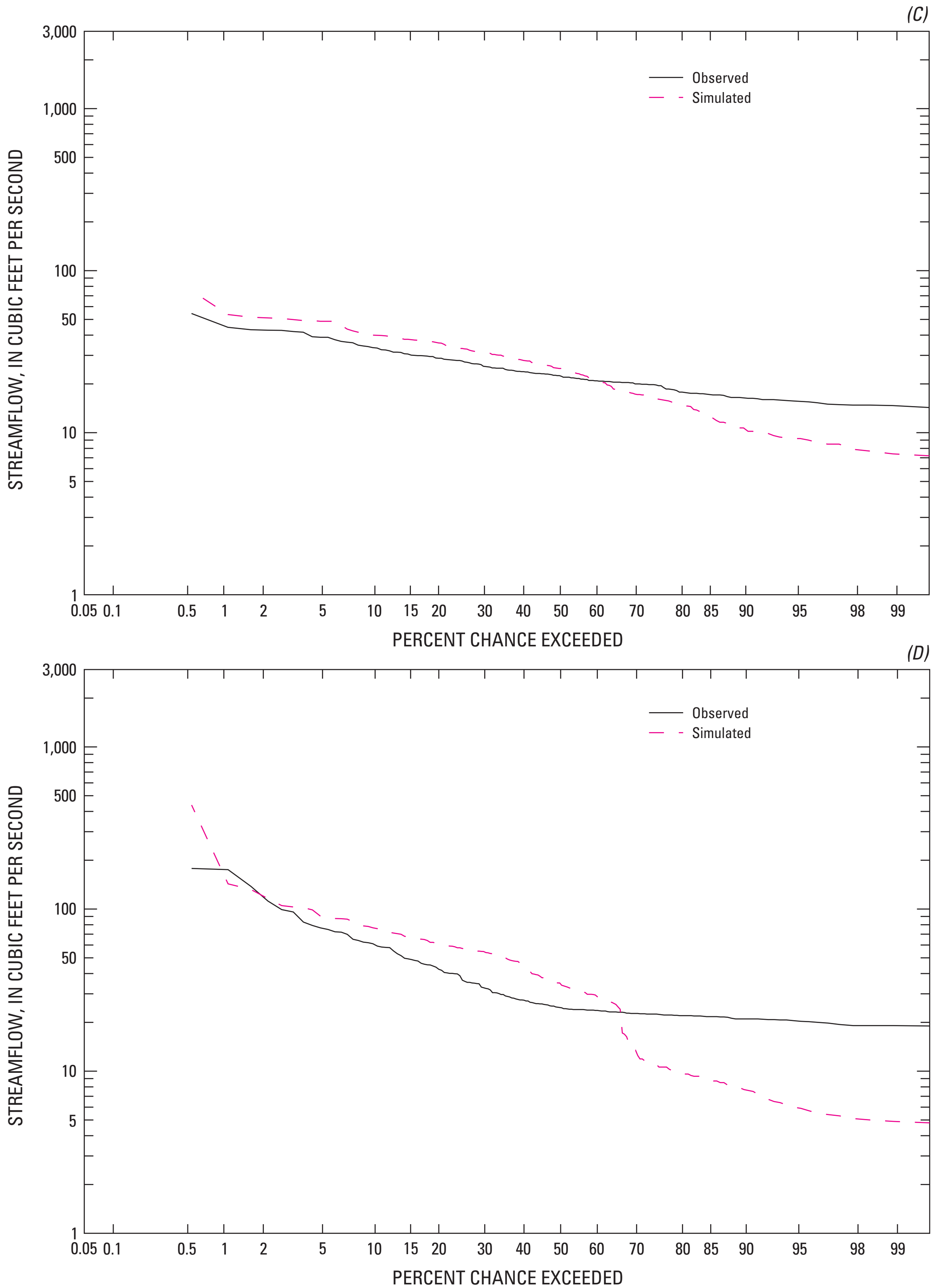


Figure 25. Seasonal flow-duration curves for observed and simulated daily mean streamflow, Winter, January-March *(A)*, Spring, April-June *(B)*, Summer, July-September *(C)*, and Fall, October-December *(D)*, in Christians Creek, Augusta County, Virginia, water years 1992-93—Continued.

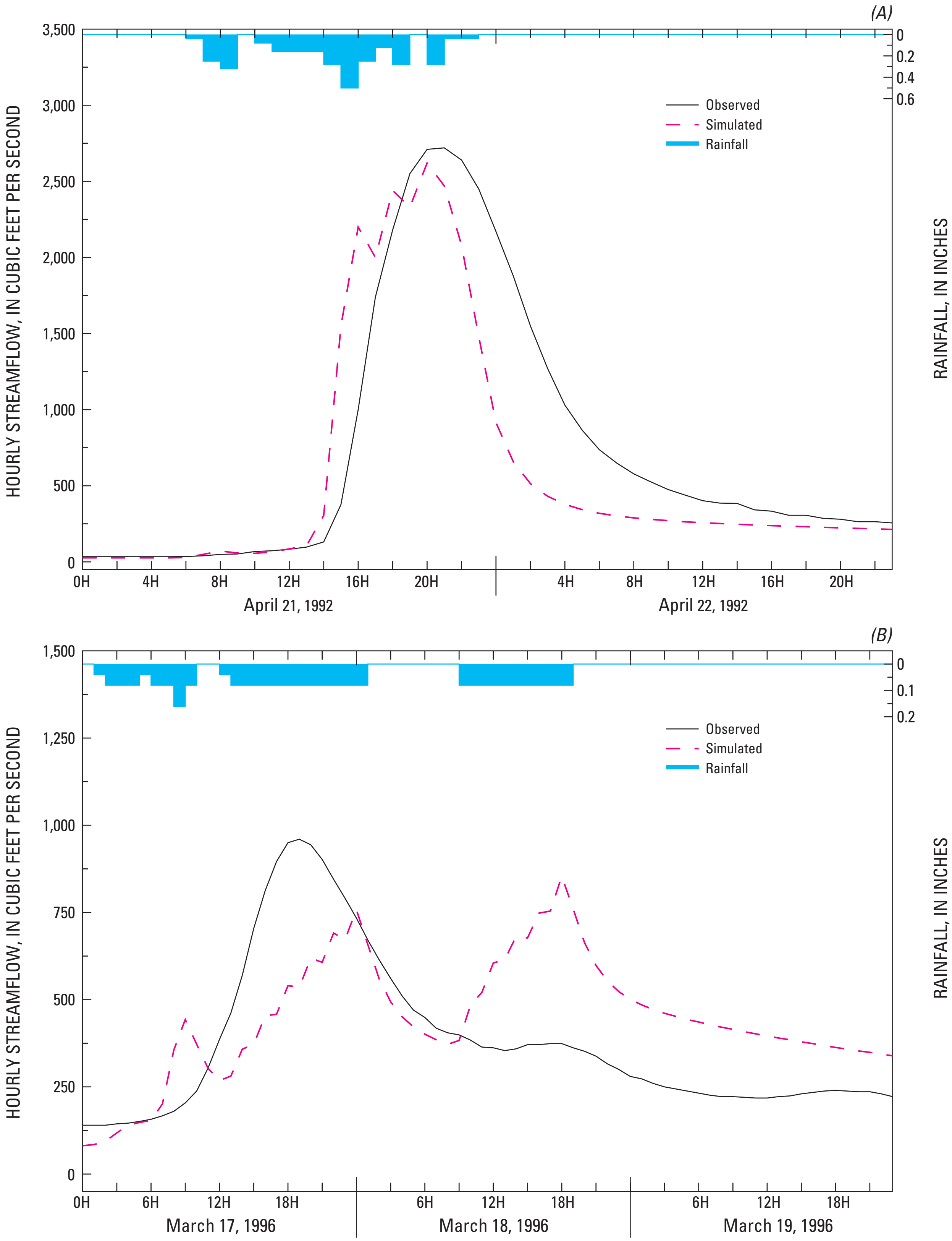


Figure 26. Hourly rainfall and observed and simulated daily mean streamflow, April 21-22, 1992 *(A)* and March 17-19, 1996 *(B)*, Christians Creek, Augusta County, Virginia.

Table 28. Final parameters and percent imperviousness used in six subwatersheds represented in the streamflow model for Christians Creek, Augusta County, Virginia

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

HRU	Imperviousness (percent)	AGWETP	AGWRC (1 per day)	BASETP	DEEPFR	INFILT (inches per hour)	INTFW	IRC (1 per day)	KVARY (1 per inch)	LZETP	LZSN (inches)	UZSN (inches)
U	–	0.00	0.965	0.00	0.11	0.03	1.00	0.60	0.00	vm	7.00	0.70
R	–	.00	.965	.00	.11	.05	1.00	.60	.00	vm	7.00	.70
P	–	.00	.965	.00	.11	.06	1.00	.60	.00	vm	8.00	.70
H	–	.00	.965	.00	.11	.06	1.00	.60	.00	vm	8.00	vm
C	–	.00	.965	.00	.11	.06	1.00	.60	.00	vm	8.00	vm
F	–	.00	.965	.00	.11	.08	3.00	.60	.00	vm	9.00	.70
UI	6	–	–	–	–	–	–	–	–	–	–	–
PI	0	–	–	–	–	–	–	–	–	–	–	–

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 Christians 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.

Data from the two DEQ long-term water-quality monitoring stations, Route 831 and Route 794, were used to calibrate portions of the fecal coliform model. These DEQ data were used primarily for the calibration of fecal coliform bacteria concentrations less than 16,000 col/100 mL (mostly base-flow and recession-flow periods) because these observed data are affected by the DEQ upper detection limit for concentrations higher than 16,000 col/100 mL. USGS data collected 1999 through 2000 were used to calibrate fecal coliform bacteria concentrations greater than 16,000 colonies per 100 mL by using the range of concentrations observed during stormflow periods. The calibration results were evaluated initially by comparing graphs of simulated and observed fecal coliform concentrations. However, observed instream 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 831 (fig. 27) and Route 794 (fig. 28). Spikes in simulated fecal coliform concentrations are the result of rainfall events where bacteria are washed off the land surface. Increases in simulated fecal coliform concentrations when spikes do not occur are the result of point source (instream cattle, straight pipes, and permitted discharges) and diffuse ground-water inputs. The capacity of the model to simulate fecal coliform concentrations during low-flow, stormflow and post-stormflow conditions was evaluated (figs. 27 and 28). In general, these conditions were simulated well in the model. The fecal coliform model had a tendency to undersimulate fecal coliform concentrations at Route 831 and oversimulate fecal coliform concentrations at Route 794. Attempts to correct Route 794 caused greater discrepancies at Route 831 and vice versa. Therefore, the resulting calibrated fecal coliform model is an average of upstream and downstream concentrations. Simulated maximum fecal coliform concentrations during storm events ranged from 1,500 to 800,000 col/100 mL. Observed maximum fecal coliform concentrations in water samples collected by the USGS at Route 794 during 1999–2000 storm events ranged from 23,000 to 730,000 col/100 mL (Hyer and Moyer, 2003). These data indicate that observed fecal

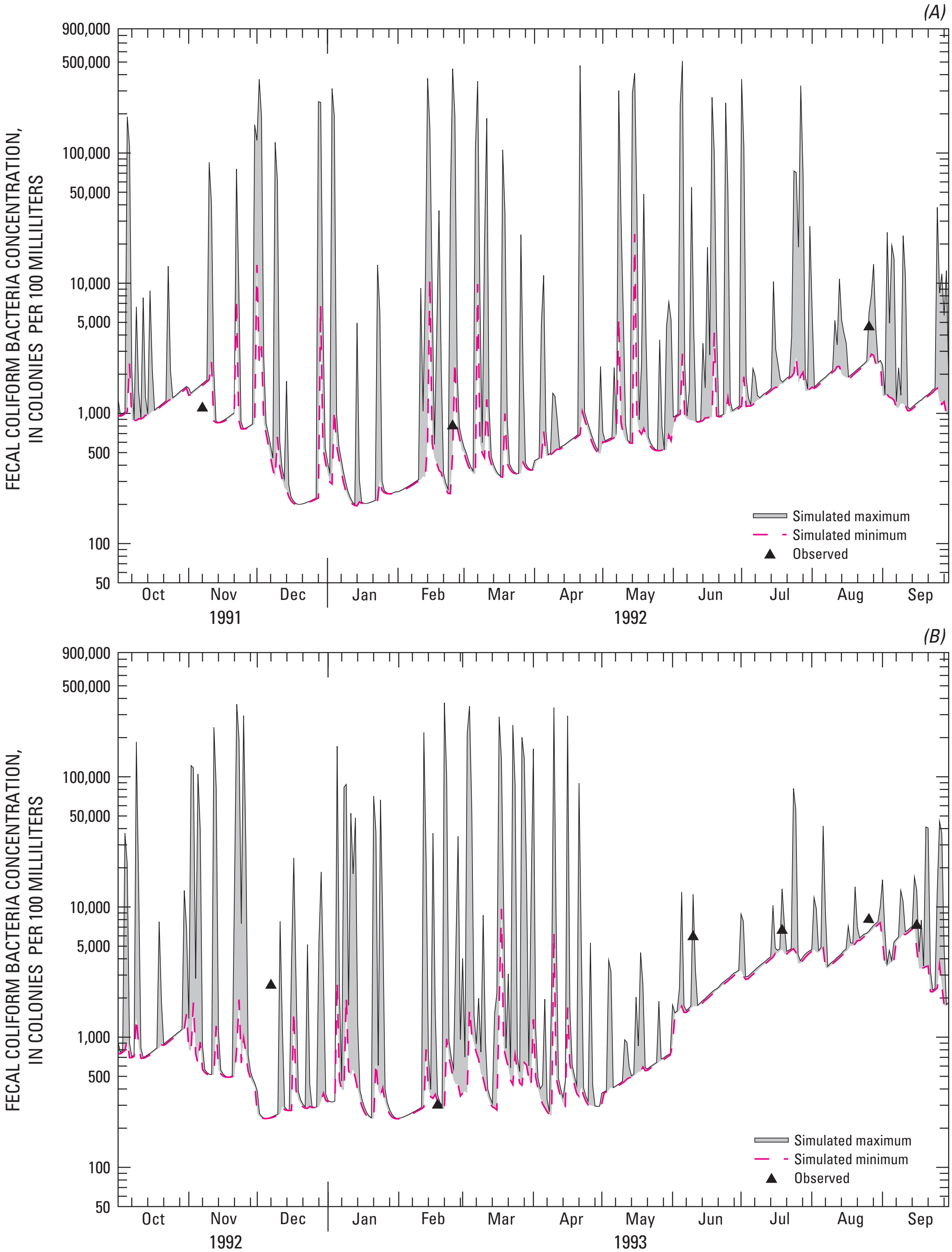
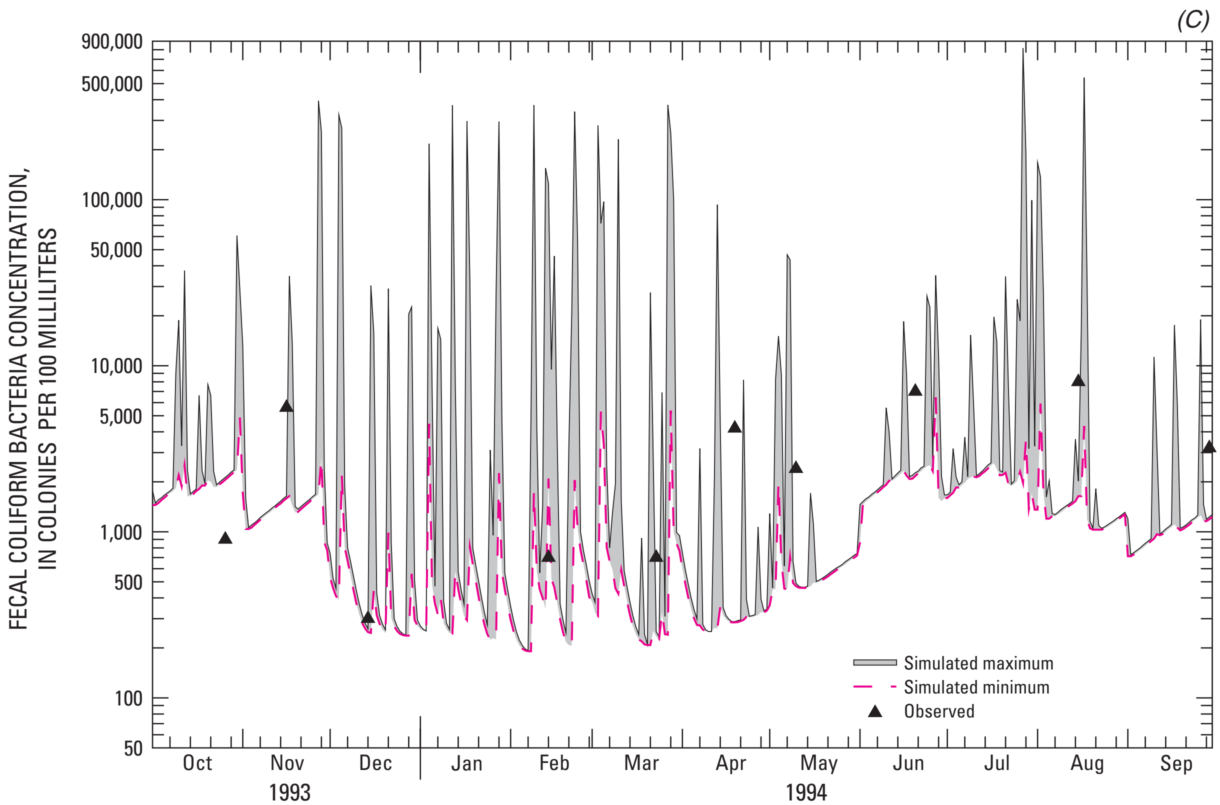
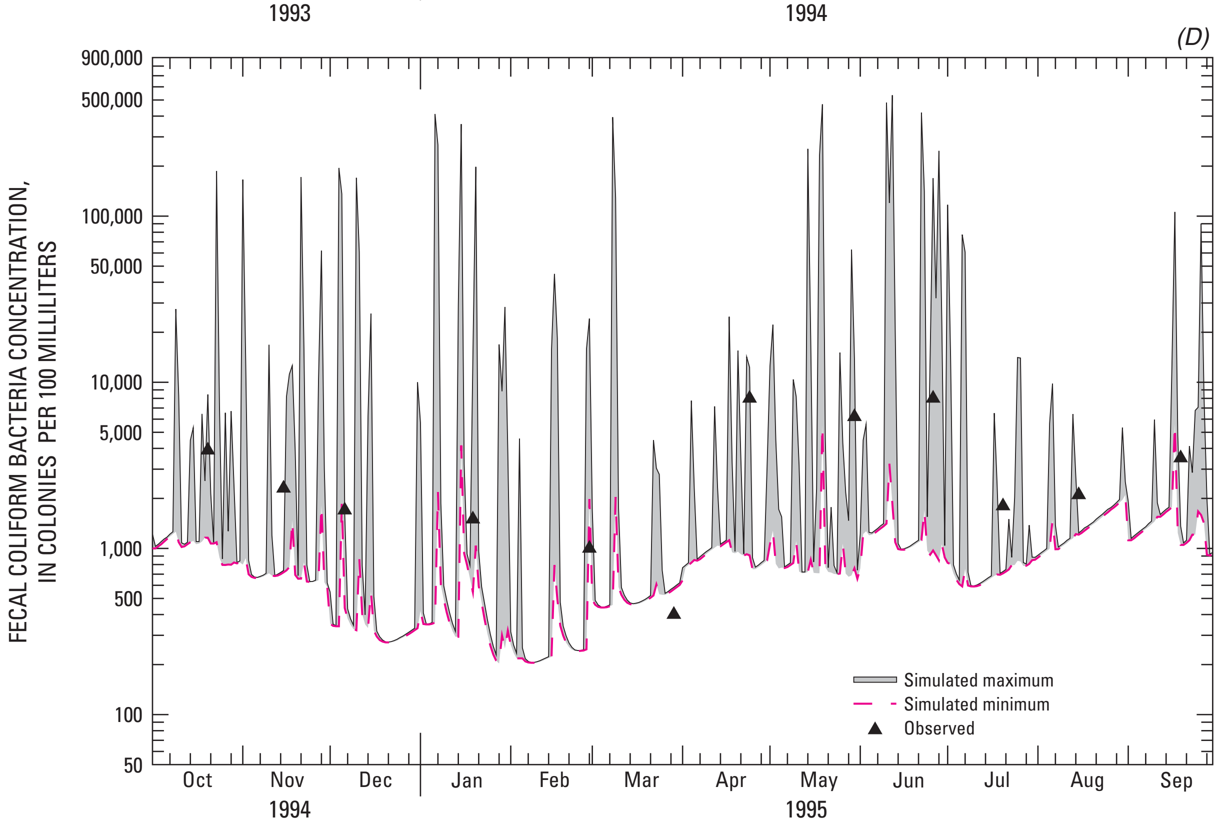


Figure 27. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 831, water years 1992 *(A)*, 1993 *(B)*, 1994 *(C)*, 1995 *(D)*, 1996 *(E)*, and 1997 *(F)*, Christians Creek, Augusta County, Virginia. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)





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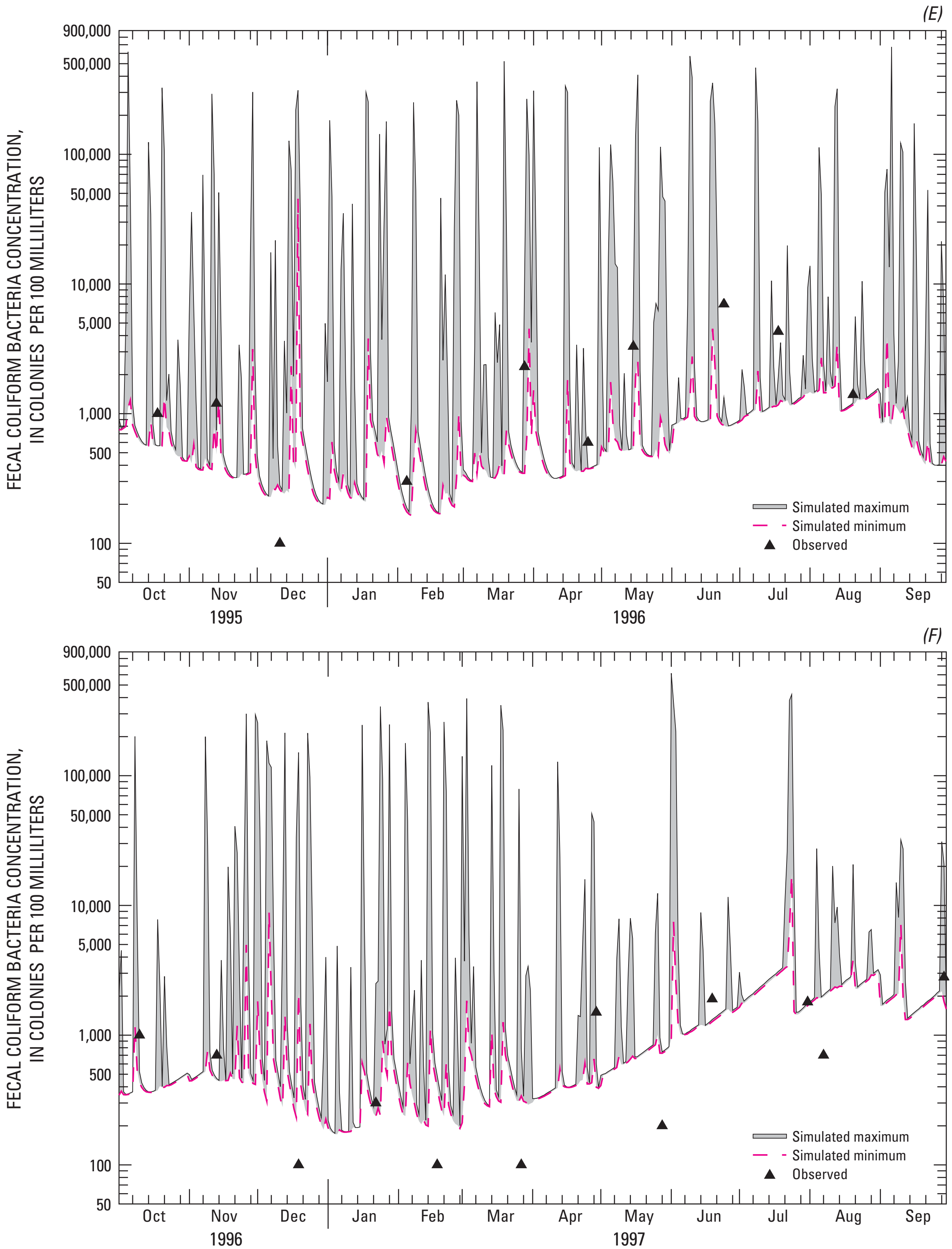


Figure 27. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 831, water years 1992 *(A)*, 1993 *(B)*, 1994 *(C)*, 1995 *(D)*, 1996 *(E)*, and 1997 *(F)*, Christians Creek, Augusta County, Virginia. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)—Continued

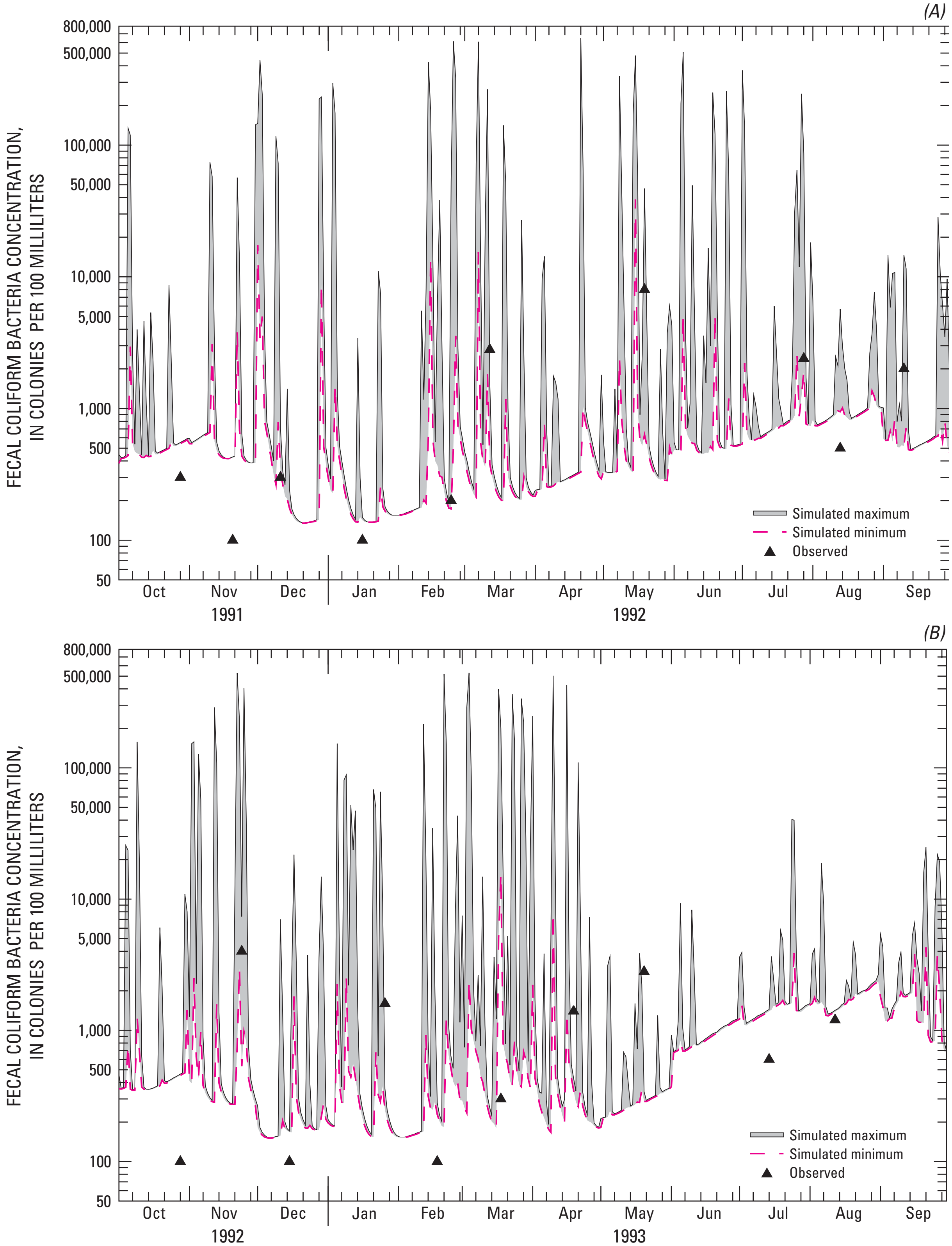
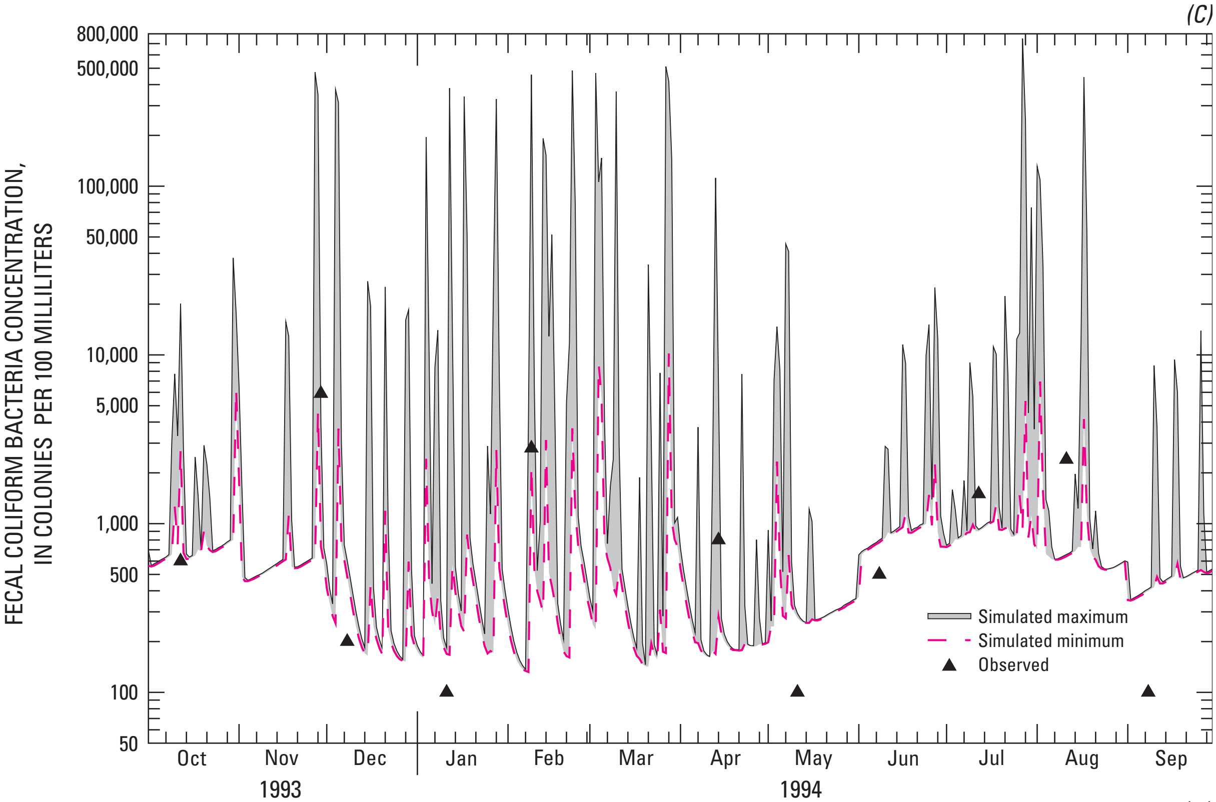


Figure 28. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 794, water years 1992 *(A)*, 1993 *(B)*, 1994 *(C)*, 1995 *(D)*, 1996 *(E)*, and 1997 *(F)*, Christians Creek, Augusta County, Virginia. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)



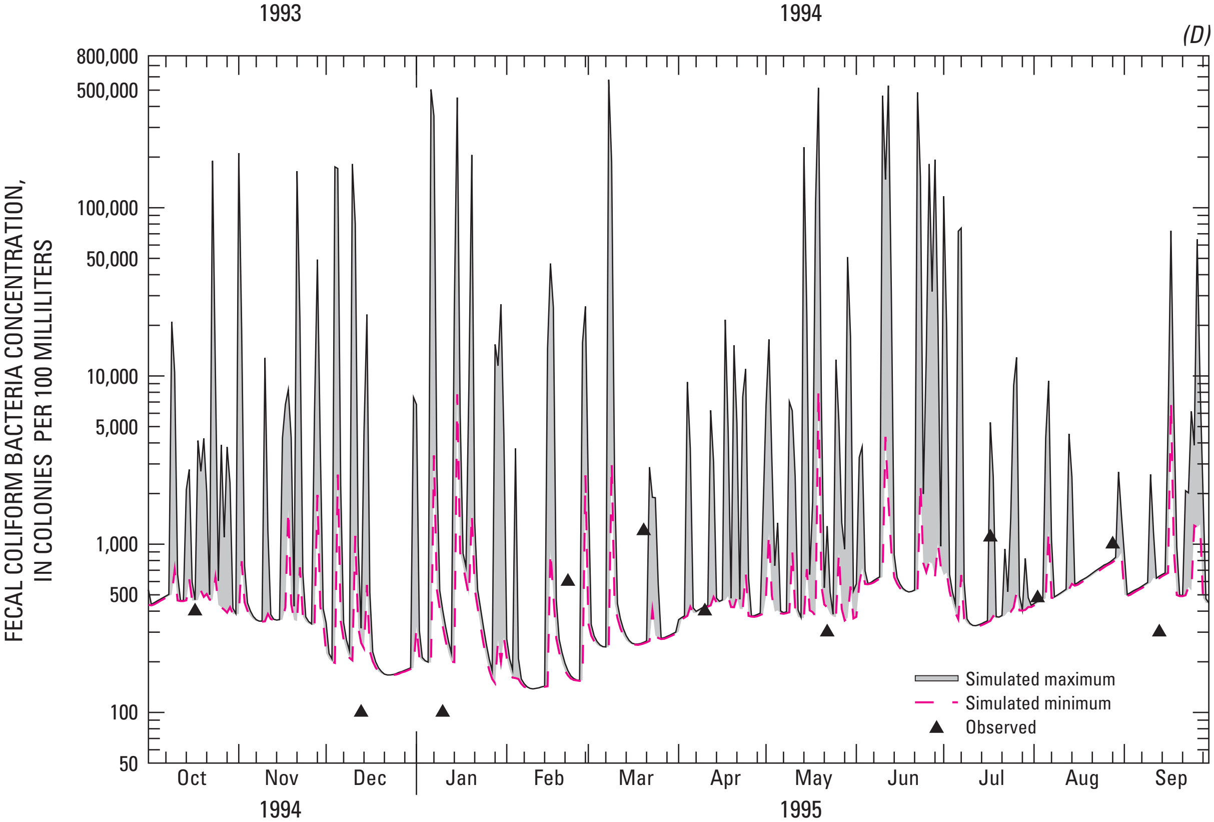


Figure 28. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 794, water years 1992 *(A)*, 1993 *(B)*, 1994 *(C)*, 1995 *(D)*, 1996 *(E)*, and 1997 *(F)*, Christians Creek, Augusta County, Virginia. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)—Continued

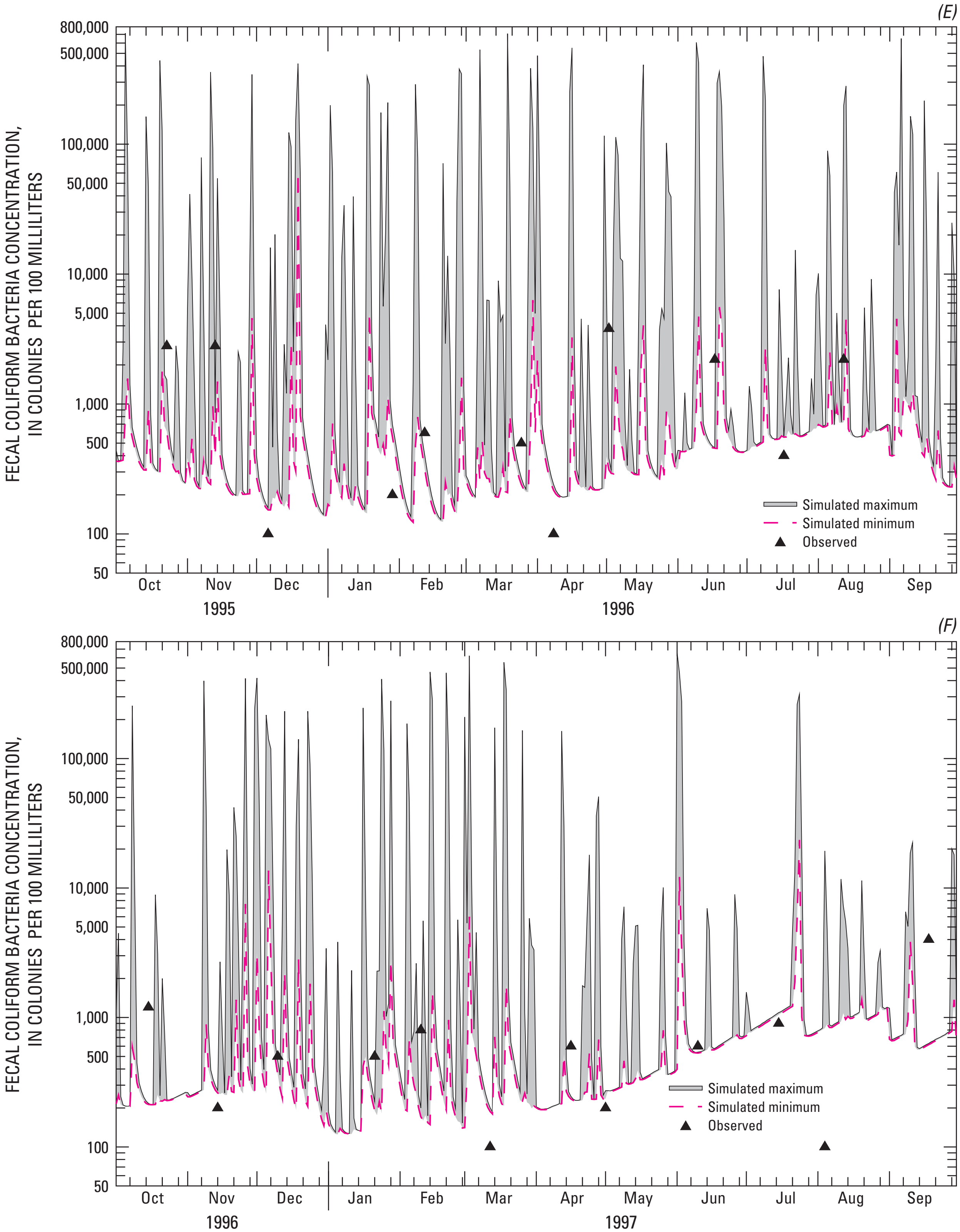


Figure 28. Simulated daily minimum and maximum concentrations, and observed instantaneous concentrations of fecal coliform bacteria at Route 794, water years 1992 *(A)*, 1993 *(B)*, 1994 *(C)*, 1995 *(D)*, 1996 *(E)*, and 1997 *(F)*, Christians Creek, Augusta County, Virginia. (Data from Roderick V. Bodkin, Virginia Department of Environmental Quality, written commun., 1999.)—Continued

coliform concentrations during stormflow periods are similar to simulated concentrations. The simulated recession of fecal coliform concentrations following a storm event ranged from 1 to 7 days (figs. 27 and 28). This range is consistent with the findings from Hyer and Moyer (2003) that elevated fecal coliform concentrations are maintained for 1 to 5 days following a storm event.

The calibrated fecal coliform model also was evaluated by comparing simulated with observed BST data collected at Route 794. These data describe the percent contribution of fecal coliform bacteria from various sources to Christians 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 cattle (68 percent), duck (9 percent), and sheep (9 percent) are overestimated, whereas the simulated contributions from the remaining sources were underestimated (fig. 29A). 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. 29B).

The calibrated fecal coliform model also was evaluated through comparison of the 30-day geometric mean for the simulated fecal coliform bacteria concentrations with the geometric mean of observed (period of record) concentrations. This comparison was a final check on the calibrated fecal coliform model but was not part of the iterative calibration process. The geometric means of the observed fecal coliform data at Route 831 and Route 794 for the period 1991-97 are 1,429 and 558 col/100 mL, respectively. Fecal coliform concentrations generally are higher at the upstream Route 831 site than the Route 794 site. The geometric means of the simulated fecal coliform concentrations at Route 831 and Route 794 are 1,619 and 1,057 col/100 mL, respectively. The pattern in the simulated geometric mean fecal coliform concentrations is similar to the observed concentrations in that the fecal coliform model simulates higher fecal coliform concentrations at the Route 831 site than the Route 794 site.

The simulated geometric mean concentrations at Route 831 and Route 794 are higher than the observed concentrations, primarily because different data sets are used to calculate the simulated and observed geometric means. 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 Christians 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 0.6 in. per hour (table 29).

Table 29. Final values of WSQOP used for the land-use types represented in the fecal coliform model for Christians Creek, Augusta County, Virginia

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

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

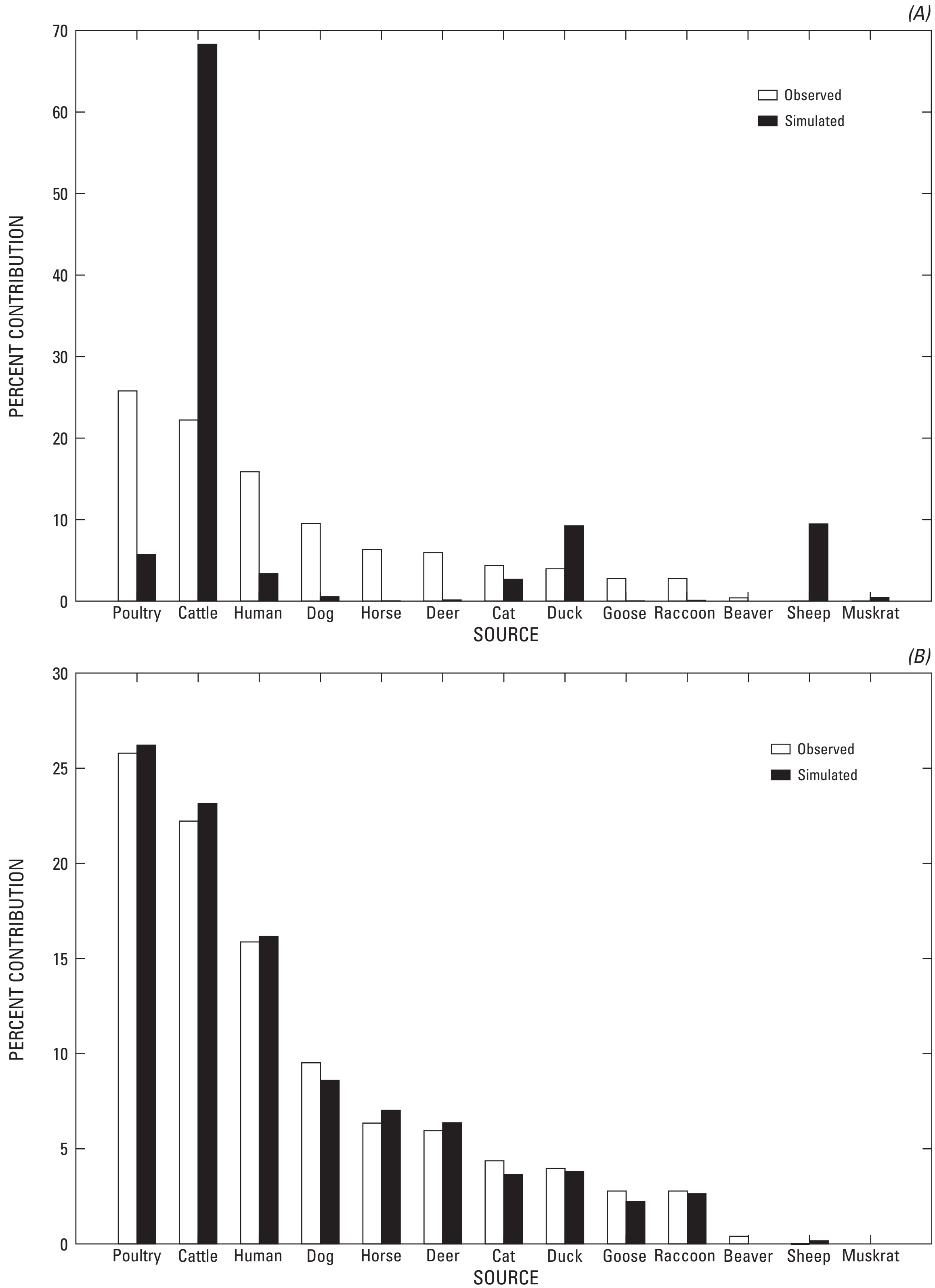


Figure 29. Observed and simulated percent contribution from the simulated sources in the watershed to the total instream fecal coliform bacteria load at Route 794, initial calibration *(A)*, and final calibration *(B)*, Christians Creek, Augusta County, Virginia.

The two source-specific model parameters adjusted during the calibration process were the fecal coliform accumulation rate on the land surface (ACCUM) and the limit of storage of fecal coliform bacteria on the land surface (SQOLIM). ACCUM for each source was manipulated during calibration; SQOLIM was maintained at 9 times ACCUM. The total fecal coliform contributions from humans, dogs, and cats were calibrated by adjusting their initial estimated population (POPN) values (table 30). The percentage of dogs depositing their feces on impervious areas was decreased from 10 percent to 1 percent. ACCUM values for cattle, poultry, horses, and sheep were calibrated by adjusting FCden (number of bacteria per gram of feces produced) (table 31). ACCUM for deer was calibrated by adjusting the FCden, whereas ACCUM values for geese, ducks, raccoons, muskrats, and beavers were calibrated through adjustments to POPN (table 32). POPN values for humans, dogs, cats, geese, ducks, raccoons, muskrats, and beavers are a result of model calibration and represent the populations 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 Christians Creek, water years 1991-97, were converted to 30-day geometric mean concentrations. The 30-day geometric mean concentrations indicate that predicted fecal coliform concentrations at both Route 831 and Route 794 exceed the State geometric mean water-quality standard of 200 col/100 mL (fig. 30A). Based on the peak fecal coliform 30-day geometric mean concentrations of 3,448 and 6,160 col/100 mL at Route 794 and Route 831, respectively, an approximately from 94- to 97-percent reduction of the current instream fecal coliform load is needed to meet the designated water-quality standard.

Most of the fecal coliform load (99.6 percent) entering Christians Creek is from nonpoint sources in the watershed (table 33). Thus, most of the fecal coliform bacteria are transported during stormflow periods. However, the incorporation of a geometric mean calculation and the need for compliance with the geometric mean water-quality standard places a greater emphasis on base-flow conditions that are dominated by point source contributions. The geometric mean calculation is used to identify an unbiased average in the presence of outliers, such as elevated concentrations of fecal coliform bacteria associated with stormflow events. In order to meet the State water-quality standard, reductions are needed in fecal coliform loads from both nonpoint sources and sources depositing directly in the streams.

Scenarios for Fecal Coliform Load Reductions

Total instream fecal coliform load reductions of approximately 94–97 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 Christians Creek were developed through discussions including DCR, DEQ, USGS (in a technical advisory role) and local stakeholders (table 34). These scenarios feature source-specific reductions in fecal coliform loads from nonpoint sources and point sources, including direct deposition from cattle in streams and straight pipes. Scenario 1 requires a 100-percent reduction in the present fecal coliform loading from cattle, poultry, sheep, horses, humans, dogs and cats (nonpoint sources), a 90-percent reduction in fecal coliform loading from parking lots and roads, and a 100-percent reduction in the fecal coliform loading from cattle in streams and straight pipes (point sources) in order to ensure that the State water-quality standard is not exceeded. Scenarios 2 and 3 require greater reductions in fecal coliform loading from wildlife sources (50 and 94 percent, respectively) and parking lots and roads (100 and 99 percent, respectively), whereas lesser reductions are needed from the livestock and pet sources in order to ensure that the State water-quality standard is not exceeded. These three scenarios were discussed and evaluated in a public review process led by DCR and DEQ, and scenario 3 was chosen for the Christians Creek watershed.

After the source-load reduction strategies in scenario 3 were incorporated into the watershed model, simulated fecal coliform concentrations at both Route 831 and Route 794 met the water-quality goals (fig. 30B). Simulated fecal coliform concentrations at the mouth of Christians Creek (reach 6, fig. 31) also

Table 30. Final values of the total amount of feces produced daily and fecal coliform per gram of feces generated by the human, dog and cat populations in the residential hydrologic response unit represented in the fecal coliform model, Christians Creek, Augusta 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–Land Applied			
1	150	4.66×10^8	272	–	289	–
2	150	4.66×10^8	176	–	206	–
3	150	4.66×10^8	339	–	309	–
4	150	4.66×10^8	224	–	485	–
5	150	4.66×10^8	330	–	808	–
6	150	4.66×10^8	209	–	261	–
			Human–Straight Pipes			
1	150	4.66×10^8	3	–	–	–
2	150	4.66×10^8	3	–	–	–
3	na	–	–	–	–	–
4	150	4.66×10^8	3	–	–	–
5	na	–	–	–	–	–
6	150	4.66×10^8	3	–	–	–
			Dog			
1	450	4.11×10^6	3,121	1,860	289	414
2	450	4.11×10^6	2,019	1,202	206	153
3	450	4.11×10^6	3,887	2,316	309	495
4	450	4.11×10^6	2,567	1,530	485	1,244
5	450	4.11×10^6	3,784	2,255	808	196
6	450	4.11×10^6	2,398	1,429	261	429
			Dog Impervious			
1	450	4.11×10^6	–	19	–	26
2	450	4.11×10^6	–	12	–	10
3	450	4.11×10^6	–	23	–	32
4	450	4.11×10^6	–	15	–	170
5	450	4.11×10^6	–	23	–	13
6	450	4.11×10^6	–	14	–	27
			Cat			
1	20	1.49×10^7	8,291	4,990	289	414
2	20	1.49×10^7	5,362	3,228	206	153
3	20	1.49×10^7	10,324	6,215	309	495
4	20	1.49×10^7	6,818	4,105	485	1,244
5	20	1.49×10^7	10,051	6,051	808	196
6	20	1.49×10^7	6,370	3,835	261	429

[1]See figure 3 for location of subwatersheds.

Table 31. Final values of the total amount of feces produced daily and fecal coliform bacteria per gram of feces generated by cattle, poultry, horses, and sheep represented in the fecal coliform model, Christians Creek, Augusta County, Virginia

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

Source	Average daily Fprod (grams)	FCden
Dairy cattle	54,545	1.98×10^5
Beef cattle	20,909	5.60×10^5
Heifers	39,091	1.41×10^6
Poultry	231	1.83×10^9
Horse	23,182	4.44×10^6
Sheep	1,091	1.80×10^6

Table 32. Final values for population, total amount of feces produced daily and fecal coliform bacteria per gram of feces for deer, goose, duck, raccoon, muskrat, and beaver represented in the watershed model, Christians Creek, Augusta County, Virginia

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

Wildlife source	Land-use type	Population density (number per acre)	POPN (number)	Fprod (grams)	FCden
Deer	F, P	0.040	975	772	2.24×10^8
Goose–Summer	U, R, P, H, C	4.87	23,293	225	3.55×10^6
Goose–Winter	U, R, P, H, C	6.23	30,359	225	3.55×10^6
Duck–Summer	U, R, P, H, C	.71	3,395	150	4.90×10^7
Duck–Summer	F	.19	413	150	4.90×10^7
Duck–Winter	U, R, P, H, C	1.50	7,175	150	4.90×10^7
Duck–Winter	F	.31	674	150	4.90×10^7
Raccoon	F	.22	4308	450	1.11×10^7
Raccoon	R, P, H, C	.09	3821	450	1.11×10^7
Muskrat	U, R, P, H, C, F	.500	479	100	2.50×10^5
Beaver	F	.016	5	200	1.00×10^3
Beaver	U, R, P, H, C	.008	5	200	1.00×10^3

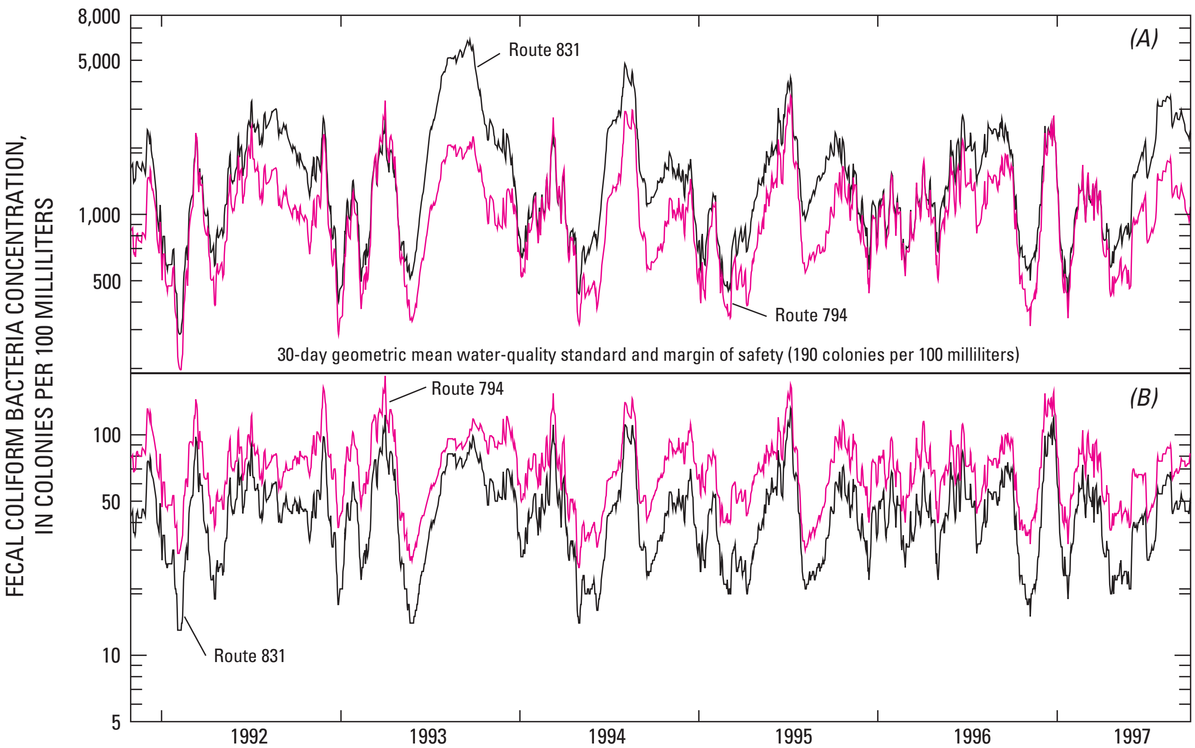


Figure 30. Simulated 30-day geometric mean fecal coliform concentrations before *(A)* and after *(B)* incorporation of the Total Maximum Daily Load (TMDL) allocation scenario at Route 831 and Route 794 for Christians Creek, Augusta County, Virginia, water years 1992-97.

will meet the water-quality goals following implementation of scenario 3, thus bringing Christians Creek into compliance with the State water-quality standard from the headwaters to the mouth. Changes to the present fecal coliform load allocation following the incorporation of the source-specific load reductions in scenario 3 are in table 35. Average annual fecal coliform loading pre- and post-TMDL allocations are 3.69 x 10^{16} and 1.39 x 10^{15} col/year, respectively. The percent reductions in the fecal coliform load delivered from the various land types ranged from 94 to 99 percent as a result of the reduction scenario. The needed percent reduction in the fecal coliform load delivered from cattle in

Table 33. Total annual load of fecal coliform bacteria delivered from the various land-use types, direct deposition by cattle and humans and permitted discharges for present conditions in Christians Creek, Augusta County, Virginia

A

Land-use types	Total annual load of fecal coliform bacteria for present conditions (colonies per year)	Contribution (percent)
Urban	2.54 x 10^{15}	6.88
Residential	1.01 x 10^{16}	27.34
Pasture	1.15 x 10^{16}	31.14
Cropland	7.05 x 10^{15}	19.09
Hayland	4.17 x 10^{15}	11.29
Forest	1.38 x 10^{15}	3.74
Urban Impervious	4.92 x 10^{13}	.13
Point Sources		
Instream deposition from cattle and humans	1.44 x 10^{14}	.39
Permitted discharges	2.36 x 10^{12}	.01
Total	3.69 x 10^{16}	100

Table 34. Scenarios for reducing fecal coliform bacteria loads and associated percent reductions from nonpoint and point sources represented in the fecal coliform model for Christians Creek, Augusta County, Virginia

Scenario number	Percent reduction from present fecal coliform load																	Average 30-day geometric mean concentration of fecal coliform bacteria (colonies per 100 milliliters)
	Nonpoint sources														Point sources			
	Cattle	Poultry	Sheep	Horse	Human	Dog	Cat	Goose	Duck	Deer	Raccoon	Muskrat	Beaver	Parking lots and roads	Cattle in streams	Straight pipes	Permitted discharges	
1	100	100	100	100	100	100	100	0	0	0	0	0	0	90	100	100	0	9
2	100	100	100	100	100	100	100	50	50	50	0	0	0	100	98	100	0	41
3	94	94	94	94	100	94	94	94	94	94	94	0	0	99	99	100	0	73

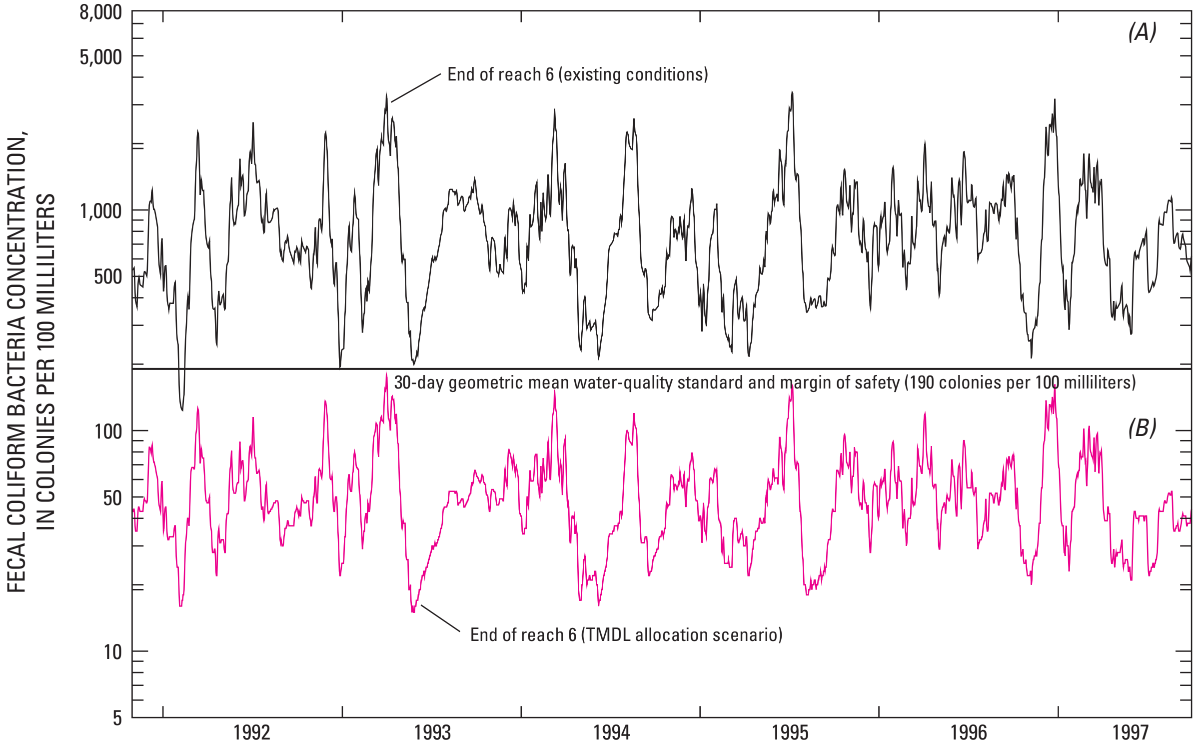


Figure 31. Simulated 30-day geometric mean fecal coliform concentrations before *(A)* and after *(B)* incorporation of the Total Maximum Daily Load (TMDL) allocation scenario at Route 831 and Route 794 at the end of storm reach 6 for Christians Creek, Augusta County, Virginia, water years 1992-97.

Table 35. Total annual loads of fecal coliform bacteria delivered from the land-use types, point sources, and permitted discharges for present conditions and after incorporation of total maximum daily load (TMDL) allocation in Christians Creek, Augusta County, Virginia

[NC, no change]

Land-use types	Total annual load of fecal coliform bacteria for present conditions (colonies per year)	Total annual load after incorporation of TMDL (colonies per year)	Reduction (percent)
Urban	2.54×10^{15}	1.01×10^{14}	96.01
Residential	1.01×10^{16}	1.23×10^{14}	98.78
Pasture	1.15×10^{16}	4.96×10^{14}	95.69
Cropland	7.05×10^{15}	4.28×10^{14}	93.94
Hayland	4.17×10^{15}	1.66×10^{14}	96.01
Forest	1.38×10^{15}	5.81×10^{13}	95.79
Urban impervious	4.92×10^{13}	3.21×10^{11}	99.35
Point Sources			
Instream deposition from cattle and humans	1.44×10^{14}	1.12×10^{12}	99.22
Permitted discharges	2.36×10^{12}	1.18×10^{13}	NC
Total	3.69×10^{16}	1.39×10^{15}	96.23

streams and straight pipes equaled 99 percent while no reduction in fecal coliform loading from permitted dischargers (sewage treatment plants) was required. The resulting TMDL equation (see eq. 1) that meets the fecal coliform bacteria water-quality goals for Christians Creek is

$$1.46 \times 10^{15} \text{ col/yr } (TMDL) = 1.18 \times 10^{13} \text{ col/yr } (\sum WLAs) + 1.38 \times 10^{15} \text{ col/yr } (\sum LAs) + 6.96 \times 10^{13} \text{ col/yr } (MOS).$$

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

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

(2) Development of a plan for reducing the current fecal coliform loading to Christians 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 Christians 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.
- 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 Christians Creek watershed. The Virginia Department of Environmental Quality (DEQ) determined that Christians 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 Christians 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 Christians 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 in Christians Creek are poultry, cattle, humans, dogs, horses, and deer.
- The calibrated fecal coliform model simulated the patterns and range of fecal coliform bacteria concentrations observed by DEQ (1991-97) and USGS (1999-2000).
- The calibrated fecal coliform model simulated source-specific instream fecal coliform loads comparable to the source-specific percent contribution identified in Christians Creek by BST.
- Incorporation of BST data reduces the uncertainty associated with determining source-specific fecal coliform loading in the watershed.
- A 96-percent reduction in the current fecal coliform load delivered to Christians Creek is required to meet the designated water-quality goals and associated TMDL.

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