Bacteria Total Maximum Daily Load Development for Mill Creek and Powhatan Creek

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Executive Summary

Background

The Mill Creek and Powhatan Creek watersheds are located in James City County in eastern Virginia. Both Mill and Powhatan Creeks discharge to the James River (USGS Hydrologic Unit Code 11010002), which flows into the Chesapeake Bay. There are tidal sections of both creeks that empty into small embayments before discharging to the James River.

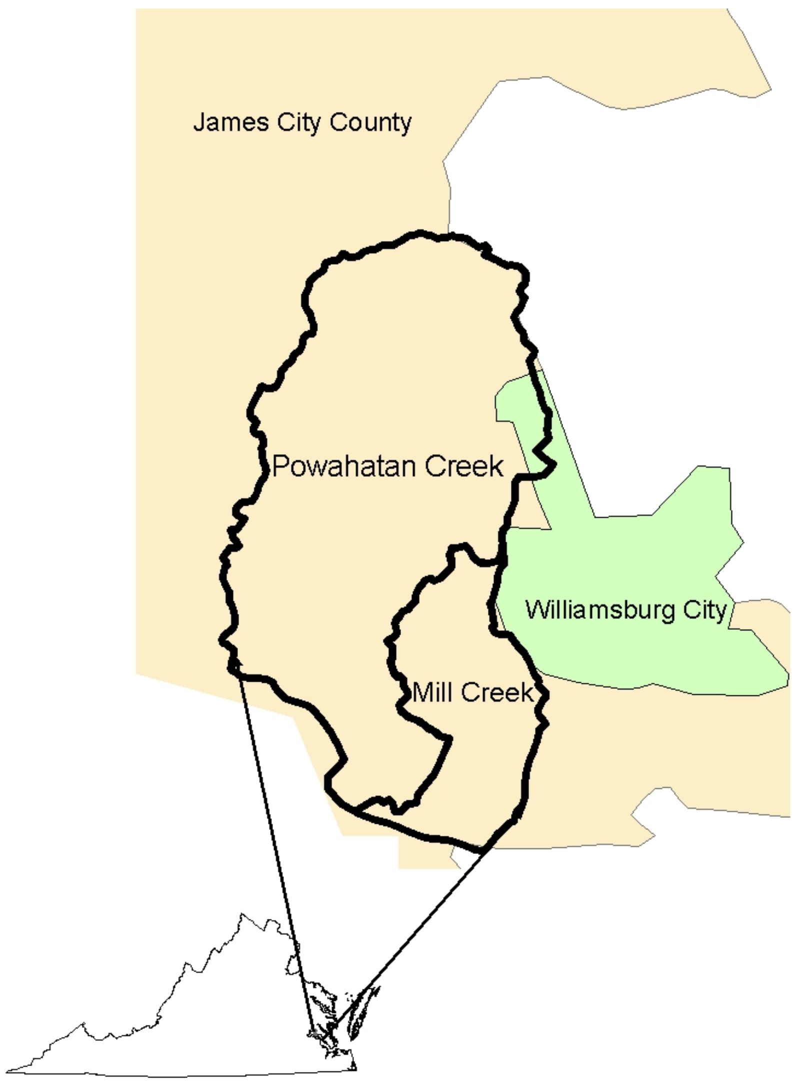

Figure ES-1. Mill Creek and Powhatan Creek watershed locations.

Mill Creek (VAT-G10E-03) and Powhatan Creek (VATG10E-01 and VAT-G10R-02) are listed as impaired on Virginia's 2006 Section 303(d) Total Maximum Daily Load Priority List and Report (VADEQ, 2006). The segments were assessed as not supporting the Primary Contact Recreation Designated Use due to violation of the indicator bacteria criterion. There is a single impairment of the tidal creek section of Mill Creek and two impairments for Powhatan Creek, one for the non-tidal and one for the tidal section. Twenty-nine (29) percent of the water quality samples collected from Mill Creek at station 2-MIC000.03 during the 2006 Assessment Period violated the interim single-sample water quality criterion for fecal coliform, 400 colony forming units (cfu) per 100 mL. For Powhatan Creek, eleven (11) percent of the water quality samples collected from the non-tidal section (2-POW006.77) and twenty-four (24) percent of the water quality samples collected from the tidal section (2-POW000.60) during the 2006 Assessment Period violated the interim (400 cfu/100 mL) fecal coliform criterion.

This document describes the Total Maximum Daily Loads (TMDLs) developed for Mill and Powhatan Creeks to address bacteria water quality impairments. The TMDLs were developed to comply with Virginia's revised bacteria water quality standards which are based on the concentration of the indicator bacteria enterococci or *E. coli*. For Mill Creek, the new transition zone waters (or tidal water) standard applies. The tidal water standard is based on enterococci bacteria and states that the calendar-month geometric mean concentration shall not exceed 35 cfu/100 mL, nor shall any single sample exceed a concentration of 104 cfu/100mL. For Powhatan Creek, both the enterococci standard and the *E. coli* standard (for fresh water) apply. The enterococci standard is the same as discussed for Mill Creek and the *E. coli* standard states that the calendar-month geometric mean concentration shall not exceed 126 cfu/100 mL, nor shall any single sample exceed 235 cfu/100mL.

Modeling

TMDL development was accomplished with the aid of watershed-based models that integrate both point and nonpoint bacteria sources. The Hydrological Simulation Program – FORTRAN (HSPF) version 12 (Bicknell *et al.*, 2001; Duda *et al.*, 2001) was used to model indicator bacteria transport and fate in the Mill and Powhatan Creek watersheds. In the case of this particular TMDL study, the presence of a tidal zone within the impaired reaches for both Mill and Powhatan Creeks required the addition of a tidal model to accurately simulate fluxes in the tidal zones. To that end, the Tidal PRISM water quality model developed for use in small coastal basins and tidal creeks (Kuo and Park, 1994) was used to model fecal coliform transport and fate in the tidal zones. As recommended by the Virginia Department of Environmental Quality (VADEQ), water quality modeling was conducted with fecal coliform inputs, and then a translator equation was used to convert the fecal coliform output to *E. coli* and enterococci for the final TMDLs. To identify localized bacteria sources within the watersheds, the Mill Creek watershed was divided into nine (9) sub-watersheds and the Powhatan Creek watershed was divided into seventeen (17) sub-watersheds. Sub-watershed delineation was based on homogeneity of land use, stream network connectivity, and monitoring station locations.

Bacteria Sources

Bacteria loads were estimated for all permitted and nonpoint sources for input to the models. There are currently four Municipal Separate Storm Sewer Systems (MS4s) permitted to discharge bacteria in the Mill Creek and Powhatan Creek watersheds. Sources of nonpoint source (NPS) bacteria pollution within the watersheds include livestock, wildlife, pets, and humans. Analysis indicates that significant bacteria loads come from wildlife directly depositing feces (defecating) in the stream. In addition to wildlife contributing bacteria directly to the stream, they also contribute to loads on land surfaces, in accordance with the habitat range for each species. Livestock directly depositing bacteria on the land surface also contribute a significant amount of bacteria to the stream during large storm events. Pets also contribute to bacteria loads from the land surface, primarily from residential areas. The amounts of bacteria produced by these nonpoint sources were estimated on a monthly basis to account for seasonal variability in wildlife behavior and livestock production and practices. Table ES-1 summarizes the bacteria produced as a function of where the bacteria are deposited e.g. in-stream or on the land.

Table ES-1. Annual fecal coliform loadings for existing conditions.

Source	Fecal Coliform Loading ($x10^{12}$ cfu/yr)		Percent of Total Loading (%)	
	Mill Creek	**Powhatan Creek**	**Mill Creek**	**Powhatan Creek**
Direct loading to streams				
Wildlife in stream	72	10	3	<1
Loading to land surfaces				
Cropland	1.5	0.1	<1	<1
Pasture	407	150	18	3
Residential	1,650	5,150	73	96
Forest	135	13	6	<1
Total	**2,266**	**5,323**		

Model calibration

Because no continuous hydrology gage was available on Mill or Powhatan Creeks, hydrologic model calibration was accomplished by using model parameter values from a previously calibrated surrogate watershed. Totopotomoy Creek was selected as the surrogate watershed because of similar landscape characteristics. Hydrologic calibration details for Totopotomoy Creek can be found in the Pamunkey River Basin Bacteria TMDL (Engineering Concepts, Inc., 2006).

The water quality calibration of both the HSPF and Tidal PRISM models was accomplished using water quality data collected in each watershed. Data from monitoring station 2-POW006.77 was used to calibrate HSPF for the non-tidal portion of Powhatan Creek. Because no monitoring data was available for the non-tidal portion of Mill Creek, the calibrated HSPF water quality parameters for the Powhatan Creek were used for simulations of the non-tidal section of Mill Creek. Data from two stations located in the tidal portions of Powhatan (2-

POW000.60) and Mill Creek (2-MIC000.03) were used for the Tidal PRISM calibration.

Existing Conditions

The transport and fate of the bacteria loads in the Mill and Powhatan Creek watersheds (Table ES-1) were simulated using HSPF and Tidal PRISM for a representative 5 and half-year period that included both low and high-flow conditions to establish an existing conditions baseline scenario.

Meteorological data were paired with bacterial loading and land use data for existing conditions to establish this baseline scenario. Results from the calibrated models showed a strong relationship among wildlife direct deposit and loads to pervious land surfaces with water quality criteria violations. Bacteria directly deposited in streams are only subject to die-off that occurs in-stream. By contrast, bacteria deposited on the land do undergo die-off while on the land surface and only reach the stream during a runoff producing precipitation event. As a result, the portion of in-stream bacteria is often dominated by direct-deposit bacteria. The relative in-stream contributions are shown in Table ES-2 for tidal section of Mill Creek. For Powhatan Creek, Table ES-3 listed the in-stream concentrations for the non-tidal section and Table ES-4 for the tidal section. The averages in these tables are the average concentration over the entire 5 and a half year simulation period. These concentrations are the results of modeling that takes into account these varied fate and transport processes and represents the fraction of in-stream bacteria attributable to each source.

Table ES-2. Relative contributions from different bacteria sources to the in-stream concentration for existing conditions in the Mill Creek watershed.

Source	In-stream Mean Fecal Coliform Concentration (cfu/100 mL)	Percent of Total Loading (%)
Direct loading to streams		
Wildlife in stream	1,491	75
Loading to land surfaces		
Agricultural	69	3
Residential	432	22
Forest	8	<1
Total	**2,000**	

Table ES-3. Relative contributions from different bacteria sources to the in-stream concentration for existing conditions in the non-tidal section of the Powhatan Creek watershed.

Source	In-stream Mean Fecal Coliform Concentration (cfu/100 mL)	Percent of Total Loading (%)
Direct loading to streams		
Wildlife in stream	219	48
Loading to land surfaces		
Residential	224	49
Forest	16	3
Total	**459**	

Table ES-4. Relative contributions from different bacteria sources to the in-stream concentration for existing conditions in the tidal section of the Powhatan Creek watershed.

Source	In-stream Mean Fecal Coliform Concentration (cfu/100 mL)	Percent of Total Loading (%)
Direct loading to streams		
Wildlife in stream	215	66
Marinas and Canal	5	2
Loading to land surfaces		
Agricultural	29	9
Residential	54	17
Forest	23	7
Total	**326**	

Allocation Scenarios

Source reduction allocation scenarios were determined to meet the applicable water quality standards for both Mill and Powhatan Creeks. Acceptable scenarios produced zero violations of the bacteria criteria during the simulation period. The bacteria loadings used to determine the allocation scenarios correspond to anticipated future conditions for the watersheds. A 50% build-out of land use changes for the James City County Comprehensive Plan was used to represent the future conditions for both watersheds. The reductions required for the impairment in Mill Creek are presented in Table ES-5 and the loadings are presented in Table ES-6. Tables ES-7 and ES-8 present the same information for Powhatan Creek.

Table ES-5. Successful allocation scenarios for Mill Creek.

Fecal Coliform Loading Reduction (%)[a]				% Violation of Enterococci Standard	
Agricultural	Wildlife DD[b]	Residential	Forest	Geometric Mean	Instantaneous
95	98	95	0	0%	0%

[a] These reductions apply to both the land areas in the non-tidal and tidal sections of the watershed.
[b] DD – direct deposition of feces in stream

Table ES-6. Annual nonpoint source fecal coliform loads under existing conditions and corresponding reductions for TMDL allocation for Mill Creek.

	Existing Conditions		Allocation Scenario	
Bacteria Source	Existing Conditions Load ($x10^{12}$ cfu/yr)	Percent of Total Load from Nonpoint Sources	TMDL nonpoint Source Allocation Load ($x10^{12}$ cfu/yr)	Percent Reduction from Existing Load (%)
Direct loading to streams				
Wildlife in stream	72	3	1	98
Loading to land surfaces		<1		
Agricultural	409	19	20	95
Residential	1650	73	83	95
Forest	135	6	135	0
Total	2266		239	95

Table ES-7. Successful allocation scenarios for Powhatan Creek.

Fecal Coliform Loading Reduction (%)[a]					% Violation of *E. coli* Standard		% Violation of Enterococci Standard	
Agricultural	Wildlife DD[b]	Residential	Forest	Marinas and Canal	Geometric Mean	Instantaneous	Geometric Mean	Instantaneous
92	92	92	0	100	0	0	0	0

[a] These reductions apply to both the land areas in the non-tidal and tidal sections of the watershed.
[b] DD – direct deposition of feces in stream

Table ES-8. Annual nonpoint source fecal coliform loads under existing conditions and corresponding reductions for TMDL allocation for Powhatan Creek.

	Existing Conditions		Allocation Scenario	
Bacteria Source	Existing Conditions Load ($x10^{12}$ cfu/yr)	Percent of Total Load from Nonpoint Sources (%)	TMDL Nonpoint Source Allocation Load ($x10^{12}$ cfu/yr)	Percent Reduction from Existing Load (%)
Direct loading to streams				
Wildlife in stream	10	<1	1	92
Marinas and Canal	<1	<1	<1	100
Loading to land surfaces				
Agricultural	150	3	12	92
Residential	5,459	97	437	92
Forest	14	<1	1	0
Total	5634	100	451	92

Equation ES-1 was used to calculate the TMDL allocations shown in Table E-9 for Mill Creek and Table E-10 and Table E-11 for Powhatan Creek.

$$TMDL = \Sigma WLA + \Sigma LA + MOS \qquad [ES-1]$$

where:

WLA = wasteload allocation (point source contributions);

LA = load allocation (nonpoint source contributions); and

MOS = margin of safety.

It is assumed that all impervious land area within the James City County (VAR040037) and City of Williamsburg (VAR040027) MS4 boundaries, including the institutional MS4s (Eastern State Hospital – VAR040076 and College of

William and Mary – VAR040039, respectively), transport runoff through storm sewer systems which discharge into the creeks. The *E. coli* and enterococci loads from the impervious land areas within the limits of the MS4 permits are included in the waste load allocation (WLA). Since there are currently no permitted domestic or industrial wastewater discharges in the watersheds, one percent (1%) of the final TMDL load allocation (LA) was added to the TMDL WLA to accommodate future growth.

Table ES-9. Annual allocated enterococci loadings (cfu/yr) for the Mill Creek TMDL.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	0.6×10^{12} (1% of LA)	60×10^{12}	–	–
James City County (VAR040037 & VAR040076)	3×10^{12}	0	–	–
City of Williamsburg (VAR040027 & VAR040039)	0.03×10^{12}	0	–	–
Total	**3.63×10^{12}**	**60×10^{12}**	–	**63.63×10^{12}**

*Implicit MOS

Table ES-10. Annual allocated *E. coli* loadings (cfu/yr) for the Powhatan Creek TMDL.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future load	2.4×10^{12} (1% of LA)	236×10^{12}	–	–
James City County (VAR040037 & VAR040076)	15×10^{12}	0	–	–
City of Williamsburg (VAR040027 & VAR040039)	0.4×10^{12}	0	–	–
Total	**17.8×10^{12}**	**236×10^{12}**	–	**253.8×10^{12}**

Table ES-11. Annual allocated enterococci loadings (cfu/yr) for the Powhatan Creek TMDL.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	0.14×10^{12} (1% of LA)	14×10^{12}	–	–
James City County (VAR040037 & VAR040076)	6.9×10^{12}	0	–	–
City of Williamsburg (VAR040027 & VAR040039)	0.2×10^{12}	0	–	–
Total	**7.24×10^{12}**	**14×10^{12}**	–	**21.24×10^{12}**

Transitional Scenario

The implementation of a transitional scenario, or Stage 1 implementation, will allow for an evaluation of the effectiveness of management practices and accuracy of model assumptions through data collection. For Mill Creek, Stage 1 implementation was developed with a target of a 10.5% violation rate of the instantaneous enterococci water quality criterion (104 cfu/100 mL). For Powhatan Creek, the Stage 1 implementation was developed with a target of a 10.5% violation rate of the instantaneous enterococci water quality criterion or of the instantaneous *E. coli* water quality criterion (235 cfu/100 mL), which ever was more limiting. Generally, Stage 1 implementation does not include reductions in wildlife sources, but this was not possible for Mill Creek, where wildlife sources alone violate the enterococci instantaneous water quality criterion more than 10.5% of the time. The Stage 1 implementation scenarios for Mill and Powhatan Creeks are listed in Table E-12.

Table ES-12. Allocation scenario for Stage 1 TMDL implementation for Mill Creek and Powhatan Creek.

Scenario Number	Single Sample Criterion Percent Violation	Required Fecal Coliform Loading Reductions to Meet the Stage 1 Goal (%)			
		Wildlife Direct Deposit	Loads from Agriculture	Marinas and Canal	Loads from Residential Areas
Mill Creek	10	98	90	NA	90
Powhatan Creek[a]	10	0	20	100	20

NA – Not applicable because there were no marinas or boat slips in tidal creek
[a] *E. coli* criterion was more limiting and was used.

Implementation

The goal of the TMDL program is to establish a three-step path that will lead to attainment of water quality standards. The first step in the process is to develop TMDLs that will result in attainment of water quality standards. This report represents the culmination of that effort for the bacteria impairments on Mill and Powhatan Creeks. The second step is to develop a TMDL implementation plan. The final step is to initiate recommendations outlined in the TMDL implementation plan and to monitor stream water quality to determine if water quality standards are being attained. Watershed stakeholders will have opportunities to provide input and to participate in the development of the implementation plan, which will also be supported by regional and local offices of VADEQ, VADCR, and other cooperating agencies.

Public Participation

The first public meeting was September 18, 2007 at the James City - Williamsburg Community Center. The purpose of this meeting was to inform the general public about the TMDL process and to receive further feedback about bacteria sources in Mill Creek and Powhatan Creek. Approximately 10 people attended this meeting, including personnel from VADEQ, VADCR, HRPDC, James City County and Virginia Tech.

The final public meeting was held on March 18, 2008 at James City - Williamsburg Community Center. Final allocation and Stage 1 scenarios were presented at this meeting. The report was available online prior to the meeting and copies of the executive summary were available at the meeting itself. Approximately 20 people attended the public meeting, including people from VADEQ, VADCR, HRPDC, James City County and Virginia Tech.

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Chapter 1: Introduction

1.1. Background

1.1.1. TMDL Definition and Regulatory Information

Section 303(d) of the Federal Clean Water Act and the U.S. Environmental Protection Agency's (USEPA) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to identify water bodies that violate state water quality standards and to develop Total Maximum Daily Loads (TMDLs) for such water bodies. A TMDL reflects the total pollutant loading a water body can receive and still meet water quality standards. A TMDL establishes the allowable daily pollutant loading from both point and nonpoint sources for a water body, allocates the load among the pollutant contributors, and provides a framework for taking actions to restore water quality.

1.1.2. Impairment Listing

Mill Creek (VAT-G10E-03) was initially listed as impaired on Virginia's 2002 303(d) Report on Impaired Waters due to exceedances of Virginia's water quality standard for fecal coliform. In January 2003, Virginia adopted a water quality standard for enterococci bacteria for saltwater and transition zones and the previous fecal coliform bacteria criteria no longer apply. Mill Creek is currently listed as not supporting the Recreation Use on Virginia's 2006 305(b)/303(d) Water Quality Assessment Integrated Report (VADEQ, 2006) due to water quality violations of the enterococci bacteria standard.

Powhatan Creek has two segments that have been identified as impaired and do not support the Recreation Use. Segment VAT-G10E-01, the tidal segment of Powhatan Creek, was listed in Virginia's 1998 303(d) TMDL Priority List and Report because of violations of the fecal coliform water quality standard. The tidal segment of Powhatan Creek is currently listed as impaired on Virginia's 2006 305(b)/303(d) Water Quality Assessment Integrated Report due to violations of the enterococci bacteria standard.

Sufficient exceedances of the fecal coliform bacteria standard in the non-tidal segment (VAT-G10R-02) led to a listing in the 2002 305(b)/303(d) Water Quality Assessment Integrated Report. The non-tidal segment of Powhatan Creek is currently listed as impaired on Virginia's 2006 305(b)/303(d) Water Quality Assessment Integrated Report due to violations of the *E. coli* bacteria standard.

The impaired segments for both Mill and Powhatan Creeks are shown in Figure 1.1. The Virginia Department of Environmental Quality (VADEQ) has described the impaired segments as presented in Table 1.1.

Table 1.1. Impaired Segments Addressed in this TMDL report.

Impaired Segment	Length	TMDL Development Target Date	Description
Powhatan Creek (tidal segment) VAT-G10E-01	0.20 sqr. miles	2008	Segment begins at the estuarine/riverine transition and extends to the confluence with James River.
Powhatan Creek (non-tidal segment VAT-G10R-02	4.85 miles	2008	Segment extends from the confluence with Long Hill Swamp downstream to the estuarine/riverine transition.
Mill Creek VAT-G10E-03	1.2 sqr. miles	2008	Segment begins at end of tidal influence and extends to the confluence with James River.

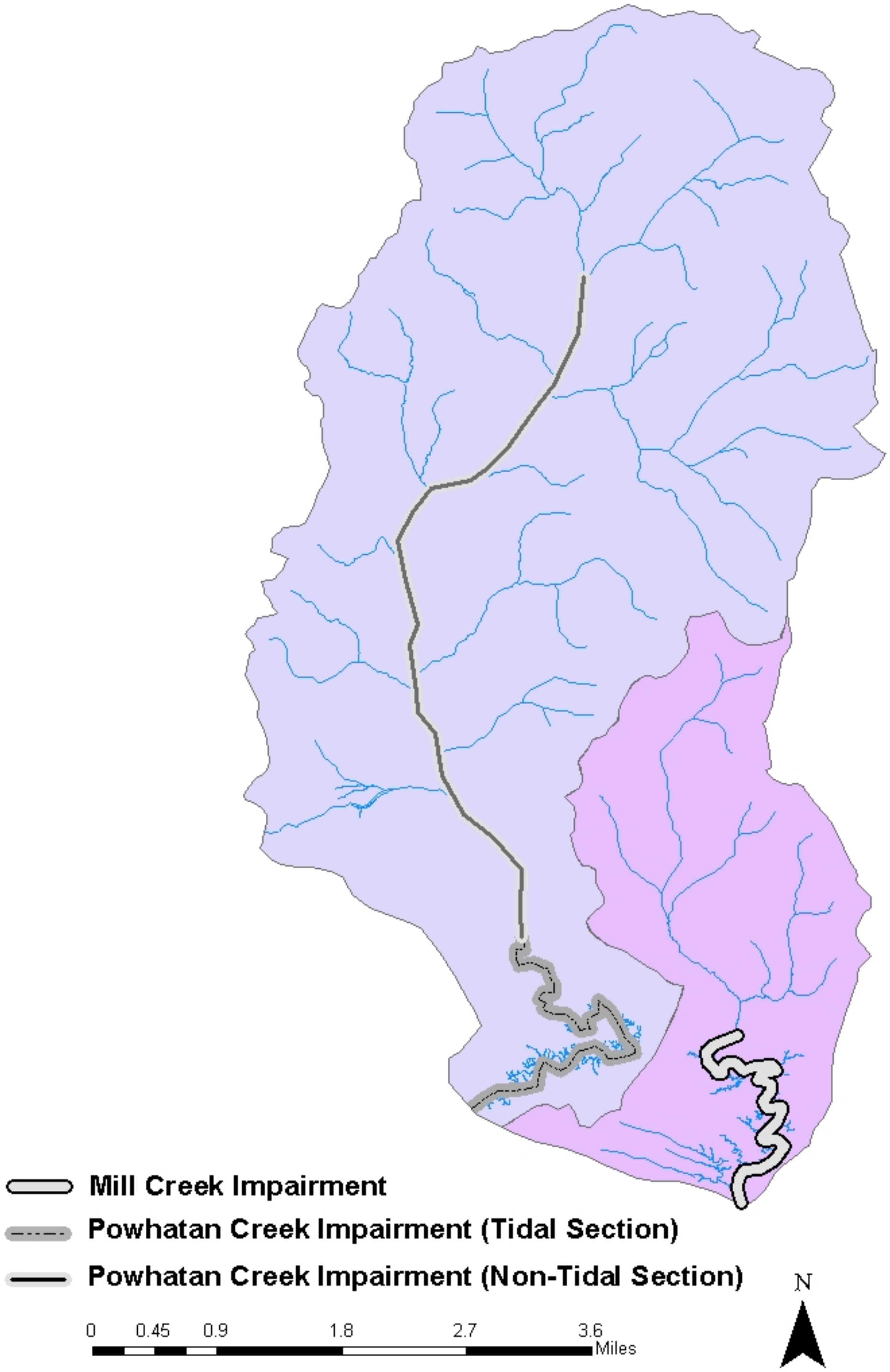

Figure 1.1. Impaired segments in the Mill Creek and Powhatan Creek watersheds.

1.1.3. Watershed Location and Description

Mill Creek and Powhatan Creek are part of the James River basin. The watersheds are mainly within James City County with a small portion in the city of Williamsburg (Figure 1.2).

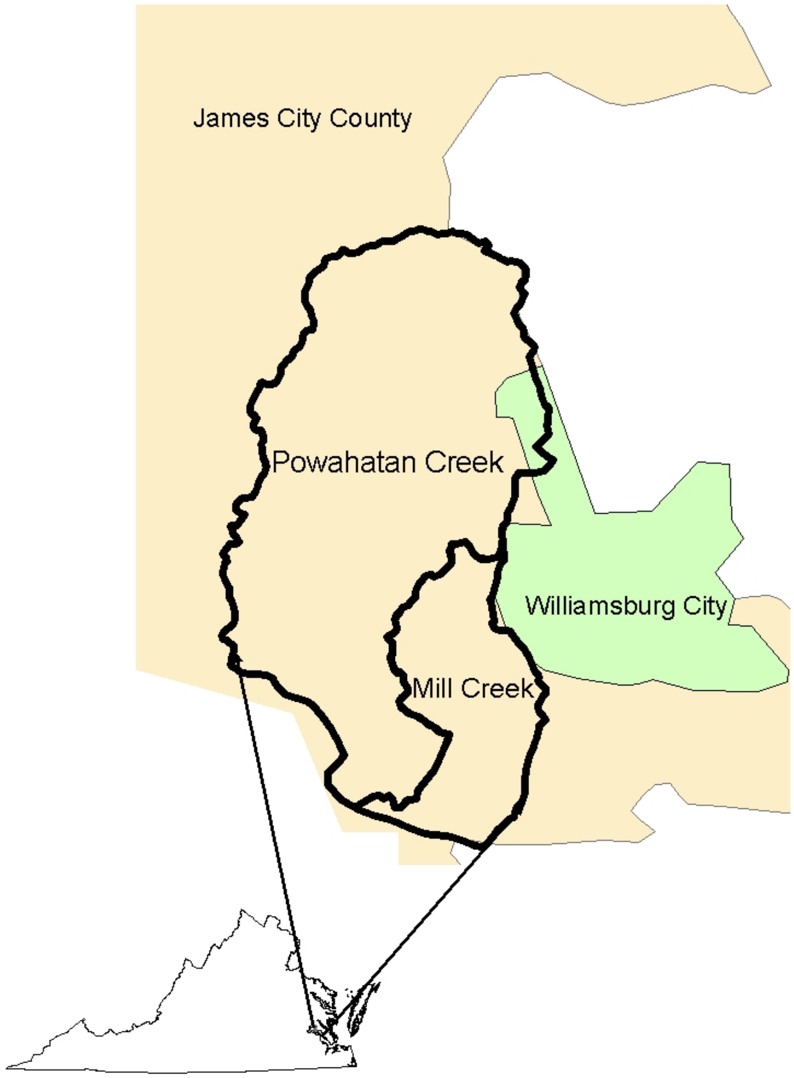

Figure 1.2. Mill Creek and Powhatan Creek watershed locations.

The land use distribution in the Mill Creek and Powhatan Creek watersheds are very similar (Table 1.2) and are mainly composed of forest, but with significant residential areas. Agricultural areas are very small and are composed of cropland with small amounts of pasture. Both Mill Creek and

Powhatan Creek flow into the James River (USGS Hydrologic Unit Code 11010002), which discharges into the Chesapeake Bay at Hampton Roads harbor in southeast Virginia.

Table 1.2. Land use description in TMDL watersheds.

Watershed	Forest	Agriculture	Residential
Mill Creek	53%	2%	45%
Powhatan Creek	51%	1%	48%

1.1.4. Pollutants of Concern

Pollution from both point and nonpoint sources can lead to fecal coliform bacteria contamination of water bodies. Fecal coliform bacteria are found in the intestinal tract of warm-blooded animals; consequently, fecal waste of warm-blooded animals contains fecal coliform. Even though most fecal coliform are not pathogenic, their presence in water indicates contamination by fecal material. Because fecal material may contain pathogenic organisms, water bodies with fecal coliform bacteria are potential sources of pathogenic organisms. For contact recreational activities such as boating and swimming, health risks increase with increasing fecal coliform counts. If the fecal coliform concentration in a water body exceeds state water quality standards, the water body is listed for violation of the state bacteria standard for contact recreational uses. As will be discussed in Section 1.2.2, Virginia has adopted an *Escherichia coli* (*E. coli*) water quality standard for freshwater and an enterococci standard for saltwater and transition zones for surface waters. The concentrations of these organisms (*E. coli* and enterococci) are considered to be better indicators of pathogenic exposure than the concentration of the broader fecal coliform group.

1.2. Designated Uses and Applicable Water Quality Standards

1.2.1. Designation of Uses (9 VAC 25-260-10)

> "A. All State waters, including wetlands, are designated for the following uses: recreational uses, e.g., swimming and boating; the propagation and growth of a balanced, indigenous population of aquatic life, including game fish, which might reasonably be expected to inhabit them; wildlife; and the

production of edible and marketable natural resources, e.g., fish and shellfish." SWCB, 2006.

Mill Creek and Powhatan Creek do not support the recreational (primary contact) designated use due to violations of the bacteria standard.

1.2.2. Applicable Bacteria Water Quality Standards (9 VAC 25-260-170)

The USEPA has recommended that all states adopt an *E. coli* standard for fresh water or an enterococci standard for marine waters as bacteria indicators. In accordance with this recommendation, Virginia adopted and published revised bacteria criteria on June 17, 2002. The revised criteria became effective on January 15, 2003. As of that date, the *E. coli* standard described below applies to all freshwater streams and the enterococci criteria for marine waters in Virginia. Additionally, prior to June 30, 2008, an interim fecal coliform standard must be applied at any sampling station that has fewer than 12 samples of *E. coli* or enterococci.

For a non-shellfish water body to be in compliance with Virginia's revised bacteria water quality standards (as amended September 11, 2007) the following criteria shall apply to protect primary contact recreational uses (9 VAC 25-260-170):

Interim Fecal Coliform Standard:
Fecal coliform bacteria shall not exceed a geometric mean of 200 fecal coliform bacteria per 100 mL of water for two or more samples over a calendar month nor shall more than 10% of the total samples taken during any calendar month exceed 400 fecal coliform bacteria per 100 mL of water.

***Escherichia coli* Standard:**
E. coli bacteria concentrations for freshwater shall not exceed a geometric mean of 126 counts per 100 mL for two or more samples taken during any calendar month and shall not exceed a single sample maximum of 235 cfu/100mL.

Enterococci Standard:
Enterococci bacteria concentrations for salt water and transition zone delineation shall not exceed a geometric mean of 35 counts per 100 mL for two or more samples taken during any calendar

month and shall not exceed a single sample maximum of 104 cfu/100mL.

During any assessment period, if more than 10% of the samples collected at a station exceed the applicable standard, the stream segment associated with that station is classified as impaired and a TMDL must be developed and implemented to bring the station into compliance with the water quality standard. Data collected from a VADEQ monitoring station on the non-tidal portion of Powhatan Creek indicates this station is in violation of the bacteria standard leading to an impairment. No monitoring station is located on the non-tidal section of Mill Creek. VADEQ monitoring stations are located in the tidal portion of both creeks. The data collected at both of these stations are in violation of the bacteria standard, leading to the impairments on the Mill Creek and Powhatan Creek tidal creek segments.

The bacteria TMDLs for the impaired tidal segments will be developed to meet the enterococci standard. The bacteria TMDL for the non-tidal segment of Powhatan Creek will be developed to meet the *E. coli* standard. As directed by the Virginia Department of Environmental Quality (VADEQ), the modeling will be conducted with fecal coliform inputs, and then a translator equation will be used to convert the output to *E. coli* and enterococci concentrations (VADEQ, 2003).

Chapter 2: Watershed Characterization

2.1. Sub-watershed Delineation

To account for the spatial distribution of fecal coliform sources, both the Mill Creek and Powhatan Creek watersheds were subdivided. Mill Creek was sub-divided into 9 sub-watersheds and Powhatan Creek into 17 sub-watersheds. The boundaries of the sub-watersheds are shown in Figure 2.1. Sub-watersheds were delineated based on a number of factors: continuity of the stream network, similarity of land use distribution, and monitoring station locations. The stream network used to help define the sub-watersheds was obtained from the National Hydrography Dataset (USGS and USEPA, 1999). It is preferable to have a sub-watershed outlet at or near monitoring station locations in order to calibrate the model chosen for this study; the three VADEQ monitoring stations used for modeling are shown in Figure 2.1.

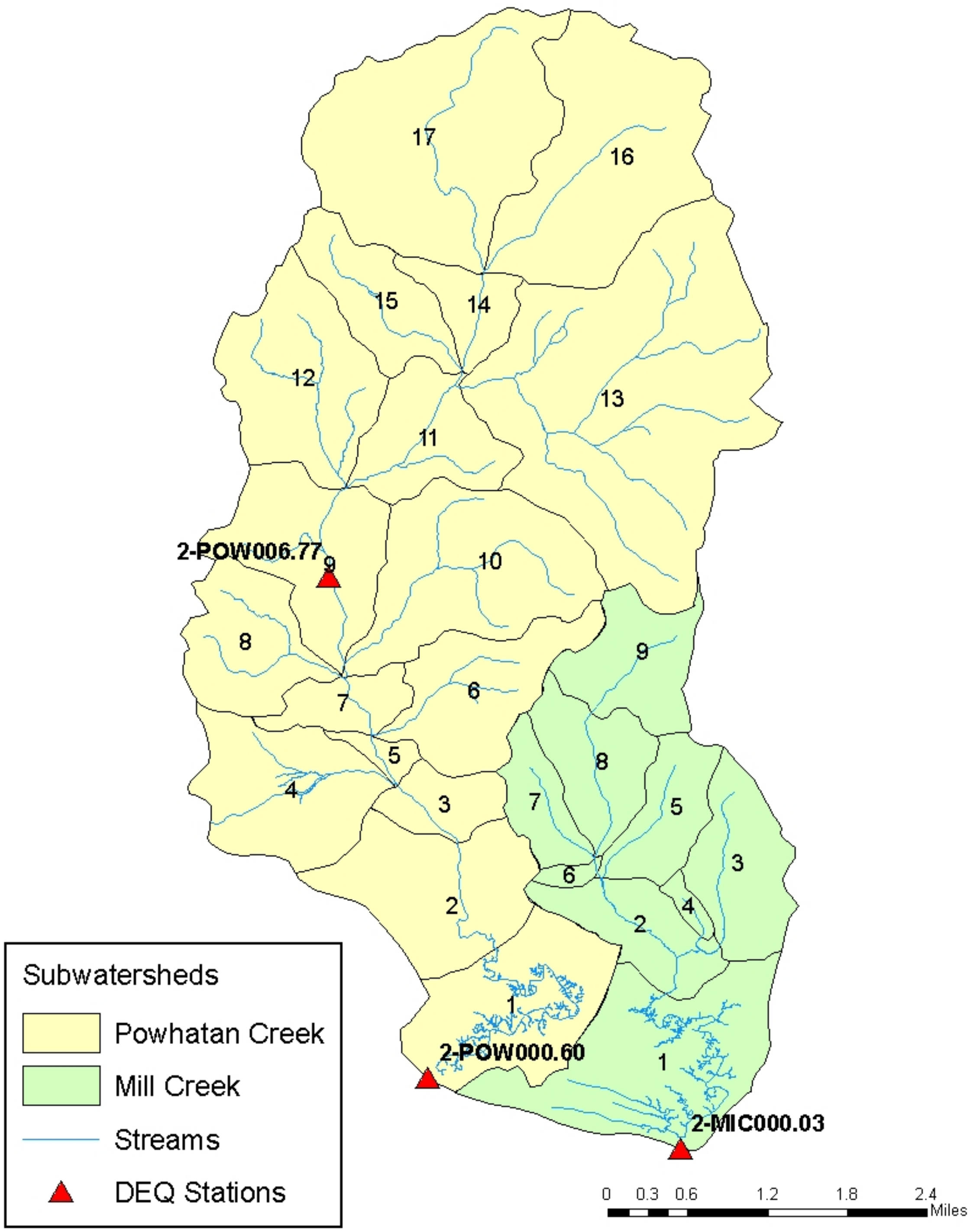

Figure 2.1. Sub-watersheds for Mill Creek and Powhatan Creek watersheds.

A Watershed Plan was previously developed for Powhatan Creek (Center for Watershed Protection, 2001). This Plan was developed prior to the Powhatan

TMDL study. The plan was developed in response to concerns about the health of the watershed in terms of water quality and natural habitats threatened by rapid development. The goals of the study were to prevent further degradation of the water quality of Powhatan Creek, maintain the quality of the creek's wetlands, maintain biological and habitat diversity, and promote habitat connectivity. The sub-watershed boundaries of the Powhatan Watershed Plan were compared to the boundaries for the TMDL (Figure 2.2). The Powhatan TMDL study sub-watersheds were delineated to match, to the extent possible, those created for the Powhatan Watershed Plan. This was done to ensure that information developed as a part of the Powhatan TMDL could also be used for implementation of the Powhatan Watershed Plan. The Powhatan Watershed Plan and Powhatan TMDL sub-watershed boundaries are very similar (Figure 2.2). However, additional sub-watersheds were delineated for the TMDL because of modeling requirements. Differences in the watershed boundaries are also due to different resolutions of the elevation data used to delineate the boundaries (Center for Watershed Protection, 2001). Higher resolution data used for the Watershed Plan was not used for the TMDL because stream network data was not available at the higher resolution.

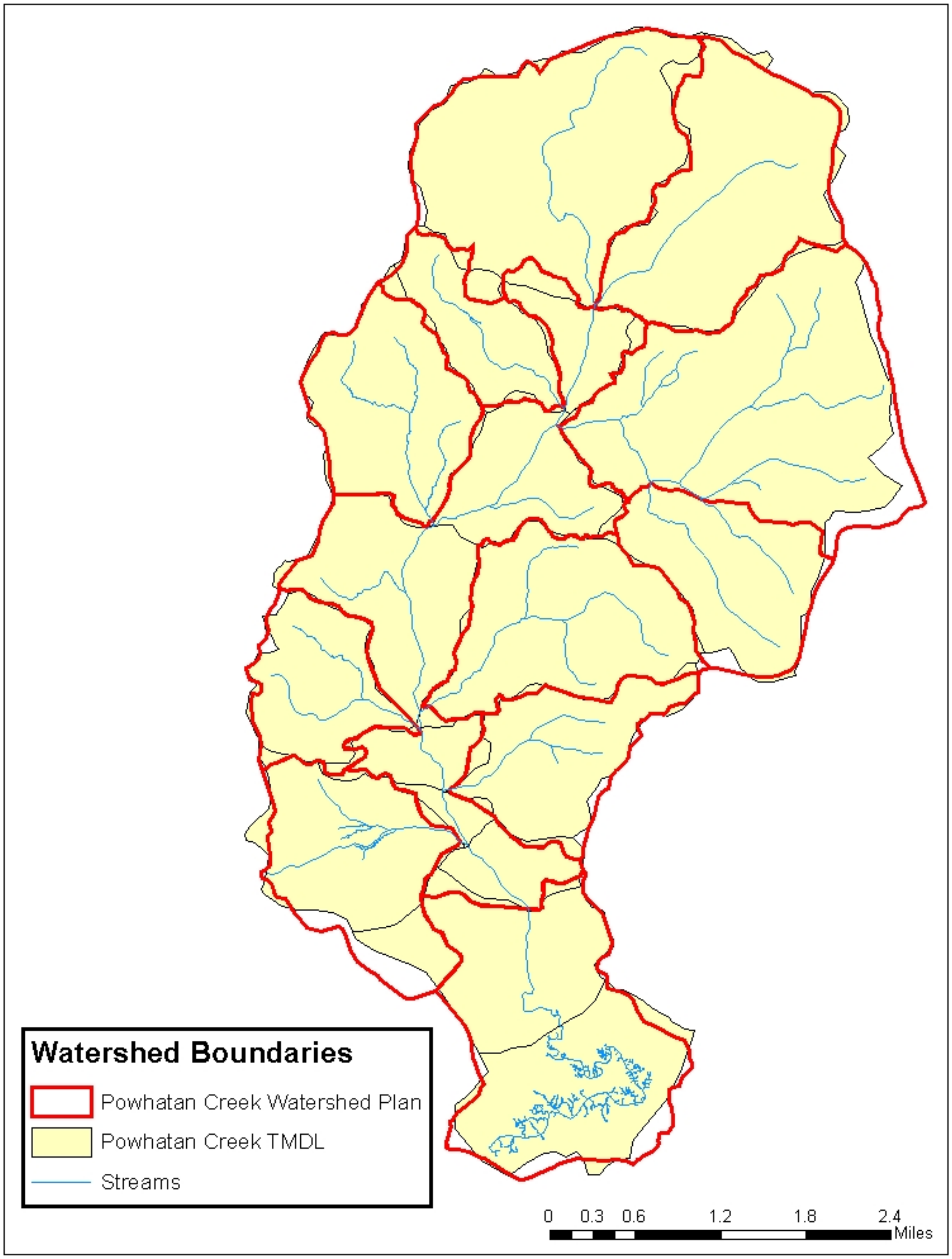

Figure 2.2. Comparison of sub-watershed boundaries for Powhatan Creek Watershed Plan and for the TMDL.

2.2. Ecoregion

The vast majority of the Mill and Powhatan watersheds is located in the Chesapeake Rolling Coastal Plain level IV ecoregion which is a subset of the Southeastern Plains ecoregion (Figure 2.3). The Chesapeake Rolling Coastal Plain ecoregion is composed of "hilly upland with narrow stream divides, incised streams, and well-drained loamy soils" (Woods et al., 1999). Natural vegetation is "mostly Oak-Hickory-Pine Forest (dominants: hickory, longleaf pine, shortleaf pine, loblolly pine, white oak and post oak)" (Woods et al., 1999). Currently, "urbanization and residential development are extensive" and "less intensive agriculture, general farming, or part time agriculture occurs; the landuse mosaic is distinct from the more forested rolling, Inner Coastal Plain" (Woods et al., 1999).

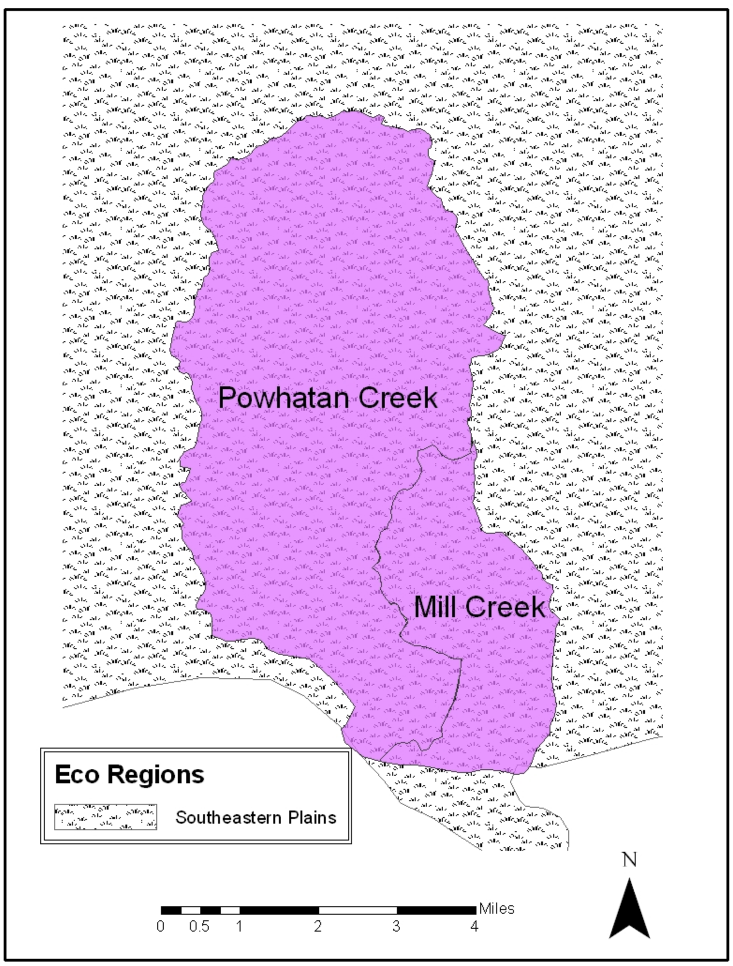

Figure 2.3. Mill Creek and Powhatan Creek watershed Eco Regions

2.3. Soils and Geology

The Mill Creek and Powhatan Creek watersheds lie entirely in the North Atlantic Coastal Plain. This physiographic section is characterized by "sedimentary deposits that range in age from Early Cretaceous to Holocene" (USGS, 1997). There are three predominant State Soil Geographic (STATSGO) soil groups found in the Mill Creek and Powhatan Creek watersheds (Figure 2.4). Hydrologic soil groups describe soil texture in terms of potential for surface runoff and infiltration rates (Table 2.1). For example, soils in hydrologic group "A" pass a larger proportion of rainfall through to groundwater than soils in hydrologic group "B." Conversely, soils in hydrologic group "D" inhibit infiltration such that a large proportion of rainfall contributes to surface runoff and therefore a more direct path to stream channels. The fraction of rainfall that either runs off or infiltrates will impact the bacteria loads transported to streams during storm events. Table 2.2 Table 2.2 is a summary of STATSGO soil characteristics in the Mill and Powhatan watersheds. Minimum and maximum slopes are taken directly from fields within the STATSGO database; mean slope is the calculated average of minimum and maximum slopes. The most prevalent soil series in both watersheds is the Suffolk-Rumford-Emporia. The dominant textures are silt-clay to loam. Hydrologic group B is most prevalent within the watersheds followed by group C, then D.

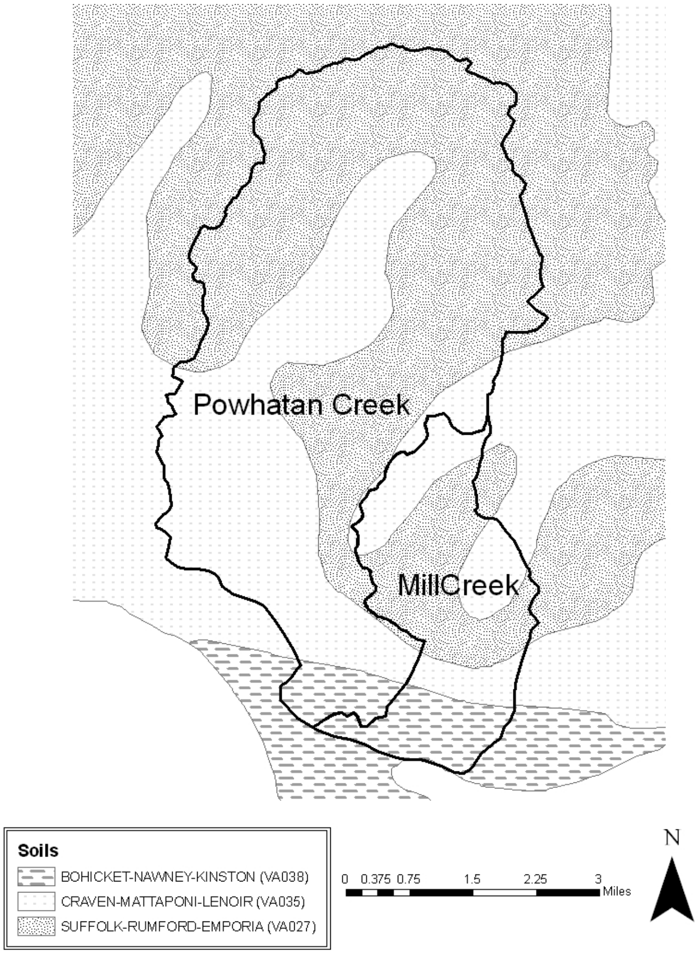

Figure 2.4. STATSGO soil groups in the Mill and Powhatan watersheds.

Table 2.1. Soil Hydrologic Groups

Hydrologic Group	Description
A	Low runoff potential, high infiltration rates. Soils are deep, well drained to excessively drained sand, loamy sand or sandy loam, and gravels.
B	Moderate infiltration rates. Deep to moderately deep, moderately well and well-drained silt or silt loam soils (moderately coarse textures).
C	Moderate to Slow infiltration rates. Sandy clay loam soils (soils with moderately fine or fine textures) or soils with layers impeding downward movement of water.
D	High runoff potential, very slow infiltration rates. Soils are clayey (sandy clay to silty clay loam), have high water table, or are shallow over an impervious cover.

Table 2.2. Summary of STATSGO data for Mill Creek and Powhatan Creek watersheds.

Soil Name	% of Watershed	Texture	Hydrologic Group	%Slope, Range	%Slope, Mean
BOHICKET-NAWNEY-KINSTON	21%[1], 3%[2]	Silt to Silt-Clay	D	0 – 2	1
CRAVEN-MATTAPONI-LENOIR	37%[1], 39%[2]	Loam	C	0 – 10	3
SUFFOLK-RUMFORD-EMPORIA	42%[1], 58%[2]	Silt-Loam	B	0 – 50	12

[1]Mill Creek, [2]Powhatan Creek

2.4. Climate

Meteorological data were obtained from National Climatic Data Center (NCDC) weather stations. Data used in this TMDL study came primarily from the National Weather Service COOP station at Williamsburg 2N (COOP ID 449151) in Williamsburg, Virginia. Williamsburg 2N is located approximately 2 miles northeast of the watershed outlet. Data from the Wakefield 1NW and Painter 2W were used to address missing data not available from the Williamsburg 2N station. A 17-year period of record (1990 - 2007) at the Williamsburg 2N station shows an average annual precipitation of 49 inches, with 55% of the precipitation occurring May - October. Average annual daily temperature is 59°F, with a highest average daily temperature of 86°F occurring in August, and a lowest average daily temperature of 31°F occurring in January.

2.5. Land Use

Using data from the Mid-Atlantic Regional Earth Science Application Center (RESAC) (RESAC, 2000), land uses were grouped into four major categories based on similarities in hydrologic features and bacteria source characteristics (Table 2.3). Land uses for the Mill Creek and Powhatan Creek watersheds are presented graphically in Figure 2.5. Tabulated land uses for the watersheds are listed in Table 2.4

The percentage of pervious and impervious area within each of the four land use categories is needed for watershed modeling purposes and was determined using values available in the literature that are valid for this region.

The percent impervious for landuse categories Low Density Residential (LDR) and High Density Residential (HDR) (Table 2.3) were based on information for the Chesapeake Bay watershed in the Costal Virginia region; LDR = 21% and HDR = 48% (Cappiella and Brown, 2001). Impervious percentages of 25% for LDR and 75% for HDR were used in this study to provide a more conservative representation.

Table 2.3. RESAC aggregation.

TMDL Land Use Categories	Pervious/Impervious (Percentage)	RESAC Land Use Categories (Class No.)
Cropland	Pervious (100%)	Row Crops (82)
Low Density Residential (LDR)	Pervious (75%) Impervious (25%)	Low Intensity Residential (21) Transitional (33) Urban/Recreational Grasses (85)
High Density Residential (HDR)	Pervious (25%) Impervious (75%)	High Intensity Residential (22) Commercial/Industrial/Transport (23) Quarries/strip mines/gravel pits (32)
Forest	Pervious (100%)	Open Water (11) Deciduous Forest (41) Evergreen Forest (42) Mixed Forest (43) Woody Wetlands (91) Emergent Herbaceous Wetlands (92)

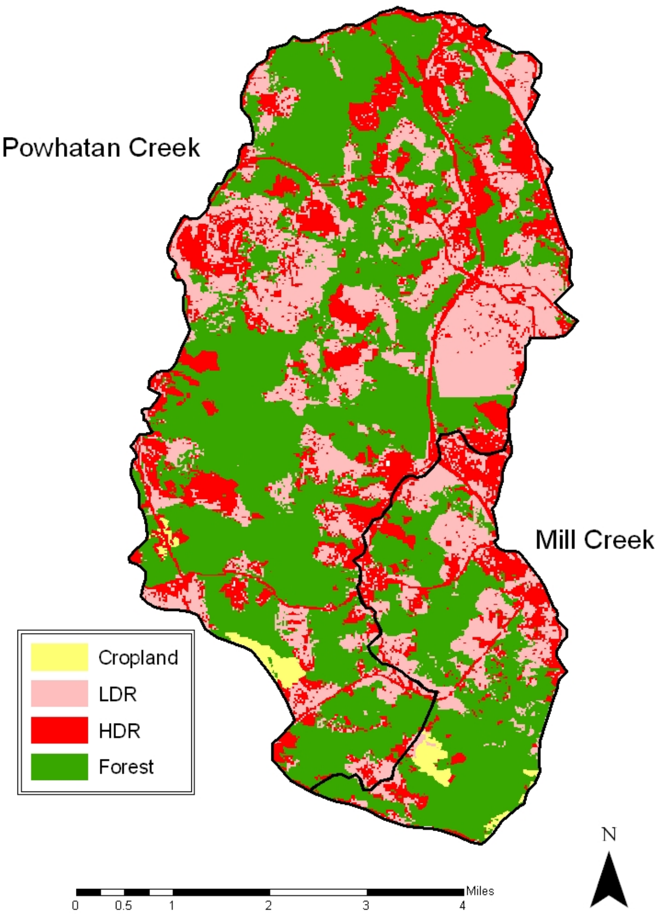

Figure 2.5. Land use in Mill Creek and Powhatan Creek watersheds.

Table 2.4. Land use distribution in Mill Creek and Powhatan Creek watersheds.

	Mill Creek		**Powhatan Creek**	
Landuse	**Area (ac.)**	**% of Watershed**	**Area (ac.)**	**% of Watershed**
Cropland	83	2	111	1
Pasture	10	<1	5	<1
LDR†	962	25	3,748	27
HDR*	742	20	2,986	21
Forest	1,988	53	7,160	51

†Low Density Residential
*High Density Residential

2.6. Water Quality Data

VADEQ monitors water quality at one station in Mill Creek and two stations in Powhatan Creek (Table 2.5). The locations of the monitoring stations used in the TMDL are shown in Figure 2.1. Details for fecal coliform data collected at each station are given in Table 2.6. Sufficiently long periods of record are available at each station for use in assessing characteristics of the pollutant loads, such as seasonality, and for calibration of the model.

Table 2.5. VADEQ monitoring stations on Mill and Powhatan Creeks.

Station ID	Station Description	Stream Name	County
2-MIC000.03 (tidal)	Colonial Parkway Bridge	Mill Creek	James City
2-POW000.60 (tidal)	Colonial Parkway Bridge	Powhatan Creek	James City
2-POW006.77 (non-tidal)	State Route 613 Bridge	Powhatan Creek	James City

Table 2.6. Details of fecal coliform data collected at monitoring stations in Mill and Powhatan Creeks.

	Sample Date†		No. of Samples	Sample Value (cfu/100 mL)			Exceedances of Single Sample Standard	
Station ID	First	Last		Min	Max	Avg	No.	%
2-MIC000.03	7/14/92	1/5/06	134	2	2400*	373	32	24
2-POW000.60	11/5/92	1/5/06	131	8	1600*	359	31	24
2-POW006.77	11/16/95	5/12/05	88	25	3200*	252	13	15

*Capped value
†As of January 2007

The bacteria source characterization of the Mill Creek and Powhatan Creek watersheds (Chapter 3) show a potential for bacteria contributions from agriculture, wildlife, and urban sources. The exceedance rates for the stations causing the impairment listings for these watersheds are given in Table 2.7. As a consequence of these exceedances, Mill Creek and Powhatan Creek were assessed as not supporting the Primary Contact Recreational Use Goal for the 2006 305(b) report and were included on the 2006 303(d) list (VADEQ, 2006). Bacteria concentrations from these monitoring stations used for model calibration are shown in Figure 2.6, Figure 2.7 and Figure 2.8, respectively, along with the 2006 assessment period and interim fecal coliform standard.

Table 2.7. Bacteria standard exceedances during the 2006 assessment period (2000-2004).

Station ID	Exceedances of Interim Fecal Coliform Standard
2-MIC000.03	11 of 38 (29%)
2-POW000.60	9 of 38 (24%)
2-POW006.77	4 of 38 (11%)

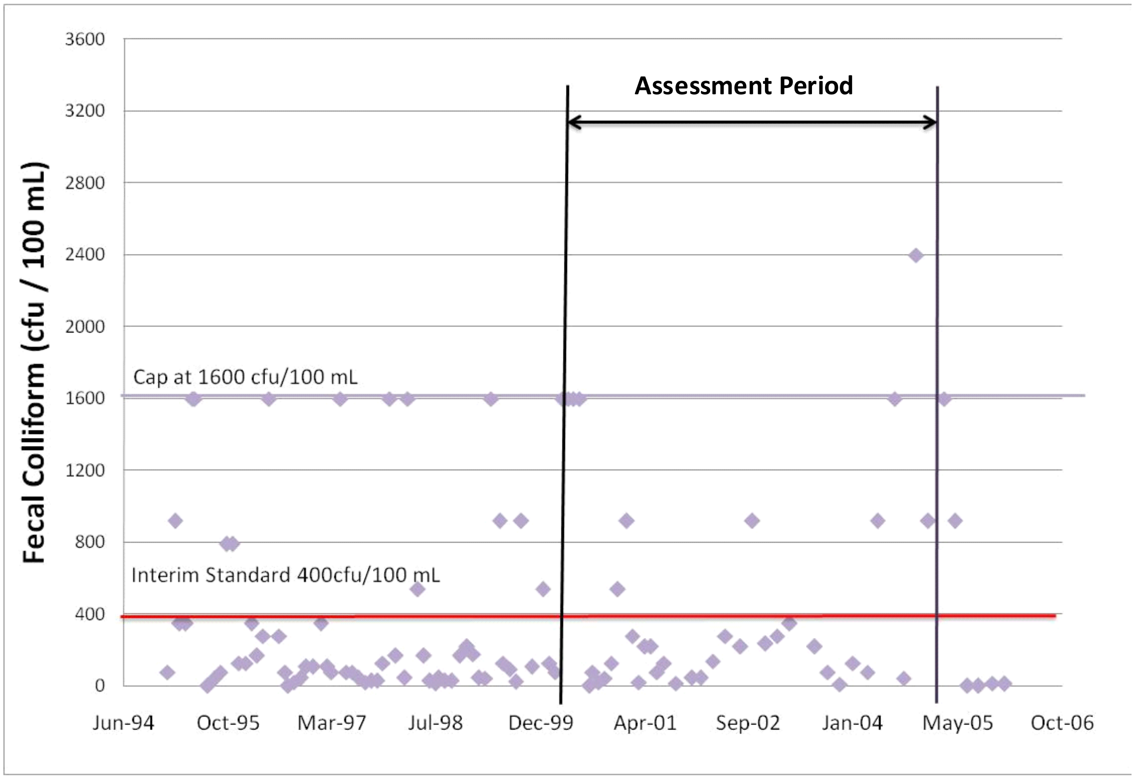

Figure 2.6. Bacteria data for Mill Creek Station 2-MIC000.03.

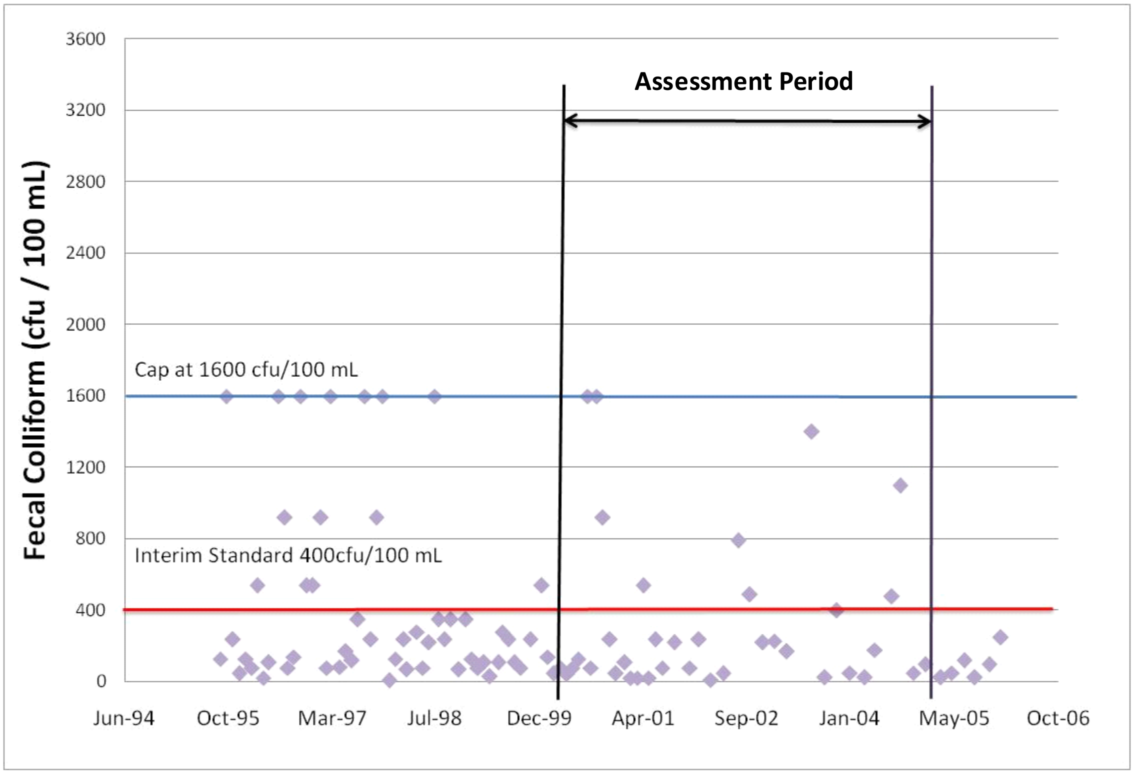

Figure 2.7. Bacteria data for Powhatan Creek Station 2-POW000.60.

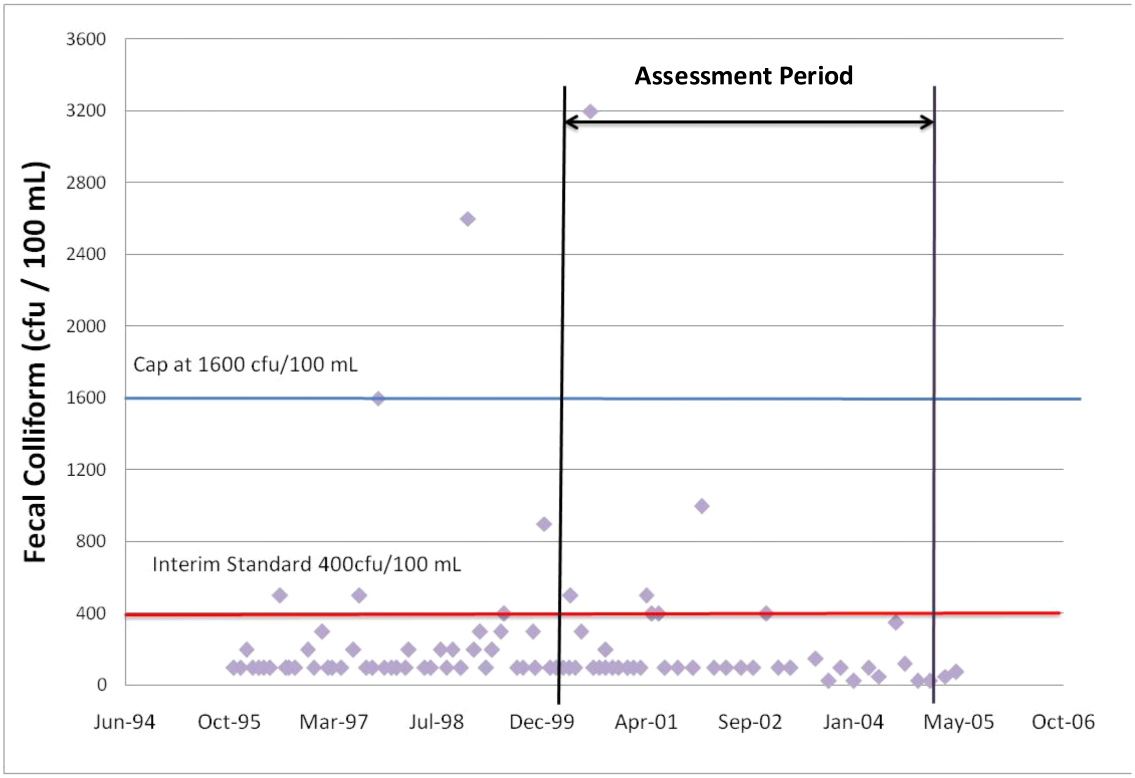

Figure 2.8. Bacteria data for Powhatan Creek Station 2-POW006.77.

Seasonality of fecal coliform concentrations in the streams was evaluated by plotting the mean monthly fecal coliform concentrations observed at the listing stations (Figure 2.9). Mean monthly fecal coliform concentration was calculated as the mean of all values in any given month for the period of record. A seasonal trend is apparent for both Mill Creek and Powhatan Creek with lower concentrations occurring during the winter and spring and higher concentrations in the summer and fall (Figure 2.9).

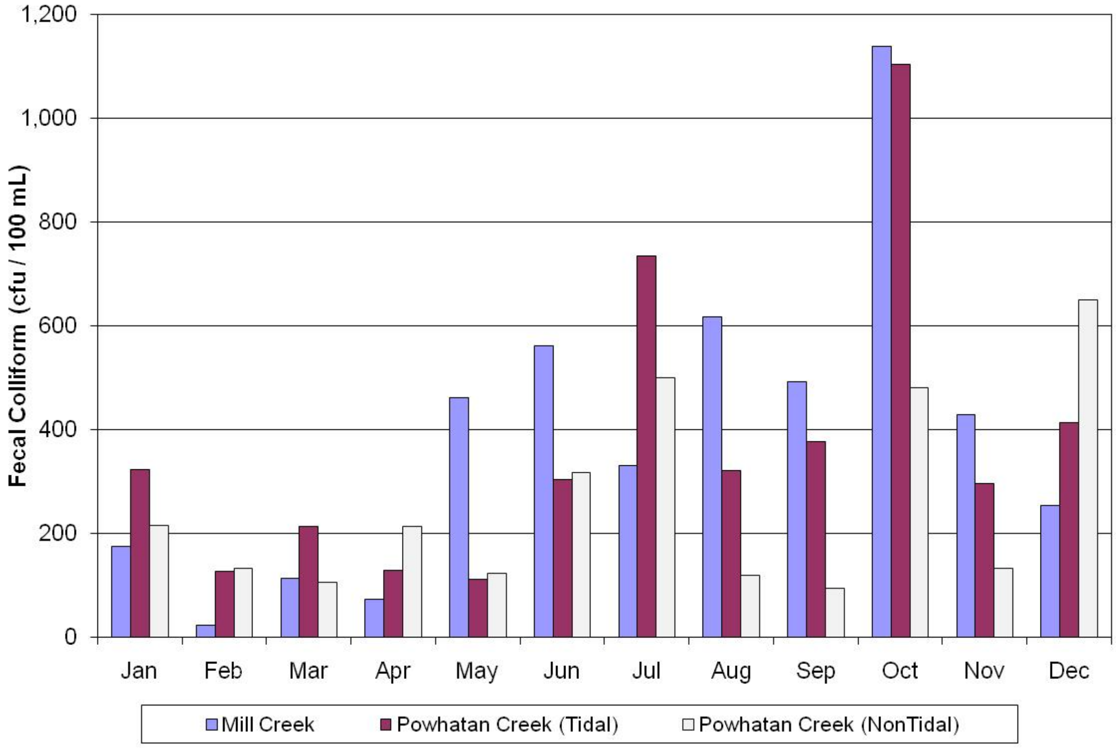

Figure 2.9. Average fecal coliform concentrations by month.

2.6.1. Bacterial Source Tracking

As part of the TMDL study, Bacterial Source Tracking (BST) data were collected at the tidal stations listed in Table 2.5 during 2006. BST is intended to assist in identifying fecal contamination sources (humans, pets, livestock, wildlife) The Antibiotic Resistance Analysis (ARA) method was used to analyze these samples (Harwood et al., 2003; Stoeckel, et al., 2004; Hagedorn, 2006). This method is also lower in cost and faster than many of the other available methods. The ARA method is classified as a biochemical or phenotype analysis. It relies on the response of the fecal bacteria to various antibiotics. VADEQ adopted this methodology because it has demonstrated to be a reliable procedure for confirming the presence or absence of various classifications of fecal coliform sources in the watersheds of Virginia. The results of the BST analyses are presented at the end of Chapter 4, where they are compared with modeled results.

Chapter 3: Fecal Coliform Source Characterization

Fecal coliform sources in the Mill and Powhatan Creek watersheds were characterized using data and anecdotal information from the following: VADEQ, Virginia Department of Conservation and Recreation (VADCR), Virginia Department of Game and Inland Fisheries (VADGIF), Virginia Department of Agricultural and Consumer Services (VDACS), Virginia Department of Health (VADOH), public participation, watershed reconnaissance and monitoring, published information, and professional judgment. Point sources and nonpoint sources of fecal coliform are summarized in Table 3.1 and Table 3.2 and described in detail in the following sections. In an effort to adequately represent the historic condition of the watershed, changes to some fecal coliform source populations were made for existing conditions and future conditions. If a particular population was affected by the different time periods, it is noted in the text in the appropriate section.

There were four point sources permitted to discharge fecal coliform bacteria in the Mill and Powhatan Creek watersheds. These permitted discharges were for the Multiple Separate Storm Sewer System (MS4) permits for James City County, the City of Williamsburg, Eastern State Hospital, and the College of William and Mary. For this study, the load generated from the College of William and Mary MS4 was aggregated with Williamsburg; Eastern State Hospital MS4 was aggregated with James City County. Though the MS4 conveys runoff from precipitation events, it is considered a point source. This permit allows for the collection and discharge of urban stormwater runoff into a surface waterbody. Methods to reduce the pollutant load from the MS4s will be considered in the individual permits.

Table 3.1. Potential fecal coliform sources and daily fecal coliform production by source for existing conditions in the Mill Creek watershed.

Fecal Coliform Sources	Population in Mill Creek	Fecal coliform produced (x 10^6 cfu/head/day)
Humans	22684	2000[a]
Beef	25[b]	10000[c]
Pets	2925	450[d]
Deer	178	380
Raccoons	131	5
Wild Turkeys	23	9.3
Muskrats	171	2.5[e]
Beavers	63	0.20
Ducks[f]	269	2400
Geese[f]	324	800
Seagulls[g]	74	2388

[a] Source: Geldreich (1978)
[b] Includes calves
[c] Source: Weiskel *et al*. (1996)
[d] Source: ASAE(1998)
[e] Source: Yagow (2001)
[f] Population given as winter; summer population
[g] Maptech (2005)

Table 3.2. Potential fecal coliform sources and daily fecal coliform production by source for existing conditions in the Powhatan Creek watershed.

Fecal Coliform Sources	Population in Powhatan Creek	Fecal coliform produced (x 10^6 cfu/head/day)
Humans	35449	2000[a]
Beef	10[b]	10000[c]
Pets	14598	450[d]
Deer	659	380
Raccoons	1085	5
Wild Turkeys	88	9.3
Muskrats	451	2.5[e]
Beavers	169	0.20
Ducks[f]	794	2400
Geese[f]	964	800
Seagulls[g]	219	2388

[a] Source: Geldreich (1978)
[b] Includes calves
[c] Source: Weiskel *et al*. (1996)
[d] Source: ASAE(1998)
[e] Source: Yagow (2001)
[f] Population given as winter; summer population
[g] Maptech (2005)

3.1. Humans and Pets

The Mill Creek watershed has an estimated population of 22,684 (8,796 households at an average of 2.58 people per household, actual people per household varies by sub-watershed). The Powhatan Creek watershed has an estimated population of 35,449 people (14,598 households with at an average of 2.43 people per household, actual people per household varies by sub-watershed). The number of people per household for both watersheds was determined from the 2000 Census of Population and Housing for Virginia (Census Bureau. 2000). Fecal coliform from humans can be transported to streams from failing septic systems, via straight pipes discharging directly into streams, sewage spills, or through leaky sewer lines. Although leaky sewer lines are not explicitly accounted for in modeling for this TMDL, they are considered to be part of the residential load, and should be addressed, where found, during implementation. Professional judgment was used to specify one pet per household for both Mill and Powhatan Creek watersheds. There were six permitted discharges in the Mill Creek watershed (Table 3.3) and ten in the Powhatan Creek watershed (Table 3.4). Only four were permitted to discharge fecal coliform and will be assigned a Waste Load Allocation (WLA) in the TMDL.

Table 3.3. Permitted facilities discharging into streams of the Mill Creek watershed.

Permit Number	Facility Name	Sub-water-shed	Permit Type	WLA*	Activity Status
VAR100304	VDOT Williamsburg	9	Stormwater Construction	No	Expired 6/04
VAR101221	Ironbound Village	7	Stormwater Construction	No	Expired 6/04
VAR040039	College of William and Mary	Multiple	MS4	Yes†	Current
VAR040076	Eastern State Hospital	Multiple	MS4	Yes†	Current
VAR040037	James City County	Multiple	MS4	Yes	Current
VAR040027	Williamsburg	Multiple	MS4	Yes	Current

*WLA – Waster load allocation for bacteria in the TMDL
†Loads generated from these MS4s were aggregated with the larger MS4 area surrounding them; College of William and Mary MS4 was aggregated with Williamsburg; Eastern State Hospital MS4 was aggregated with James City County.

Table 3.4. Permitted facilities discharging into streams of the Powhatan Creek watershed.

Permit Number	Facility Name	Sub-water-shed	Permit Type	WLA*	Activity Status
VAG253005[a]	Eastern State Hospital	13	Cooling	No	3/98-3/03
VAG250002[b]	Eastern State Hospital	13	Cooling	No	3/03-3/13
VAR100462	US - AFETA Camp Peary	16	Stormwater Construction	NA	Expired 6/04
VAR101201	Scotts Pond Subdivision	16	Stormwater Construction	NA	Expired 6/04
VAR100311	Waterford at Powhatan Secondary	6	Stormwater Construction	NA	Expired 6/04
VAR100511	Powhatan Townhomes	6	Stormwater Construction	NA	Expired 6/04
VAR040039	College of William and Mary	Multiple	MS4	Yes[†]	Current
VAR040076	Eastern State Hospital	Multiple	MS4	Yes[†]	Current
VAR040037	James City County	Multiple	MS4	Yes	Current
VAR040027	Williamsburg	Multiple	MS4	Yes	Current

*WLA – Waste load allocation for bacteria in the TMDL
[a] Design Discharge = 0.0001 million gallons per day
[b] Design Discharge = 0.002 million gallons per day
[†]Loads generated from these MS4s were aggregated with the larger MS4 area surrounding them; College of William and Mary MS4 was aggregated with Williamsburg; Eastern State Hospital MS4 was aggregated with James City County.

3.1.1. Failing Septic Systems

When septic systems fail, effluent can rise to the soil surface. Surface runoff can transport the effluent, containing fecal coliform, to receiving waters. In order to estimate the number of failing septic systems, it was necessary to determine both the number and age of houses in the watersheds. It was estimated that 43 and 59 homes were on septic systems in Mill and Powhatan Creek, respectively, based on pumpout records provided by James City County (Darryl Cook, personal communication, 27 September, 2007). The remaining homes in both watersheds were connected to the sewer system. These records were then geo-coded to determine the spatial location of each septic system. Next, the age of the homes using a septic system was estimated using 2000 Census data with the assumption that the newest homes were connected to the sewer system. For homes not connected to the sewer system, 40% of old homes (built before 1967), 20% of middle-aged homes (built between 1967 and 1987), and 3% of new homes (built after 1987) were assumed to have failing septic systems (R.B. Reneau, personal communication, 3 December 1999, Blacksburg, Va.). These failure rate estimates are similar to those used in the Holmans Creek Watershed Study (a watershed located in Rockingham County), which found that over 30% of all septic systems checked in the watershed were either failing or not functioning at all (SAIC, 2001).

Daily total fecal coliform load to the land surface from a failing septic system in a particular sub-watershed was determined by multiplying the average occupancy rate for that sub-watershed by the per capita fecal coliform production rate of 2.0×10^9 cfu/day (Geldreich, 1978). Hence, the total fecal coliform loading to the land from a single failing septic system in a sub-watershed with an occupancy rate of one person/household would be 2.0×10^9 cfu/day. The number of failing septic systems in the watersheds is given in Table 3.5 for Mill Creek and Table 3.6 for Powhatan Creek.

3.1.2. Straight Pipes

Older houses without septic systems and located near a stream may have a straight-pipe. Bacteria discharged from straight pipes enter the stream directly, without treatment or die-off. The number of straight-pipes was estimated from Census data. The number of houses lacking basic plumbing facilities (Census Bureau. 2000) was estimated for each watershed. These houses were considered to potentially have straight-pipes. For both watersheds, the number of straight pipes was not greater than 0.0001. Even if we considered that there was the potential for a straight-pipe because the number was not zero, it would be a 1/10000 chance there was one. Therefore, it was assumed that there were no straight-pipes in either watershed.

Table 3.5. Estimated Household and Pet Population Breakdown by Sub-watershed for Mill Creek.

Sub-watershed	Sewered Houses	People per House (un-sewered)	Unsewered houses in each age category: Straight Pipes	Old	Mid-age	New	Failing Septic Systems	Pet Population
1	1,057	2.55	0	2	9	0	3	1,068
2	1,011	2.55	0	5	6	0	3	1,022
3	863	2.38	0	4	4	0	2	871
4	873	NA	0	0	0	0	0	873
5	943	3.00	0	0	1	0	0	944
6	1,091	NA	0	0	0	0	0	1,091
7	1,048	NA	0	0	0	0	0	1,048
8	932	2.50	0	3	5	0	2	940
9	935	2.50	0	1	3	0	1	939
Total	8,753	2.58*	0	15	28	0	11	8,796

NA – Not Applicable
* Average

Table 3.6. Estimated Household and Pet Population Breakdown by Sub-watershed for Powhatan Creek.

Sub-watershed	Sewered Houses	People per House (un-sewered)	Unsewered houses in each age category: Straight Pipes	Old	Mid-age	New	Failing Septic Systems	Pet Population
1	1,191	2.61	0	5	13	0	5	1,209
2	1,212	2.50	0	0	2	0	0	1,214
3	742	NA	0	0	0	0	0	742
4	1,130	NA	0	0	0	0	0	1,130
5	740	NA	0	0	0	0	0	740
6	742	2.33	0	1	2	0	1	745
7	740	NA	0	0	0	0	0	740
8	796	NA	0	0	0	0	0	796
9	829	2.50	0	0	2	0	0	831
10	743	2.18	0	5	17	0	5	765
11	822	NA	0	0	0	0	0	822
12	895	NA	0	0	0	0	0	895
13	512	2.40	0	25	38	0	18	575
14	702	2.33	0	0	3	0	1	705
15	881	2.20	0	1	4	0	1	886
16	826	2.54	0	5	21	0	6	852
17	936	2.60	0	4	11	0	4	951
Total	14,439	2.42	0	46	113	0	41	14,598

NA – Not Applicable
* Average

3.1.3. Sewage Spills

Sewage spills can occur at many places along the collection system. Leaks in lines or overflows at pumping stations are two examples. There were several sewage spills in both Mill and Powhatan Creek watersheds over the past two years, Table 3.7 (Sanitary Sewer Overflow Reporting System-SSORS, HRPDC 2004). Addresses were provided with the spills and geo-coding was used to locate each spill in a sub-watershed. The spills will be modeled as unique events occurring on the report date.

Table 3.7. Sewage Spill Incidents in Mill and Powhatan Creeks.

DEQ IR	Watershed	Sub-Watershed	Report Date	Quantity (Gallons)	Where (ground/water body)
2006-T-10057	Mill	2	4/18/2006	800	Ground
2005-T-10014	Powhatan	13	1/18/2005	200	Small Drainage Ditch
2005-T-10024	Powhatan	13	4/14/2005	500	Chisel Run
2007-T-10072	Powhatan	13	8/24/2006	999	Chisel Run
2007-T-10091	Powhatan	4	10/6/2006	70	Ground
2008-T-10124	Powhatan	4	8/19/2007	755	Powhatan Creek

3.2. Cattle

Fecal coliform in cattle manure can be directly excreted to the stream, or it can be transported to the stream via surface runoff from animal waste deposited on pastures or applied to crops or pasture. For the TMDL study, future conditions were assumed to be the same as the existing.

3.2.1. Distribution of Beef Cattle

There are currently no dairy farms in either Mill Creek or Powhatan Creek watersheds; however, there are beef farms. The existence and locations of the beef farms was discussed at the first public meeting.

During the watershed and source characterization process, a fraction of cropland was reclassified as pasture and distributed within the watersheds to account for the cattle, (10 acres in Mill Creek and 5 acres in Powhatan Creek). Based on stakeholder input, aerial imagery and field reconnaissance, the reclassified pasture areas and associated cattle were located in sub-watershed 1 of each watershed. Given the swampy nature of the areas around the creeks near the watershed outlets, it was assumed that the cattle did not have access to the streams and spent all of the time on the pastures. As a result, 25 beef cattle were accounted for in Mill Creek sub-watershed 1 and 10 beef cattle were accounted for in Powhatan Creek sub-watershed 1.

3.2.2. Direct Manure Deposition on Pastures

Manure loading on pasture was estimated by multiplying the total number of cattle on pasture by the amount of manure produced per day. The total amount of manure produced was divided by the pasture acreage to obtain manure loading (lb/ac-day) on pasture. Fecal coliform loading (cfu/ac-day) on pasture was calculated by multiplying the manure loading (lb/ac-day) by the fecal coliform content (cfu/lb) of the manure.

Pasture has a daily cattle manure loading of 150 lb/ac-day for Mill Creek and 120 lb/ac-day for Powhatan Creek. The associated fecal coliform loadings from cattle to pasture on a daily basis, averaged over the year, are 8.25×10^{10} cfu/day for Mill Creek and 6.6×10^{10} cfu/day for Powhatan Creek. Fecal coliform bacteria deposited on the pasture surface are subject to die-off due to desiccation and ultraviolet (UV) radiation. Runoff can transport part of the remaining viable fecal coliform to receiving waters.

3.3. Wildlife

Wildlife fecal coliform contributions can come from excretion of waste on land and from excretion directly into streams. Information provided by VADGIF and watershed residents was used to estimate wildlife populations. Wildlife species that were found in quantifiable numbers in the watershed included deer, raccoon, muskrat, beaver, wild turkey, goose, wood duck and seagull. Population numbers for each species and fecal coliform amounts were determined using preferred habitat and habitat area.

Estimations were made in the percent of each wildlife species depositing directly into streams, considering each habitat area occupied (Table 3.8). Fecal loading from wildlife was estimated for each sub-watershed. The wildlife populations were distributed among the sub-watersheds based on the area of appropriate habitat in each sub-watershed. For example, the deer population was evenly distributed across the watershed, whereas muskrat and raccoons had variable population densities based on land use and proximity to a water source. Therefore, a sub-watershed with more stream length and impoundments and more area in crop land use would have more muskrats than a sub-watershed with shorter stream length, fewer impoundments, and less area in crop land use. Distribution of wildlife among sub-watersheds is given in Table 3.9 for Mill Creek and Table 3.10 for Powhatan Creek.

Table 3.8. Wildlife habitat, population density, and direct fecal deposition in streams.

Wildlife type	Habitat and Estimation Method	Population Density (animal / mi² -habitat)	Direct fecal deposition in streams (%)
Deer	Entire Watershed	30	1
Raccoon	low density on forests not in high density area; high density on forest within 600 ft of a permanent water source or 0.5 mile of cropland; highest density in residential areas	Low density: 10 High density: 30 Highest density: 50	10
Muskrat	16/mile of ditch or medium sized stream intersecting cropland; 8/mile of ditch or medium sized stream intersecting pasture; 10/mile of pond or lake edge; 50/mile of slow-moving river edge	-see habitat column-	25
Beaver	3/mile of perennial streams; and 3.8/mile of lake or pond shore	-see habitat column-	50
Geese	300 ft buffer around main streams	50 – off season 70 – peak season	25
Wood Duck	300 ft buffer around main streams	40 – off season 60 – peak season	25
Wild Turkey	Forest	28	0
Seagull	308 ft buffer around water bodies	38	65

Table 3.9. Wildlife populations in the Mill Creek watershed.

Sub-watershed	Deer	Raccoon	Muskrat	Beaver	Goose		Wood Duck		Wild Turkey	Seagull
					Off-peak	Peak	Off-peak	Peak		
1	54	14	9	4	7	10	6	9	10	30
2	20	13	94	35	39	55	32	47	3	8
3	25	27	15	5	10	14	8	12	2	9
4	3	2	3	1	2	3	2	3	0	2
5	17	14	17	6	12	17	10	15	2	7
6	2	2	1	0	1	2	1	1	0	1
7	13	11	7	3	6	8	4	7	2	4
8	21	16	13	5	9	13	7	11	3	6
9	23	32	12	4	9	12	7	10	1	7
Total	178	131	171	63	95	134	77	115	23	74

Table 3.10. Wildlife populations in the Powhatan Creek watershed.

Sub-watershed	Deer	Raccoon	Muskrat	Beaver	Goose		Wood Duck		Wild Turkey	Seagull
					Off-peak	Peak	Off-peak	Peak		
1	41	68	83	31	57	80	46	69	7	21
2	39	57	86	32	27	38	22	33	5	5
3	12	20	10	4	7	10	6	8	3	3
4	37	59	5	2	4	6	3	5	6	11
5	4	6	4	1	3	4	2	4	1	2
6	31	52	26	10	15	20	12	17	3	9
7	12	19	5	2	4	5	3	5	2	3
8	27	44	16	6	12	16	9	14	4	10
9	36	60	17	6	13	18	10	15	8	10
10	51	86	19	7	13	19	11	16	9	18
11	25	42	31	12	23	32	18	27	2	10
12	42	70	51	19	36	50	29	43	3	14
13	126	209	26	10	18	25	15	22	10	44
14	12	20	18	7	13	18	10	15	2	4
15	22	37	14	5	10	14	8	12	2	8
16	65	108	6	2	5	7	4	6	7	19
17	77	128	34	13	24	34	19	29	14	28
Total	659	1085	451	169	284	396	227	340	88	219

3.4. Summary: Source Contributions

Based on the source characterization discussed in this chapter, a summary of the annual fecal coliform loadings from the Mill Creek and Powhatan Creek watersheds is shown in Table 3.11. From Table 3.11, it is clear that nonpoint source loadings to the land surface are approximately 30 and 530 times (for Mill Creek and Powhatan Creek, respectively) greater than direct nonpoint source loadings to the stream. Residential areas receive the greatest portion of the total load for both Mill Creek and Powhatan Creek. However, factors such as the amount and pattern of precipitation, die-off rates, type of waste, and proximity to the streams impact the amount of fecal coliform from upland areas that reaches the streams. Due to their nature, direct nonpoint source loadings to streams are not modified before transmission to the stream. Chapter 4: discusses these factors and how they are accounted for when estimating fecal coliform concentrations in receiving waters.

Table 3.11. Annual fecal coliform loadings to the stream and the various land use categories for Mill Creek and Powhatan Creek watersheds.

Source	Fecal coliform loading ($x10^{12}$ cfu/yr)		Percent of total loading	
	Mill Creek	Powhatan Creek	Mill Creek	Powhatan Creek
Direct loading to streams				
Wildlife in stream	72	10	3	<1
Loading to land surfaces				
Cropland	1.5	0.1	<1	<1
Pasture	407	150	18	3
Residential	1650	5150	73	96
Forest	135	13	6	<1
Total	**2266**	**5323**		

Chapter 4: Modeling Process for Bacteria TMDL Development

A key component in developing a TMDL is establishing the relationship between pollutant loadings (both point and nonpoint) and in-stream water quality. Once this relationship is developed, management options for reducing pollutant loadings to streams can be assessed. In developing a TMDL, it is critical to understand the processes that affect the fate and transport of the pollutants, and cause the impairment to the waterbody of concern. Pollutant transport to water bodies is evaluated using a variety of tools, including monitoring, geographic information systems (GIS), and computer simulation models. In this chapter, modeling processes, input data requirements, and model calibration procedures and results are discussed.

TMDL development requires the use of a watershed-based model that integrates both point and nonpoint sources and simulates in-stream water quality processes. The Hydrologic Simulation Program – FORTRAN (HSPF) version 12 (Bicknell *et al.*, 2001; Duda *et al.*, 2001) was used to model fecal coliform transport and fate in the Mill and Powhatan Creek watersheds. In the case of this particular TMDL study, the presence of a tidal zone within the impaired reaches for both Mill and Powhatan Creeks required the addition of a tidal model to accurately model tidal fluxes in the tidal zones. To that end, a Tidal PRISM water quality model for small coastal basins and tidal creeks (Kuo and Park, 1994) was used to model fecal coliform transport and fate in the tidal zones.

4.1. HSPF

The HSPF model simulates nonpoint source runoff and pollutant loadings, performs flow routing through streams, and simulates in-stream water quality. HSPF estimates runoff from both pervious and impervious surfaces in the watershed and stream flow in the channel network. The sub-module PWATER within the module PERLND simulates runoff, and hence, estimates the water budget on pervious areas (e.g., agricultural land). Runoff from impervious areas is modeled using the IWATER sub-module within the IMPLND module. The simulation of flow through the stream network is performed using the sub-modules HYDR and ADCALC within the module RCHRES. HYDR routes the water through the stream network, and ADCALC calculates variables used for simulating convective transport of the pollutant in the stream. Fate of fecal coliform on pervious and impervious land segments is simulated using the PQUAL (PERLND module) and IQUAL (IMPLND module) sub-modules, respectively. Fate of fecal coliform in stream water is simulated using the general constituent pollutant (GQUAL) sub-module within RCHRES module. Fecal coliform bacteria are simulated as dissolved pollutants in the GQUAL sub-module.

4.1.1. Input Data Requirements

HSPF requires a wide variety of input data to describe hydrology, water quality, and land use characteristics of the watershed. The sources of input data discussed in Chapters 2 and 3 were used to develop the TMDLs for Mill Creek and Powhatan Creek.

Climatological Data

Hourly precipitation data were obtained from three National Weather Service COOP stations. The majority of the precipitation data came from Williamsburg 2N (449151). Williamsburg 2N is located approximately 2 miles northeast of the watershed outlet. The following stations were used to fill in missing records of Williamsburg 2N: Wakefield 1NW (448800), and Painter 2W (446475). Wakefield 1NW is located approximately 20 miles southwest of the watershed, and Painter 2W 30 miles south of the watershed. Detailed descriptions of the weather data and the procedure for converting the raw data into the required data set are presented in Appendix D.

Model Parameters

The hydrology parameters required by HSPF were defined for each land use category within each sub-watershed. Required hydrology parameters are listed in the HSPF Version 12 User's Manual (Bicknell *et al.*, 2001). Initial estimates for the hydrology parameters were generated based on guidance in BASINS Technical Note 6 (USEPA, 2000); these parameters were refined during calibration. Each reach requires a function table (FTABLE) to describe the relationship between water depth, surface area, volume, and discharge (Bicknell *et al.*, 2001). FTABLE parameters were estimated from cross-section data collected during a windshield survey of the watershed. Information on the calculated stream geometry for each sub-watershed is presented in Table 4.1 and Table 4.2 for bankfull conditions.

Required water quality parameters are also given in the HSPF User's Manual (Bicknell *et al.*, 2001). Initial estimates for bacteria loading parameters were based on estimates of bacteria production in the watershed; estimates of die-off rates and subsurface bacteria concentrations, which were based on values commonly used in previous TMDLs.

Table 4.1. Reach characteristics for Mill Creek.

Sub-watershed	Stream length (mile)	Slope (ft/ft)
1*	–	–
2	1.83	0.0005
3	2.09	0.0044
4	0.35	0.0144
5	1.47	0.0063
6	0.11	0.0069
7	0.88	0.0097
8	1.18	0.0035
9	1.60	0.0050

* Tidal Creek

Table 4.2. Reach characteristics for Powhatan Creek.

Sub-watershed	Stream length (mile)	Slope (ft/ft)
1*	–	–
2	1.18	0.0001
3	0.64	0.0004
4	1.55	0.0032
5	0.48	0.0003
6	1.25	0.0087
7	0.60	0.0001
8	1.32	0.0083
9	1.52	0.0012
10	2.50	0.0051
11	1.38	0.0014
12	1.76	0.0072
13	2.95	0.0035
14	0.77	0.0001
15	1.69	0.0075
16	1.90	0.0037
17	2.60	0.0047

* Tidal Creek

4.1.2. Accounting for Pollutant Sources

Overview

Bacteria loads were estimated for all sources (human, livestock, pets, and wildlife) for input to the models (Chapter 3). There were four point sources permitted to discharge fecal coliform bacteria in the Mill and Powhatan Creek watersheds. These permitted discharges were for the Multiple Separate Storm Sewer System (MS4) permits for James City County, the City of Williamsburg, Eastern State Hospital, and the College of William and Mary. For this study, the load generated from the College of William and Mary MS4 was aggregated with Williamsburg; Eastern State Hospital MS4 was aggregated with James City County. Bacteria loads directly deposited by sewage spills or cattle and wildlife in streams were treated as direct nonpoint sources in the model. Direct nonpoint source loading was applied to the stream reach in each sub-watershed as appropriate. Bacteria that were land-applied or deposited on land were treated as nonpoint source loadings; all or part of this load may be transported to the stream as a result of surface runoff during rainfall events.

The nonpoint source loading was applied in the form of fecal coliform counts to each land use category in a sub-watershed. Fecal coliform die-off was simulated while it was on the land and while it was transported in streams. Both direct nonpoint and nonpoint source loadings were varied by month to account for seasonal differences such as cattle and wildlife access to streams.

The Bacteria Source Load Calculator (Zeckoski et al., 2005) was used to generate the nonpoint source fecal coliform inputs for HSPF. This program takes inputs of animal numbers, land use, and management practices by sub-watershed and outputs hourly direct deposition to streams and monthly loads to each land use type. The program only allows direct deposition in the stream by dairy cows, beef cattle, ducks, and geese to occur during daylight hours. The program calculates the manure produced in confinement by each animal type (dairy cows, beef cattle, and poultry) and distributes this manure to available lands (crops and pasture) within each sub-watershed. If a sub-watershed does not have sufficient land to apply all the manure its animals generate, the excess manure is distributed equally to other sub-watersheds that have land that has not yet received manure.

4.1.3. Model Calibration and Validation Procedure

Model calibration is the process of selecting model parameters that provide an accurate representation of the watershed. In this section, the procedures used for calibrating the hydrology and water quality components of the HSPF model are discussed.

Hydrology

Because no continuous hydrology gauge was available on Mill or Powhatan Creeks, the Totopotomoy Creek watershed was chosen as a surrogate based on an analysis of landscape characteristics of nearby gaged watersheds. Details of the hydrologic calibration for Totopotomoy Creek can be found in the Bacteria TMDL Development for the Pamunkey River Basin (Engineering Concepts, Inc., 2006).

4.1.4. HSPF Water Quality Calibration for Powhatan Creek

Only one water quality monitoring station (2-POW006.77) was available for the non-tidal portion of Powhatan Creek that could be used for calibration of the non-tidal Powhatan Creek water quality simulations (Figure 4.1). There was no monitoring station available for the non-tidal portion of Mill Creek. The calibrated parameters for Powhatan Creek were also used in Mill Creek. The two other stations (2-POW000.60 and 2-POW003.38) include the tidal portion of the creek and were not used for the HSPF calibration. Data from station 2-POW006.77 (Table 2-6) includes 88 fecal coliform observations.

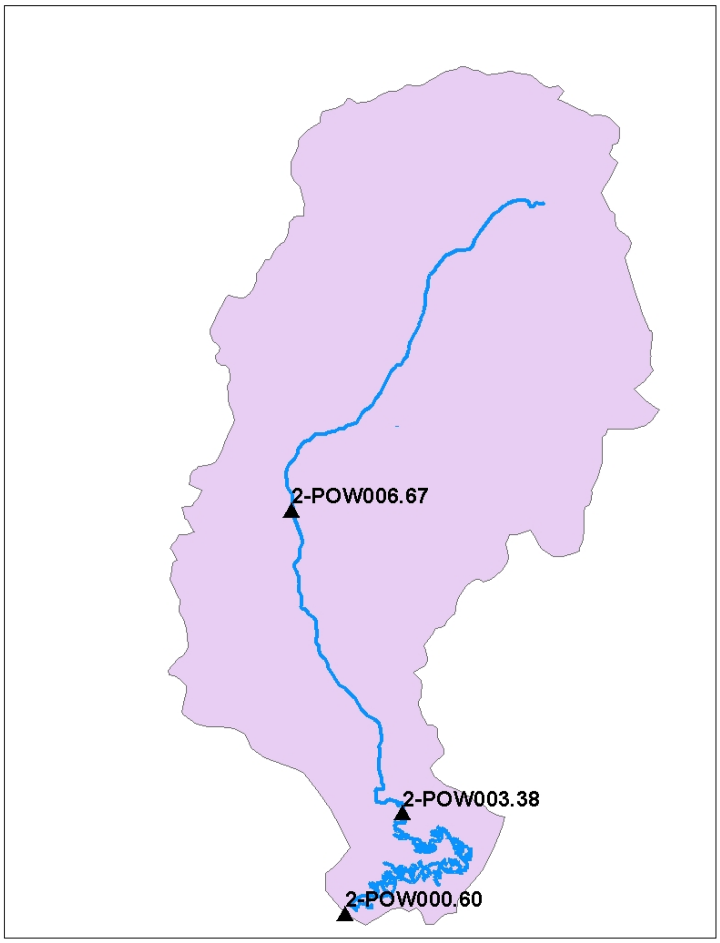

Figure 4.1. Powhatan Creek watershed boundaries and locations of DEQ monitoring stations.

The HSPF water quality calibration was performed at an hourly time step and included the period of January 1, 1995 to May 31, 2005, which included almost all of the data from station 2-POW006.77. The simulation period was ended in May 2005 due to the lack of meteorological data for dew point temperature beyond this date. Output from the HSPF model was generated as an hourly timeseries and daily average timeseries of fecal coliform concentration at the sub-watershed outlet corresponding to the monitoring station location.

Since the observed data from station 2-POW006.77 are collected via grab samples on a monthly basis (at best); it is not practical to expect a daily-average simulated value on a specific day to exactly match such data. Therefore, the standard methods used for calibration of water quality models, such as correlation coefficients, and descriptive statistics, were augmented. The procedures outlined in Kim *et al.* (2007); which include a minimum-maximum 5-day window statistic, instantaneous violation rates, geometric mean, arithmetic mean, and other statistics, were used in addition to the standard calibration methods. The minimum-maximum 5-day window statistic counts the number of observed values that fall within 5-day windows around each observed value. This statistic assumes that the observed data should fall roughly within the max-min range of hourly values simulated near the date that the observed data was collected. The instantaneous violation rate, averages, medians, geometric means, etc. were also used in the calibration process. Finally, visual comparisons of the simulated daily average to the observed data were considered to provide the best overall picture of the quality of the calibration run.

Several key input parameters were adjusted during the calibration process. These parameters included the washoff factor (WSQOP) and fecal coliform density for wildlife feces. The first calibration run indicated that the model over predicted bacteria concentrations. Figure 4.2 shows the five-day window of simulated in-stream bacteria concentrations for the initial run and Figure 4.3 is for the final run. For the initial run, the simulated geometric mean, arithmetic mean, and instantaneous violation rate tended to be higher than that of observed statistics (Table 4.3). For the final run, the simulated geometric mean was 120 cfu/100 mL, and the observed was 144 cfu/100 mL, resulting in an -17% relative error. The violation rates were 15% (simulated) and 15% (observed). Finally, the percent of five-day window, which includes observed data, was 17% for initial run and 57% for final run.

The parameters that were adjusted during model calibration are listed in Table 4.4. Even though the decrease in the fecal density for wildlife feces could be considered large, the magnitudes were still very large (on the order of 10^7 to 10^9). It should be noted that the parameters adjusted during the calibration process were those that had the most uncertainty in their initial estimation.

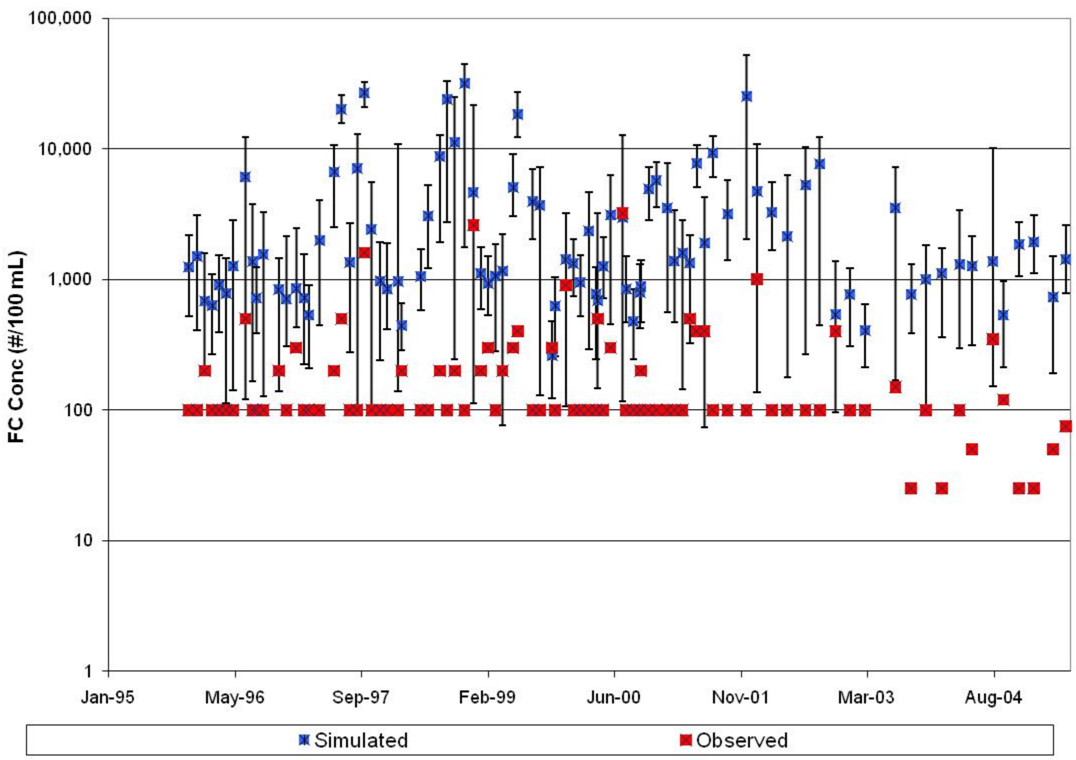

Figure 4.2. Five-day window of simulated in-stream bacteria concentrations surrounding each observed value for initial run at station 2-POW006.77.

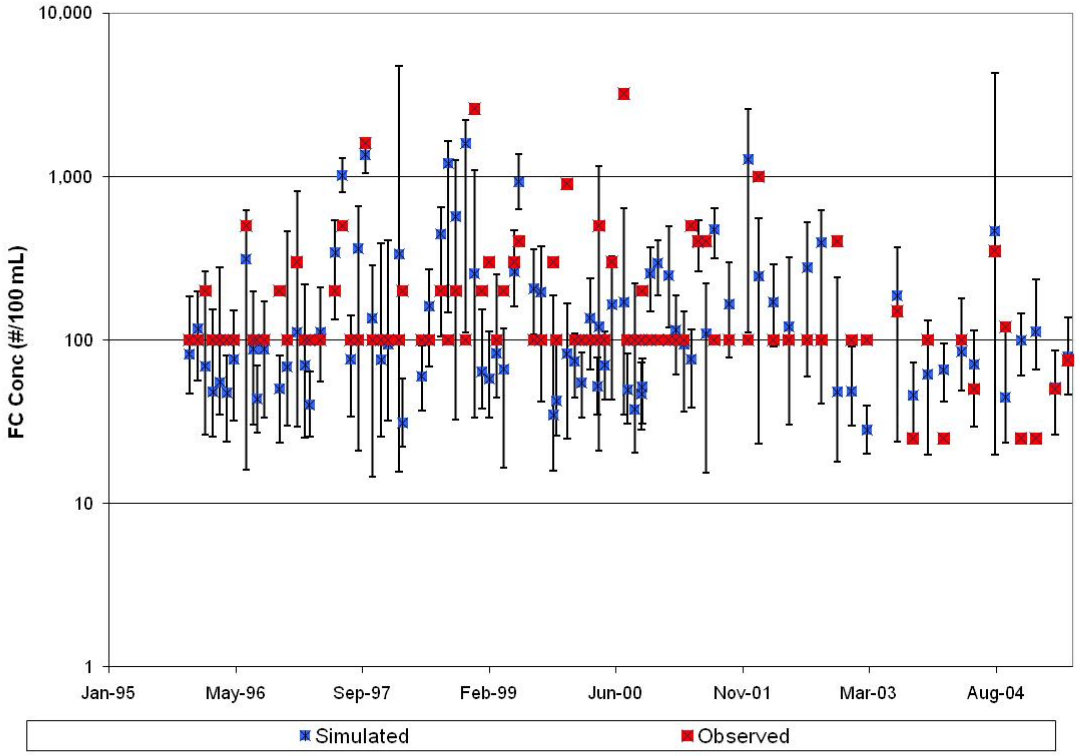

Figure 4.3. Five-day window of simulated in-stream bacteria concentrations surrounding each observed value for final run at station 2-POW006.77.

Table 4.3. Summarized goodness-of-fit measures for simulated and observed fecal coliform concentrations for the calibration period for Powhatan Creek.

2-POW006.77		Geo-metric Mean	Average	Median	MIN	MAX	IVR (%)	% in Range
		(cfu/100 mL)						
Observed		144	252	100	25	3,200	15	
Simulated	Initial Run	1,864	3,821	1,359	73	51,974	94	17
	Final Run	120	214	91	15	4,735	15	57

*IVR = instantaneous violation rate
†Capped value

Table 4.4. Parameters altered during calibration of Powhatan Creek.

Parameter	Adjustment
WSQOP	Increased to 0.74
Wildlife Fecal Density	Decreased by 95%

Calibration Results

After 8 runs, a set of input parameters were selected that were considered to be in good agreement with the observed fecal coliform concentrations. A plot of the observed data with the simulated average daily fecal coliform concentrations is shown in Figure 4.4. Figure 4.5 presents the min-max range of concentrations simulated on each day. Observed values are expected to fall within this min-max range (Figure 4.5) and this was achieved in the final calibration run. Most of the observed data are within the range of maximum and minimum simulated values shown in Figure 4.5.

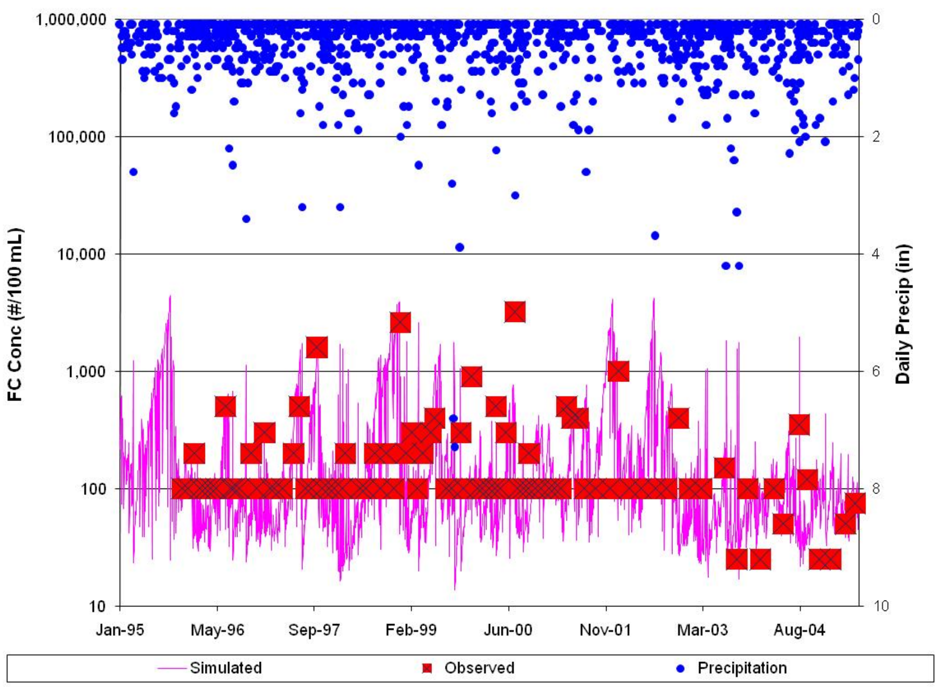

Figure 4.4. Observed and simulated fecal coliform concentrations at station 2-POW006.77 for Powhatan Creek.

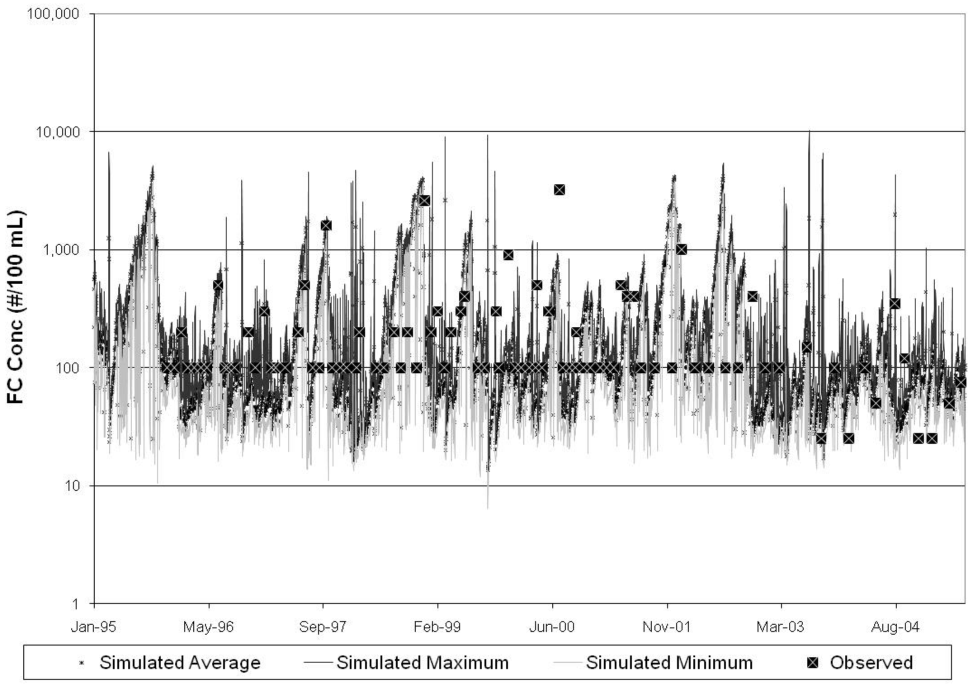

Figure 4.5. Observed fecal coliform data plotted with the daily maximum, minimum, and average simulated fecal coliform values for station 2-POW006.77 for Powhatan Creek.

4.2. Tidal PRISM

The Tidal PRISM model is a mass balance model, simulating the physical transport processes and biogeochemical kinetic processes (including fecal coliform) in small coastal basins and associated tributaries, using the concept of tidal flushing (Kuo and Park, 1994). The physical and biogeochemical processes are decoupled; non-conservative substances are calculated in time steps within the tidal cycle and physical processes are modeled with a tidal cycle time step. The original model was calibrated and validated with data from Lynnhaven Bay, a small coastal basin in the lower Chesapeake Bay (Kuo and Park, 1994). The model was further tested in four additional small coastal basins in the lower Chesapeake Bay, using calibrated parameters from Lynnhaven Bay for both the physical transport processes and biogeochemical kinetic processes. Comparison of model results among the five modeled basins indicates the set of physical transport and kinetic processes "may be applicable to all of Virginia's small coastal basins …" (Kuo *et al.*, 2005). Two of the test basins are located on either side of the James River outlet. Both Mill Creek and Powhatan Creek are located approximately 45 miles upstream on the James River. The set of calibrated parameters from Lynnhaven Bay were used in the modeling of Mill Creek and Powhatan Creek.

4.2.1. Input Data Requirements

The tidal prism model requires cross sections at specific intervals throughout a modeled reach, including tributaries, in order to model changes in intertidal and stream inflow volumes within the reach. The model also requires stream flow and fecal coliform inputs from all sources; including tributaries, marinas and canals. These input datasets are discussed in detail in the following sections.

Channel Geometry

The Tidal Prism Geometry Processor was used to determine appropriate sectional lengths. The Processor requires the following information: tidal range, geometry (length, width, and depth) of the main channel, number of tributaries, tributary geometry (length, width, and depth) and the distance upstream that the tributaries enter the main channel.

Distance, length, and width were determined from digital aerial photos. An example of the aerial imagery used is shown in Figure 4.6 for Mill Creek and Figure 4.7 for Powhatan Creek. Depths were determined from bathymetry data from a 1948 mean low water survey by the Department of Commerce (U.S. Coast and Geodetic Survey). Tidal range was obtained from the Kingsmill, VA NOAA station (ID: 8638424), which states a mean tidal range of 2.26 feet. The Kingsmill station is located approximately 6.6 miles east (downstream on the James River) of the outlet of Sandy Bay, which is the tidal bay of Mill and Powhatan Creeks. The upstream extent of each tidal zone was determined from digital aerial photos based on visual interpretation of changes in vegetation and stream width, and was estimated to be 2.46 miles upstream of cross section 1 on Mill Creek and 4.31 miles upstream of cross section 1 on Powhatan Creek.

Figure 4.6. Aerial imagery and bathymetry used to estimate Mill Creek geometry.

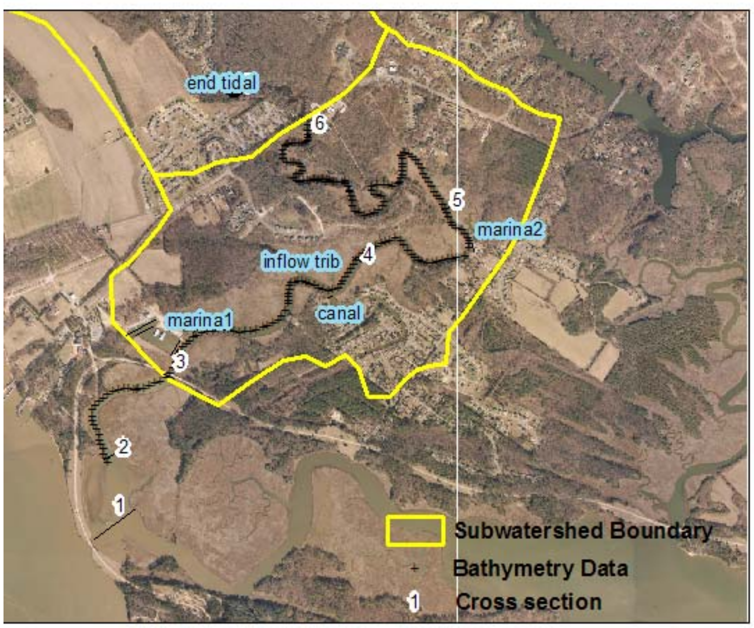

Figure 4.7. Aerial imagery and bathymetry used to estimate Powhatan Creek geometry.

4.2.2. Stream flow and fecal coliform

Mill Creek

HSPF was used to generate the inflows to the tidal creek portion of Mill Creek. These modeled results of stream flow and fecal coliform concentrations were the inflow to the upstream end of the tidal zone. Also, the area immediately around the tidal creek was simulated using HSPF and treated as inflow within the tidal zone. The output from the HSSPF simulations was used to create a time-series input of flow and fecal coliform load for the Tidal PRISM model. The locations of the inflows for Mill Creek are described in Table 4.5.

Table 4.5. Inflows and fecal coliform loads to Mill Creek tidal zone.

Tributary	Description	Distance Upstream (mi)	Input
Outlet	Water quality station (2-MIC000.03)	0.50	
1	Tributary	1.20	Flow, Fecal coliform load
5	Mill Creek	2.46	Flow, Fecal coliform load

Powhatan Creek

HSPF-modeled results of stream flow and fecal coliform concentrations at the upstream end of the tidal zone and from a tributary within the tidal zone provided flow and fecal coliform input for Tidal PRISM. HSPF-modeled flow and fecal coliform loads generated from within the tidal zone were input to one tributary (see inflow trib, Figure 4.7). The two marinas and a canal were modeled as tributaries with no inflow, but included a fecal coliform load (Figure 4.7). Table 4.6 describes the tributaries and inflows into the tidal system modeled by tidal prism.

Table 4.6. Inflows and fecal coliform loads to Powhatan Creek tidal zone.

Tributary	Description	Distance Upstream (mi)	Input
Outlet	Water quality station (2-POW000.60)	0.75	
1	Marina 1	0.85	Fecal coliform load
2	Tributary	1.47	Flow, Fecal coliform load
3	Canal	1.56	Fecal coliform load
4	Marina 2	2.24	Fecal coliform load
6	Powhatan Creek	4.31	Flow, Fecal coliform load

Model Setup

All inflow and fecal coliform sources in Mill and Powhatan Creeks were input as point sources in Tidal Prism. Downstream boundary conditions of fecal coliform concentrations in Sandy Bay were set to zero, i.e., an assumption of no fecal coliform input from the James River via Sandy Bay. The date range modeled was January 1, 1992 to May 31, 2005. Point source inputs (output from HSPF) were in increments of tidal cycles (TC), i.e., 12 hours. All variables other than flow and fecal coliform were taken from Lynnhaven Bay: first-order die-off rate, temperature effect on bacteria die-off, temperature variables (max, min), physical characteristics of the ocean water (specific heat, density, heat exchange coefficient, equilibrium temperature) and the return ratio (fraction of water volume that returns during each tidal cycle). Temperature was modeled as sinusoidally varying, with parameters set to those of Lynnhaven Bay.

4.2.3. Tidal Prism Water Quality Calibration for Mill Creek

There was only one water quality monitoring station, 2-MIC000.03, available for the tidal portion of the Mill Creek watershed (see Figure 4.8). This station has 134 observations of fecal coliform data across 14 years (Table 2-6). The period of January 1, 1995 to May 31, 2005 included almost all of the data from station 2-MIC000.03. The simulation period was ended in May 2005 due to the lack of meteorological data for dew point temperature beyond this date.

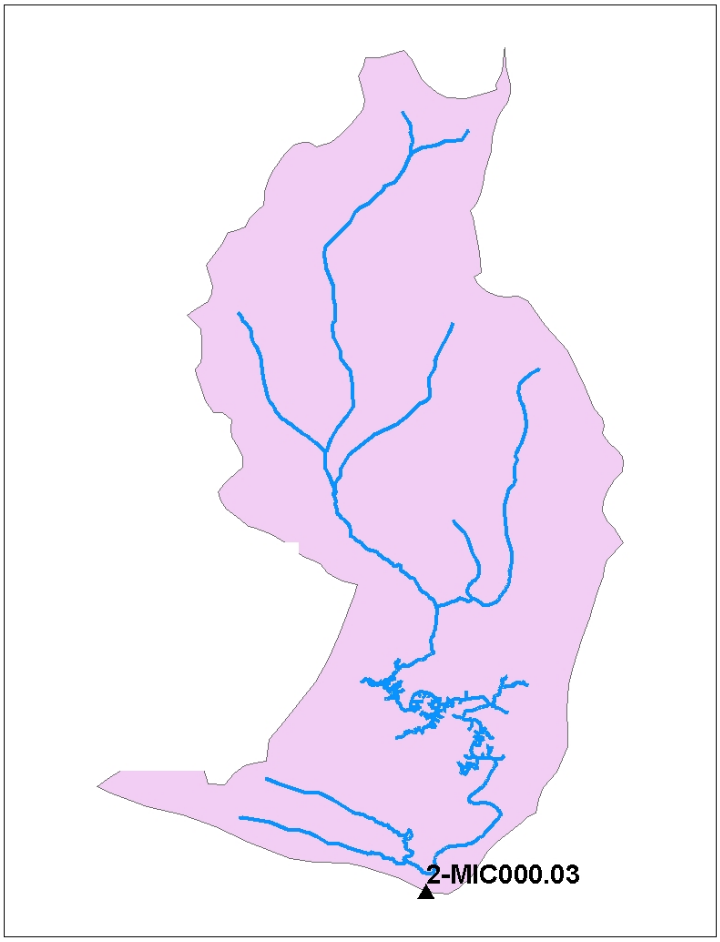

Figure 4.8. Mill Creek watershed boundary and locations of DEQ monitoring stations.

The procedures outlined in Kim *et al.* (2007), which include calculations of instantaneous violation rates, geometric mean, arithmetic mean, and other statistics, were used to assess the quality of the calibration. Also, visual comparisons of the simulated daily average to the observed data were considered to provide the best overall picture of the quality of the calibration run.

Tidal Prism Calibration Process

The input parameters adjusted during the calibration process for the Tidal PRISM model were the washoff factor (WSQOP) and the fecal coliform production rate in the HSPF model in the non-tidal area of the watershed. The upstream non-tidal area in Mill Creek was the main source of bacteria for the downstream tidal portion of the creek. For the initial run of the Tidal PRISM model, the simulated geometric mean, arithmetic mean, and instantaneous violation rate tended to be higher than that of observed statistics (Table 4.7). For the final run, the simulated geometric mean was 168 cfu/100 mL and the observed was 129 cfu/100 mL resulting in a 30% relative error. The violation rates were 25% (simulated) and 25% (observed).

The parameters that were adjusted during model calibration are listed in Table 4.8. It should be noted that the parameters altered during the calibration process were those that had the most uncertainty in their initial estimation.

Table 4.7. Summarized goodness-of-fit measures for simulated and observed fecal coliform concentration.

2-MIC000.03		Geometric Mean	Average	Median	MIN	MAX	IVR
		(cfu/100 mL)					(%)
Observed		129	378	130	2	2,400	25
	Initial Run	195	333	367	0	7,740	43
Simulated	Final Run	168	285	303	0	4,520	25

*IVR = instantaneous violation rate

Table 4.8. Parameters altered during calibration to fix high bacteria predictions.

Parameter	Adjustment
Wildlife Fecal Coliform Production	Decreased by 12%
WSQOP	Increased to 0.75

Tidal Prism Calibration Results

After several runs, a set of input parameters were selected that produced good agreement between Tidal Prism output and the observed fecal coliform concentrations. A plot of the observed data with the simulated average daily fecal coliform concentrations is shown in Figure 4.9. Figure 4.10 presents the min-max range of concentrations simulated on each day.

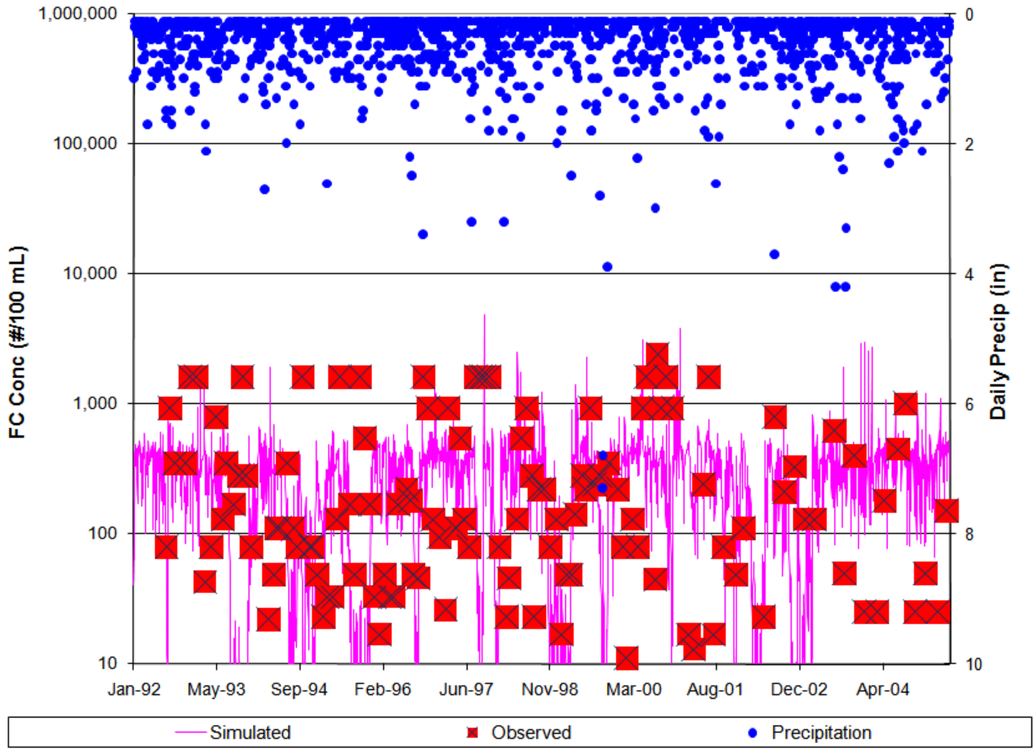

Figure 4.9. Observed and simulated fecal coliform concentrations at station 2-MIC000.03.

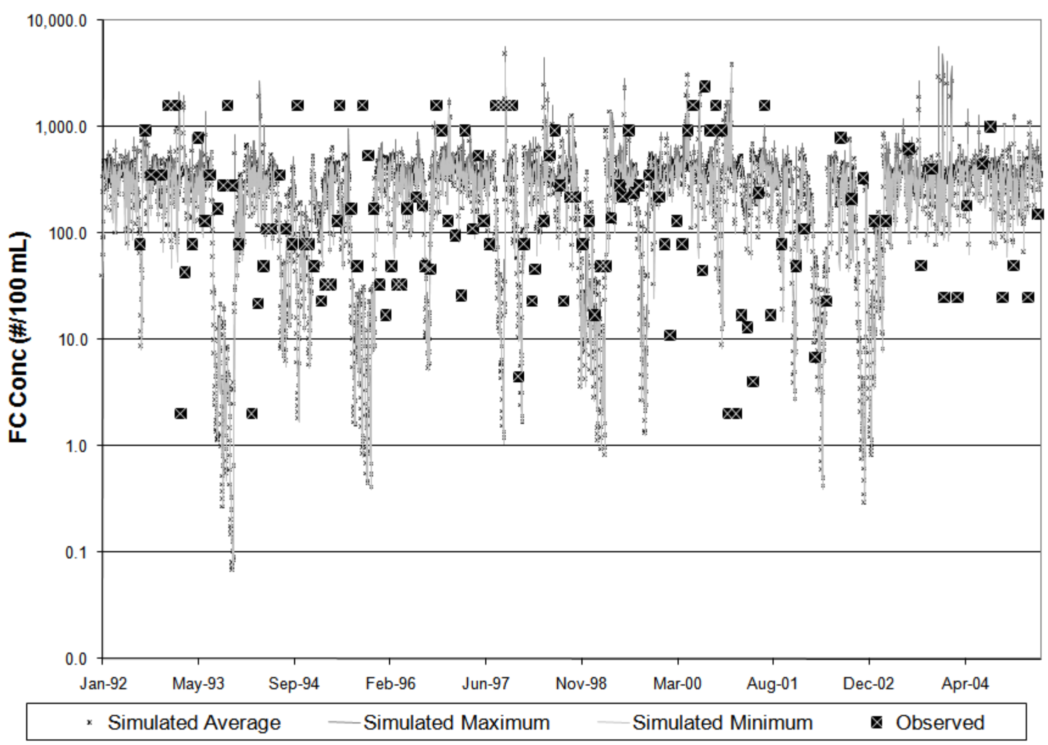

Figure 4.10. Observed fecal coliform data plotted with the daily maximum, minimum, and average simulated fecal coliform values for station 2-MIC000.03.

BST Comparison

Bacterial Source Tracking (BST) data were collected at the tidal water quality station, 2-MIC000.03. BST results are typically reported as a flow- and concentration-weighted average of the twelve samples. Because observed flow rates in Mill Creek were not available, the observed values were flow-weighted according to the average of the simulated flows for the 5 days surrounding the observed date. For comparison, Tidal Prism model outputs from different sources were generated and were also flow- and concentration- weighted. The BST results are presented in Table 4.9 along with the simulated breakdown. The minimum and maximum observed and simulated values are also presented in this table; flow- and concentration-weighted averages are given in bold.

Table 4.9. Observed and Simulated Source Breakdown of Mill Creek Results (percent contributions).

Observed/ Simulated	Livestock (Min; Max)	Wildlife (Min; Max)	Human (Min; Max)	Pet (Min; Max)
Observed	15 (0; 62)	44 (0; 84)	22 (0; 61)	19 (0; 80)
Simulated	19 (0; 79)	53 (0; 100)	6 (0; 14)	22 (0; 74)

It is difficult to draw exact conclusions from BST analysis; however, it can provide information in determining sources of fecal coliform bacteria in the watershed. The ranges of data (both simulated and observed) are evidence that the breakdown of sources will vary considerably according to the time and location a sample is collected. This variance is largely dependent on the time since the last storm event – the relative contributions from sources at high flows are not the same as those at low flows. Constant sources like wildlife direct deposition in streams are primary contributors most of the time, but during high flow events, overland sources, such as pets and failing septic systems, dominate. Wildlife sources in general tend to contribute more during low flow events (via direct deposition in the streams) and only contribute a small amount during high flow events.

4.2.4. Tidal Prism Water Quality Calibration for Powhatan Creek

There was only one water quality monitoring station, 2-POW000.60, available for the tidal portion of the Powhatan Creek watershed (see Figure 4.1). The 2-POW000.60 station has 131 observations of fecal coliform data across 14 years (Table 2-6). The period of January 1, 1995 to May 31, 2005 included almost all of the data from station 2-POW000.60. The simulation period was ended in May 2005 due to the lack of meteorological data for dew point temperature beyond this date.

The procedures outlined in Kim *et al.* (2007), which include calculations of instantaneous violation rates, geometric mean, arithmetic mean, and other statistics, were used to assess the quality of the calibration. Also, visual comparisons of the simulated daily average to the observed data were considered to provide the best overall picture of the quality of the calibration run.

Tidal PRISM Calibration Process

The input parameters adjusted during the calibration process for the Tidal Prism model were the washoff factor (WSQOP) and the fecal coliform production rate in the HSPF model in the non-tidal area of the watershed and the load from boats in the marinas and canal for the tidal portion of the creek. In addition to the upland sources, there were two marinas and a canal with boat slips that were the additional sources of bacteria to the tidal creek. Fecal coliform load from the boats was another calibration parameter. For the initial run of the Tidal PRISM model, the simulated geometric mean was higher and the arithmetic mean was lower than the values for the observed data. However, the instantaneous violation rate was close to observed value (Table 4.10). For the final run, the simulated geometric mean was 148 cfu/100 mL and the observed was 170 cfu/100 mL, resulting in a -13% relative error. The violation rates were 26% (simulated) and 16% (observed), resulting in a -38% relative error.

The parameters that were adjusted during model calibration are listed in Table 4.11. It should be noted that the parameters altered during the calibration process were those that had the most uncertainty in their initial estimation.

Table 4.10. Summarized goodness-of-fit measures for simulated and observed fecal coliform concentration.

2-POWC000.60		Geometric Mean	Average	Median	MIN	MAX	IVR (%)
		(cfu/100 mL)					
Observed		170	377	140	8	1,600	26
	Initial Run	148	800	153	0	41,800	25
Simulated	Final Run	78	401	77	0	20,900	16

*IVR = instantaneous violation rate

Table 4.11. Parameters altered during calibration to fix high bacteria predictions.

Parameter	Adjustment
Wildlife Fecal Coliform Production	Decreased by 12%
WSQOP	Increased to 0.75
Load from Marina and Canal	Set to 10,000 cfu/100 mL

Tidal PRISM Calibration Results

After over 30 runs, a set of input parameters was selected that produced good agreement between Tidal Prism output and the observed fecal coliform concentrations. A plot of the observed data with the simulated average daily fecal coliform concentrations is shown in Figure 4.10. Figure 4.11 presents the min-max range of concentrations simulated on each day.

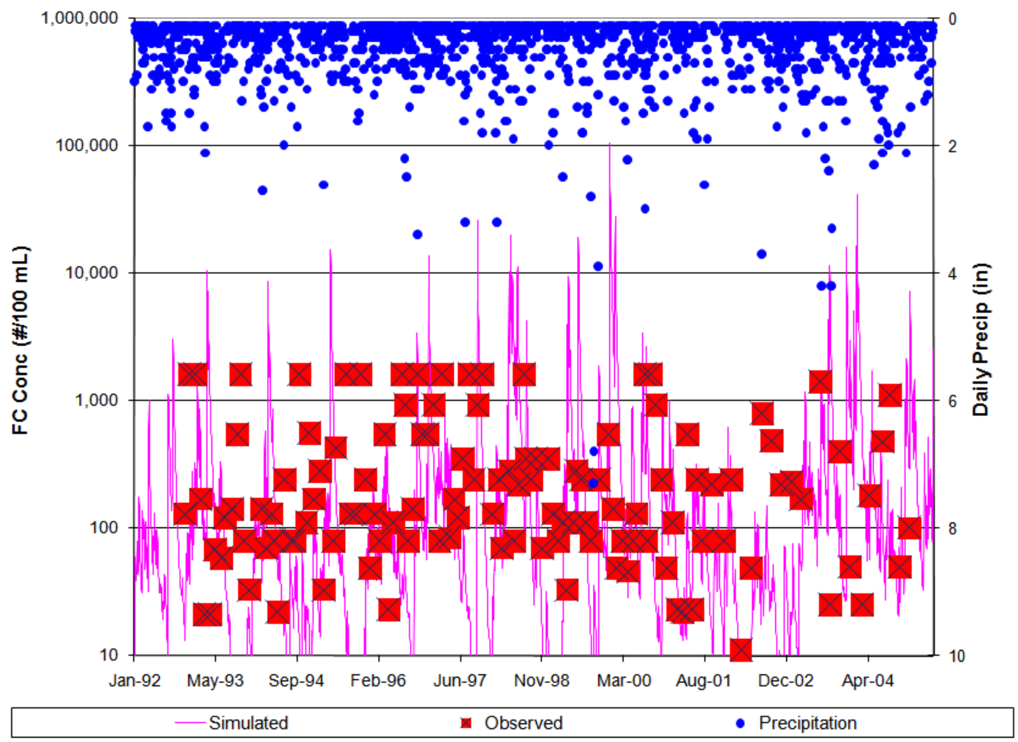

Figure 4.10. Observed and simulated fecal coliform concentrations at station 2-POW000.60.

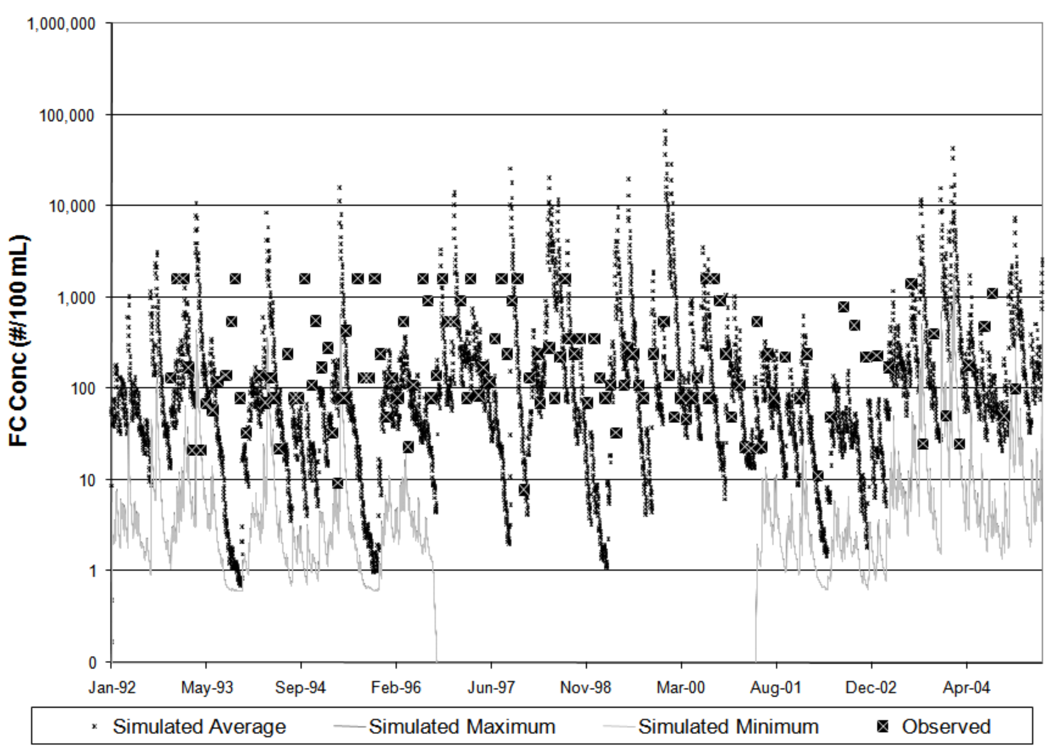

Figure 4.11. Observed fecal coliform data plotted with the daily maximum, minimum, and average simulated fecal coliform values for station 2-POW00.60.

BST Comparison

Bacterial Source Tracking (BST) data were collected at the tidal water quality station, 2-POW000.60. BST results are typically reported as a flow- and concentration-weighted average of the twelve samples. Because observed flow rates in Powhatan Creek were not available, the observed values were flow-weighted according to the average of the simulated flows for the 5 days surrounding the observed date. For comparison, Tidal Prism model outputs from different sources were generated and were also flow- and concentration-weighted. The BST results are presented in Table 4.12 along with the simulated breakdown. The minimum and maximum observed and simulated values are also presented in this table; flow- and concentration-weighted averages are given in bold.

Table 4.12. Observed and Simulated Source Breakdown Results (percent contributions).

Observed/ Simulated	Livestock (Min; Max)	Wildlife (Min; Max)	Human (Min; Max)	Pet (Min; Max)
Observed	38 (0; 79)	32 (0; 100)	11 (0; 72)	19 (0; 96)
Simulated	20 (0; 79)	40 (0; 100)	20 (0; 50)	20 (0; 74)

It is difficult to draw exact conclusions from BST analysis; however, it can provide information in determining sources of fecal coliform bacteria in the watershed. The ranges of data (both simulated and observed) are evidence that the breakdown of sources will vary considerably according to the time and location a sample is collected. This variance is largely dependent on the time since the last storm event – the relative contributions from sources at high flows are not the same as those at low flows. Constant sources like wildlife direct deposition in streams are primary contributors most of the time, but during high flow events, overland sources, such as pets and failing septic systems, dominate. Wildlife sources in general tend to contribute more during low flow events (via direct deposition in the streams) and only contribute a small amount during high flow events.

Chapter 5: TMDL Allocations

The objective of a TMDL is to allocate allowable loads among different pollutant sources so that the appropriate control actions can be taken to achieve water quality standards (USEPA, 1991).

5.1. Background

The objectives of the bacteria TMDLs for Mill and Powhatan Creeks were to determine what reductions in fecal coliform, *E. coli*, and enterococci loadings from point and nonpoint sources are required to meet state water quality standards. The state water quality standard for *E. coli* used in the development of the TMDL for the non-tidal section of Powhatan Creek included two criteria: 126 cfu/100 mL (calendar-month geometric mean) and 235 cfu/100 mL (single sample maximum). The state water quality standard for enterococci used in the development of the TMDLs for Mill Creek and the tidal section of Powhatan Creek included two criteria: 35 cfu/100 mL (calendar-month geometric mean) and 104 cfu/100 mL (single sample maximum). The TMDL consider all significant sources contributing bacteria to the impaired streams. The sources can be separated into nonpoint and point sources. The different sources in the TMDL are defined in the following equation:

$$TMDL = WLA + LA + MOS \qquad [5.1]$$

Where: WLA = waste load allocation (point source contributions)
LA = load allocation (nonpoint source contributions); and
MOS = margin of safety.

An implicit MOS was used in these bacteria TMDLs by using conservative estimations of all factors that would affect bacteria loadings in the watershed (e.g., populations, production rates, contributions to the stream). These factors were estimated in such a way as to represent the worst-case scenario; i.e., they describe the worst stream conditions that could exist in the watersheds. Creating TMDLs with conservative estimates ensures that the worst-case scenario has been considered and that no water quality standard violations will occur if the TMDL plan is followed.

Translator equations developed by VADEQ were used to convert the fecal coliform model output to *E. coli* (equation 5.2) and enterococci (equation 5.3) for comparison with the water quality standards. The *E. coli* translator equation was implemented in the HSPF simulation using the GENER block. In order to develop the actual TMDL equation, it was necessary to generate *loads* (rather than concentrations) of *E. coli*. Daily *E. coli* loads were obtained by using the *E. coli* concentrations calculated from the translator equation and multiplying them by the average daily flow. Annual loads were obtained by summing the daily loads and dividing by the number of years in the allocation period. The enterococci equation was implemented in a spreadsheet and calculated as post-processing.

$$\log_2 EC(cfu/100mL) = -0.0172 + 0.91905 * \log_2 FC(cfu/100mL) \qquad [5.2]$$

$$\log_2 Ent(cfu/100mL) = 1.2375 + 0.59984 * \log_2 FC(cfu/100mL) \qquad [5.3]$$

When developing a bacteria TMDL, the required bacteria load reductions are modeled by decreasing the amount of bacteria running off the land surface that reach the stream or decreasing the amount of bacteria directly deposited in the stream; these reductions are presented in the tables in the following sections. The reductions called for in the following sections indicate the need to decrease the amount of bacteria reaching the stream in order to meet the applicable water quality standards. The reductions shown in these sections are not intended to infer that animal populations must be reduced in size, or residential areas made smaller. Rather, it is assumed that the required reductions from affected source categories will be accomplished by implementing BMPs, such as repairing aging septic systems, installing rain gardens, and other appropriate measures included in the TMDL Implementation Plan.

The period of January 1, 2001 to May 31, 2005 was used for allocation modeling. Observed meteorological data from the Williamsburg 2N weather station were used. This period included average rainfall, low rainfall, and high rainfall; and the climate during these years caused a wide range of hydrologic events including both low and high flow conditions (for a stream flow chart for the allocation period, see Appendix G). The bacteria loading in the model for allocation scenarios was representative of anticipated future conditions.

The calendar-month geometric mean values used in this report are geometric means of the simulated daily concentrations. Because HSPF was operated with a one-hour time step in this study, 24 hourly concentrations were generated each day. To estimate the calendar-month geometric mean from the hourly HSPF output, the arithmetic mean of the hourly values was computed for each day, and then the geometric mean was calculated from these average daily values. For the Tidal PRISM model, a 12-hour time step was used in this study; two concentrations were generated each day. The mid-point of the two values generated for each day was used to calculate the calendar-month geometric mean from the output of the Tidal Prism model.

5.2. Existing Conditions

5.2.1. Mill Creek

Analysis of the simulation results for the existing conditions in the watershed (Table 5.1) shows that contributions from wildlife direct deposit and residential areas are the primary sources of bacteria to the stream. The results in this table were taken as the average daily contributions for the allocation simulation period, irrespective of the magnitude of the concentration or the flow rate (factors that were considered in the earlier section detailing the source breakdown used in the calibration). Table 5.1 gives an idea of what sources will be the dominant contributors to the instantaneous concentrations, and thus what sources will control the violations of the single sample criterion: loadings from wildlife direct deposit and residential areas will each violate the single sample criterion by themselves. The concentrations shown in Table 5.1 are the average concentrations over the entire 5 and a half year simulation period.

Table 5.1. Relative contributions of different enterococci sources to the in-stream concentration for existing conditions in the Mill Creek watershed.

Source	In-stream Mean Fecal Coliform Concentration (cfu/100 mL)	Percent of Total Loading (%)
Direct loading to streams		
Wildlife in stream	1,491	75
Loading to land surfaces		
Agricultural	69	3
Residential	432	22
Forest	8	<1
Total	**2,000**	

The contribution of each of the sources listed in Table 5.1 to the daily enterococci concentration is shown in Figure 5.1. As indicated in Table 5.1 above, wildlife direct deposit and residential loadings are the largest contributors of bacteria. The contributions from wildlife direct deposit and residential areas dominate the mean concentration. From this graph, it is evident that violations of the water quality criteria will be most controlled by contributions from direct in-stream sources (wildlife direct deposit) and residential areas.

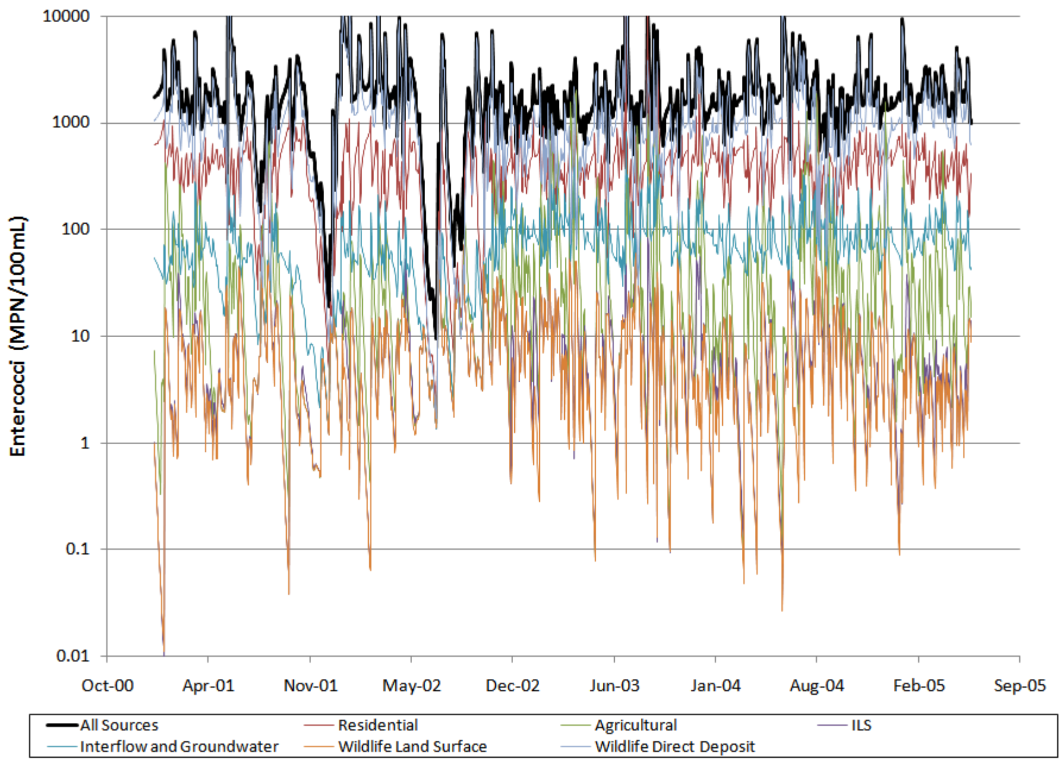

Figure 5.1. Contributions of different sources to the daily average enterococci concentration at the outlet of Mill Creek for existing conditions.

5.2.2. Powhatan Creek

Since there were two impairments, analyses of the simulation results for the existing conditions in the watershed were made for both the non-tidal and tidal sections of Powhatan Creek. For the non-tidal section of Powhatan Creek, contributions from wildlife direct deposit and residential areas are the primary sources of bacteria (Table 5.2). The results in this table were taken as the average daily contributions for the allocation simulation period, irrespective of the magnitude of the concentration or the flow rate (factors that were considered in the earlier section detailing the source breakdown used in the calibration). Table 5.2 gives an idea of what sources will be the dominant contributors to the instantaneous concentrations, and thus what sources will control the violations of the single sample criterion: loadings from wildlife direct deposit and residential areas will each violate the single sample criterion by themselves. The concentrations shown in Table 5.2 are the average concentrations over the entire 5 and a half year simulation period.

Table 5.2. Relative contributions of different *E. coli* sources to the in-stream concentration for existing conditions in the non-tidal section of Powhatan Creek watershed.

Source	In-stream Mean Fecal Coliform Concentration (cfu/100 mL)	Percent of Total Loading (%)
Direct loading to streams		
Wildlife in stream	219	48
Loading to land surfaces		
Residential	224	49
Forest	16	3
Total	**459**	

The contribution of each of the sources listed in Table 5.2 to the daily *E. coli* concentration is shown in Figure 5.2. As indicated in Table 5.2 above, wildlife direct deposit and residential loadings are the largest contributors of bacteria. The contributions from wildlife direct deposit and residential areas dominate the mean concentration. From this graph, it is evident that violations of the water quality criteria will be most controlled by contributions from direct in-stream sources (wildlife direct deposit) and residential areas.

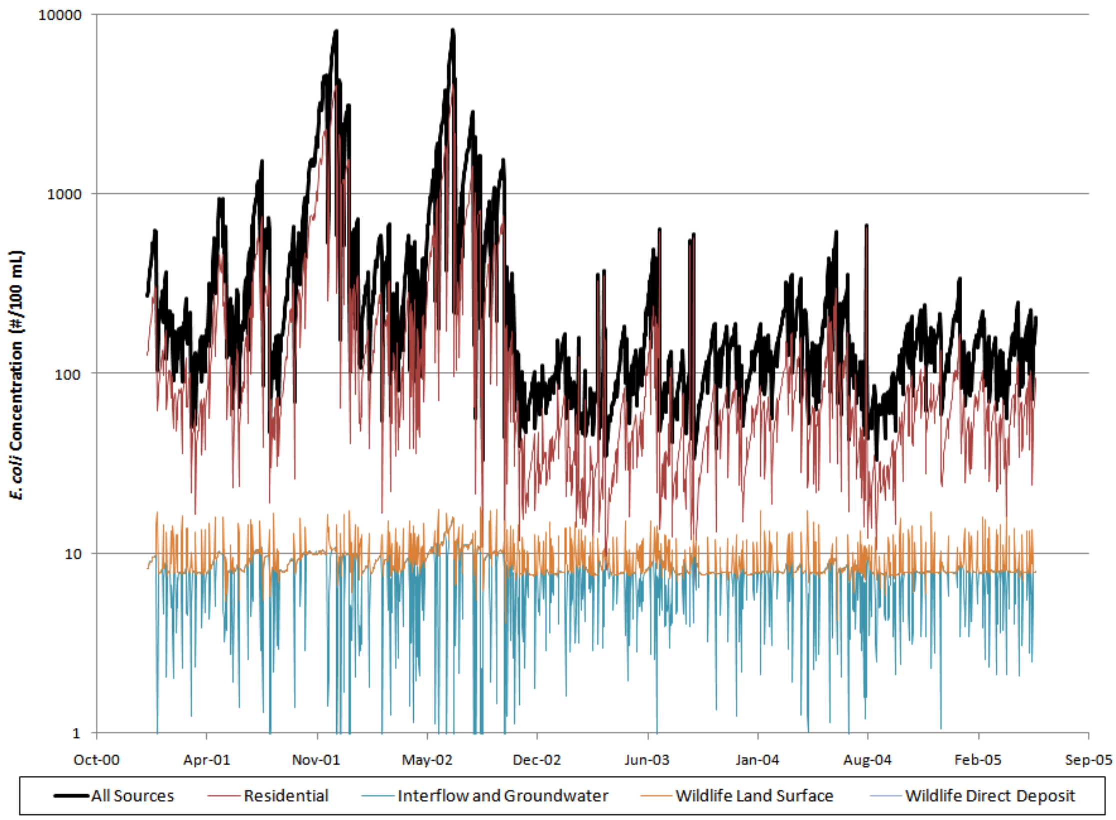

Figure 5.2. Contributions of different sources to the daily average *E. coli* concentration at the outlet of non-tidal section of Powhatan Creek for existing conditions.

As would be expected, contributions from wildlife direct deposit and to a lesser extent residential areas are the main source of bacteria to the stream for the tidal section of the Powhatan Creek (Table 5.3). The results in this table were taken as the average daily contributions for the allocation simulation period. Table 5.3 identifies what sources will be the dominant contributors to the instantaneous concentrations, and thus what sources will control the violations of the single sample criterion: mainly loadings from wildlife direct deposit will violate the single sample criterion by themselves.

Table 5.3. Relative contributions of different enterococci sources to the concentration for existing conditions in the tidal section of Powhatan Creek watershed.

Source	In-stream Mean Fecal Coliform Concentration (cfu/100 mL)	Percent of Total Loading (%)
Direct loading to streams		
Wildlife in stream	215	66
Marinas and Canal	5	2
Loading to land surfaces		
Agricultural	29	9
Residential	54	17
Forest	23	7
Total	**326**	

The contribution of each of the sources listed in Table 5.3 to the daily enterococci concentration is shown in Figure 5.3. As indicated in the Table 5.3 above, wildlife direct deposit is the largest contributor of bacteria. The contributions from wildlife direct deposit dominate the mean concentration.

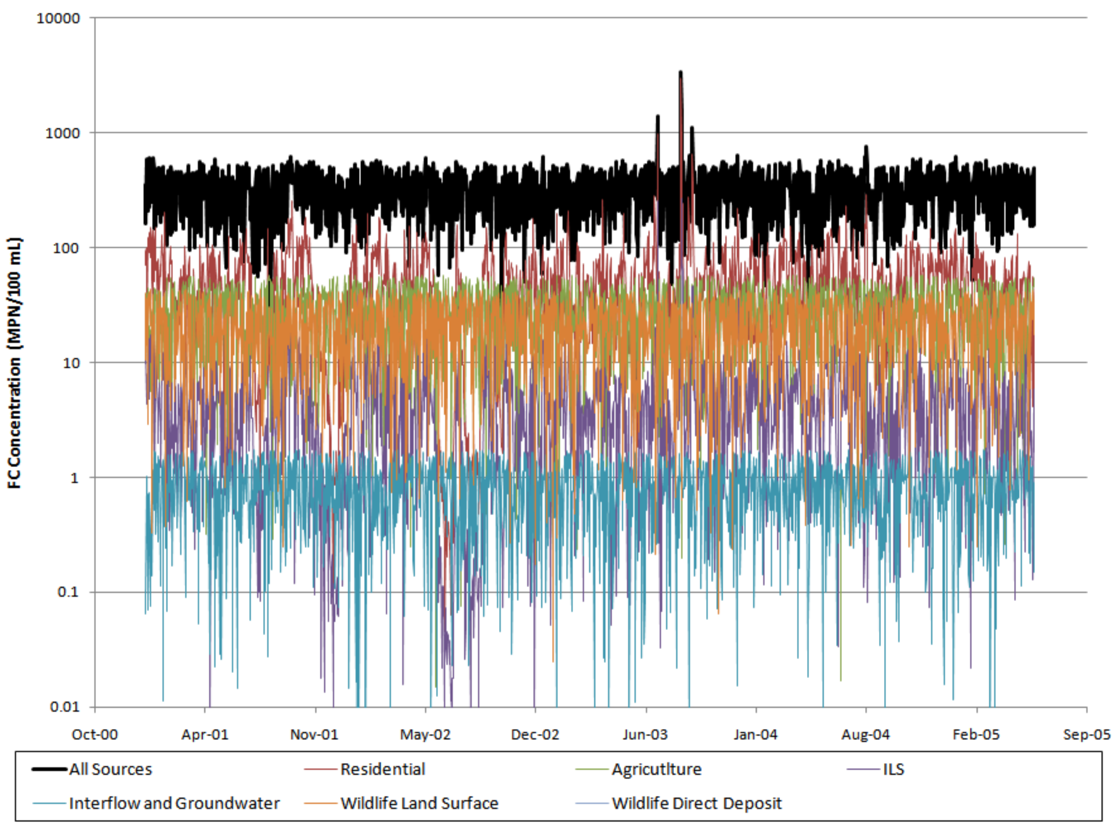

Figure 5.3. Contributions of different sources to the daily average enterococci concentration at the outlet of the tidal section of Powhatan Creek for existing conditions.

5.3. Future Conditions

Future conditions were represented in the simulations by using the land use distribution that corresponded with a 50% build-out of land use changes given in the comprehensive plan for James City County. The change is land use between existing conditions and 50% build out of the comprehensive plan are listed Table 5.4 and Table 5.5.

Table 5.4. Change in land use between existing and 50%-build out of comprehensive plan for Mill Creek.

	Agricultural (acres)	Forest (acres)	Residential and Open Space (acres)
Existing	93	1,988	1,705
50%-Build-out	170	1,236	2,388
% Change	83%	-38%	40%

Table 5.5. Change in land use between existing and 50%-build out of comprehensive plan for Powhatan Creek.

	Agricultural (acres)	Forest (acres)	Residential and Open Space (acres)
Existing	116	7,160	6,736
50%-Build-out	69	4,676	9,284
% Change	-41%	-35%	38%

5.3.1. Allocation Scenarios

A variety of allocation scenarios were evaluated to meet the TMDL goals of a calendar-month geometric mean concentration less than 126 cfu/100 mL and a single-sample maximum concentration of less than 235 cfu/100 mL for *E. coli* for the non-tidal section of Powhatan Creek. A calendar-month geometric mean concentration less than 35 cfu/100 mL and a single-sample maximum concentration of less than 104 cfu/100 mL for enterococci were used to evaluate allocation scenarios for Mill Creek and the tidal section of Powhatan Creek. The scenarios and results are summarized in for Mill Creek, and Table 5.8 and Table 5.9 for Powhatan Creek; recall that these reductions are those used for modeling, and implementation of these reductions will require implementation of BMPs as discussed at the beginning of this chapter. Only, one successful TMDL allocation scenario was found. The recommended scenario (6) for Mill Creek is highlighted in Table 5.6. It should be noted that direct deposit from wildlife was identified as a major contributor to violations as discussed in the previous section. Also, BST data identified wildlife as a major source of bacteria in Mill Creek. Although Virginia does not advocate the elimination of wildlife to comply with water quality standards, wildlife populations can be significantly influenced by human activities. Bacteria concentrations resulting from the preferred scenario (6) are presented in Figure 5.4. The concentrations for both of the enterococci standards are also shown in the figure.

Table 5.6. Bacteria allocation scenarios for Mill Creek watershed.

Scenario	Fecal Coliform Loading Reduction (%)				% Violation of enterococci Standard	
	Agriculture	Wildlife DD	Residential	Forest	Geometric Mean	Instantaneous
Baseline	0	0	0	0	92%	67%
01	70	0	70	0	92%	40%
02	95	0	95	0	92%	40%
03	99	0	99	0	92%	40%
04	99	50	99	0	92%	30%
05	99	60	99	0	92%	28%
06	95	98	95	0	0%	0%

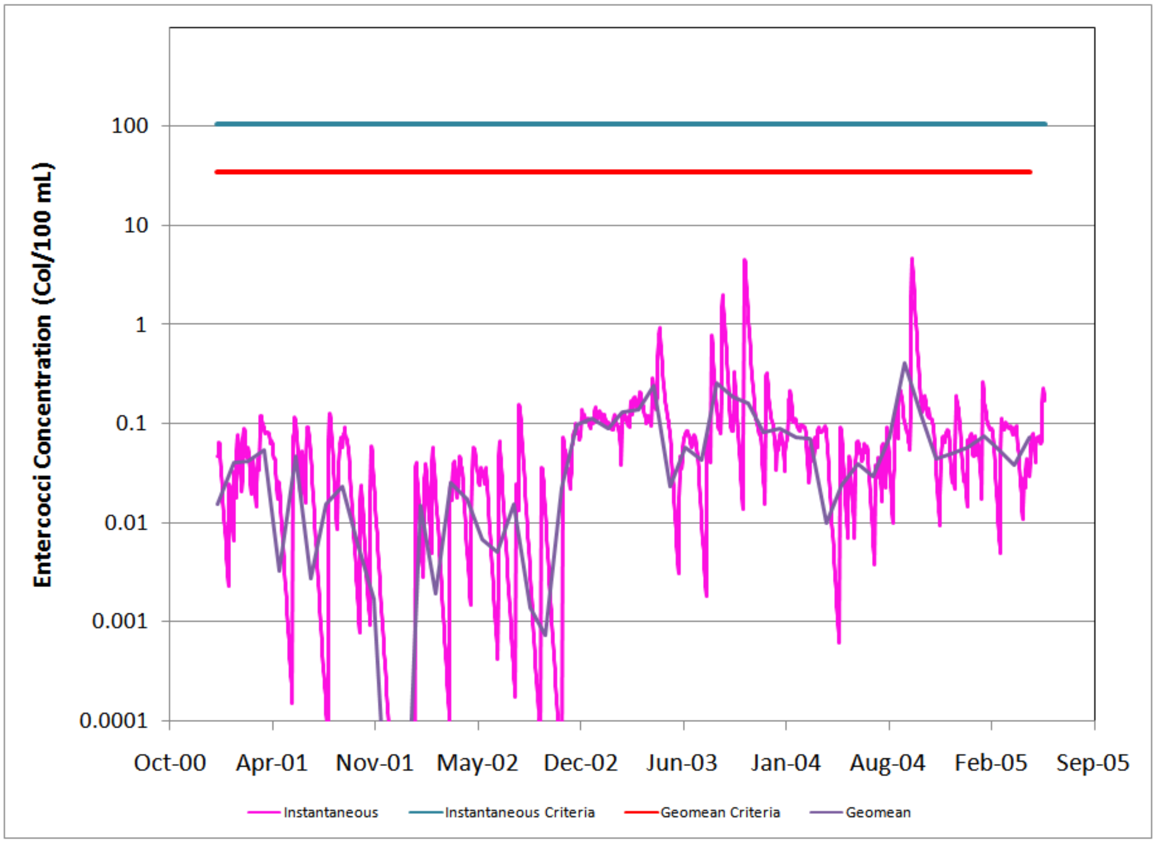

Figure 5.4. Bacteria concentrations for successful allocation scenario 6 from Table 5.6 plotted with the enterococci standard (the daily average concentration must fall below the blue single sample standard line; the calendar-month geometric mean concentration must fall below the red calendar-month standard line).

Loadings for the existing conditions and the chosen successful TMDL allocation scenario (6) are presented for nonpoint sources by land use and for direct nonpoint sources in Table 5.7. For sub-watershed specific loadings and reductions, see Appendix E. These are the loading from the watershed that meet the enterococci standard for Mill Creek. The fecal coliform loads presented in Table 5.7 are the fecal coliform loads that result in in-stream enterococci concentrations that meet the applicable water quality standard after application of the VADEQ fecal coliform to enterococci translator to the predicted mean daily fecal coliform concentrations.

Table 5.7. Annual nonpoint source fecal coliform loads under existing conditions and corresponding reductions for TMDL allocation scenario 6 for Mill Creek.

	Existing Conditions		Allocation Scenario	
Land Use Category	Existing Conditions Load ($x10^{12}$ cfu/yr)	Percent of Total Load from Nonpoint Sources (%)	TMDL Nonpoint Source Allocation Load ($x10^{12}$ cfu/yr)	Percent Reduction from Existing Load (%)
Agricultural	409	18	20	95
Residential	1,650	73	83	95
Forest	135	6	135	0
Wildlife in Streams	72	3	1	98
Total	2,266		239	89

The strategy for developing the allocation scenarios for Powhatan Creek was to first identify reductions that meet the *E. coli* standard in the non-tidal section of the creek. Then the outflow from the non-tidal section for the scenario that meets the *E. coli* standard was used as input to the tidal section. The simulated results for the tidal section were then compared to the enterococci standard. Unsuccessful scenarios 1-3 are shown in Table 5.8 to illustrate the need for the reductions in wildlife direct deposit. Scenarios 1 to 3 demonstrate that compliance with the standard cannot be achieved through anthropogenic reductions alone. Scenario 2 demonstrates that even an extreme reduction in anthropogenic sources of bacteria does not result in compliance with the standard. A large decrease is required in wildlife direct deposit to eliminate violations of the standard.

Table 5.8. Bacteria allocation scenarios runs for non-tidal section of Powhatan Creek.

Scenario	Fecal Coliform Loading Reduction (%)				% Violation of *E. Coli* Standard	
	Agricultural	Wildlife DD	Residential	Forest	Geometric Mean	Instantaneous
Baseline	0	0	0	0	13%	12%
01	20	0	20	0	13%	10%
02	100	0	100	0	13%	8%
03	100	30	100	0	9%	6%
04	92	92	92	0	0%	0%

It was much easier to meet the enterococci standard for the tidal section of Powhatan Creek once the *E. coli* standard was met. The load from the marinas and the canal were eliminated in addition to the reductions in the loads to the non-tidal section of Powhatan Creek. The reductions listed in Table 5.9 are reductions for the land areas directly around the tidal section of Powhatan Creek. These reductions (marinas, canal, and land area around tidal creek) would be made in addition to the reductions identified for the non-tidal section.

Table 5.9. Bacteria allocation scenarios for tidal section of Powhatan Creek.

Scenario	Non-tidal Scenario[a]	Fecal Coliform Loading Reduction (%)					% Violation of enterococci Standard	
		Agricultural	Wildlife DD	Marinas	Residential	Forest	Geometric Mean	Instantaneous
Baseline	**Baseline**	0	0	0	0	0	100%	1%
01	**01**	20	0	100	20	0	4%	0%
02	**02**	100	0	100	100	0	0%	0%
03	**03**	100	0	100	100	0	0%	0%
04	**04**	92	0	100	92	0	0%	0%

[a] Reduction made in the non-tidal section of the watershed used as input to tidal creek.

Bacteria concentrations resulting from the preferred scenario (4) for the non-tidal section of Powhatan Creek are presented in Figure 5.5. The two *E. coli* criteria are shown in Figure 5.5. The daily average concentration must fall below the blue single sample standard line and the calendar-month geometric mean concentration must fall below the red calendar-month standard line.

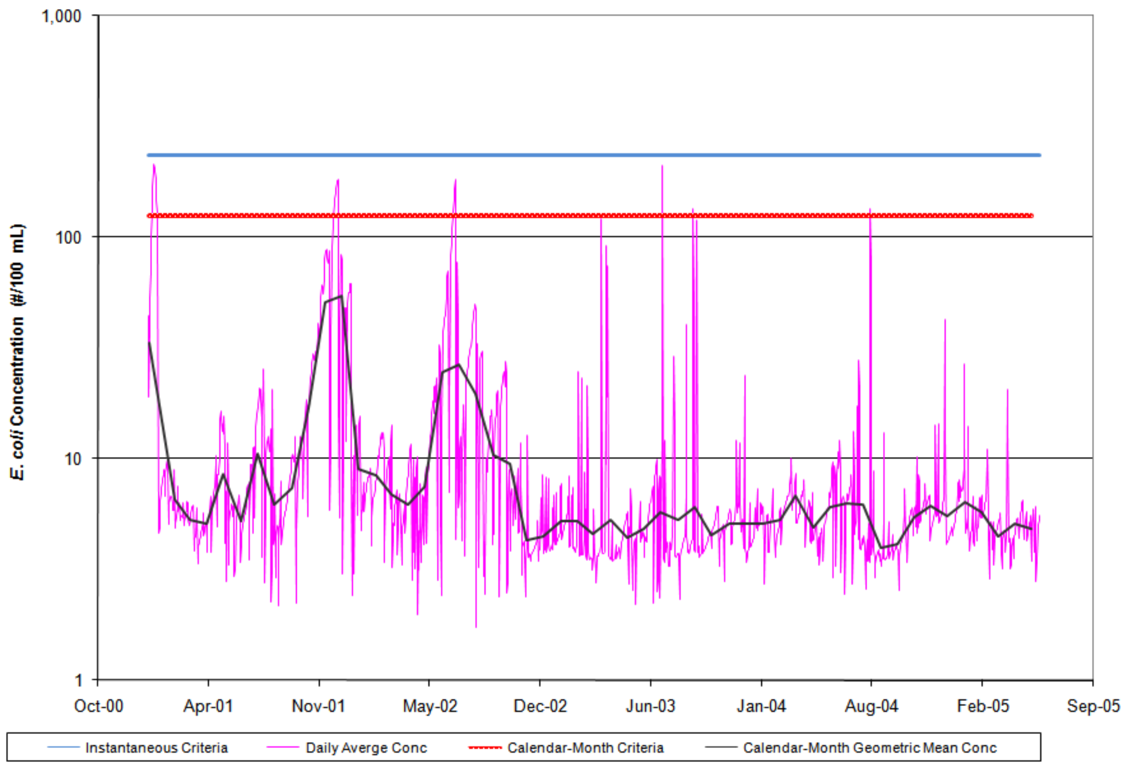

Figure 5.5. Bacteria concentrations for successful allocation scenario 4 from Table 5.8 plotted with the *E. coli* standard (the daily average concentration must fall below the blue single sample standard line; the calendar-month geometric mean concentration must fall below the red calendar-month standard line).

Loadings for the existing conditions and the chosen successful TMDL allocation scenario (7) are presented for nonpoint sources by land use in Table 5.10. For sub-watershed specific loadings and reductions, see Appendix E.

Table 5.10. Annual nonpoint source fecal coliform loads under existing conditions and corresponding reductions for TMDL allocation scenario 4 for non-tidal section of Powhatan Creek.

	Existing Conditions		Allocation Scenario	
Land Use Category	Existing Conditions Load ($x10^{12}$ cfu/yr)	Percent of Total Load from Nonpoint Sources (%)	TMDL nonpoint Source Allocation Load ($x10^{12}$ cfu/yr)	Percent Reduction from Existing Load (%)
Residential	5,150	97	412	92
Forest	13	<1	13	0
Wildlife in Streams	10	<1	1	92
Total	5,173		426	92

Bacteria concentrations resulting from the preferred scenario (4) for the tidal section of Powhatan Creek are presented in Figure 5.6. The two *E. coli* criteria are shown in Figure 5.6. The daily average concentration must fall below the blue single sample standard line and the calendar-month geometric mean concentration must fall below the red calendar-month standard line.

The fecal coliform loads presented in Table 5.11 and are the fecal coliform loads that result in in-stream enterococci concentrations that meet the applicable water quality standards after application of the VADEQ fecal coliform to enterococci translator to the Tidal PRISM mean daily fecal coliform concentrations.

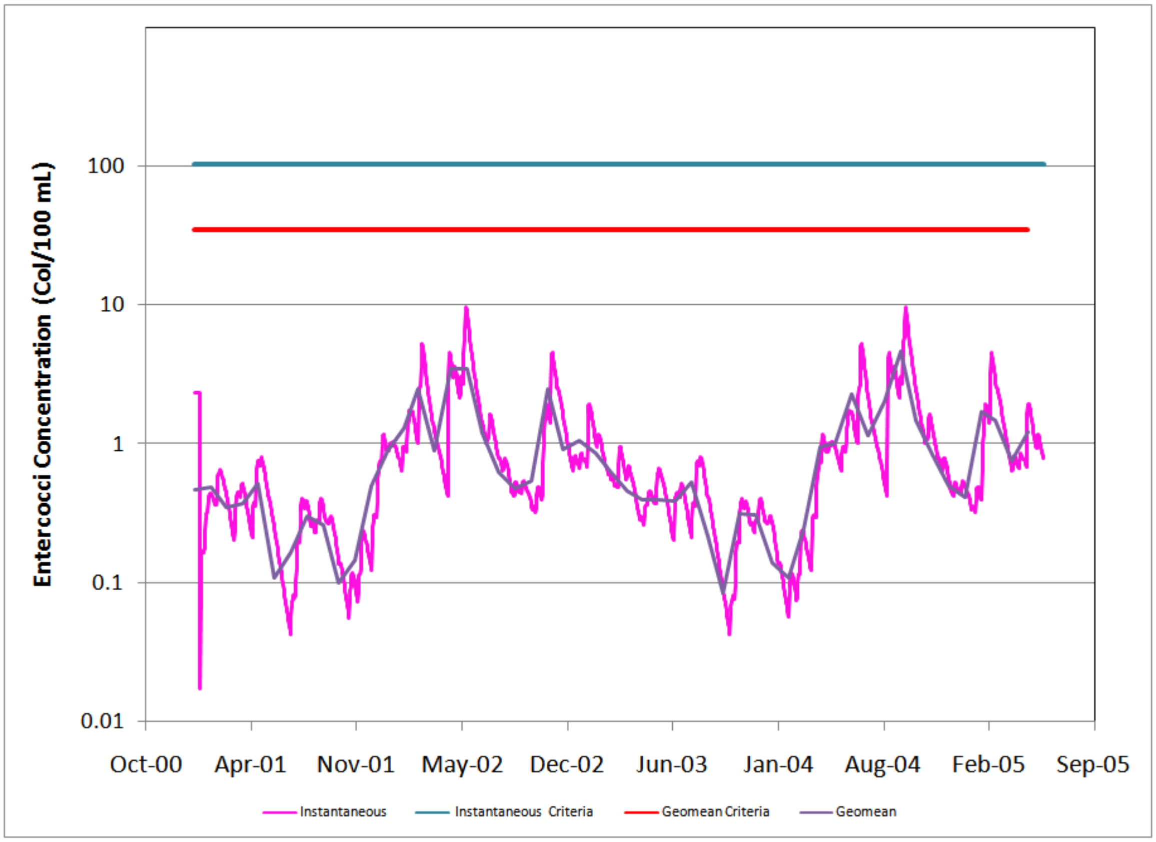

Figure 5.6. Bacteria concentrations for successful allocation scenario 4 from Table 5.9 plotted with the enterococci standard (the daily average concentration must fall below the blue single sample standard line; the calendar-month geometric mean concentration must fall below the red calendar-month standard line).

Table 5.11. Annual nonpoint source fecal coliform loads under existing conditions and corresponding reductions for TMDL allocation scenario 4 for tidal section of Powhatan Creek.

	Existing Conditions		Allocation Scenario	
Land Use Category	**Existing Conditions Load ($x10^{12}$ cfu/yr)**	**Percent of Total Load from Nonpoint Sources (%)**	**TMDL Nonpoint Source Allocation Load ($x10^{12}$ cfu/yr)**	**Percent Reduction from Existing Load (%)**
Agricultural	150	3	12	92
Residential	309	97	25	92
Forest	1	<1	1	0
Marinas and Canal	<1	<1	0	100
Total	460		38	92

5.3.2. Waste Load Allocation

It is assumed that all impervious land area within the James City County (VAR040037) and City of Williamsburg (VAR040027) MS4 boundaries, including the institutional MS4s (Eastern State Hospital – VAR040076 and College of William and Mary – VAR040039, respectively), transport runoff through storm sewer systems which discharge into the creeks. The *E. coli* and enterococci loads from the impervious land areas within the limits of the MS4 permits are included in the waste load allocation (WLA). Since there are currently no permitted domestic or industrial wastewater discharges in the watersheds, one percent (1%) of the final TMDL load allocation (LA) was added to the TMDL WLA to accommodate future growth.

5.3.3. Summary of Mill and Powhatan Creek's TMDL Allocation Scenario for Bacteria

A TMDL for enterococci has been developed for Mill Creek and TMDLs have been developed for both *E. coli* and enterococci for Powhatan Creek. The TMDL addresses the following issues:

1. The TMDL meets both the calendar-month geometric mean and single sample components of each water quality standard.
2. Because *E. coli* and enterococci loading data were not available to quantify nonpoint source bacterial loads, available fecal coliform loading data were used as input to HSPF and Tidal PRISM. HSPF and Tidal PRISM were then used to simulate in-stream fecal coliform concentrations. The VADEQ fecal coliform to *E. coli* and to enterococci concentration translator equations were used to convert the simulated fecal coliform concentrations.
3. The TMDL was developed taking into account all fecal bacteria sources (anthropogenic and natural) from both point and nonpoint sources.
4. An implicit margin of safety (MOS) was incorporated by utilizing professional judgment and conservative estimates of model parameters.

5. Both high- and low-flow stream conditions were considered while developing the TMDL. For both Mill and Powhatan Creek watersheds, low stream flow and low tide were found to be the environmental condition most likely to cause violations of the water quality standard; because the TMDL was developed using a continuous simulation model, it applies to both high- and low-flow conditions.
6. Both the flow regime and bacteria loading are seasonal and the TMDLs accounted for these seasonal effects.

For Mill Creek, the selected enterococci TMDL allocation that meets both enterococci criteria requires a 95% reduction in the amount of bacteria coming from agricultural and residential areas throughout the watershed delivered to the stream and a 98% reduction in wildlife direct deposits to the stream. Using equation 5.1, the summary of the bacteria TMDL for Mill Creek for the selected allocation scenario (6) is given in Table 5.12.

Table 5.12. Annual allocated enterococci loadings (cfu/yr) used for the Mill Creek bacteria TMDL.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	6×10^{11} (1% of LA)	60×10^{12}	–	–
James City County (VAR040037 & VAR040076)	3×10^{12}	–	–	–
City of Williamsburg (VAR040027 & VAR040039)	0.03×10^{12}	–	–	–
Total	**3.63×10^{12}**	**60×10^{12}**	–	**63.63×10^{12}**

*Implicit MOS

For Powhatan Creek, the selected *E. coli* TMDL allocation that meets both criteria requires a 92% reduction in the amount of bacteria coming from residential areas throughout the watershed delivered to the stream and a 92% reduction in wildlife direct deposits to the stream. Using equation 5.1, the summary of the *E. coli* TMDL for Powhatan Creek for the selected allocation scenario (4) is given in Table 5.13.

Table 5.13. Annual allocated *E. coli* loadings (cfu/yr) for the non-tidal Powhatan Creek bacteria TMDL.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	2.4×10^{12} (1% of LA)	236×10^{12}	–	–
James City County (VAR040037 & VAR040076)	15×10^{12}	–	–	–
City of Williamsburg (VAR040027 & VAR040039)	0.4×10^{12}	–	–	–
Total	**17.8×10^{12}**	**236×10^{12}**	–	**253.8×10^{12}**

*Implicit MOS

For Powhatan Creek, the selected enterococci TMDL allocation that meets both criteria requires a 92% reduction in the amount of bacteria coming from residential areas throughout the watershed delivered to the stream and a 100% reduction in load from marinas and canals to the stream. Using equation 5.1, the summary of the enterococci TMDL for Powhatan Creek for the selected allocation scenario (4) is given in Table 5.14.

Table 5.14. Annual allocated enterococci loadings (cfu/yr) for the tidal Powhatan Creek bacteria TMDL.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	0.14×10^{12} (1% of LA)	14×10^{12}	–	–
James City County (VAR040037 & VAR040076)	6.9×10^{12}	–	–	–
City of Williamsburg (VAR040027 & VAR040039)	0.2×10^{12}	–	–	–
Total	**7.24×10^{12}**	**14×10^{12}**	–	**21.24×10^{12}**

*Implicit MOS

5.3.4. Daily *E. coli* and enterococci TMDL

The USEPA has mandated that TMDL studies completed in 2007 and later include a daily maximum load as well as the average annual load shown in the previous section. The daily load was determined as the product of a representative flow rate from the watershed and the appropriate concentration criterion from the water quality standard. This section summarizes the daily maximum load for Mill and Powhatan Creeks.

Hydrologic Considerations

According to guidance from EPA (USEPA, 2006), it was necessary to assess the flow duration curve to determine an appropriate flow rate to use in the load calculation. EPA guidance suggests that the flow duration curve should be plotted using observed continuous flow data. Because continuous flow data were not available for the Mill Creek or Powhatan Creek watersheds, flows from the surrogate watershed used in calibration (Totopotomoy Creek) were used instead. As specified in the EPA guidance, the observed flows from Totopotomoy Creek were multiplied by the ratio of the TMDL watershed area to the drainage area above the Totopotomoy Creek gage. This area correction was also done for the MS4 areas to estimate the flow. The flow rate corresponding to the 99^{th} percentile flow (that is, the flow rate exceeded by only 1% of the observed flows) was used in calculation in order to determine the *maximum* daily load after correcting for differences in the watershed areas. This flow was used for the non-tidal section of Powhatan Creek and as the inflow during slack tide (time when tidal water is mostly fresh water) to the tidal creeks (MapTech, 2007). The area-corrected 99^{th} percentile flows were 58 cfs for Mill Creek and 214 cfs for Powhatan Creek.

Daily Load

Setting a *maximum daily* load will help ensure that the annual loads given in the previous section are appropriately distributed such that on any given day the single sample component of the bacteria water quality standard will be met. The loadings in the annual load table given in the previous section, being of a long-term nature, will more directly assure compliance with the geometric mean component of the standard. Thus, the maximum daily load was computed as the product of the critical flow condition and the single sample criterion (235 cfu/100 mL for *E. coli*; 104 cfu/100 mL for enterococci). The TMDL was divided amongst the WLA, LA, and MOS categories using ratios calculated from the annual TMDL;

that is, if the WLA was set to 1% of the annual LA, it will also account for 1% of the daily LA. The daily WLA was also calculated for each MS4 area, with the loads from the institutional MS4s aggregated within the larger, surrounding, MS4s. The resulting daily maximum loadings are shown in Table 5.15 for Mill Creek and for Powhatan Creek, Table 5.16 and Table 5.17. The actual maximum daily load is dependent upon flow conditions, and progress toward water quality improvement will be assessed against the numeric *E. coli* and enterococci water quality criteria.

Table 5.15. Maximum daily enterococci loadings (cfu/day) at the Mill Creek watershed outlet.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	1.47×10^{7} (1% of LA)	1.47×10^{9}	–	–
James City County (VAR040037 & VAR040076)	2.63×10^{8}	–	–	–
City of Williamsburg (VAR040027 & VAR 040039)	2.85×10^{7}	–	–	–
Total	$\mathbf{3.06 \times 10^{8}}$	$\mathbf{1.47\times 10^{9}}$	–	$\mathbf{1.78 \times 10^{9}}$

* Implicit Margin of Safety (MOS)

Table 5.16. Maximum daily *E. coli* loadings (cfu/day) at the Powhatan Creek watershed outlet.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	1.23×10^{8} (1% of LA)	1.23×10^{10}	–	–
James City County (VAR040037 & VAR040076)	1.51×10^{9}	–	–	–
City of Williamsburg (VAR040027 & VAR 040039)	3.85×10^{7}	–	–	–
Total	$\mathbf{1.67 \times 10^{9}}$	$\mathbf{1.23 \times 10^{10}}$	–	$\mathbf{1.40 \times 10^{10}}$

* Implicit Margin of Safety (MOS)

Table 5.17. Maximum daily enterococci loadings (cfu/day) at the Powhatan Creek watershed outlet.

Parameter	ΣWLA	ΣLA	MOS*	TMDL
Future Load	5.44×10^7 (1% of LA)	5.44×10^9	–	–
James City County (VAR040037 & VAR040076)	6.69×10^8	–	–	–
City of Williamsburg (VAR040027 & VAR 040039)	1.07×10^7	–	–	–
Total	**7.34×10^8**	**5.44×10^9**	–	**6.17×10^9**

* Implicit Margin of Safety (MOS)

Chapter 6: TMDL Implementation and Reasonable Assurance

Once a TMDL has been approved by USEPA, measures must be taken to reduce pollution levels from both point and non point sources in the streams (see Section 1.2.2). For point sources, all new or revised VPDES/NPDES permits must be consistent with the TMDL WLA pursuant to 40 CFR §122.44 (d)(1)(vii)(B) and must be submitted to USEPA for approval. The measures for non point source reductions, which can include the use of better treatment technology and the installation of best management practices (BMPs), are implemented in an iterative process that is described along with specific BMPs in a TMDL implementation plan. The process for developing a TMDL implementation plan has been described in the "TMDL Implementation Plan Guidance Manual", published in July 2003 and available upon request from the VADEQ and VADCR TMDL project staff or at http://www.deq.virginia.gov/tmdl/implans/ipguide.pdf. With successful completion of implementation plans, local stakeholders should have a road map that can aid in restoring impaired waters. Having an approved implementation plan may enhance opportunities for obtaining financial and technical assistance during implementation.

6.1. Staged Implementation

In general, Virginia intends for bacteria reductions specified herein to be implemented in an iterative process that first addresses those sources with the largest impact on water quality.

Additionally, in both urban and rural areas, reducing the human bacteria loading from failing septic systems should be a primary implementation focus because of their health implications. These components could be implemented through education about septic tank pump-outs, a septic system installation/repair/replacement program, and the use of alternative waste treatment systems where needed. In urban areas, reducing the human bacteria loading from leaking sewer lines could be accomplished through a sanitary sewer inspection and management program. Other BMPs that might be readily implementable and that are appropriate for controlling urban wash-off from parking lots and roads include more restrictive ordinances to reduce fecal loads from pets, improved garbage collection and control, and improved street cleaning.

Implementing BMPs iteratively has several benefits:

1. It enables tracking of water quality improvements following BMP implementation through follow-up stream monitoring;
2. It provides a measure of quality control, given the uncertainties inherent in computer simulation modeling;
3. It provides a mechanism for developing public support through periodic updates on BMP implementation and water quality improvements;
4. It helps ensure that the most cost effective practices are implemented first; and
5. It allows for the evaluation of the adequacy of the TMDL in achieving water quality standards.

Watershed stakeholders will have opportunity to participate in the development of the TMDL implementation plan. While specific goals for BMP implementation will be established as part of the implementation plan development, the following Stage 1 scenarios are provided as guidance.

6.2. Stage 1 Scenarios

The goal of the Stage 1 implementation allocation scenarios is to reduce the bacteria loadings from controllable sources (excluding wildlife if possible) such that violations of the instantaneous criterion (235 cfu/100mL for *E. coli* and 104 cfu/100mL for enterococci) are less than 10.5 percent. The Stage 1 scenarios were generated with the same that was used to develop the TMDL allocation scenarios.

Because wildlife alone causes the instantaneous criterion to be violated more than 10.5% of the time, successful Stage 1 scenarios required wildlife reductions. For Mill Creek, the Stage 1 scenario requires extreme reductions from all anthropogenic and Wildlife sources (Table 6.1). Enterococci concentrations resulting from application of the fecal coliform to enterococci translator equation for the fecal coliform resulting from the source reductions shown in Table 6.1 are presented graphically in Figure 6.1 for Mill Creek.

Table 6.1. Allocation scenario for Stage 1 TMDL implementation for Mill Creek.

Fecal Coliform Loading Reduction (%)					% Violation of *enterococci* Standard	
Cropland	Pasture	Wildlife DD[a]	Residential	Forest	Geometric Mean	Instantaneous
90	90	98	90	0	49%	10%

[a] DD – Direct Deposit: Direct deposition of feces in stream.

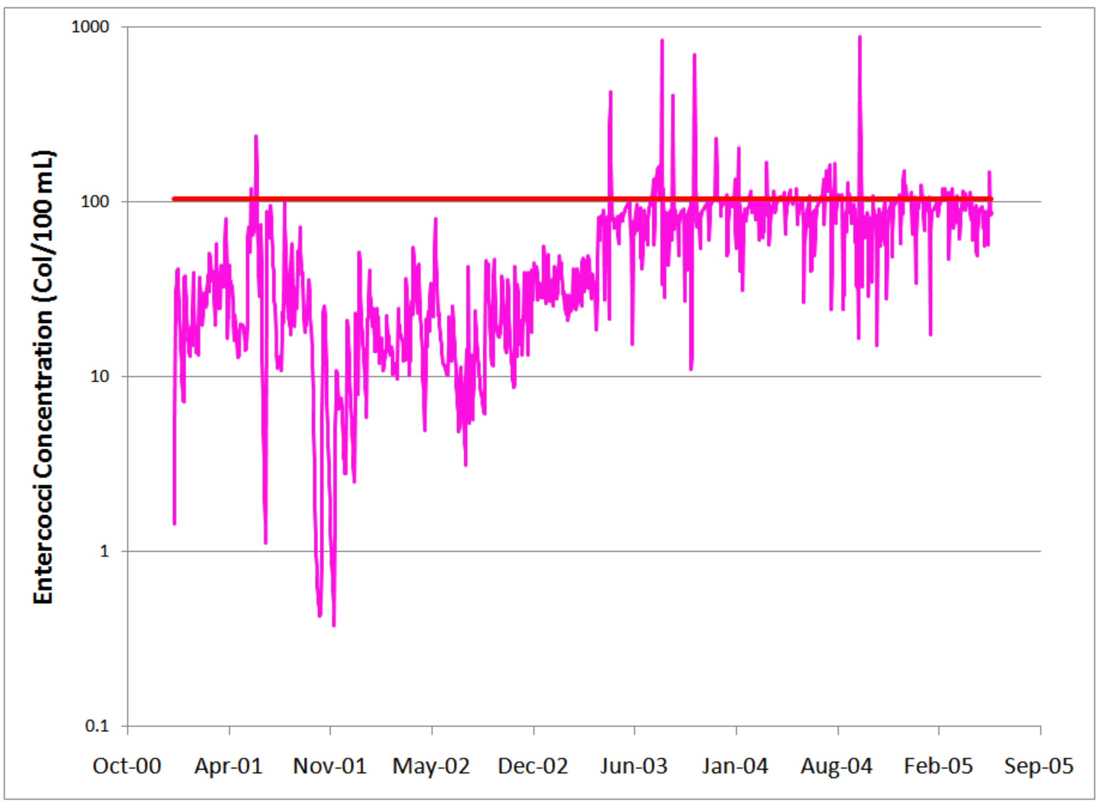

Figure 6.1. Simulated enterococci concentrations with the instantaneous criteria component of the bacteria standard for Stage 1 implementation for Mill Creek.

For Powhatan Creek, small reductions in land surface loads (agriculture) reduce the frequency of the instantaneous water quality criteria below the required 10.5%. The non-tidal section of the creek was more limiting than the tidal section. Therefore, the reductions determined for the non-tidal section were also applied to the land area immediately around the tidal section. The successful Stage 1 scenario for Powhatan Creek requires modest reductions in anthropogenic sources (Table 6.2 and Table 6.3). The *E.* coli and enterococci concentrations resulting from application of the translator equations to the Stage 1 fecal coliform concentrations for the scenarios in Table 6.2 and Table 6.3 are presented graphically in Figure 6.2 for the non-tidal section and Figure 6.3 for the tidal section of Powhatan Creek.

Table 6.2. Allocation scenarios for Stage 1 TMDL implementation for riverine section of Powhatan Creek.

Fecal Coliform Loading Reduction (%)				% Violation of *E. Coli* Standard	
Agriculture	**Wildlife DD**	**Residential**	**Forest**	**Geometric Mean**	**Instantaneous**
20	0	20	0	13%	10%

Table 6.3. Allocation scenarios for Stage 1 TMDL implementation for tidal section of Powhatan Creek.

Fecal Coliform Loading Reduction (%)					% Violation of *enterococci* Standard	
Agriculture	**Wildlife DD**	**Marinas**	**Residential**	**Forest**	**Geometric Mean**	**Instantaneous**
20	0	100	20	0	4%	<1%

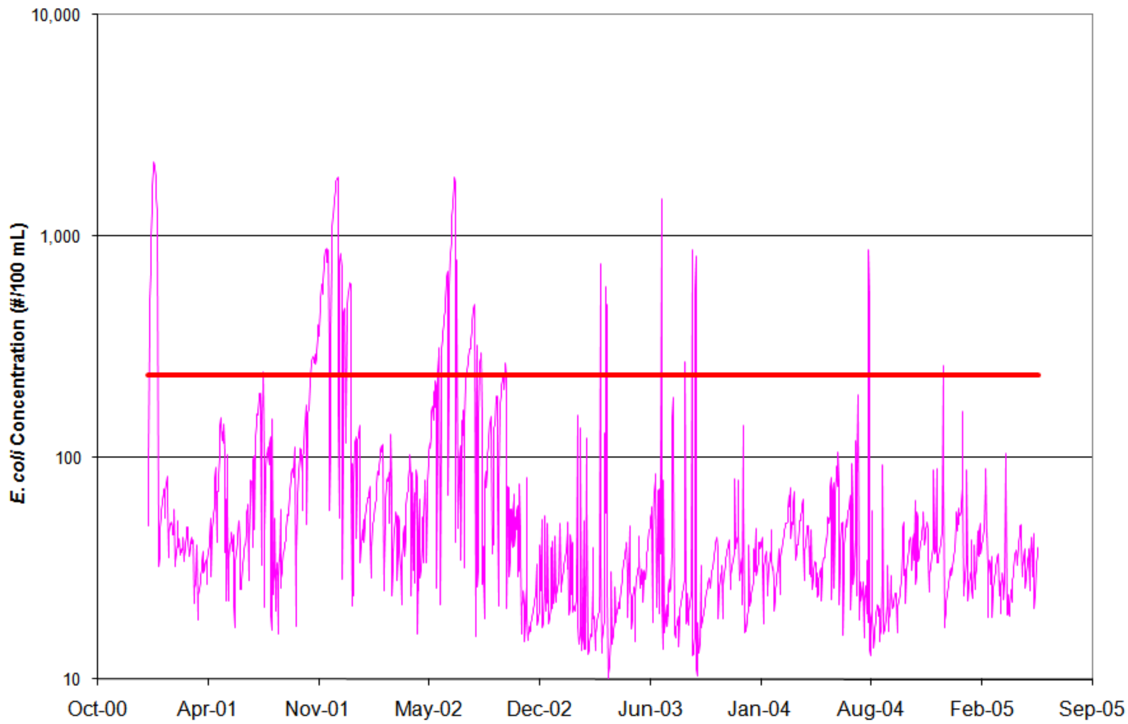

Figure 6.2. Simulated *E. coli* concentrations with the instantaneous criteria component of the bacteria standard for Stage 1 implementation for Powhatan Creek.

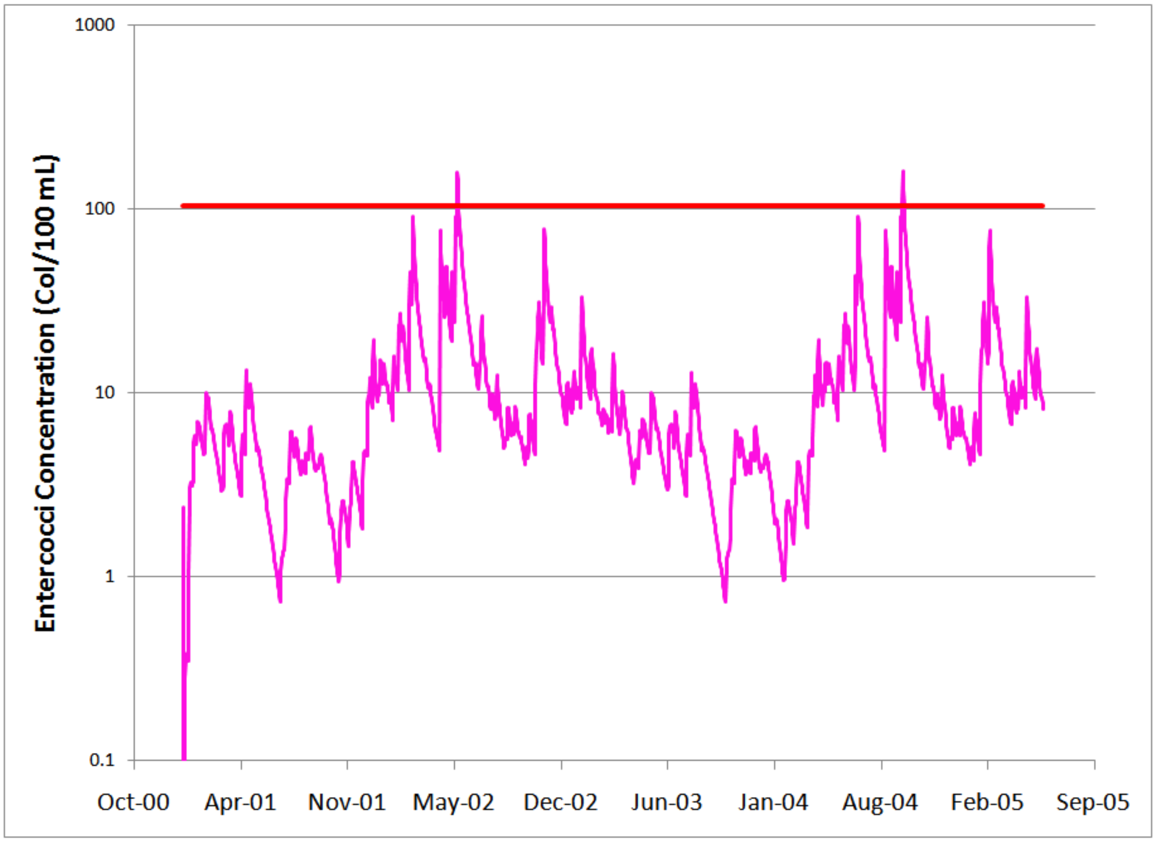

Figure 6.3. Simulated enterococci concentrations with the instantaneous criteria component of the bacteria standard for Stage 1 implementation for Powhatan Creek.

6.3. Link to Ongoing Restoration Efforts

Implementation of these TMDLs will contribute to on-going water quality improvement efforts aimed at restoring water quality in the both Mill Creek and Powhatan Creek watersheds.

6.4. Reasonable Assurance for Implementation

6.4.1. Follow-up Monitoring

Following the development of the TMDL, the VADEQ will make every effort to continue to monitor the impaired stream in accordance with its ambient monitoring program. VADEQ's Ambient Watershed Monitoring Plan for conventional pollutants calls for watershed monitoring to take place on a rotating basis, bi-monthly for two consecutive years of a six-year cycle. In accordance with VADEQ Guidance Memo No. 03-2004, during periods of reduced resources, monitoring can be temporarily discontinued until the TMDL staff determines that implementation measures to address the source(s) of impairments are being installed. Monitoring can resume at the start of the following fiscal year, next scheduled monitoring station rotation, or where deemed necessary by the regional office or TMDL staff, as a new special study.

The purpose, location, parameters, frequency, and duration of the monitoring will be determined by the VADEQ staff, in cooperation with VADCR staff, the TMDL Implementation Plan Steering Committee, and local stakeholders. Whenever possible, the location of the follow-up monitoring station(s) will be the same as the listing station. At a minimum, the monitoring station must be representative of the original impaired segment. The details of the follow-up monitoring will be outlined in an Annual Water Monitoring Plan prepared by each VADEQ Regional Office. Other agency personnel, watershed stakeholders, etc. may provide input on the Annual Water Monitoring Plan. These recommendations must be made to the VADEQ regional TMDL coordinator by September 30 of each year.

VADEQ staff, in cooperation with VADCR staff, the TMDL Implementation Plan Steering Committee, and local stakeholders, will continue to use data from the ambient monitoring stations to evaluate reductions in pollutants ("water quality milestones" as established in the TMDL Implementation Plan), the effectiveness of the TMDL in attaining and maintaining water quality standards, and the success of implementation efforts. Recommendations may then be made, when necessary, to target implementation efforts in specific areas and continue or discontinue monitoring at follow-up stations.

In some cases, watersheds will require monitoring above and beyond what is included in VADEQ's standard monitoring plan. Ancillary monitoring by citizens, watershed groups, local government, or universities is an option that may be used in such cases. An effort should be made to ensure that ancillary monitoring follows established QA/QC guidelines in order to maximize compatibility with VADEQ monitoring data. In instances where citizens' monitoring data are not available and additional monitoring is needed to assess the effectiveness of targeting efforts, TMDL staff may request of the monitoring managers in each regional office an increase in the number of stations or monitor existing stations at a higher frequency in the watershed. The additional monitoring beyond the original bimonthly single station monitoring will be contingent on staff resources and available laboratory budget. More information on citizen monitoring in Virginia and QA/QC guidelines is available at http://www.deq.virginia.gov/cmonitor/.

To demonstrate that the watershed is meeting water quality standards in watersheds where corrective actions have taken place (whether or not a TMDL or TMDL Implementation Plan has been completed), VADEQ must meet the minimum data requirements from the original listing station or a station representative of the originally listed segment. The minimum data requirement for conventional pollutants (bacteria, dissolved oxygen, etc) is bi-monthly monitoring for two consecutive years. For biological monitoring, the minimum requirement is two consecutive samples (one in the spring and one in the fall) in a one-year period.

6.4.2. Regulatory Framework

While section 303(d) of the Clean Water Act and current USEPA regulations do not require the development of TMDL implementation plans as part of the TMDL process, they do require reasonable assurance that the load and wasteload allocations (LA and WLA, respectively) can and will be implemented. USEPA also requires that all new or revised NPDES permits must be consistent with the TMDL WLA pursuant to 40 CFR §122.44 (d)(1)(vii)(B). All such permits should be submitted to USEPA for review.

Additionally, Virginia's 1997 Water Quality Monitoring, Information and Restoration Act (WQMIRA) directs the State Water Control Board (SWCB) to "develop and implement a plan to achieve fully supporting status for impaired waters" (Section 62.1-44.19.7). WQMIRA also establishes that the implementation plan shall include the date of expected achievement of water quality objectives, measurable goals, corrective actions necessary and the associated costs, benefits and environmental impacts of addressing the impairments. USEPA outlines the minimum elements of an approvable TMDL Implementation Plan in its 1999 "Guidance for Water Quality-Based Decisions: The TMDL Process." The listed elements include implementation actions/management measures, timelines, legal or regulatory controls, time required to attain water quality standards, monitoring plans and milestones for attaining water quality standards.

For the implementation of the WLA component of the TMDL, the Commonwealth intends to utilize the VPDES program, which typically includes consideration of the WQMIRA requirements during the permitting process. Requirements of the permit process should not be duplicated in the TMDL process, and with the exception of stormwater related permits, permitted sources are not usually addressed during the development of a TMDL implementation plan.

For the implementation of the TMDL's LA component, a TMDL Implementation Plan addressing at a minimum the WQMIRA requirements will be developed

Watershed stakeholders will have opportunities to provide input and to participate in the development of the TMDL Implementation Plan. Regional and local offices of VADEQ, VADCR, and other cooperating agencies are technical resources to assist in this endeavor.

In response to a Memorandum of Understanding (MOU) between USEPA and VADEQ, VADEQ also submitted a draft Continuous Planning Process to USEPA in which VADEQ commits to regularly updating the Water Quality Management Plans (WQMPs). Thus, the WQMPs will be, among other things, the repository for all TMDLs and TMDL Implementation Plans developed within a river basin.

VADEQ staff will present both USEPA-approved TMDLs and TMDL Implementation Plans to the SWCB for inclusion in the appropriate WQMP, in accordance with the Clean Water Act's Section 303(e) and Virginia's Public Participation Guidelines for Water Quality Management Planning.

VADEQ staff will also request that the SWCB adopt TMDL WLAs as part of the Water Quality Management Planning Regulation (9VAC 25-720), except in those cases when permit limitations are equivalent to numeric criteria contained in the Virginia Water Quality Standards, such as is the case for bacteria. This regulatory action is in accordance with §2.2-4006A.4.c and §2.2-4006B of the Code of Virginia. SWCB actions relating to water quality management planning are described in the public participation guidelines referenced above and can be found on VADEQ's web site under http://www.deq.state.va.us/tmdl/pdf/ppp.pdf.

6.4.3. Stormwater Permits

VADEQ and VADCR coordinate separate programs that regulate the management of pollutants carried by storm water runoff. VADEQ regulates storm water discharges associated with "industrial activities", while VADCR regulates storm water discharges from construction sites, and from municipal separate storm sewer systems (MS4s).

It is the intent of the Commonwealth that TMDL implement existing regulations and programs where they apply. More information is available on VADCR's web site through the following link: http://www.dcr.virginia.gov/soil_&_water/vsmp.shtml. Additional information on Virginia's Stormwater Management program and a downloadable menu of Best Management Practices and Measurable Goals Guidance can be found at http://www.dcr.virginia.gov/soil_&_water/stormwat.shtml.

6.4.4. Implementation Funding Sources

Cooperating agencies, organizations and stakeholders must identify potential funding sources available for implementation during the development of the implementation plan in accordance with the "Virginia Guidance Manual for Total Maximum Daily Load Implementation Plans". Potential sources for implementation may include the U.S. Department of Agriculture's Conservation Reserve Enhancement and Environmental Quality Incentive Programs, USEPA Section 319 funds, the Virginia State Revolving Loan Program, Virginia Agricultural Best Management Practices Cost-Share Programs, the Virginia

Water Quality Improvement Fund, tax credits and landowner contributions. The TMDL Implementation Plan Guidance Manual contains additional information on funding sources, as well as government agencies that might support implementation efforts and suggestions for integrating TMDL implementation with other watershed planning efforts.

6.4.5. Attainability of Primary Contact Recreation Use

In some streams for which TMDLs have been developed, including Mill and Powhatan Creeks, water quality modeling indicates that even after removal of all bacteria sources (other than wildlife), the stream will not attain standards under all flow regimes at all times. These streams may not be able to attain standards without some reduction in wildlife load.

With respect to these potential reductions in bacteria loads attributed to wildlife, Virginia and USEPA are not proposing the elimination of wildlife to allow for the attainment of water quality standards. However, if bacteria levels remain high and localized overabundant populations of wildlife are identified as the source, then measures to reduce such populations may be an option if undertaken in consultation with the Department of Game and Inland Fisheries (DGIF) or the United States Fish and Wildlife Service (USFWS). Additional information on DGIF's wildlife programs can be found at http://www.dgif.virginia.gov/wildlife/game/. While managing such overpopulations of wildlife remains as an option to local stakeholders, the reduction of wildlife or changing a natural background condition is not the intended goal of a TMDL.

To address the overall issue of attainability of the primary contact criteria, Virginia proposed during its latest triennial water quality standards review a new "secondary contact" category for protecting the recreational use in state waters. On March 25, 2003, the Virginia SWCB adopted criteria for "secondary contact recreation" which means "a water-based form of recreation, the practice of which has a low probability for total body immersion or ingestion of waters (examples include but are not limited to wading, boating and fishing)". These new criteria became effective on February 12, 2004 and can be found at http://www.deq.virginia.gov/wqs/rule.html.

In order for the new criteria to apply to a specific stream segment, the primary contact recreational use must be removed. To remove a designated use, the state must demonstrate 1) that the use is not an existing use, 2) that downstream uses are protected, and 3) that the source of contamination is natural and uncontrollable by effluent limitations and by implementing cost-effective and reasonable best management practices for nonpoint source control (9 VAC 25-260-10). This and other information is collected through a special study called a Use Attainability Analysis (UAA). All site-specific criteria or designated use changes must be adopted as amendments to the water quality standards regulations. Watershed stakeholders and EPA will be able to provide comment during this process. Additional information can be obtained at http://www.deq.virginia.gov/wqs/documents/WQS06_EDIT_001.pdf.

The process to address potentially unattainable reductions based on the above is as follows. First is the development of a stage 1 scenario such as those presented previously in this chapter. The pollutant reductions in the stage 1 scenario are targeted primarily at the controllable, anthropogenic bacteria sources identified in the TMDL, setting aside control strategies for wildlife except for cases of nuisance populations. During the implementation of the stage 1 scenario, all controllable sources would be reduced to the maximum extent practicable using the iterative approach described in Section 6.1 above. VADEQ will re-assess water quality in the stream during and subsequent to the implementation of the stage 1 scenario to determine if the water quality standard is attained. This effort will also evaluate if the modeling assumptions were correct. If water quality standards are not being met, and no additional cost-effective and reasonable best management practices can be identified, a UAA may be initiated with the goal of re-designating the stream for secondary contact recreation.

Chapter 7: Public Participation

The first public meeting was September 18, 2007 at the James City - Williamsburg Community Center. The purpose of this meeting was to inform the general public about the TMDL process and to receive further feedback about bacteria sources in Mill Creek and Powhatan Creek. Approximately 10 people attended this meeting, including personnel from VADEQ, VADCR, HRPDC, James City County and Virginia Tech.

The final public meeting was held on March 18, 2008 at James City - Williamsburg Community Center. Final allocation and Stage 1 scenarios were presented at this meeting. The report was available online prior to the meeting and copies of the executive summary were available at the meeting itself. Approximately 20 people attended the public meeting, including people from VADEQ, VADCR, HRPDC, James City County and Virginia Tech.

References

ASAE Standards, 45th edition. 1998. D384.1 DEC93. Manure production and characteristics. St. Joseph, Mich.: ASAE.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., T.H. Jobes, A.S. Donigian, Jr. and Johanson, R.C. 2001. *Hydrological Simulation Program – FORTRAN: HSPF Version 12 User's Manual*. Mountain View, CA: AQUA TERRA Consultants. In Cooperation with the U.S. Geological Survey and U.S. Environmental Protection Agency. 845 pp. Available at: http://www.epa.gov/waterscience/basins/b3docs/HSPF12.zip

Cappiella, K., and Brown, K. (2001). Impervious cover and land use in the Chesapeake Bay watershed. Ellicott City, MD: Center for Watershed Protection.

Census Bureau. 2000. Washington, D.C.: U.S. CensusBureau.(http://www.census.gov)

Duda, P., J. Kittle, Jr., M. Gray, P. Hummel, R. Dusenbury. 2001. WinHSPF, Version 2.0, An Interactive Windows Interface to HSPF, User Manual. Contract No. 68-C-98-010. USEPA. Washington D.C. pp. 95.

Engineering Concepts, Inc. 2006. Bacteria Total Maximum Daily Load Development for the Pamunkey River Basin. Virginia Department of Environmental Quality.

Geldreich, E.E. 1978. Bacterial populations and indicator concepts in feces, sewage, stormwater and solid wastes. In *Indicators of Viruses in Water and Food*, ed. G. Berg, ch. 4, 51-97. Ann Arbor, Mich.: Ann Arbor Science Publishers, Inc.

Hagedorn, C. 2006. Bacterial Source Tracking (BST): BST Methodologies. Available at: http://filebox.vt.edu/users/chagedor/biol_4684/BST/BSTmeth.html. Accessed 30 May 2007.

Harwood, V.J., B. Wiggins, C. Hagedorn, R.D. Ellender, J. Gooch, J. Kern, M. Samadpour, A.H. Chapman, and B.J. Robinson. Phenotypic library-based microbial source tracking methods: efficacy in the California collaborative study. *J. Water & Health*. 1:153-156.

Kim, S. M., B. L. Benham, K. M. Brannan, R. W. Zeckoski, G. R. Yagow, 2007b. Water Quality Calibration Criteria for Bacteria TMDL Development. Applied Engineering in Agriculture, 23(2): 171-176.

Kuo, A. Y. and K. Park, 1994, A PC-Based Tidal Prism Water Quality Model for Small Coastal Basins and Tidal Creeks. Special Report No. 324 in Applied Marine Science and Ocean Engineering, School of Marine Science/Virginia Institute of Marine Science, College of William and Mary, VA to the Virginia Coastal Resources Management Program, VADEQ.

Kuo, A. Y., K. Park, S. C. Kim, J. Lin, 2005, A Tidal Prism Water Quality Model for Small Coastal Basins. Coastal Management, 33:101–117, 2005

MapTech. 2007. Fecal Bacteria Total Maximum Daily Load Development for Pagan River. Draft TMDL Report.

McAllister, T. L., M. F. Overton, E. D. Brill, Jr., 1996, Cumulative Impact of Marinas on Estuarine Water Quality. Environmental Management, Vol. 20, No. 3, pp 385 – 396.

OEHS, 2004, Environmental Impact Review Varsity Hall Relocation Project, Charlottesville, VA, Office of Environmental health and Safety, University of Virginia, Wenger, Jessica S and Sitler, CPG, Jeffrey A,

RESAC. 2000. Overview of land cover mapping for the Mid-Atlantic RESAC. Regional Earth Science Application Center, University of Maryland. Available at: http://www.geog.umd.edu/resac/overview.htm. Accessed 24 May 2007.

SERCC. 2007. WISE 1 SE, VIRGINIA (449215) Period of Record Monthly Climate Summary. Southeast Regional Climate Center. Available at: http://cirrus.dnr.state.sc.us/cgi-bin/sercc/cliMAIN.pl?va9215. Accessed 24 May 2007.

Stoeckel, D.M., M.V. Mathes, K.E. Hyer, C. Hagedorn, H. Kator, J. Lukasik, T. O'Brien, T.W. Fenger, M. Samadpour, K.M. Strickler, and B.A. Wiggins. 2004. Comparison of seven protocols to identify fecal contamination sources using *Escherichia coli*. *Env. Sci. and Tech.* 38(22):6109-6117.

SWCB (State Water Control Board). 2006. 9 VAC 25-260 Virginia Water Quality Standards. Available at: http://www.deq.virginia.gov/wqs/documents/WQS06_EDIT_001.pdf. Accessed 30 May 2007.
USEPA. 1991. Guidance for Water Quality-based Decisions: The TMDL Process. EPA 440/4-91-001. Washington, D.C.: Office of Water, USEPA.
USEPA. 2000. BASINS Technical Note 6: Estimating Hydrology and Hydraulic Parameters for HSPF. EPA-823-R00-012. Washington, D.C.: Office of Water, USEPA. Available at: http://www.epa.gov/waterscience/basins/docs/tecnote6.pdf. Accessed 30 May 2007.
USEPA, 2002, Onsite Wastewater Treatment Systems Manual. EPA/625/R-00/008. Washington, DC
USEPA. 2006. An Approach for Using Load Duration Curves in Developing TMDLs. Draft document received via email from DEQ on June 20, 2007. Electronic name: Duration Curve Guide(Draft – 2006-12-15).pdf. Washington, D.C.: Office of Wetlands, Oceans, & Watersheds, USEPA.
USGS, 1997, GROUND WATER ATLAS of the UNITED STATES: Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia, Henry Trapp, Jr. and Marilee A. Horn, U.S. Geological Survey, HA 730-L. http://capp.water.usgs.gov/gwa/ch_l/index.html.
USGS and USEPA. 1999. National Hydrography Dataset. http://nhd.usgs.gov/.
VADEQ, 2003. Guidence Memo No. 03-XXXXa – Bacteria TMDLs: Model Calibration and Verification. 1/23/2003.
VADEQ. 2006. 2006 303(d) Report on Impaired Waters. Richmond, Va: VADEQ. Available at: http://www.deq.virginia.gov/wqa/ir2006.html Accessed 30 June 2007.
Woods, A.J., J.M. Omernik, and D.D. Brown. 1999. Level III and IV Ecoregions of Delaware, Maryland, Pennsylvania, Virginia, and West Virginia. USEPA: Corvallis, Oregon. Available at: ftp://ftp.epa.gov/wed/ecoregions/reg3/reg3_eco_desc.doc. Accessed 30 May 2007.
Yagow, G. 2001. Fecal Coliform TMDL: Mountain Run Watershed, Culpeper County, Virginia. Available at: http://www.deq.state.va.us/tmdl/apptmdls/rapprvr/mtrnfec.pdf. Accessed 30 May 2007.
Zeckoski, R.W., B.L. Benham, S.B. Shah, M.L. Wolfe, K.M. Brannan, M. Al-Smadi, T.A. Dillaha, S. Mostaghimi, and C.D. Heatwole. 2005. BSLC: A Tool for Bacteria Source Characterization for Watershed Management. *Applied Engineering*. 21(5): 879-889.

Appendix A: Glossary of Terms

Allocation

That portion of a receiving water's loading capacity that is attributed to one of its existing or future pollution sources (nonpoint or point) or to natural background sources.

Allocation Scenario

A proposed series of point and nonpoint source allocations (loadings from different sources), which are being considered to meet a water quality planning goal.

ARA (Antibiotic Resistance Analysis)

A bacterial source tracking technique that uses the expected varying antibiotic resistance of bacteria from different sources to identify the contributors of fecal bacteria. Bacteria from humans are expected to have the highest antibiotic resistance, while domestic and wildlife animal sources are expected to have lower antibiotic resistance (Hagedorn, 2006).

Background levels

Levels representing the chemical, physical, and biological conditions that would result from natural geomorphological processes such as weathering and dissolution.

BASINS (Better Assessment Science Integrating Point and Nonpoint Sources)

A computer-run tool that contains an assessment and planning component that allows users to organize and display geographic information for selected watersheds. It also contains a modeling component to examine impacts of pollutant loadings from point and nonpoint sources and to characterize the overall condition of specific watersheds.

Best Management Practices (BMP)

Methods, measures, or practices that are determined to be reasonable and cost-effective means for a land owner to meet certain, generally nonpoint source, pollution control needs. BMPs include structural and nonstructural controls and operation and maintenance procedures.

Bacteria Source Tracking

A collection of scientific methods used to track sources of fecal coliform.

Calibration

The process of adjusting model parameters within physically defensible ranges until the resulting predictions give a best possible good fit to observed data.

Die-off (of fecal coliform)

Reduction in the fecal coliform population due to predation by other bacteria as well as by adverse environmental conditions (e.g., UV radiation, pH).

Direct nonpoint sources

Sources of pollution that are defined statutorily (by law) as nonpoint sources that are represented in the model as point source loadings due to limitations of the model. Examples include: direct deposits of fecal material to streams from livestock and wildlife.

Failing septic system

Septic systems in which drain fields have failed such that effluent (wastewater) that is supposed to percolate into the soil, now rises to the surface and ponds on the surface where it can flow over the soil surface to streams or contribute pollutants to the surface where they can be lost during storm runoff events.

Fecal coliform

A type of bacteria found in the feces of various warm-blooded animals that is used as indicator of the possible presence of pathogenic (disease causing) organisms. *E. coli* bacteria are a subset of this group found to more closely correlate with human health problems.

Geometric mean

The geometric mean is simply the nth root of the product of n values. Using the geometric mean lessens the significance of a few extreme values (extremely high or low values). In practical terms, this means that if you have just a few bad samples, their weight is lessened.

Mathematically the geometric mean, $\overline{x}_g$, is expressed as:

$$\overline{x}_g = \sqrt[n]{x_1 \cdot x_2 \cdot x_3 \ldots \cdot x_n}$$

where n is the number of samples, and x_i is the value of sample i.

HSPF (Hydrological Simulation Program-Fortran)

A computer-based model that calculates runoff, sediment yield, and fate and transport of various pollutants to the stream. The model was developed under the direction of the U.S. Environmental Protection Agency (EPA).

Hydrology

The study of the distribution, properties, and effects of water on the earth's surface, in the soil and underlying rocks, and in the atmosphere.

Instantaneous or Single Sample criterion

The instantaneous criterion or instantaneous water quality standard is the value of the water quality standard that should not be exceeded at any time. For example, the Virginia instantaneous water quality standard for *E. coli* is 235 cfu/100 mL. If this value is exceeded at any time, the water body is in violation of the state water quality standard.

Load allocation (LA)

The portion of a receiving water's loading capacity that is attributed either to one of its existing or future nonpoint sources of pollution or to natural background.

Margin of Safety (MOS)

A required component of the TMDL that accounts for the uncertainty about the relationship between the pollutant loads and the quality of the receiving waterbody. The MOS is normally incorporated into the conservative assumptions used to develop TMDLs (generally within the calculations or models).

Model

Mathematical representation of hydrologic and water quality processes. Effects of land use, slope, soil characteristics, and management practices are included.

Nonpoint source

Pollution that is not released through pipes but rather originates from multiple sources over a relatively large area. Nonpoint sources can be divided into source activities related to either land or water use including failing septic tanks, improper animal-keeping practices, forest practices, and urban and rural runoff.

Pathogen

Disease-causing agent, especially microorganisms such as bacteria, protozoa, and viruses.

Point source

Pollutant loads discharged at a specific location from pipes, outfalls, and conveyance channels from either municipal wastewater treatment plants or industrial waste treatment facilities. Point sources can also include pollutant loads contributed by tributaries to the main receiving water stream or river.

Pollution

Generally, the presence of matter or energy whose nature, location, or quantity produces undesired environmental effects. Under the Clean Water Act for example, the term is defined as the man-made or man-induced alteration of the physical, biological, chemical, and radiological integrity of water.

Reach

Segment of a stream or river.

Runoff

That part of rainfall or snowmelt that runs off the land into streams or other surface water. It can carry pollutants from the air and land into receiving waters.

Septic system

An on-site system designed to treat and dispose of domestic sewage. A typical septic system consists of a tank that receives liquid and solid wastes from a residence or business and a drainfield or subsurface absorption system consisting of a series of tile or percolation lines for disposal of the liquid effluent. Solids (sludge) that remain after decomposition by bacteria in the tank must be pumped out periodically.

Simulation

The use of mathematical models to approximate the observed behavior of a natural water system in response to a specific known set of input and forcing conditions. Models that have been validated, or verified, are then used to predict the response of a natural water system to changes in the input or forcing conditions.

Straight pipe

Delivers wastewater directly from a building, e.g., house, milking parlor, to a stream, pond, lake, or river.

Total Maximum Daily Load (TMDL)

The sum of the individual wasteload allocations (WLA's) for point sources, load allocations (LA's) for nonpoint sources and natural background, plus a margin of safety (MOS). TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures that relate to a state's water quality standard.

Urban Runoff

Surface runoff originating from an urban drainage area including streets, parking lots, and rooftops.

Validation (of a model)

Process of determining how well the mathematical model's computer representation describes the actual behavior of the physical process under investigation. This follows the calibration of the model and ensures that the calibrated values adequately represent the watershed.

Wasteload allocation (WLA)

The portion of a receiving water's loading capacity that is allocated to one of its existing or future point sources of pollution. WLAs constitute a type of water quality-based effluent limitation.

Water quality standard

Law or regulation that consists of the beneficial designated use or uses of a water body, the numeric and narrative water quality criteria that are necessary to protect the use or uses of that particular water body, and an anti-degradation statement.

Watershed

A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

For more definitions, see the Virginia Cooperative Extension publications available online:

Glossary of Water-Related Terms. Publication 442-758.
http://www.ext.vt.edu/pubs/bse/442-758/442-758.html

and

TMDLs (Total Maximum Daily Loads) - Terms and Definitions. Publication 442-550.
http://www.ext.vt.edu/pubs/bse/442-550/442-550.html

Appendix B: Sample Calculation of Cattle
(Sub-watershed 01 Mill Creek)

Sample Calculation: Distribution of Cattle

(Sub-watershed 01 during October for Existing Conditions)

(Note: Due to rounding, the numbers may not add up.)

There are 25 beef cattle in sub-watershed 01.

1. During October, no stockers are present, so reduce population accordingly (there are 25 pairs and no bulls in sub-watershed 01; in October there are just cows and no calves, so each pair is 1000 lb worth of cattle):
2. Because there is no confinement, cattle are on pasture or in the stream.

   Beef cattle on pasture = 25
3. There is no stream access.
4. After calculating the number of cattle defecating in the stream, the number of cattle defecating on the pasture is calculated by subtracting the number of cattle defecating in the stream (Step 5) from the number of cattle in pasture and stream (Step 2):

   Beef cattle defecating on pasture = 25

Appendix C: Weather Data Preparation

Introduction

A weather data file for providing the weather data inputs into the HSPF Model was created for the period January 1992 through May 2005 using the Watershed Data Management Utility (WDMUtil). Raw data required for creating the weather data file included daily precipitation (in.), average daily temperatures (maximum, minimum, and dew point) (°F), average daily wind speed (mi/hr), total daily solar radiation (Langleys), and percent sun. The primary data source was the National Climatic Data Center's (NCDC) Cooperative Weather Station 449151 in Williamsburg, Virginia, which was located about 2 miles east of the watersheds. Data from other NCDC stations were also used where Williamsburg data were missing. The raw data required varying amounts of preprocessing within WDMUtil to obtain the following hourly values: precipitation (PREC) (in), air temperature (ATEM) (°F), dew point temperature (DEWP) (°F), solar radiation (SOLR) (Langleys), wind speed (WIND) (mi/hr), potential evapotranspiration (PEVT) (in), potential evaporation (EVAP) (in), and cloud cover (CLOU) (tenths, range 0-10). The final WDM file contains these hourly datasets.

Raw data collection and processing

Weather data were obtained from the NCDC's weather stations in Williamsburg, VA (449151, Lat./Long. 37°18'N / 76°42'W, elevation 70 ft); Wakefield, VA (448800, LAT/LON: 36°59'N / 77°00'W, elevation 200 ft); Painter, VA (446475, LAT/LON: 37°35'N / 75°49'W elevation 30 ft); Lynchburg Airport, VA (445120, Lat./Long. 37°20'N/79°12'W, elevation 286.5 ft), and Richmond Airport, VA (447201 LAT/LON: 37°30'N / 77°19'W. elevation 164). While deciding on the period of record for the weather WDM file, availability of flow and water quality data was considered in addition to the availability and quality of weather data. Percent sun (PSUN) data were available from Lynchburg Airport and then only through July 1996. The majority of the water quality data were collected from 1995 through 2006. In order to make the best use of the available water quality data, the period of record was chosen to be July 1992-May 2005. The period ended on May-2005 due to the lack of dewpoint temperature available at a nearby station past this date. There are 1,611 days within this period. Substitutions for missing data are described below. The procedures used to process the raw data to obtain finished data required for input to HSPF are also described in the following sections.

1. Hourly Precipitation
   Daily precipitation (PRCP) data were downloaded from NCDC's web site for Williamsburg, VA for the July 1992-October 2006 period. Missing values from Williamsburg data were filled in with the hourly precipitation (PRCP) from Wakefield and disaggregated daily data from Williamsburg. The resulting file was imported into WDMUtil, disaggregated to hourly precipitation using WDMUtil's disaggregation routine and given the constituent label "PREC."

2. Temperature
   Separate daily maximum temperature (TMAX) and daily minimum temperature (TMIN) files were downloaded from the NCDC website for Williamsburg. Daily dew point temperature (DPTP) was taken from the Richmond Airport. These data had units of tenths of degrees Fahrenheit. The *disaggregate temperature* function in WDMUtil was used to create an hourly average temperature file (ATEM). The *disaggregate dewpoint temperature* function in WDMUtil was used to create an hourly dewpoint temperature file (DEWP).

3. Average Daily Wind Speed
   Average daily wind speed (AWND) was not recorded at the Williamsburg station; therefore, average daily wind speed was obtained from the Richmond Airport. The units of the data were tenths of miles per hour; therefore, the timseries was divided by a factor of 10 prior to use in the WDM file. The *compute wind travel* function in WDMUtil was used to calculate the total wind travel in miles/day. Then the *disaggregate wind travel* function in WDMUtil was used to calculate the hourly wind speed throughout the day (WIND) using the distribution coefficients shown in Table C. 1.

Table C. 1. Hourly Distribution Coefficients for Wind Speed.

Hour	12	1	2	3	4	5	6	7	8	9	10	11
AM	0.035	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.035	0.037	0.041	0.046
PM	0.05	0.053	0.054	0.058	0.057	0.056	0.05	0.043	0.04	0.038	0.036	0.036

4. Cloud cover and solar radiation
   In the absence of daily cloud cover, percent sun (PSUN) can be used to estimate DCLO. DCLO is used by WDMUtil to estimate hourly cloud cover in tenths (CLOU) as well as solar radiation (SOLR) in Langleys. The closest weather station that recorded PSUN was Lynchburg and Richmond Airports, and these data was used to develop the weather file. The *compute percent cloud cover* function in WDMUtil was used to calculate the daily percent cloud cover in tenths (DCLO) from PSUN. Because there is not a *disaggregate percent cloud cover* function available, the *disaggregate wind travel* function was used with hourly distribution coefficients all set to 1 to calculate the hourly percent cloud cover in tenths (CLOU).

   The *compute solar radiation* function in WDMUtil was used to calculate the daily solar radiation in Langleys (DSOL) from DCLO and the Williamsburg station latitude (37°18'N). The *disaggregate solar radiation* function was then used to calculate the hourly solar radiation (SOLR).

5. Evaporation/Evapotranspiration
   Two types of evaporation/evapotranspiration are required for input to HSPF: potential evaporation from a reach or reservoir surface (EVAP), represented as Penman pan evaporation; and potential evapotranspiration (PEVT), represented as Hamon potential evapotranspiration.

   The *compute Penman pan evaporation* function in WDMUtil was used to calculate daily Penman pan evaporation (DEVP) from TMIN, TMAX, DPTP, TWND, and DSOL. Then the *disaggregate evapotranspiration* function was used to calculate EVAP from DEVP.

   The *compute Hamon PET* function in WDMUtil was used to calculate daily potential evapotranspiration (DEVT) from TMIN, TMAX, the Willaimsburg station latitude (37°18'N), and monthly coefficients all equal to 0.005. Then the *disaggregate evapotranspiration* function was used to calculate PEVT from DEVT.

Summary of weather data preparation

The weather data were prepared for input to HSPF as described in the previous section. A summary of the NCDC input parameters, WDMUtil functions used, and final HSPF parameters is presented in Table C.2

Table C. 2. Weather parameters and processing in WDMUtil required for HSPF modeling.

NCDC Input Parameters	Intermediate Input	WDMUtil Functions	Intermediate Output	Final HSPF Parameter
PRCP	--	Disaggregate precipitation	--	PREC
TMAX, TMIN	--	Disaggregate temperature	--	ATEM
DPTP	--	Disaggregate dewpoint temperature	--	DEWP
PSUN	--	Compute percent cloud cover	DCLO	--
	DCLO	Disaggregate wind travel[1]	--	CLOU
	DCLO	Compute solar radiation	DSOL	--
	DSOL	Disaggregate solar radiation	--	SOLR
AWND	--	Compute wind travel	TWND	--
	TWND	Disaggregate wind travel	--	WIND
TMAX, TMIN, DPTP	TWND, DSOL	Compute Penman pan evaporation	DEVP	--
	DEVP	Disaggregate evapotranspiration	--	EVAP
TMAX, TMIN	--	Compute Hamon PET	DEVT	--
	DEVT	Disaggregate evapotranspiration	--	PEVT

[1]all hourly coefficients set to 1

Appendix D: HSPF Parameters that Vary by Month or Land Use

Table D. 1. PWAT-PARM2 parameters varying by land use.

Land Use	INFILT (in/hr)	SLSUR (ft/ft)	
		MC*	PC**
Forest	0.200	0.0433	0.0433
Pasture	0.200	0.0433	0.0433
Cropland	0.200	0.0433	0.0433
High Density Residential	0.200	0.0433	0.0433
Low Density Residential	0.200	0.0433	0.0433

*MC – Mill Creek
*PC – Powhatan Creek

Table D. 2. MON-INTERCEP (monthly CEPSC) - Monthly Interception Storage.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Forest	0.08	0.08	0.20	0.21	0.23	0.25	0.25	0.25	0.25	0.11	0.10	0.06
HDR	0.06	0.06	0.09	0.10	0.14	0.12	0.12	0.12	0.12	0.09	0.04	0.09
LDR	0.06	0.06	0.09	0.10	0.14	0.12	0.12	0.12	0.12	0.09	0.04	0.09
Pasture	0.06	0.06	0.15	0.16	0.18	0.17	0.19	0.19	0.18	0.08	0.07	0.04
Crop	0.07	0.07	0.17	0.18	0.20	0.19	0.22	0.22	0.22	0.14	0.08	0.08

Table D. 3. MON-LZETP - Monthly Lower Zone Evapotranspiration Parameter.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Forest	0.20	0.20	0.56	1.63	1.70	1.95	1.17	1.17	1.17	0.31	0.20	0.12
HDR	0.77	0.77	0.65	1.52	1.94	1.55	0.93	0.93	0.93	0.22	0.22	0.46
LDR	0.77	0.77	0.65	1.52	1.94	1.55	0.93	0.93	0.93	0.22	0.22	0.46
Pasture	0.20	0.20	0.58	1.64	1.70	1.95	1.17	1.17	1.17	0.31	0.20	0.12
Crop	0.20	0.20	0.58	1.64	1.70	1.95	1.17	1.17	1.17	0.31	0.20	0.12

Table D. 4. MON-ACCUM (monthly accumulation) table - values in cfu/acre/day for fecal coliform for Mill Creek.

Sub[†]	Land Use[*]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Pasture	9.50E+10	1.10E+11	1.20E+11	1.20E+11	1.20E+11	1.20E+11	1.30E+11	1.30E+11	1.30E+11	8.30E+10	8.70E+10	9.10E+10
1	Cropland	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07	4.80E+07
1	LDR	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09
1	HDR	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10	2.10E+10
1	Forest	7.20E+07	7.20E+07	6.40E+07	6.40E+07	6.40E+07	6.40E+07	6.40E+07	6.40E+07	7.20E+07	7.20E+07	7.20E+07	7.20E+07
2	LDR	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09	5.60E+09
2	HDR	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10
2	Forest	5.20E+08	5.20E+08	3.80E+08	3.80E+08	3.80E+08	3.80E+08	3.80E+08	3.80E+08	5.20E+08	5.20E+08	5.20E+08	5.20E+08
3	LDR	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08	9.20E+08
3	HDR	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09	8.80E+09
3	Forest	2.60E+08	2.60E+08	2.10E+08	2.10E+08	2.10E+08	2.10E+08	2.10E+08	2.10E+08	2.60E+08	2.60E+08	2.60E+08	2.60E+08
4	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	HDR	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10	6.90E+10
4	Forest	4.40E+08	4.40E+08	3.30E+08	3.30E+08	3.30E+08	3.30E+08	3.30E+08	3.30E+08	4.40E+08	4.40E+08	4.40E+08	4.40E+08
5	LDR	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06	7.90E+06
5	HDR	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10
5	Forest	2.70E+08	2.70E+08	2.10E+08	2.10E+08	2.10E+08	2.10E+08	2.10E+08	2.10E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08
6	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	HDR	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10	7.80E+10
6	Forest	2.90E+08	2.90E+08	2.60E+08	2.60E+08	2.60E+08	2.60E+08	2.60E+08	2.60E+08	2.90E+08	2.90E+08	2.90E+08	2.90E+08
7	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	HDR	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10	3.30E+10
7	Forest	2.00E+08	2.00E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	2.00E+08	2.00E+08	2.00E+08	2.00E+08
8	LDR	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09	1.20E+09
8	HDR	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10
8	Forest	1.60E+08	1.60E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.60E+08	1.60E+08	1.60E+08	1.60E+08
9	LDR	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08
9	HDR	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09	7.20E+09
9	Forest	5.10E+08	5.10E+08	4.20E+08	4.20E+08	4.20E+08	4.20E+08	4.20E+08	4.20E+08	5.10E+08	5.10E+08	5.10E+08	5.10E+08

[†] Sub = sub-watershed number
[*] LDR = low density residential
HDR = high density residential

Table D. 5. MON- SQOLIM (monthly accumulation) table - values in cfu/acre/day for fecal coliform for Mill Creek.

Sub[†]	Land Use[*]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Pasture	8.50E+11	1.10E+12	1.10E+12	1.10E+12	1.10E+12	1.10E+12	1.20E+12	1.20E+12	1.10E+12	7.40E+11	7.40E+11	8.20E+11
1	Cropland	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08	4.30E+08
1	LDR	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10	2.30E+10
1	HDR	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11	1.90E+11
1	Forest	6.50E+08	6.50E+08	5.80E+08	5.80E+08	5.80E+08	5.80E+08	6.40E+07	5.80E+08	6.50E+08	6.50E+08	6.50E+08	6.50E+08
2	LDR	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10	5.00E+10
2	HDR	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11	1.30E+11
2	Forest	4.70E+09	4.70E+09	3.40E+09	3.40E+09	3.40E+09	3.40E+09	3.40E+09	3.40E+09	4.70E+09	4.70E+09	4.70E+09	4.70E+09
3	LDR	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09	8.30E+09
3	HDR	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10	7.90E+10
3	Forest	2.30E+09	2.30E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	2.30E+09	2.30E+09	2.30E+09	2.30E+09
4	LDR	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01
4	HDR	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11	6.20E+11
4	Forest	3.90E+09	3.90E+09	3.00E+09	3.00E+09	3.00E+09	3.00E+09	3.00E+09	3.00E+09	3.90E+09	3.90E+09	3.90E+09	3.90E+09
5	LDR	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07	7.10E+07
5	HDR	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11
5	Forest	2.50E+09	2.50E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	2.50E+09	2.50E+09	2.50E+09	2.50E+09
6	LDR	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01
6	HDR	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11	1.40E+11
6	Forest	2.50E+09	2.50E+09	1.90E+08	2.60E+08	2.60E+08	2.60E+08	2.60E+08	2.60E+08	2.90E+08	2.90E+08	2.90E+08	2.90E+08
7	LDR	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01
7	HDR	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11	3.30E+11
7	Forest	1.80E+09	1.80E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.80E+09	1.80E+09	1.80E+09	1.80E+09
8	LDR	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10	1.10E+10
8	HDR	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10
8	Forest	1.50E+09	1.50E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09
9	LDR	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09
9	HDR	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10	6.50E+10
9	Forest	4.60E+09	4.60E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	4.60E+09	4.60E+09	4.60E+09	4.60E+09

[†] Sub = sub-watershed number
[*] LDR = low density residential
HDR = high density residential

Table D. 6. MON-ACCUM (monthly accumulation) table - values in cfu/acre/day for fecal coliform for Powhatan Creek.

Sub[†]	Land Use[*]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Pasture	4.60E+10	5.40E+10	9.40E+10	9.60E+10	9.80E+10	1.00E+11	1.00E+11	1.10E+11	1.10E+11	6.70E+10	7.00E+10	4.40E+10
1	Cropland	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09
1	LDR	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09
1	HDR	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10	1.40E+10
1	Forest	4.90E+07	4.90E+07	4.40E+07	4.40E+07	4.40E+07	4.40E+07	4.40E+07	4.40E+07	4.90E+07	4.90E+07	4.90E+07	4.90E+07
2	Cropland	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07	5.10E+07
2	LDR	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07
2	HDR	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10
2	Forest	2.30E+08	2.30E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	1.70E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08
3	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	HDR	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11
3	Forest	1.30E+08	1.30E+08	1.00E+08	1.00E+08	1.00E+08	1.00E+08	1.00E+08	1.00E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08
4	Cropland	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07	5.00E+07
4	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	HDR	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11	1.10E+11
4	Forest	7.70E+07	7.70E+07	3.30E+08	3.30E+08	3.30E+08	3.30E+08	3.30E+08	3.30E+08	7.70E+07	7.70E+07	7.70E+07	7.70E+07
5	HDR	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12	1.40E+12
5	Forest	1.60E+08	1.60E+08	1.10E+08	1.10E+08	1.10E+08	1.10E+08	1.10E+08	1.10E+08	1.60E+08	1.60E+08	1.60E+08	1.60E+08
6	LDR	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06	7.80E+06
6	HDR	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09	6.80E+09
6	Forest	2.70E+08	2.70E+08	2.20E+08	2.20E+08	2.20E+08	2.20E+08	2.20E+08	2.20E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08
7	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	HDR	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08
7	Forest	1.50E+08	1.50E+08	1.20E+08	1.20E+08	1.20E+08	1.20E+08	1.20E+08	1.20E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08
8	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	HDR	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10	1.50E+10
8	Forest	1.90E+08	1.90E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.90E+08	1.90E+08	1.90E+08	1.90E+08
9	LDR	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08
9	HDR	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10	4.60E+10
9	Forest	9.70E+07	9.70E+07	7.80E+07	7.80E+07	7.80E+07	7.80E+07	7.80E+07	7.80E+07	9.70E+07	9.70E+07	9.70E+07	9.70E+07

[†] Sub = sub-watershed number
[*] LDR = low density residential
HDR = high density residential

Table D. 7. MON-ACCUM (monthly accumulation) table - values in cfu/acre/day for fecal coliform for Powhatan Creek (Continued).

Sub[†]	Land Use[*]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10	LDR	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09	6.10E+09
10	HDR	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09	5.90E+09
10	Forest	1.00E+08	1.00E+08	8.60E+07	8.60E+07	8.60E+07	8.60E+07	8.60E+07	8.60E+07	1.00E+08	1.00E+08	1.00E+08	1.00E+08
11	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	HDR	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09	6.30E+09
11	Forest	4.20E+08	4.20E+08	3.20E+08	3.20E+08	3.20E+08	3.20E+08	3.20E+08	3.20E+08	4.20E+08	4.20E+08	4.20E+08	4.20E+08
12	LDR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	HDR	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09	4.20E+09
12	Forest	6.00E+08	6.00E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	6.00E+08	6.00E+08	6.00E+08	6.00E+08
13	LDR	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10	1.30E+10
13	HDR	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08	7.30E+08
13	Forest	1.80E+08	1.80E+08	1.60E+08	1.60E+08	1.60E+08	1.60E+08	1.60E+08	1.60E+08	1.80E+08	1.80E+08	1.80E+08	1.80E+08
14	LDR	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09
14	HDR	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10	2.00E+10
14	Forest	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08	2.70E+08
15	LDR	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08
15	HDR	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09	9.50E+09
15	Forest	2.90E+08	2.90E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.30E+08	2.90E+08	2.90E+08	2.90E+08	2.90E+08
16	LDR	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09	2.60E+09
16	HDR	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09	3.80E+09
16	Forest	1.10E+08	1.10E+08	9.50E+07	9.50E+07	9.50E+07	9.50E+07	9.50E+07	9.50E+07	1.10E+08	1.10E+08	1.10E+08	1.10E+08
17	LDR	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09	1.50E+09
17	HDR	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09	9.40E+09
17	Forest	1.60E+09	1.60E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.40E+09	1.60E+09	1.60E+09	1.60E+09	1.60E+09

[†] Sub = sub-watershed number
[*] LDR = low density residential
HDR = high density residential

Table D. 8. MON-SQOLIM (monthly limit on surface accumulation) table - values in cfu/day for fecal coliform for Powhatan Creek.

1	Pasture	4.14E+11	4.86E+11	8.46E+11	8.64E+11	8.82E+11	9.00E+11	9.00E+11	9.90E+11	9.90E+11	6.03E+11	6.30E+11	3.96E+11
1	Cropland	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10
1	LDR	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10
1	HDR	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11	1.26E+11
1	Forest	4.41E+08	4.41E+08	3.96E+08	3.96E+08	3.96E+08	3.96E+08	3.96E+08	3.96E+08	4.41E+08	4.41E+08	4.41E+08	4.41E+08
2	Cropland	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08	4.59E+08
2	LDR	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07	9.00E+07
2	HDR	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11
2	Forest	2.07E+09	2.07E+09	1.53E+09	1.53E+09	1.53E+09	1.53E+09	1.53E+09	1.53E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09
3	LDR	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
3	HDR	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11
3	Forest	1.17E+09	1.17E+09	9.00E+08	9.00E+08	9.00E+08	9.00E+08	9.00E+08	9.00E+08	1.17E+09	1.17E+09	1.17E+09	1.17E+09
4	Cropland	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08	4.50E+08
4	LDR	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
4	HDR	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11	9.90E+11
4	Forest	6.93E+08	6.93E+08	2.97E+09	2.97E+09	2.97E+09	2.97E+09	2.97E+09	2.97E+09	6.93E+08	6.93E+08	6.93E+08	6.93E+08
5	HDR	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13	1.26E+13
5	Forest	1.44E+09	1.44E+09	9.90E+08	9.90E+08	9.90E+08	9.90E+08	9.90E+08	9.90E+08	1.44E+09	1.44E+09	1.44E+09	1.44E+09
6	LDR	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07	7.02E+07
6	HDR	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10	6.12E+10
6	Forest	2.43E+09	2.43E+09	1.98E+09	1.98E+09	1.98E+09	1.98E+09	1.98E+09	1.98E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09
7	LDR	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
7	HDR	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09
7	Forest	1.35E+09	1.35E+09	1.08E+09	1.08E+09	1.08E+09	1.08E+09	1.08E+09	1.08E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09
8	LDR	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
8	HDR	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11	1.35E+11
8	Forest	1.71E+09	1.71E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.35E+09	1.71E+09	1.71E+09	1.71E+09	1.71E+09
9	LDR	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09	1.17E+09
9	HDR	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11	4.14E+11
9	Forest	8.73E+08	8.73E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08	8.73E+08	8.73E+08	8.73E+08	8.73E+08

† Sub = sub-watershed number
* LDR = low density residential
HDR = high density residential

Table D. 9. MON-SQOLIM (monthly limit on surface accumulation) table - values in cfu/day for fecal coliform for Powhatan Creek (Continued).

Sub[†]	Land Use[*]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10	LDR	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10	5.49E+10
10	HDR	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10	5.31E+10
10	Forest	9.00E+08	9.00E+08	7.74E+08	7.74E+08	7.74E+08	7.74E+08	7.74E+08	7.74E+08	9.00E+08	9.00E+08	9.00E+08	9.00E+08
11	LDR	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
11	HDR	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10	5.67E+10
11	Forest	3.78E+09	3.78E+09	2.88E+09	2.88E+09	2.88E+09	2.88E+09	2.88E+09	2.88E+09	3.78E+09	3.78E+09	3.78E+09	3.78E+09
12	LDR	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
12	HDR	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10	3.78E+10
12	Forest	5.40E+09	5.40E+09	4.05E+09	4.05E+09	4.05E+09	4.05E+09	4.05E+09	4.05E+09	5.40E+09	5.40E+09	5.40E+09	5.40E+09
13	LDR	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11	1.17E+11
13	HDR	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09	6.57E+09
13	Forest	1.62E+09	1.62E+09	1.44E+09	1.44E+09	1.44E+09	1.44E+09	1.44E+09	1.44E+09	1.62E+09	1.62E+09	1.62E+09	1.62E+09
14	LDR	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09	9.90E+09
14	HDR	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11	1.80E+11
14	Forest	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09	2.43E+09
15	LDR	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09
15	HDR	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10	8.55E+10
15	Forest	2.61E+09	2.61E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.07E+09	2.61E+09	2.61E+09	2.61E+09	2.61E+09
16	LDR	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10	2.34E+10
16	HDR	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10	3.42E+10
16	Forest	9.90E+08	9.90E+08	8.55E+08	8.55E+08	8.55E+08	8.55E+08	8.55E+08	8.55E+08	9.90E+08	9.90E+08	9.90E+08	9.90E+08
17	LDR	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10	1.35E+10
17	HDR	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10	8.46E+10
17	Forest	1.44E+10	1.44E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.26E+10	1.44E+10	1.44E+10	1.44E+10	1.44E+10

[†] Sub = sub-watershed number
[*] LDR = low density residential
HDR = high density residential

Appendix E: Fecal Coliform Loading in Sub-watersheds

Table E. 1. Monthly nonpoint fecal coliform loadings in sub-watershed MC-1.

Month	Fecal Coliform loadings (x10^{10} cfu/month)			
	Cropland	Pasture	Forest	Residential[1]
Jan.	1	2,941	10	2,011
Feb.	1	3,146	9	1,832
Mar.	1	3,555	9	2,011
Apr.	1	3,539	8	1,946
May.	1	3,760	9	2,011
Jun.	1	3,737	8	1,946
Jul.	1	3,964	9	2,011
Aug.	1	4,066	9	2,011
Sep.	1	4,034	9	1,946
Oct.	1	2,558	10	2,011
Nov.	1	2,599	9	1,946
Dec.	1	2,813	10	2,011
Total	7	40,714	109	23,690

[1] Includes High and Low Density Residential

Table E. 2. Monthly nonpoint fecal coliform loadings in sub-watershed MC-2.

Month	Fecal Coliform loadings (x10^{10} cfu/month)	
	Forest	Residential[1]
Jan.	20	1,946
Feb.	19	1,774
Mar.	15	1,946
Apr.	14	1,884
May.	15	1,946
Jun.	14	1,884
Jul.	15	1,946
Aug.	15	1,946
Sep.	20	1,884
Oct.	20	1,946
Nov.	20	1,884
Dec.	20	1,946
Total	208	22,934

[1] Includes High and Low Density Residential

Table E. 3. Monthly nonpoint fecal coliform loadings in sub-watershed MC-3.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	7	1,568
Feb.	7	1,429
Mar.	6	1,568
Apr.	6	1,518
May.	6	1,568
Jun.	6	1,518
Jul.	6	1,568
Aug.	6	1,568
Sep.	7	1,518
Oct.	7	1,568
Nov.	7	1,518
Dec.	7	1,568
Total	78	18,480

[1] Includes High and Low Density Residential

Table E. 4. Monthly nonpoint fecal coliform loadings in sub-watershed MC-4.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	2	1,218
Feb.	1	1,110
Mar.	1	1,218
Apr.	1	1,179
May.	1	1,218
Jun.	1	1,179
Jul.	1	1,218
Aug.	1	1,218
Sep.	1	1,179
Oct.	2	1,218
Nov.	1	1,179
Dec.	2	1,218
Total	16	14,349

[1] Includes High and Low Density Residential

Table E. 5. Monthly nonpoint fecal coliform loadings in sub-watershed MC-5.

Month	Fecal Coliform loadings (x10^{10} cfu/month)	
	Forest	Residential[1]
Jan.	8	1,317
Feb.	7	1,200
Mar.	6	1,317
Apr.	6	1,274
May.	6	1,317
Jun.	6	1,274
Jul.	6	1,317
Aug.	6	1,317
Sep.	7	1,274
Oct.	8	1,317
Nov.	7	1,274
Dec.	8	1,317
Total	80	15,516

[1] Includes High and Low Density Residential

Table E. 6. Monthly nonpoint fecal coliform loadings in sub-watershed MC-6.

Month	Fecal Coliform loadings (x10^{10} cfu/month)	
	Forest	Residential[1]
Jan.	1	1,522
Feb.	1	1,387
Mar.	1	1,522
Apr.	1	1,473
May.	1	1,522
Jun.	1	1,473
Jul.	1	1,522
Aug.	1	1,522
Sep.	1	1,473
Oct.	1	1,522
Nov.	1	1,473
Dec.	1	1,522
Total	8	17,932

[1] Includes High and Low Density Residential

Table E. 7. Monthly nonpoint fecal coliform loadings in sub-watershed MC-7.

Month	Fecal Coliform loadings ($\times 10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	4	1,462
Feb.	4	1,332
Mar.	3	1,462
Apr.	3	1,415
May.	3	1,462
Jun.	3	1,415
Jul.	3	1,462
Aug.	3	1,462
Sep.	4	1,415
Oct.	4	1,462
Nov.	4	1,415
Dec.	4	1,462
Total	41	17,225

[1] Includes High and Low Density Residential

Table E. 8. Monthly nonpoint fecal coliform loadings in sub-watershed MC-8.

Month	Fecal Coliform loadings ($\times 10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	6	1,559
Feb.	6	1,421
Mar.	5	1,559
Apr.	5	1,509
May.	5	1,559
Jun.	5	1,509
Jul.	5	1,559
Aug.	5	1,559
Sep.	6	1,509
Oct.	6	1,559
Nov.	6	1,509
Dec.	6	1,559
Total	66	18,372

[1] Includes High and Low Density Residential

Table E. 9. Monthly nonpoint fecal coliform loadings in sub-watershed MC-9.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	6	1,372
Feb.	6	1,250
Mar.	5	1,372
Apr.	5	1,328
May.	5	1,372
Jun.	5	1,328
Jul.	5	1,372
Aug.	5	1,372
Sep.	6	1,328
Oct.	6	1,372
Nov.	6	1,328
Dec.	6	1,372
Total	67	16,164

[1] Includes High and Low Density Residential

Table E. 10. Monthly nonpoint fecal coliform loadings in sub-watershed PC-1.

Month	Fecal Coliform loadings (x10^{10} cfu/month)		
	Pasture	Forest	Residential[1]
Jan.	706	32	3,144
Feb.	760	29	2,865
Mar.	1,446	24	3,144
Apr.	1,435	23	3,042
May.	1,509	24	3,144
Jun.	1,500	23	3,042
Jul.	1,591	24	3,144
Aug.	1,632	24	3,144
Sep.	1,624	31	3,042
Oct.	1,033	32	3,144
Nov.	1,049	31	3,042
Dec.	675	32	3,144
Total	14,961	328	37,038

[1] Includes High and Low Density Residential

Table E. 11. Monthly nonpoint fecal coliform loadings in sub-watershed PC-2.

Month	Fecal Coliform loadings (x10^{10} cfu/month)		
	Cropland	Forest	Residential[1]
Jan.	1	15	1,694
Feb.	1	14	1,543
Mar.	1	11	1,694
Apr.	1	11	1,639
May.	1	11	1,694
Jun.	1	11	1,639
Jul.	1	11	1,694
Aug.	1	11	1,694
Sep.	1	15	1,639
Oct.	1	15	1,694
Nov.	1	15	1,639
Dec.	1	15	1,694
Total	9	158	19,954

[1] Includes High and Low Density Residential

Table E. 12. Monthly nonpoint fecal coliform loadings in sub-watershed PC-3.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	4	1,035
Feb.	4	943
Mar.	4	1,035
Apr.	3	1,002
May.	4	1,035
Jun.	3	1,002
Jul.	4	1,035
Aug.	4	1,035
Sep.	4	1,002
Oct.	4	1,035
Nov.	4	1,002
Dec.	4	1,035
Total	47	12,196

[1] Includes High and Low Density Residential

Table E. 13. Monthly nonpoint fecal coliform loadings in sub-watershed PC-4.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	6	1,576
Feb.	5	1,437
Mar.	5	1,576
Apr.	5	1,526
May.	5	1,576
Jun.	5	1,526
Jul.	5	1,576
Aug.	5	1,576
Sep.	6	1,526
Oct.	6	1,576
Nov.	6	1,526
Dec.	6	1,576
Total	63	18,573

[1] Includes High and Low Density Residential

Table E. 14. Monthly nonpoint fecal coliform loadings in sub-watershed PC-5.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	2	1,032
Feb.	2	941
Mar.	1	1,032
Apr.	1	999
May.	1	1,032
Jun.	1	999
Jul.	1	1,032
Aug.	1	1,032
Sep.	2	999
Oct.	2	1,032
Nov.	2	999
Dec.	2	1,032
Total	20	12,163

[1] Includes High and Low Density Residential

Table E. 15. Monthly nonpoint fecal coliform loadings in sub-watershed PC-6.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	10	1,039
Feb.	9	947
Mar.	8	1,039
Apr.	8	1,006
May.	8	1,039
Jun.	8	1,006
Jul.	8	1,039
Aug.	8	1,039
Sep.	10	1,006
Oct.	10	1,039
Nov.	10	1,006
Dec.	10	1,039
Total	105	12,245

[1] Includes High and Low Density Residential

Table E. 16. Monthly nonpoint fecal coliform loadings in sub-watershed PC-7.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	3	1,032
Feb.	3	941
Mar.	2	1,032
Apr.	2	999
May.	2	1,032
Jun.	2	999
Jul.	2	1,032
Aug.	2	1,032
Sep.	3	999
Oct.	3	1,032
Nov.	3	999
Dec.	3	1,032
Total	32	12,163

[1] Includes High and Low Density Residential

Table E. 17. Monthly nonpoint fecal coliform loadings in sub-watershed PC-8.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	8	1,110
Feb.	8	1,012
Mar.	7	1,110
Apr.	7	1,075
May.	7	1,110
Jun.	7	1,075
Jul.	7	1,110
Aug.	7	1,110
Sep.	8	1,075
Oct.	8	1,110
Nov.	8	1,075
Dec.	8	1,110
Total	90	13,083

[1] Includes High and Low Density Residential

Table E. 18. Monthly nonpoint fecal coliform loadings in sub-watershed PC-9.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	10	1,159
Feb.	9	1,056
Mar.	8	1,159
Apr.	8	1,122
May.	8	1,159
Jun.	8	1,122
Jul.	8	1,159
Aug.	8	1,159
Sep.	9	1,122
Oct.	10	1,159
Nov.	9	1,122
Dec.	10	1,159
Total	102	13,659

[1] Includes High and Low Density Residential

Table E. 19. Monthly nonpoint fecal coliform loadings in sub-watershed PC-10.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	12	2,555
Feb.	11	2,329
Mar.	10	2,555
Apr.	10	2,473
May.	10	2,555
Jun.	10	2,473
Jul.	10	2,555
Aug.	10	2,555
Sep.	12	2,473
Oct.	12	2,555
Nov.	12	2,473
Dec.	12	2,555
Total	130	30,106

[1] Includes High and Low Density Residential

Table E. 19. Monthly nonpoint fecal coliform loadings in sub-watershed PC-11.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	13	1,147
Feb.	12	1,045
Mar.	10	1,147
Apr.	10	1,110
May.	10	1,147
Jun.	10	1,110
Jul.	10	1,147
Aug.	10	1,147
Sep.	13	1,110
Oct.	13	1,147
Nov.	13	1,110
Dec.	13	1,147
Total	139	13,511

[1] Includes High and Low Density Residential

Table E. 20. Monthly nonpoint fecal coliform loadings in sub-watershed PC-12.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	21	1,249
Feb.	19	1,138
Mar.	16	1,249
Apr.	16	1,208
May.	16	1,249
Jun.	16	1,208
Jul.	16	1,249
Aug.	16	1,249
Sep.	21	1,208
Oct.	21	1,249
Nov.	21	1,208
Dec.	21	1,249
Total	219	14,710

[1] Includes High and Low Density Residential

Table E. 21. Monthly nonpoint fecal coliform loadings in sub-watershed PC-13.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	23	17,654
Feb.	21	16,088
Mar.	20	17,654
Apr.	19	17,084
May.	20	17,654
Jun.	19	17,084
Jul.	20	17,654
Aug.	20	17,654
Sep.	22	17,084
Oct.	23	17,654
Nov.	22	17,084
Dec.	23	17,654
Total	250	208,001

[1] Includes High and Low Density Residential

Table E. 22. Monthly nonpoint fecal coliform loadings in sub-watershed PC-14.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	7	1,027
Feb.	7	936
Mar.	5	1,027
Apr.	5	994
May.	5	1,027
Jun.	5	994
Jul.	5	1,027
Aug.	5	1,027
Sep.	7	994
Oct.	7	1,027
Nov.	7	994
Dec.	7	1,027
Total	74	12,099

[1] Includes High and Low Density Residential

Table E. 23. Monthly nonpoint fecal coliform loadings in sub-watershed PC-15.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	7	1,304
Feb.	7	1,188
Mar.	6	1,304
Apr.	5	1,262
May.	6	1,304
Jun.	5	1,262
Jul.	6	1,304
Aug.	6	1,304
Sep.	7	1,262
Oct.	7	1,304
Nov.	7	1,262
Dec.	7	1,304
Total	75	15,366

[1] Includes High and Low Density Residential

Table E. 24. Monthly nonpoint fecal coliform loadings in sub-watershed PC-16.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month)	
	Forest	Residential[1]
Jan.	9	3,644
Feb.	8	3,321
Mar.	8	3,644
Apr.	8	3,526
May.	8	3,644
Jun.	8	3,526
Jul.	8	3,644
Aug.	8	3,644
Sep.	9	3,526
Oct.	9	3,644
Nov.	9	3,526
Dec.	9	3,644
Total	103	42,931

[1] Includes High and Low Density Residential

Table E. 25. Monthly nonpoint fecal coliform loadings in sub-watershed PC-17.

Month	Fecal Coliform loadings ($x10^{10}$ cfu/month) Forest	Residential[1]
Jan.	20	2,294
Feb.	18	2,090
Mar.	16	2,294
Apr.	16	2,220
May.	16	2,294
Jun.	16	2,220
Jul.	16	2,294
Aug.	16	2,294
Sep.	19	2,220
Oct.	20	2,294
Nov.	19	2,220
Dec.	20	2,294
Total	215	27,027

[1] Includes High and Low Density Residential

Appendix F: Required Reductions in Fecal Coliform Loads by Sub-watershed – Allocation Scenario

Table F.1. Required annual reductions in nonpoint sources in sub-watershed MC-01.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	1,609	0%	80	95%
Pasture	4,071,385	70%	203,570	95%
Forest	9,924	0.2%	9,924	0%
Residential	1,755,392	30%	87,770	95%
Total	5,838,309	100%	301,343	95%

Table F.2. Required annual reductions in direct nonpoint sources in sub-watershed MC-01.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	9,661	100%	193	98%
Marinas and Canal	16,094	100%	1,188	92%
Total	9,661	100%	193	98%

Table F.3. Required annual reductions in nonpoint sources in sub-watershed MC-02.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	374	0%	19	95%
Forest	20,616	1%	20,616	0%
Residential	1,679,785	99%	83,989	95%
Total	1,700,774	100%	104,624	94%

Table F.4. Required annual reductions in direct nonpoint sources in sub-watershed MC-02.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	8,421	100%	168	98%
Total	8,421	100%	168	98%

Table F.5. Required annual reductions in nonpoint sources in sub-watershed MC-03.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	397	0%	20	95%
Forest	7,251	0.5%	7,251	0%
Residential	1,431,597	99%	71,580	95%
Total	1,439,246	100%	78,851	95%

Table F.6. Required annual reductions in direct nonpoint sources in sub-watershed MC-03.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	4,110	100%	82	98%
Total	4,110	100%	82	98%

Table F.7. Required annual reductions in nonpoint sources in sub-watershed MC-04.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	1,588	0.1%	1,588	0%
Residential	1,434,885	100%	71,744	95%
Total	1,436,473	100%	73,332	95%

Table F.8. Required annual reductions in direct nonpoint sources in sub-watershed MC-04.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	935	100%	19	98%
Total	935	100%	19	98%

Table F.9. Required annual reductions in nonpoint sources in sub-watershed MC-05.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	7,872	0.5%	7,872	0%
Residential	1,551,582	99%	77,579	95%
Total	1,559,454	100%	85,451	95%

Table F.10. Required annual reductions in direct nonpoint sources in sub-watershed MC-05.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	3,906	100%	78	98%
Total	3,906	100%	78	98%

Table F.11. Required annual reductions in nonpoint sources in sub-watershed MC-06.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	771	0%	771	0%
Residential	1,793,195	100%	89,660	95%
Total	1,793,966	100%	90,431	95%

Table F.12. Required annual reductions in direct nonpoint sources in sub-watershed MC-06.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	449	100%	9	98%
Total	449	100%	9	98%

Table F.13. Required annual reductions in nonpoint sources in sub-watershed MC-07.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	4,044	0.2%	4,044	0%
Residential	1,722,519	100%	86,126	95%
Total	1,726,563	100%	90,169	95%

Table F.14. Required annual reductions in direct nonpoint sources in sub-watershed MC-07.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	2,005	100%	40	98%
Total	2,005	100%	40	98%

Table F.15. Required annual reductions in nonpoint sources in sub-watershed MC-08.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	6,466	0.4%	6,466	0%
Residential	1,545,008	100%	77,250	95%
Total	1,551,473	100%	83,716	95%

Table F.16. Required annual reductions in direct nonpoint sources in sub-watershed MC-08.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	3,112	100%	62	98%
Total	3,112	100%	62	98%

Table F.17. Required annual reductions in nonpoint sources in sub-watershed MC-09.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	6,485	0.4%	6,485	0%
Residential	1,543,364	100%	77,168	95%
Total	1,549,849	100%	83,653	95%

Table F.18. Required annual reductions in direct nonpoint sources in sub-watershed MC-09.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	3,320	100%	66	98%
Total	3,320	100%	66	98%

Table F.19. Required annual reductions in nonpoint sources in sub-watershed PC-01.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Pasture	1,496,126	42%	119,690	92%
Forest	32,266	0.9%	32,266	0%
Residential	2,016,728	57%	161,338	92%
Total	3,545,120	100%	313,294	91%

Table F.20. Required annual reductions in direct nonpoint sources in sub-watershed PC-01.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	14,851	100%	1,188	92%
Total	14,851	100%	1,188	92%

Table F.21. Required annual reductions in nonpoint sources in sub-watershed PC-02.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	852	0%	68	92%
Forest	15,371	0.8%	15,371	0%
Residential	1,998,648	99%	159,892	92%
Total	2,014,872	100%	175,331	91%

Table F.22. Required annual reductions in direct nonpoint sources in sub-watershed PC-02.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	5,735	100%	459	92%
Total	5,735	100%	459	92%

Table F.23. Required annual reductions in nonpoint sources in sub-watershed PC-03.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	4,511	0.4%	4,511	0%
Residential	1,219,570	100%	97,566	92%
Total	1,224,081	100%	102,077	92%

Table F.24. Required annual reductions in direct nonpoint sources in sub-watershed PC-03.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	1,945	100%	156	92%
Total	1,945	100%	156	92%

Table F.25. Required annual reductions in nonpoint sources in sub-watershed PC-04.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	189	0%	15	92%
Forest	5,844	0.3%	5,844	0%
Residential	1,857,296	100%	148,584	92%
Total	1,863,330	100%	154,443	92%

Table F.26. Required annual reductions in direct nonpoint sources in sub-watershed PC-04.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	3,763	100%	301	92%
Total	3,763	100%	301	92%

Table F.27. Required annual reductions in nonpoint sources in sub-watershed PC-05.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	1,949	0.2%	1,949	0%
Residential	1,216,283	100%	97,303	92%
Total	1,218,232	100%	99,252	92%

Table F.28. Required annual reductions in direct nonpoint sources in sub-watershed PC-05.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	1,029	100%	82	92%
Total	1,029	100%	82	92%

Table F.29. Required annual reductions in nonpoint sources in sub-watershed PC-06.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	10,074	0.8%	10,074	0%
Residential	1,229,432	99%	98,354	92%
Total	1,239,505	100%	108,428	91%

Table F.30. Required annual reductions in direct nonpoint sources in sub-watershed PC-06.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	4,820	100%	386	92%
Total	4,820	100%	386	92%

Table F.31. Required annual reductions in nonpoint sources in sub-watershed PC-07.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	3,063	0.3%	3,063	0%
Residential	1,216,283	100%	97,303	92%
Total	1,219,345	100%	100,365	92%

Table F.32. Required annual reductions in direct nonpoint sources in sub-watershed PC-07.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	1,464	100%	117	92%
Total	1,464	100%	117	92%

Table F.33. Required annual reductions in nonpoint sources in sub-watershed PC-08.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	80	0%	6	92%
Forest	8,595	0.7%	8,595	0%
Residential	1,308,326	99%	104,666	92%
Total	1,317,000	100%	113,267	91%

Table F.34. Required annual reductions in direct nonpoint sources in sub-watershed PC-08.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	4,632	100%	371	92%
Total	4,632	100%	371	92%

Table F.35. Required annual reductions in nonpoint sources in sub-watershed PC-09.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Cropland	74	0%	6	92%
Forest	9,775	0.7%	9,775	0%
Residential	1,369,140	99%	109,531	92%
Total	1,378,989	100%	119,312	91%

Table F.36. Required annual reductions in direct nonpoint sources in sub-watershed PC-09.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	4,809	100%	385	92%
Total	4,809	100%	385	92%

Table F.37. Required annual reductions in nonpoint sources in sub-watershed PC-10.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	12,357	0.9%	12,357	0%
Residential	1,293,533	99%	103,483	92%
Total	1,305,890	100%	115,839	91%

Table F.38. Required annual reductions in direct nonpoint sources in sub-watershed PC-10.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	7,208	100%	577	92%
Total	7,208	100%	577	92%

Table F.39. Required annual reductions in nonpoint sources in sub-watershed PC-11.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	13,557	1.0%	13,557	0%
Residential	1,351,060	99%	108,085	92%
Total	1,364,616	100%	121,641	91%

Table F.40. Required annual reductions in direct nonpoint sources in sub-watershed PC-11.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	6,345	100%	508	92%
Total	6,345	100%	508	92%

Table F.41. Required annual reductions in nonpoint sources in sub-watershed PC-12.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	21,386	1%	21,386	0%
Residential	1,471,044	99%	117,684	92%
Total	1,492,430	100%	139,069	91%

Table F.42. Required annual reductions in direct nonpoint sources in sub-watershed PC-12.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	9,552	100%	764	92%
Total	9,552	100%	764	92%

Table F.43. Required annual reductions in nonpoint sources in sub-watershed PC-13.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	23,368	2%	23,368	0%
Residential	1,048,633	98%	83,891	92%
Total	1,072,000	100%	107,258	90%

Table F.44. Required annual reductions in direct nonpoint sources in sub-watershed PC-13.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	15,363	100%	1,229	92%
Total	15,363	100%	1,229	92%

Table F.45. Required annual reductions in nonpoint sources in sub-watershed PC-14.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	7,217	0.6%	7,217	0%
Residential	1,163,687	99%	93,095	92%
Total	1,170,904	100%	100,312	91%

Table F.46. Required annual reductions in direct nonpoint sources in sub-watershed PC-14.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	3,094	100%	247	92%
Total	3,094	100%	247	92%

Table F.47. Required annual reductions in nonpoint sources in sub-watershed PC-15.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	7,247	0.5%	7,247	0%
Residential	1,464,470	100%	117,158	92%
Total	1,471,717	100%	124,404	92%

Table F.48. Required annual reductions in direct nonpoint sources in sub-watershed PC-15.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	3,823	100%	306	92%
Total	3,823	100%	306	92%

Table F.49. Required annual reductions in nonpoint sources in sub-watershed PC-16.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	9,460	0.7%	9,460	0%
Residential	1,443,103	99%	115,448	92%
Total	1,452,563	100%	124,908	91%

Table F.50. Required annual reductions in direct nonpoint sources in sub-watershed PC-16.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	6,188	100%	495	92%
Total	6,188	100%	495	92%

Table F.51. Required annual reductions in nonpoint sources in sub-watershed PC-17.

Land Use	Current conditions load (x 10^8 cfu/year)	Percent of total load from nonpoint sources	TMDL nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Forest	20,500	1%	20,500	0%
Residential	1,587,742	99%	127,019	92%
Total	1,608,242	100%	147,520	91%

Table F.52. Required annual reductions in direct nonpoint sources in sub-watershed PC-17.

Source	Current Conditions load (x 10^8 cfu/year)	Percent of total load to stream from direct nonpoint sources	TMDL direct nonpoint source allocation load (x 10^8 cfu/year)	Percent Reduction
Wildlife in Streams	11,694	100%	936	92%
Total	11,694	100%	936	92%

Appendix G: Simulated Stream Flow Chart for TMDL Allocation Period

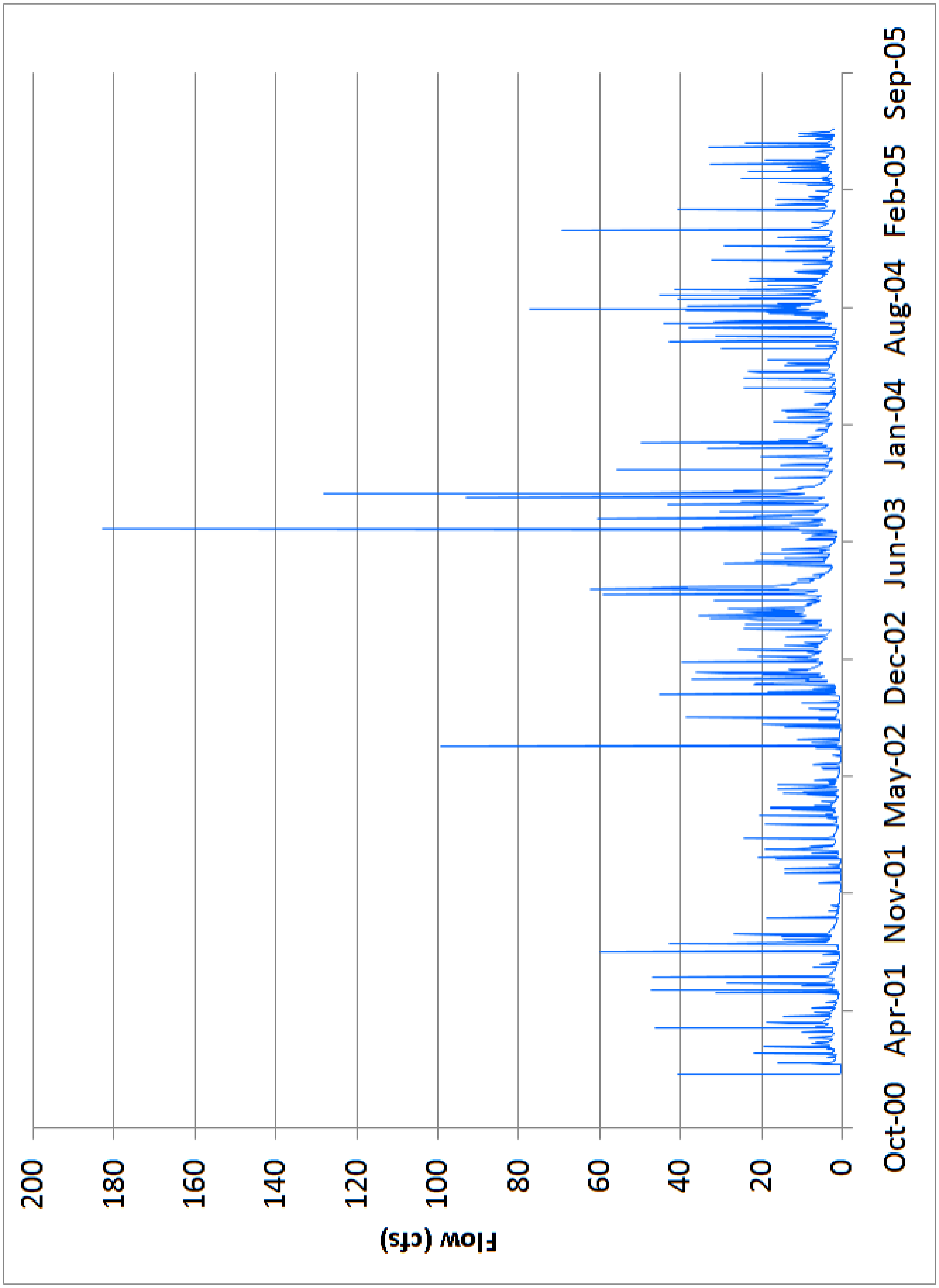

Figure G. 1. Simulated stream flow for the allocation period for Mill Creek.

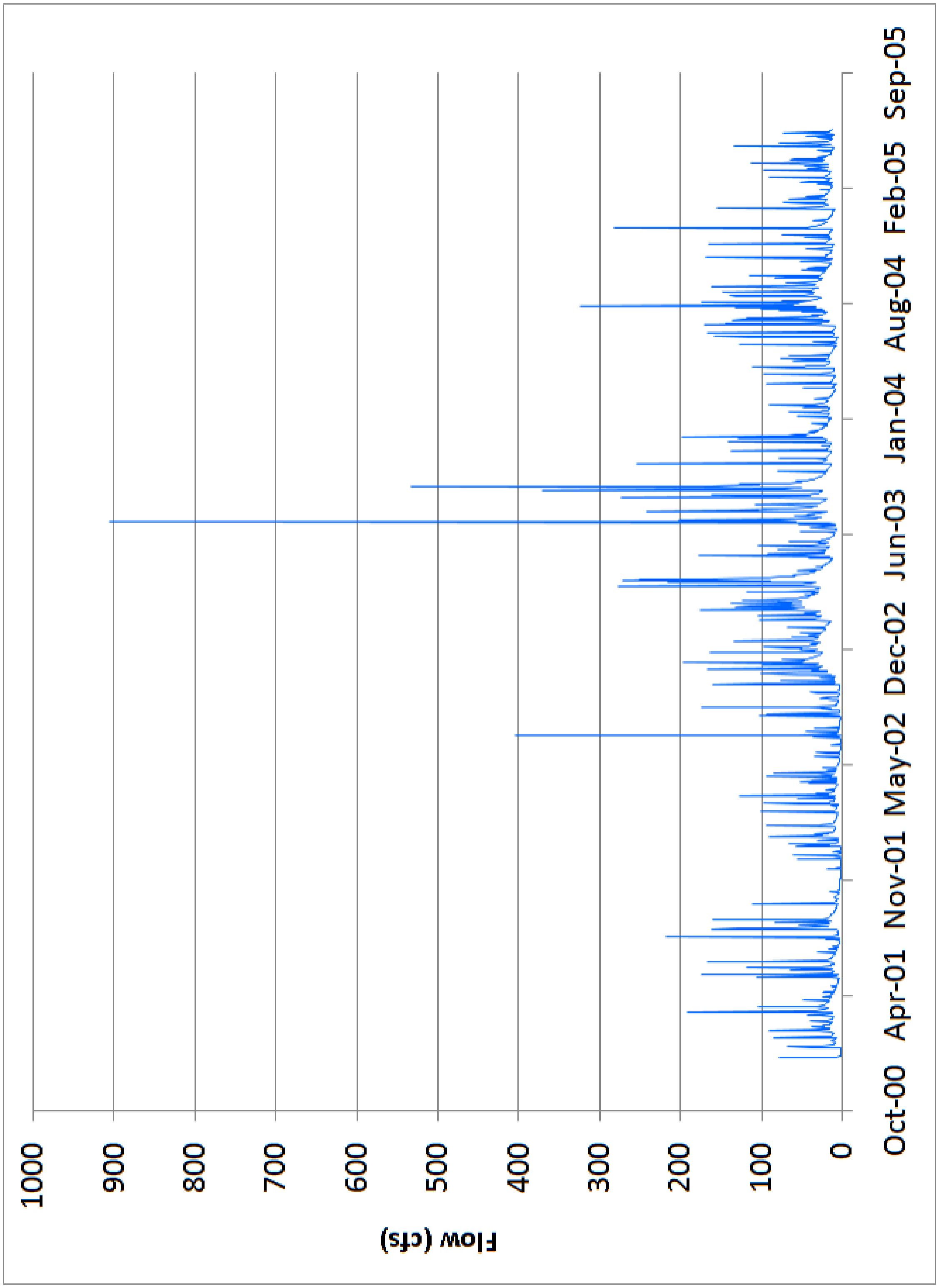

Figure G. 2. Simulated stream flow for the allocation period for Powhatan Creek.

Appendix H: Observed Bacteria Concentrations and Antecedent Rainfall

This appendix presents the observed bacteria concentrations and antecedent rainfall for stations 2-MIC000.03 (Table H.1), 2-POW000.60 (Table H.2), and 2-POW006.77 (Table H.3).

Table H.1. Observed bacteria concentrations and antecedent rainfall at 2-MIC000.03.

Type of Bacteria	Sampling Date	Bacteria Concentration (cfu/100mL)	Total Rainfall for Sampling Day and Preceding 5 days (inches)
Fecal Coliform	7/14/1992	79	0
	8/10/1992	920	1.1
	9/10/1992	350	0.4
	11/5/1992	350	1.4
	12/7/1992	1600	0
	1/13/1993	1600	2
	2/10/1993	2	0
	3/3/1993	43	1.1
	4/14/1993	79	0.2
	5/12/1993	790	0.7
	5/12/1993	790	0.7
	6/17/1993	130	0
	6/17/1993	130	0
	7/13/1993	350	0
	8/25/1993	170	0
	9/22/1993	280	0.5
	10/13/1993	1600	0.1
	11/9/1993	280	0.7
	12/8/1993	79	0.8
	2/17/1994	2	0
	3/22/1994	22	0.6
	4/19/1994	49	0.1
	5/3/1994	110	0.7
	6/1/1994	110	0
	7/14/1994	350	0.3
	8/16/1994	110	1
	9/13/1994	79	0
	10/13/1994	1600	0
	11/21/1994	79	2.4
	12/12/1994	79	0.4
	1/9/1995	49	0.8
	2/14/1995	23	0
	3/8/1995	33	2.7
	4/6/1995	33	0
	5/9/1995	130	0
	5/20/1995	1600	0.3
	7/20/1995	170	1
	8/21/1995	49	0
	9/18/1995	1600	1.2
	10/17/1995	540	1.7

Type of Bacteria	Sampling Date	Bacteria Concentration (cfu/100mL)	Total Rainfall for Sampling Day and Preceding 5 days (inches)
Fecal Coliform	11/16/1995	170	1.1
	12/18/1995	33	0.3
	1/17/1996	17	0.8
	2/15/1996	49	0.2
	3/14/1996	33	0
	4/11/1996	33	1.2
	5/8/1996	170	0.9
	6/26/1996	220	0.9
	7/24/1996	180	0.7
	8/8/1996	49	0.2
	9/5/1996	46	0.1
	10/8/1996	1600	3.7
	11/5/1996	920	0.6
	12/5/1996	130	1.6
	1/13/1997	95	1.3
	2/13/1997	26	0.8
	3/4/1997	920	1.4
	4/15/1997	110	0.4
	5/14/1997	540	0.3
	6/11/1997	130	0
	7/10/1997	79	0.2
	8/13/1997	1600	0
	9/11/1997	1600	0.9
	10/9/1997	1600	0
	11/6/1997	1600	0.8
	12/10/1997	4.5	0.5
	1/7/1998	79	0.2
	2/19/1998	23	1.4
	3/5/1998	46	0.1
	4/22/1998	130	1.9
	5/20/1998	540	0
	6/18/1998	920	0.6
	7/16/1998	280	0.5
	8/3/1998	23	0.4
	9/1/1998	220	0.9
	10/1/1998	220	0.5
	11/9/1998	79	0
	12/14/1998	130	2.7
	1/12/1999	17	0.1
	2/10/1999	49	0.1
	3/11/1999	49	0.4
	4/8/1999	140	0.1
	5/20/1999	280	0
	6/7/1999	220	0
	7/7/1999	920	0.7
	8/5/1999	240	0.1
	9/2/1999	280	0.1
	10/21/1999	350	5.1

Type of Bacteria	Sampling Date	Bacteria Concentration (cfu/100mL)	Total Rainfall for Sampling Day and Preceding 5 days (inches)
Fecal Coliform	12/14/1999	220	1.1
	1/13/2000	79	0.9
	2/9/2000	11	0
	3/14/2000	130	0.2
	4/12/2000	79	0.5
	5/10/2000	920	0
	6/8/2000	1600	0.4
	7/25/2000	45	3.1
	8/8/2000	2400	1.2
	9/6/2000	920	2.8
	10/5/2000	1600	0
	11/6/2000	920	0
	12/6/2000	2	0
	1/18/2001	2	0.4
	2/15/2001	17	0.3
	3/19/2001	13	0.6
	4/17/2001	4	0.5
	5/15/2001	240	0.1
	6/14/2001	1600	0
	7/17/2001	17	0
	9/13/2001	79	0.1
	11/27/2001	49	0.4
	1/8/2002	110	1.8
	3/7/2002	6.8	1
	5/7/2002	23	1.5
	7/18/2002	790	3.7
	9/12/2002	210	0
	11/14/2002	330	1.1
	1/9/2003	130	0.3
	3/11/2003	130	0.4
	7/8/2003	620	0
	9/9/2003	50	0.2
	11/6/2003	400	0.8
	1/8/2004	25	0.3
	3/18/2004	25	0.9
	5/6/2004	180	0.7
	7/27/2004	450	3.4
	9/7/2004	1000	1.1
	11/8/2004	25	0.6
	1/5/2005	50	0.2
	3/22/2005	25	0.8
	5/12/2005	150	0
	7/12/2005	50	0.8
	9/1/2005	180	0
	11/9/2005	380	0.1
	1/5/2006	25	1.2

Type of Bacteria	Sampling Date	Bacteria Concentration (cfu/100mL)	Total Rainfall for Sampling Day and Preceding 5 days (inches)
E. Coli	11/14/2002	210	1.1
	1/9/2003	60	0.3
	3/11/2003	10	0.4
	7/8/2003	70	0
	9/9/2003	130	0.2
	11/6/2003	240	0.8
	1/8/2004	10	0.3
	3/18/2004	10	0.9