Updated Model Report for
Christina River Basin, Pennsylvania-Delaware-Maryland
Bacteria and Sediment TMDL Development

Draft

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U.S. Environmental Protection Agency
Region 3
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Reasons for Updating the Model

On April 8, 2005, the Region III (Philadelphia, PA) office of the Environmental Protection Agency (EPA) established Total Maximum Daily Loads (TMDLs) for bacteria and sediment for the portions of the Christina River Basin listed on the Clean Water Act Section 303(d) lists for the Commonwealth of Pennsylvania and the State of Delaware.

Following the establishment of the Christina River Basin bacteria and sediment TMDLs, the City of Wilmington and Delaware DNREC completed a storm-monitoring program. The goal of the storm-monitoring program was to collect nutrient and bacteria data from four storm events to establish characteristic concentrations for the CSO discharges in the City of Wilmington. Two storm events had been available in time for the April 2005 TMDL modeling effort. After April 2005, the monitoring data from two additional storm events were available. This updated model incorporates data from the four storm events to establish updated *enterococci* event mean concentrations (EMCs) for the Wilmington CSO discharges as shown in the following table.

Updated *enterococci* event mean concentrations for Wilmington CSOs

CSO ID	Event Mean Concentration (cfu/100mL)
CSO 4b	34,917
CSO 25	57,885
CSO 3	121,635
Other CSOs	45,888

The EFDC model domain used for the April 2005 bacteria TMDL did not explicitly include representation of Little Mill Creek. Ten grid cells, each having a length of 500 meters, have been added to the EFDC *enterococci* model. It was deemed important to include Little Mill Creek in the model domain because three CSOs discharge to this water body.

The revisions to the April 8, 2005 modeling effort only affect *enterococci* bacteria in the EFDC model of lower Brandywine Creek, tidal Christina River, and Little Mill Creek. The model updates do not impact the previous modeling work for sediment or the fecal coliform bacteria in Pennsylvania. Also, no revisions were made to the HSPF *enterococci* models. Other than as noted above, no changes were made to the technical analysis and modeling framework used as the basis to develop the Christina River Basin TMDLs.

Specific updates to this report include:

- Additional CSO storm monitoring data added to Table 2-29 and text changed accordingly
- Revised EFDC calibration time-series results in Appendix I
- Revised EFDC calibration results in Appendix J
- Revised EFDC calibration probability distribution results in Appendix K
- MS4 land use areas for Delaware were added to Appendix L
- Added Appendix O to document annual average baseline and TMDL volumes and loads for CSO discharges

1.0 Introduction

A scientifically justifiable Total Maximum Daily Load (TMDL) for a waterbody can only be developed based on a quantitative understanding of the system. In practice, water quality modeling offers a feasible tool to establish this quantitative understanding. A water quality model that is customized for a specific waterbody can simulate the major physical, chemical, and biological processes that occur in the system, and thus provide quantitative relationships between the water quality response and external forcing functions. A customized modeling framework was developed to support determination of bacteria and sediment TMDLs for the Christina River Basin. The TMDLs are presented in the report titled *Bacteria and Sediment TMDL for Christina River Basin, Pennsylvania-Delaware-Maryland* (USEPA, 2005). This report is intended to accompany the TMDL report and provide a more detailed discussion on the models used for the nutrient TMDL analysis, including assumptions, parameters, and references.

The modeling framework used in this study consisted of three major components: (1) a watershed loading model (HSPF) developed for each of the four primary subwatersheds in the Christina River Basin (USGS, 2003a, 2003b, 2003c, 2003d), (2) a CSO flow model (XP-SWMM) developed by the City of Wilmington, and (3) a hydrodynamic model developed using the computational framework of the Environmental Fluid Dynamics Code (EFDC) (Hamrick, 1992). A linkage interface was also developed to allow for smooth communication between EFDC and the HSPF and XP-SWMM model components. In addition to the core modules available in EFDC, a key update was made to the model and implemented during this effort to incorporate sediment-water partition capabilities for bacteria including the effects of sediment settling and re-suspension effects on bacteria.

Under the HSPF model framework, the Christina River Basin was configured into 70 subbasins (see Figure 1-1 and Table 1-1) with each subbasin having 12 land use categories. The land use category areas are assumed to be constant throughout the modeling period since HSPF does not allow time variable land use areas. This is considered a valid assumption for the calibration purposes. When dealing with load allocations, the impacts of land use changes are considered in the implementation period. The land uses in the HSPF model are based on land-use surveys in 1992 in DE and 1995 in PA. A comparison of land use changes with the Anderson Classification is shown in Appendix N. The XP-SWMM model calculated hourly CSO flow rates from rainfall events. Storm monitoring data were used to determine event mean concentrations to estimate CSO loads for bacteria. The EFDC model framework includes the main channels of Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, Red Clay Creek, White Clay Creek, Christina River, Delaware River, and several other smaller tributaries. The EFDC receiving water model was linked to the HSPF and XP-SWMM models to incorporate watershed and CSO loads. The EFDC hydrodynamic fate and transport model was used to predict the bacteria concentrations in the tidal Christina River, tidal Brandywine Creek, and tidal White Clay Creek reaches of the model. The bacteria and sediment constituents were calibrated using monitoring data for the period October 1, 1994 to October 1, 1998 (a period of 4 years). This period included two dry summers (1995 and 1997) as well as a number of high-flow periods, both of which are important to satisfy the TMDL seasonality requirements.

Table 1-1. Description of subbasins in the HSPF models of Christina River Basin

Subbasin	Stream Name	Area (mi2)	Subbasin	Stream Name	Area (mi2)
	Brandywine Creek Watershed			*White Clay Creek Watershed*	
B01	Upper Brandywine Creek West Br.	18.39	W01	White Clay Creek West Br.	10.23
B02	Brandywine Creek West Branch	7.38	W02	Upper White Clay Creek Middle Br.	9.51
B03	Brandywine Creek West Branch	6.76	W03	White Clay Creek Middle Br.	6.35
B04	Brandywine Creek West Branch	0.80	W04	Trib. to White Clay Creek East Br.	6.20
B05	Brandywine Creek West Branch	8.82	W05	Trib. to White Clay Creek East Br.	2.65
B06	Brandywine Creek West Branch	8.06	W06	Upper White Clay Creek East Br.	8.57
B07	Brandywine Creek West Branch	13.46	W07	Trout Run	1.37
B08	Brandywine Creek West Branch	3.62	W08	White Clay Creek East Branch	7.47
B09	Upper Brandywine Creek East Br.	14.68	W09	White Clay Creek East Branch	6.85
B10	Brandywine Creek East Branch	18.31	W10	White Clay Creek	3.58
B11	Brandywine Creek East Branch	6.31	W11	White Clay Creek	6.53
B12	Brandywine Creek East Branch	3.70	W12	White Clay Creek	8.76
B13	Brandywine Creek East Branch	7.94	W13	White Clay Creek	2.08
B14	Brandywine Creek East Branch	12.92	W14	White Clay Creek	3.41
B15	Brandywine Creek	10.36	W15	Muddy Run	3.89
B16	Brandywine Creek	14.06	W16	Pike Creek	6.65
B17	Brandywine Creek	7.51	W17	Mill Creek	13.00
B18	Brandywine Creek	10.37		*Red Clay Creek Watershed*	
B19	Brandywine Creek	8.64	R01	Upper Red Clay Creek West Branch	10.08
B20	Upper Buck Run	25.54	R02	Red Clay Creek West Branch	7.39
B21	Upper Doe Run	11.05	R03	Red Clay Creek East Branch	9.90
B22	Lower Doe Run	10.96	R04	Red Clay Creek	5.11
B23	Lower Buck Run	1.95	R05	Red Clay Creek	5.24
B24	Tributary to Broad Run	0.60	R06	Burroughs Run	7.10
B25	Broad Run	5.83	R07	Hoopes Reservoir	2.10
B26	Marsh Creek	2.61	R08	Red Clay Creek	5.38
B27	Marsh Creek	11.54	R09	Red Clay Creek	1.72
B28	Tributary to Valley Creek	2.40		*Christina River Watershed*	
B29	Valley Creek	18.21	C01	Christina River West Branch	6.70
B30	Beaver Creek	18.08	C02	Upper Christina River	9.73
B31	Pocopson Creek	9.19	C03	Christine River	4.47
B32	Birch Run	4.66	C04	Upper Little Mill Creek	5.37
B33	Rock Run	8.03	C05	Little Mill Creek	3.84
B34	Lower Brandywine Creek	6.05	C06	Muddy Run	8.64
B35	Upper Marsh Creek	5.80	C07	Belltown Run	6.37
			C08	Christina River	10.70
			C09	Lower Christina River	21.90

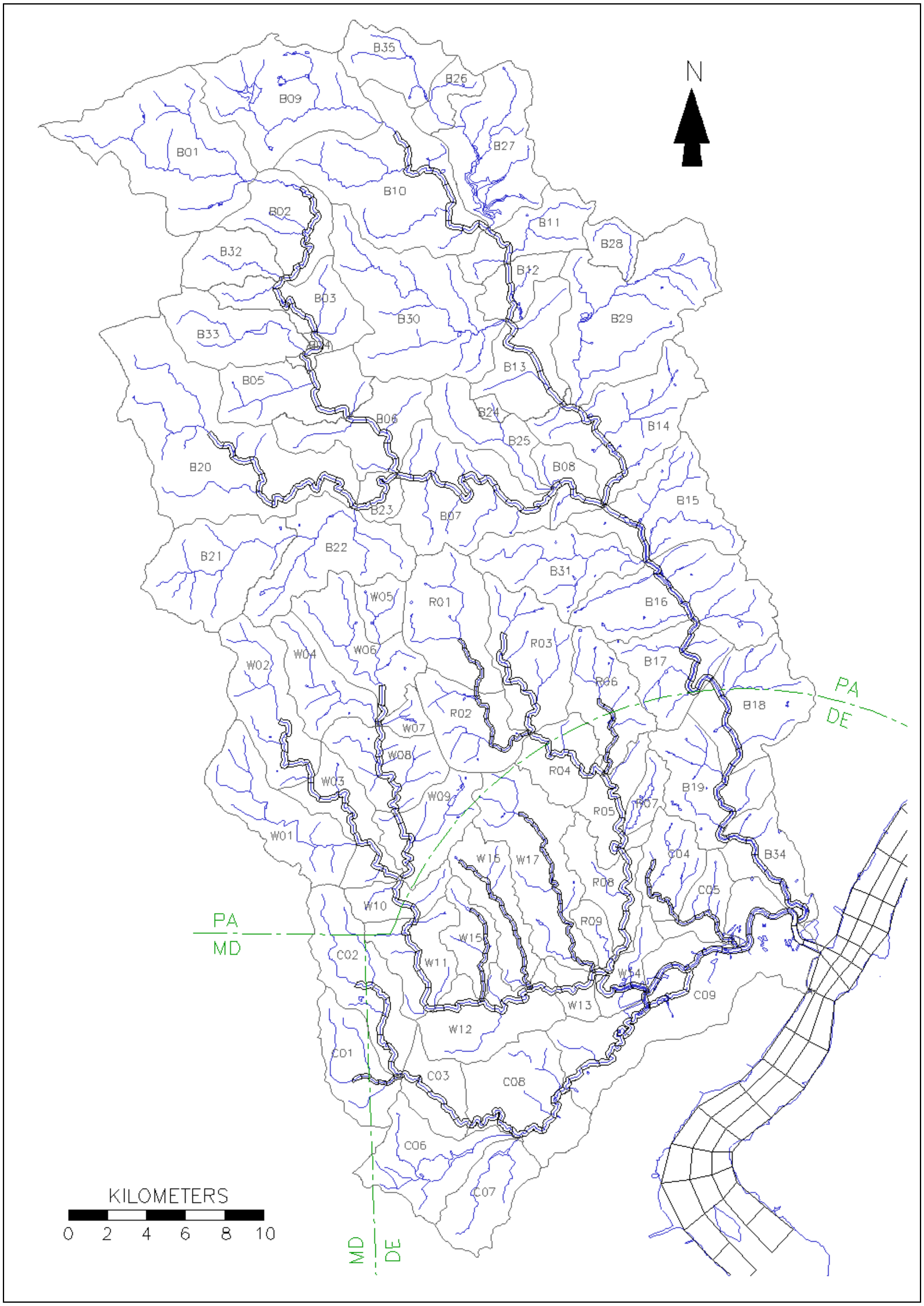

Figure 1-1. Christina River Basin showing HSPF model subbasins and EFDC model grid

2.0 Watershed Loading Model

2.1 HSPF Model Overview

The Hydrologic Simulation Program—Fortran (HSPF), is a U.S. EPA supported model for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants. The HSPF model uses information such as the time history of rainfall, temperature and solar radiation; land surface characteristics such as land-use patterns; and land management practices to simulate the processes that occur in a watershed. The result of this simulation is a time history of the quantity and quality of runoff from an urban or agricultural watershed. Flow rate, sediment load, and nutrient and pesticide concentrations are predicted. HSPF includes an internal database management system to process the large amounts of simulation input and output. HSPF includes the source code, executable version, user's guide, and technical support. HSPF can simulate the watershed hydrology and associated water quality on pervious and impervious land surfaces as well as in streams and well-mixed impoundments. The HSPF model incorporates the watershed-scale Agricultural Runoff Model (ARM) and Non-Point Source (NPS) models into a basin-scale analysis framework that includes pollutant transport and transformation in stream channels.

The Christina River Basin drains 565 square miles in Pennsylvania, Delaware, and Maryland. Water from the basin is used for recreation, drinking-water supply, and to support aquatic life. The Christina River Basin includes four main watersheds: Brandywine Creek, Red Clay Creek, White Clay Creek, and Christina River. Brandywine Creek is the largest of the watersheds and drains an area of 327 square miles. Water quality in some parts of the Christina River Basin is impaired and does not support designated uses of the streams.

A multi-agency water-quality management strategy included a modeling component to evaluate the effects of point and nonpoint-source contributions of nutrients and suspended sediment on stream water quality. To assist in nonpoint-source evaluation, four independent models, one for each of the four main watersheds of the Christina River Basin, were developed and calibrated using the HSPF modeling framework.

The HSPF models simulate streamflow, suspended sediment, nitrogen, phosphorus, BOD, water temperature, and dissolved oxygen. For the models, the Christina River Basin was subdivided into 70 reaches. Ten different pervious land uses and two impervious land uses were selected for simulation. Land-use areas were determined from 1995 land-use data. The predominant land uses in the basin are forested, agricultural, residential, and urban.

The hydrologic component of the model was run at an hourly time step and calibrated using streamflow data for eight U.S. Geological Survey (USGS) streamflow-measurement stations for the period of October 1, 1994 to October 1, 1998. Daily precipitation data for three National Oceanic and Atmospheric Administration (NOAA) gages and hourly data for one NOAA gage were used for model input.

More detailed descriptions of the HSPF models developed for the Christina River Basin can be found in Senior and Koerkle (2003a, 2003b, 2003c, and 2003d).

2.2 XP-SWMM Model Overview

The City of Wilmington has developed a model (XP-SWMM) to simulate stormwater flows and CSO events in the city's sewer collection system. XP-SWMM is a link-node model that performs hydrology, hydraulics, and water quality analysis of stormwater and wastewater drainage systems including sewage treatment plants, water quality control devices, and best management practices (BMPs). XP-SWMM can be used to model the full hydrologic cycle from stormwater and wastewater flow and pollutant generation to simulation of the hydraulics in any combined system of open and/or closed conduits with any boundary conditions.

Typical XP-SWMM applications include predicting combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs), interconnected pond analysis, open and closed conduit flow analysis, major/minor flow analysis, design of new developments, and analysis of existing stormwater and sanitary sewer systems.

XP-SWMM uses a self-modifying dynamic wave solution algorithm. Like all implicit solutions, which solve for the unknown values at a given time simultaneously, XP-SWMM is not Courant-limited. However, XP-SWMM uses the Courant number as a guide, to prevent numerical attenuation that can occur if excessively large time steps are used. This is important in models where pumps are involved or in urban systems where steeply rising hydrographs, requiring responses in seconds or fractions of a second will predominate, or where checks are being made against empirical procedures like the FHWA inlet control scheme for culverts. XP-SWMM will use small time steps when required and larger time steps when appropriate.

XP-SWMM has three computational modules. There is a stormwater module for hydrology and water quality generation, a wastewater module for generation of wastewater flows including Storage/Treatment for BMP and water quality routing, and a hydrodynamic hydraulics module for the hydraulic simulation of open and closed conduit wastewater or stormwater systems.

Hourly flow rates at each of the city's 38 CSO outfalls were calculated by XP-SWMM for the calibration period (1994-1998) based on hourly rainfall measured at New Castle County Airport and Porter Reservoir. Water quality was monitored at three CSO locations (CSO 25, CSO 4b, and the 11th Street Pump Station) for two storm events on 10/27/2003 and 12/17/2003. Event mean concentrations (EMCs) were estimated for *enterococci* bacteria, and the EMCs were used in conjunction with the hourly CSO flow rates to determine *enterococci* bacteria loads for each CSO outfall. CSO flows and loads were then input to the EFDC receiving water model to simulate the impact on bacteria levels in the tidal Christina River, tidal Brandywine Creek, and tidal White Clay Creek.

2.3 Modeling Assumptions

The simulation of streamflow in the Christina River Basin HSPF models considered the following assumptions: (1) inputs of hourly precipitation would be estimated reasonably well by disaggregated 24-hour precipitation data; (2) the average precipitation over a given land segment would be represented adequately by weighted data from a single precipitation gage; and (3) a simplified set of pervious land uses (PERLND) and impervious land uses (IMPLND) would not limit a satisfactory hydrologic calibration (Senior and Koerkle, 2003a).

The simulation of water quality in the HSPF models considered the following assumptions: (1) land-based contributions of sediment and bacteria could be simulated by a simplified set of land-use categories; (2) water quality could be represented by the condition where chemical transformation of bacteria are simulated explicitly in the stream channel but not in land processes; and (3) the contribution of sediment from bank erosion in the stream channel can be estimated by sediment from pervious land areas (Senior and Koerkle, 2003a).

Simulation of CSO enterococci loads assumes that the event mean concentrations are the same regardless of the intensity or duration of the storm event. Enterococci concentrations were monitored at two outfalls, CSO 4b (34,917 cfu/100mL) and CSO 25 (57,885 cfu/100mL). The EMC at CSO 3 was assumed to be equal to that measured at the 11th Street Pump Station (121,635 cfu/100mL). The EMC for the other 35 CSOs was assumed to be equal to the geometric mean of all storm monitoring data from CSO 4b and CSO 25 (45,888 cfu/100mL).

2.4 Model Configuration

2.4.1 HSPF Subbasins

Four separate HSPF models were developed to simulate watershed runoff and sediment and bacteria loading in the Christina River Basin. One model was developed for each of the four main watersheds: Brandywine Creek, White Clay Creek, Red Clay Creek, and Christina River. The Christina River Basin was delineated into 70 subbasins (or reaches) for the modeling effort (see Figure 1-1). The size of the subbasins ranged from 0.6 to 25.5 mi^2. The subbasins were delimited based on major tributary inflows, calibration locations (stream gages and water quality monitoring stations), and time-of-travel considerations.

2.4.2 Land Use Classifications

Spatial data input to the HSPF model are used to define the structure fixed characteristics of the model. The principal structural unit of the HSPF model is the hydrologic response units PERLND (pervious land) and IMPLND (impervious land). Fifteen original land-use categories (circa 1995) from several sources were simplified and reclassified into 10 pervious and 2 impervious land-use categories that were expected to have distinct nonpoint-source water-quality characteristics (Table 2-1).

Agricultural land use was divided into three characteristic subtypes for the model. Agricultural-livestock land use identifies relatively small acreage farms with high animals-per-acre densities, limited pasture areas, and rowcrops. Small acreage dairy operations typify this land-use type. Agricultural-rowcrop landuse identifies farms with lower animals-per-acre densities (typically beef cattle and horses) and substantial pasture and crop acreage. Agricultural-mushroom land use is the third type of agriculture land use delimited, but mushroom production operations are much more prevalent in the Red Clay Creek and White Clay Creek Basins than in the Brandywine Creek Basin.

Residential land use is distributed throughout the basin and is divided into two types: sewered and non-sewered land. Sewered residential areas tend to have higher housing densities and are nearer to urban/suburban areas than non-sewered areas. Non-sewered residential areas tend to have lower densities and are more rural. For example, Chester County requires a minimum one-acre lot size for on-site sewerage. Other urban land use is in small boroughs and along major roadways. Forested land is distributed throughout the basin and tends to be along stream channels.

Table 2-1. Land-use categories used in HSPF models for Christina River Basin

Land-use category for HSPF model		Description
Pervious	Residential-septic	Residential land not within a sewer service area
	Residential-sewer	Residential land within a sewer service area
	Urban	Commercial, industrial, institutional, and transportation uses
	Agricultural-livestock	Predominantly mixed agricultural activities of dairy cows, pasture, and other livestock operations
	Agricultural-rowcrop	Predominantly row crop cultivation (corn, soybean, alfalfa), may include some hay or pasture land
	Agricultural-mushroom	Mushroom-growing activities including compost preparation, mushroom-house operations, spent compost processing
	Open	Recreational and other open land not used for agricultural
	Forested	Predominantly forested land
	Wetlands/water	Wetlands and open water
	Undesignated	Land use not defined
Impervious	Residential	Impervious residential land
	Urban	Impervious commercial, industrial, and other urban land

2.4.3 Bacteria Sources

Fecal coliform and enterococci bacteria are found in the intestines of warm blood animals including humans. They can enter a receiving waterbody mainly through several pathways, for example, from the land surface along with rainfall runoff, direct discharge from grazing animals in streams, failed septic tank seepage, discharge from municipal waste water treatment plants, and combined sewer overflow discharges. Estimates of the bacteria load from each of these sources was required in order to model the fecal coliform and enterococci concentrations in the receiving water.

2.4.3.1 Bacteria accumulation on land surface

Fecal coliform and enterococci bacteria accumulate on land surface due to manure applications and animal grazing. Manure applications and livestock grazing were estimated from the livestock numbers in the watershed. The bacteria load contribution from wild animals was estimated from literature values.

To estimate the accumulation rate of fecal coliform on land surface from livestock, the number of animals associated with different land uses was required for each delineated subbasin. However, in Christina River Basin, the only available livestock data were at the county level, i.e. Chester County in Pennsylvania, and New Castle County in Delaware. Therefore, the number of livestock in the each subbasin was derived from the county level data. A rough estimate was made by multiplying the ratio of the subbasin areas to the area of the counties to the county level livestock amount (see data report, USEPA 2004). However, the approach taken for the watershed modeling was to determine the ratios of the appropriate land use areas within each subbasin to the county area, which is more realistic since manure application and livestock grazing occur only on cropland and pastureland.

To estimate the ratios of land uses in the subbasins to the counties, both the areas of land uses in the subbasin and in the counties are required. The USGS HSPF model used the 1995 land use in the Christina River Basin, which was developed originally by the University of Delaware. The original 14 land uses in the Anderson classification system were then grouped to 7 categories. The seven categories were finally redistributed to 10 pervious (PERLND) and 2 impervious (IMPLND) modules in the HSPF model. The 1995 land use coverage was developed by the USGS for the Christina River Basin HSPF model and does not include county level data for Chester and New Castle counties. Therefore, both the 1992 and 2001 MRLC land use data were obtained, which included the modeling domain as well as the two counties. The subbasin shapefiles provided with the HSPF model were used to tabulate the areas of different land uses for the two MRLC data sets. The boundaries of the two counties were used to tabulate the land use areas for the two counties. Due to the different MRLC land use classifications for the 1992 and 2001 data (Table 2-2), the land uses cannot be compared directly for certain categories. In addition, since the HSPF model used the land use in Anderson classification system (Table 2-3), the land uses cannot be compared with MRLC data directly either.

Table 2-2. The MRLC land use classification

MRLC 1992		MRLC 2001	
Landuse ID	Land Use Type	Landuse ID	Land Use Type
VALUE_11	Open Water	VALUE_11	Open Water
VALUE_21	Low intensity residential	VALUE_21	Low intensity residential
VALUE_22	High intensity residential	VALUE_22	High intensity residential
VALUE_23	Commercial/industrial/transportation	VALUE_23	Commercial/industrial/transportation
VALUE_32	Barren	VALUE_24	Recreation
VALUE_33	Barren	VALUE_31	Barren
VALUE_41	Forest	VALUE_41	Forest
VALUE_42	Forest	VALUE_42	Forest
VALUE_43	Forest	VALUE_43	Forest
VALUE_81	Pasture	VALUE_81	Pasture
VALUE_82	Row crops	VALUE_82	Row crops
VALUE_85	Recreational grass	VALUE_90	Wetland
VALUE_91	Wetland	VALUE_95	Wetland
VALUE_92	Wetland		

Table 2-3. The Anderson land use classification

Landuse ID	Land Use Type
VALUE_1	UNKNOWN
VALUE_7	OFFICE
VALUE_15	INDUSTRIAL
VALUE_28	INSTITUTIONAL
VALUE_50	WATER
VALUE_115	COMMERCIAL
VALUE_150	SINGLE FAMILY
VALUE_213	TRANSPORTATION/UTILITY
VALUE_530	PUBLIC/PRIVATE OPEN SPACE
VALUE_539	WOODED
VALUE_706	AGRICULTURE
VALUE_762	MINING
VALUE_885	MULTI FAMILY
VALUE_901	VACANT

As stated above, the HSPF PERLND and IMPLND characteristics were derived from the grouped Anderson land uses. The seven grouped land uses developed by the USGS for the HSPF model are Agriculture, Forested, Residential, Urban, Open, Undesignated, and Water. The HSPF agriculture-livestock, agriculture-rowcrop, and agriculture mushroom land uses were obtained from the total agriculture. The residential-septic and residential-sewer land uses were obtained from the total residential area. The agriculture and residential areas are most important since the manure application and livestock grazing occur on agriculture land, and septic tank failure events, which are potentially important, occur primarily in residential areas. The estimation of the county level agriculture land is discussed here and the estimation of the county level residential area is discussed later when dealing with septic tanks.

The total agriculture area in the HSPF model, from the original Christina River Basin land use delineation as well as the land uses from the MRLC agriculture areas as shown in Figure 2-1.

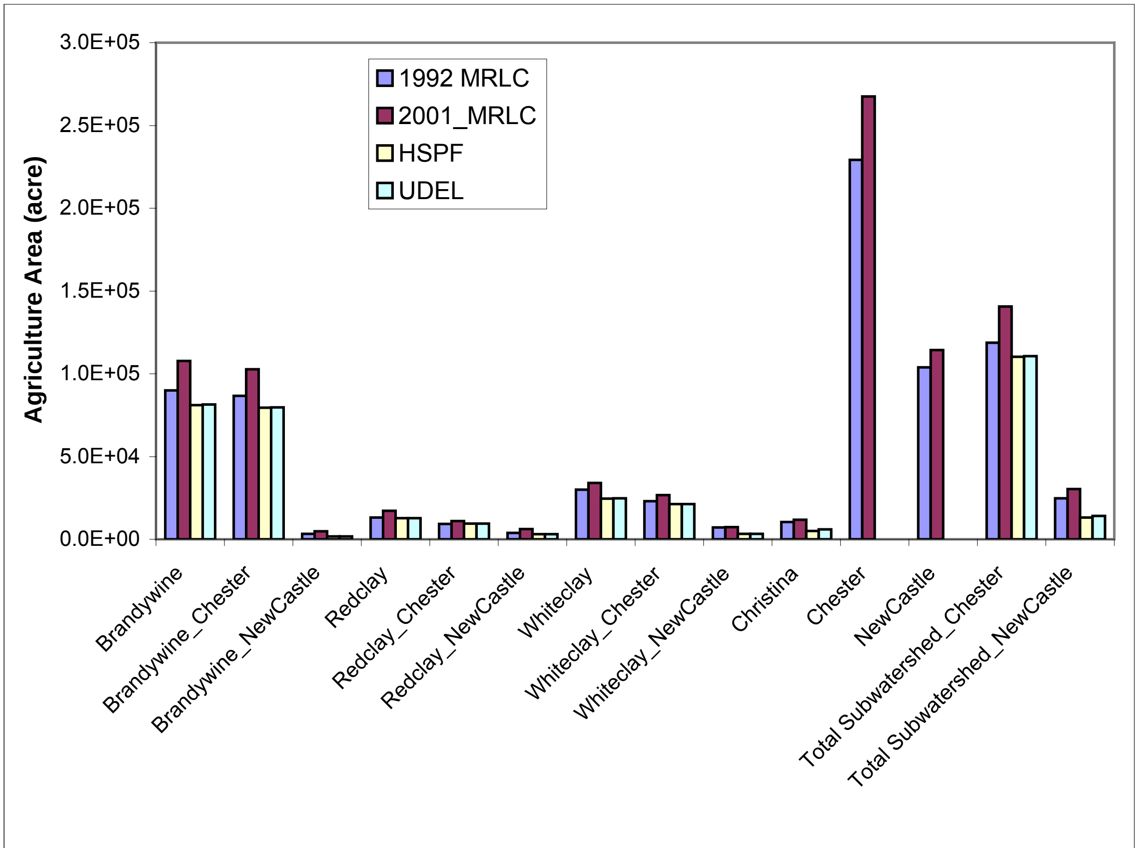

Figure 2-1. Comparison of Agriculture Areas with Different Land Use Classification in 1992, 1995 (HSPF and UDEL), and 2001

The total agriculture areas are different for all the three years. The differences between 1992 and 1995 are smaller than those between 1995 and 2001. In general, the 1995 land use shows less agriculture area than both the 1992 and 2001 land use. The agriculture areas in Chester County are similar between 1992 and 1995. However, the 1995 agriculture area in New Castle is only approximately half of 1992. The difference may be caused by various reasons such as the satellite images and land use identification methods. It is assumed that the ratios between the subbasin and two county level land uses for these three years do not change. The county level agriculture areas in 1995 are then estimated using the ratios in 1992. The estimated agriculture areas in Chester County and New Castle County are listed in Table 2-4. The agriculture areas are further divided into agriculture-livestock, agriculture-rowcrop, and agriculture-mushroom based on the same ratios in the whole Christina River Basin.

Table 2-4. The estimated county level agriculture areas in 1995

County	Total Agriculture (Acre)	Agriculture-rowcrop (Acre)	Agriculture-Livestock (Acre)	Agriculture-Mushroom (Acre)
Chester, PA	212,620.79	169,307.65	33,025.80	10,287.33
New Castle, DE	55,338.26	53,498.26	1,216.59	623.41

The definition of agriculture-livestock and agriculture-rowcrop are different from the MRLC pastureland and cropland, respectively. The MRLC pastureland includes the areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops. The HSPF agriculture-livestock identifies "relatively small acreage farms with high animals-per-acre densities, limited pasture areas, and rowcrops. Small acreage dairy operations typify this land-use type." (Senior and Koerkle, 2003). The MRLC Row Crops land use includes crops, such as corn, soybeans, vegetables, tobacco, and cotton. The HSPF agriculture-rowcrop identifies "farms with lower animals-per-acre densities (typically beef cattle and horses) and substantial pasture and crop acreage."

The current EPA bacterial indicator tool (BIT) is a widely used tool to estimate the load from land surface based on the provided areas of buildup, pasture, cropland, and forest (USEPA, 2000; see Appendix M for user's guide). The animals such as beef cow, milk cow, swine, horse, sheep, chicken, and wildlife are also required. BIT uses the MRLC pastureland and cropland definitions. It assumes that cropland only uses the manure from cattle, swine, and poultry. Pastureland uses the manure from cattle, horses, sheep, and other agricultural animals grazing on the land. However, the USGS agriculture-livestock only includes the milk cow pastureland, while the agriculture-rowcrop includes the beef cow pastureland, horses, and other animals. The agriculture-mushroom land is assumed not to receive any manure application. A comparison of the agriculture land uses for the 1992, 1995, and 2001 years within the Christina River Basin is shown in Figure 2-2. A cross-reference table showing manure application to MRCL land uses to the USGS HSPF land uses is summarized in Table 2-5. Similarly, livestock grazing activities assigned to MRLC land uses and HSPF land uses are shown in Table 2-6.

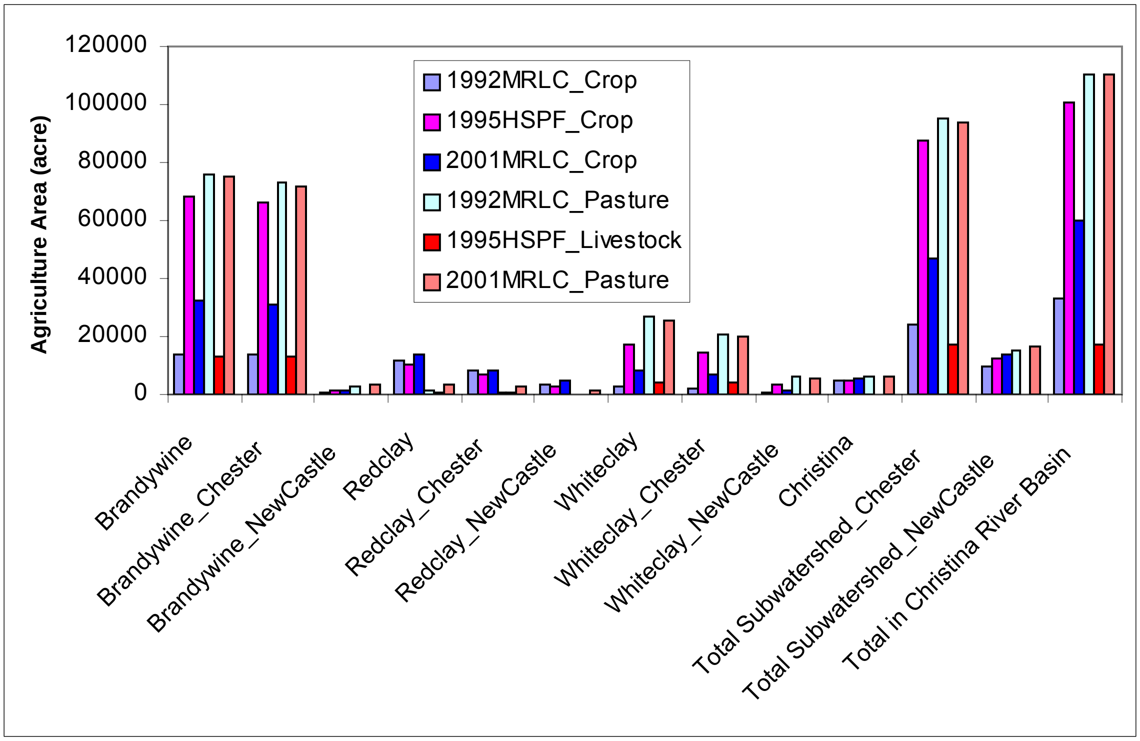

Figure 2-2. Agriculture areas in Christina River Basin

Table 2-5. Manure application for MRLC and HSPF land uses

Animals	MRLC Cropland	MRLC Pastureland	USGS HSPF Agriculture-Rowcrop	USGS HSPF Agriculture-Livestock
BEEF CATTLE	√	√	√	
SWINE (HOGS)	√		√	
DAIRY CATTLE	√	√	√	√
CHICKENS	√		√	
HORSES		√	√	
OTHER		√	√	

Table 2-6. Livestock grazing for MRLC and HSPF land uses

Animals	MRLC Cropland	MRLC Pastureland	USGS HSPF Agriculture-Rowcrop	USGS HSPF Agriculture-Livestock
BEEF CATTLE		√	√	
HORSES		√	√	
SHEEP		√	√	
OTHER		√	√	

The bacterial indicator tool was modified to adapt to the USGS HSPF agriculture land uses. The manure is applied to all the rowcrop land, while only the manure from milk cow is applied to the pastureland. The manure from milk cow is also applied to the rowcrop land with a ratio specified in the BIT spreadsheet. Animal grazing is assumed to occur on both the agriculture-rowcrop land and agriculture-livestock land. The estimated fecal coliform accumulation rates and storage limits for the Chester County and New Castle County are listed in Tables 2-15 through 2-16.

The county level agriculture animal data were obtained from the Census of Agriculture (http:///www.nass.usda.gov). The most recent data available are from 1992 and 1997. The cattle and calves inventory, sheep and lambs inventory, layers and pullets inventory, and broilers and other meat-type chicken inventory for these two years are similar in both Chester County and New Castle County. Therefore, the average inventories were calculated and used for the model simulation period. Unlike the other agricultural animals, the hogs and pigs inventory was significantly reduced from 1992 to 1997. Since the model calibration period is from 1994 to 1998, the amount of hogs and pigs in the five years were calculated based on a linear reduction assumption. The average number for the five years was then used in the BIT spreadsheet file. BIT calculates the fecal coliform load based on the amount of waste the animals produce and the average weight of adult animals. The calves were converted to cattle before the calculation by assuming that the average weight of a calf is half of a grown cow. The total number of beef and milk cows are then calculated. In the census data, two types, layers and pullets 13 weeks old and older, and the broilers and other meat-type chickens sold, are listed. It is usually assumed that the chicken raising period is 12 weeks. Therefore, the average number of meat-type chicken in the farms at any given time is calculated by multiplying the annual number of chickens sold by the ratio of 12/52 weeks. This value is further adjusted by multiplying by a factor of 0.5 to account for weight difference between a fully-grown chicken (at 12 weeks of age) and the average size of a chicken being raised on the farms. The USDA agriculture census inventory data for the years 1992, 1997, and 2002 as well as the numbers of agricultural animals used to estimate the bacteria load are listed in Table 2-7.

Table 2-7. Livestock Inventories from 1992, 1997, and 2002 USDA Agriculture Census

Category	Chester County, PA			New Castle County, DE		
	1992	1997	2002	1992	1997	2002
Cattle and calves	50,795	48,897	41,878	3,446	2,628	2,665
Hogs and pigs	11,855	2,357	12,860	630	51	86
Poultry (layers, broilers, turkeys)	734,087	599,360	696,361	209,195	220,308	NA
Horses and ponies	4,330	5,293	8,597	770	737	833
Sheep and lambs	3,421	2,154	2,856	238	222	366
Numbers used in watershed model for 1994-1998 calibration period:						
BEEF CATTLE	5,286			633		
DAIRY CATTLE	31,900			1,736		
SWINE (HOGS)	6,540			280		
POULTRY	740,480			220,308		
HORSES	5,293			737		
SHEEP	2,580			222		
OTHER	350			0		

NA = not available

Wildlife also generates bacteria on the land surfaces and in streams. Wild animals are also assumed to be the only source of bacteria on Forested land. A precise estimate of the number of wild animals in the Christina River Basin is not available. Literature and empirical values are used in this study, as shown in Table 2-8, to estimate wild animal population densities for different land use categories. Monthly adjustment factors were added in the BIT spreadsheet tool to account for possible seasonal variations in wild animal populations.

Table 2-8. Estimated wild animal density in Christina River Basin

Wild Animals	Agricutlure-Rowcrop (Animals/sq mile)	Agricutlure-livestock (Animals/sq mile)	FOREST Animals/sq mile)
Ducks	30	30	10
Geese	50	50	0
Deer	0	35	35
Beaver	5	5	10
Raccoons	2.5	2.5	5
Other	320	160	160

The bacteria indicator tool spreadsheet calculates the bacteria load based on the daily fecal coliform and enterococci amounts generated per animal. No observation data of actual fecal coliform and enterococci production rates are available in the Christina River Basin. Therefore, literature values from various sources are used as listed in Table 2-9 for fecal coliform. For enterococci, even literature values are very limited. An extensive online search was conducted to find literature values. No direct measurements of enterococci production rates for human beings or animals were found. However, the ratios of enterococci to fecal streptococci for certain animals were found as presented in Table 2-10.

Table 2-9. Fecal coliform production rate

Animal	Fecal Coliform (cfu/animal/day)
Dairy cow	1.01E+11
Beef cow	1.04E+11
Hog	1.08E+10
Sheep	1.20E+10
Horse	4.20E+08
Chicken	1.36E+08
Turkey	9.30E+07
Duck	2.43E+09
Goose	4.90E+10
Deer	5.00E+08
Beaver	2.50E+08
Raccoon	1.25E+08
Dog	4.09E+09
Other Ag Animal	0.00E+00
Other Wildlife	0.00E+00

Table 2-10. Ratios of Enterococci to Fecal Streptococci

Source	ENT / FS
Human (sewer and streams)	80-91%
Beaver	0%
Sheep	1.20%
Horse	3.70%
Cow	29%
Chicken	98.80%

(From Mark Hicks, Setting Standards for the bacteriological quality of Washington's surface waters, www.ecy.wa.gov)

In addition to the ratios of enterococci to fecal streptococci, the literature values of daily production rates of fecal streptococci from ASAE and other sources were used to compute the daily production rates of enterococci as shown in Table 2-11.

Table 2-11. Enterococci production rate

Animal	Enterococci (cfu/animal/day)
Dairy cow	1.70E+10
Beef cow	6.60E+09
Hog	1.90E+09
Sheep	2.00E+08
Horse	9.80E+09
Chicken	2.90E+08

The production rate values in Table 2-9 were used to estimate the fecal coliform accumulation rate on cropland, pastureland, and forest. For the build-up land uses, the rates were directly specified with literature values. In the original BIT, the road, commercial areas, and residential areas are grouped into one build-up land use, and an average fecal coliform accumulation rate is calculated using the ratios of the developed areas. The accumulation rates are assumed to be constant throughout the year. In the USGS HSPF model, these land uses were not grouped together. Hence, the literature values are directly used as listed in Table 2-12. For enterococci, since no literature values were found in developed areas, the accumulation rates were obtained during calibration.

Table 2-12. Fecal coliform accumulation rates on developed land uses

Land Use	Accumulation Rate cfu/acre/day
Road	2.00E+05
Urban	6.21E+06
Open	1.03E+07
Residential-Septic	1.66E+07
Residential-Sewer	2.33E+07

With the estimated county-level land uses and animal population numbers, the accumulation rates for the USGS HSPF land uses were obtained. The accumulation rates of fecal coliform are listed in Table 2-13 and Table 2-14 for Chester County and New

Castle County, respectively. The accumulation rates of enterococci are listed in Table 2-17 and Table 2-18 for Chester County and New Castle County, respectively.

Once the accumulation rates of bacteria were obtained, the storage limits can be computed using the following method. The original BIT uses the following equation to represent the fecal coliform die-off on the land surface follows:

$$N_t = N_0(10^{(-kt)}) \qquad (1)$$

Where: N_t = number of fecal coliforms at time t
N_0 = number of fecal coliforms at time 0
t = time in days
k = first order die-off rate constant.

A more direct way is to use:

$$N_t = N_0 e^{(-kt)} \qquad (2)$$

Equation (2) is the direct solution of the first-order die-off ordinary differential equation. The relationship between these two equation is in that the k in (2) is equal to k in (1) times ln(10). Therefore, when a literature value of die-off rate is used, it is very important to check the corresponding equation. The maximum fecal coliform amount on a land surface (storage limit) can be calculated by summing the Nt for several days until the value reaches steady state. The original BIT uses net die-off rates for warm months are 0.51/day and for cold months 0.36/day from Horsley and Witten (1984). Using the equation and die-off rates above, the storage limits for the fecal coliform is approximately 1.5 and 1.8 times of the value of the accumulation rates, respectively. However, various studies on the survival of fecal coliform and *e. coli* bacteria in soil show that the die-off rates of these bacteria in soil is significantly lower. Therefore, using the Horsley and Witten decay rates will underestimate the total fecal coliform accumulated on the land surface. The maximum storage limits for fecal coliform in HSPFPARM database are around 50 times the value of accumulation rate. Since the die-off rate varies over a wide range, the resultant storage limit varies correspondingly. Obtaining the ratio from the equation is not necessarily better than directly specifying a ratio. Therefore, in this project, a ratio was directly assigned to the accumulation rate for both the fecal coliform and enterococci bacteria. The ratio was set to 10 for fecal coliform and 15 for enterococci since enterococci usually survive longer than fecal coliform under various conditions. The final ratios were determined during calibration. The calculated storage limits of fecal coliform for the different land uses by month are listed in Tables 2-15 and 2-16 for Chester County and New Castle County, respectively. The calculated storage limits of enterococci for the different land uses by month are listed in Tables 2-19 and 2-20 for Chester County and New Castle County, respectively.

Table 2-13. Estimated fecal coliform accumulation rates in Chester County (cfu/ac/day)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	4.6E+09	4.6E+09	9.4E+09	1.4E+10	1.3E+10	1.3E+10
Agricultural-livestock	7.0E+07	7.0E+07	6.7E+09	1.4E+10	1.2E+10	1.2E+10
Forested	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07
Road	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05

Urban	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06
Open	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07
Residential-Septic	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07
Residential-sewer	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	1.2E+10	1.2E+10	1.4E+10	1.1E+10	7.6E+09	4.6E+09
Agricultural-livestock	1.2E+10	1.2E+10	1.5E+10	6.7E+09	7.0E+07	7.0E+07
Forested	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07
Road	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05
Urban	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06
Open	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07
Residential-Septic	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07
Residential-sewer	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07

Table 2-14. Estimated fecal coliform accumulation rates in New Castle County (cfu/ac/day)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	4.2E+09	4.2E+09	6.1E+09	8.4E+09	7.8E+09	7.4E+09
Agricultural-livestock	7.0E+07	7.0E+07	4.8E+10	1.0E+11	8.5E+10	8.8E+10
Forested	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07
Road	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05
Urban	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06
Open	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07
Residential-Septic	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07
Residential-sewer	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	7.3E+09	7.3E+09	7.9E+09	7.9E+09	6.4E+09	4.2E+09
Agricultural-livestock	8.5E+10	8.5E+10	1.0E+11	4.8E+10	7.0E+07	7.0E+07
Forested	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07	7.0E+07
Road	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05	2.0E+05
Urban	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06	6.2E+06
Open	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07	1.0E+07
Residential-Septic	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07	1.7E+07
Residential-sewer	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07	2.3E+07

Table 2-15. Estimated fecal coliform storage limits in Chester County (cfu/ac)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	4.6E+10	4.6E+10	9.4E+10	1.4E+11	1.3E+11	1.3E+11
Agricultural-livestock	7.0E+08	7.0E+08	6.7E+10	1.4E+11	1.2E+11	1.2E+11
Forested	7.0E+08	7.0E+08	7.0E+08	7.0E+08	7.0E+08	7.0E+08
Road	2.0E+06	2.0E+06	2.0E+06	2.0E+06	2.0E+06	2.0E+06
Urban	6.2E+07	6.2E+07	6.2E+07	6.2E+07	6.2E+07	6.2E+07
Open	1.0E+08	1.0E+08	1.0E+08	1.0E+08	1.0E+08	1.0E+08
Residential-Septic	1.7E+08	1.7E+08	1.7E+08	1.7E+08	1.7E+08	1.7E+08
Residential-sewer	2.3E+08	2.3E+08	2.3E+08	2.3E+08	2.3E+08	2.3E+08
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	1.2E+11	1.2E+11	1.4E+11	1.1E+11	7.6E+10	4.6E+10
Agricultural-livestock	1.2E+11	1.2E+11	1.5E+11	6.7E+10	7.0E+08	7.0E+08

Forested	7.0E+08	7.0E+08	7.0E+08	7.0E+08	7.0E+08	7.0E+08
Road	2.0E+06	2.0E+06	2.0E+06	2.0E+06	2.0E+06	2.0E+06
Urban	6.2E+07	6.2E+07	6.2E+07	6.2E+07	6.2E+07	6.2E+07
Open	1.0E+08	1.0E+08	1.0E+08	1.0E+08	1.0E+08	1.0E+08
Residential-Septic	1.7E+08	1.7E+08	1.7E+08	1.7E+08	1.7E+08	1.7E+08
Residential-sewer	2.3E+08	2.3E+08	2.3E+08	2.3E+08	2.3E+08	2.3E+08

Table 2-16. Estimated fecal coliform storage limits in New Castle County (cfu/ac)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	4.21E+10	4.21E+10	6.13E+10	8.37E+10	7.76E+10	7.41E+10
Agricultural-livestock	7.02E+08	7.02E+08	4.77E+11	1.03E+12	8.49E+11	8.77E+11
Forested	7.02E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08
Road	1995753	1995753	1995753	1995753	1995753	1995753
Urban	62090108	62090108	62090108	62090108	62090108	62090108
Open	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08
Residential-Septic	1.66E+08	1.66E+08	1.66E+08	1.66E+08	1.66E+08	1.66E+08
Residential-sewer	2.33E+08	2.33E+08	2.33E+08	2.33E+08	2.33E+08	2.33E+08
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	7.32E+10	7.32E+10	7.94E+10	7.88E+10	6.42E+10	4.21E+10
Agricultural-livestock	8.49E+11	8.49E+11	1.04E+12	4.77E+11	7.02E+08	7.02E+08
Forested	7.02E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08	7.02E+08
Road	1995753	1995753	1995753	1995753	1995753	1995753
Urban	62090108	62090108	62090108	62090108	62090108	62090108
Open	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08
Residential-Septic	1.66E+08	1.66E+08	1.66E+08	1.66E+08	1.66E+08	1.66E+08
Residential-sewer	2.33E+08	2.33E+08	2.33E+08	2.33E+08	2.33E+08	2.33E+08

Table 2-17. Estimated enterococci accumulation rates in Chester County (cfu/ac/day)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	2.34E+08	2.34E+08	8.30E+08	2.34E+09	2.12E+09	1.15E+09
Agricultural-livestock	8.42E+08	8.42E+08	2.48E+09	3.25E+09	3.06E+09	2.81E+09
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04
Urban	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06
Open	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06
Residential-Septic	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06
Residential-sewer	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	1.12E+09	1.12E+09	1.32E+09	4.80E+09	4.54E+09	2.33E+08
Agricultural-livestock	2.78E+09	2.78E+09	3.26E+09	2.69E+09	1.88E+09	8.42E+08
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04
Urban	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06
Open	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06
Residential-Septic	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06
Residential-sewer	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06

Table 2-18. Estimated enterococci accumulation rates in New Castle County (cfu/ac/day)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	5.32E+07	5.32E+07	1.83E+08	1.26E+09	1.19E+09	2.57E+08
Agricultural-livestock	6.07E+09	6.07E+09	1.79E+10	2.34E+10	2.21E+10	2.03E+10
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04
Urban	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06
Open	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06
Residential-Septic	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06
Residential-sewer	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	2.51E+08	2.51E+08	2.92E+08	3.92E+09	3.95E+09	5.27E+07
Agricultural-livestock	2.00E+10	2.00E+10	2.35E+10	1.94E+10	1.35E+10	6.07E+09
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04	6.59E+04
Urban	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06
Open	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06	3.40E+06
Residential-Septic	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06	5.49E+06
Residential-sewer	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06	7.68E+06

Table 2-19. Estimated enterococci storage limits in Chester County (cfu/ac)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	3.5E+09	3.5E+09	1.2E+10	2.3E+10	2.1E+10	1.1E+10
Agricultural-livestock	1.3E+10	1.3E+10	3.7E+10	3.2E+10	3.1E+10	2.8E+10
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	9.88E+05	9.88E+05	9.88E+05	6.59E+05	6.59E+05	6.59E+05
Urban	3.07E+07	3.07E+07	3.07E+07	2.05E+07	2.05E+07	2.05E+07
Open	5.10E+07	5.10E+07	5.10E+07	3.40E+07	3.40E+07	3.40E+07
Residential-Septic	8.23E+07	8.23E+07	8.23E+07	5.49E+07	5.49E+07	5.49E+07
Residential-sewer	1.15E+08	1.15E+08	1.15E+08	7.68E+07	7.68E+07	7.68E+07
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	1.1E+10	1.1E+10	1.3E+10	7.2E+10	6.8E+10	3.5E+09
Agricultural-livestock	2.8E+10	2.8E+10	3.3E+10	4.0E+10	2.8E+10	1.3E+10
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	6.59E+05	6.59E+05	6.59E+05	9.88E+05	9.88E+05	9.88E+05
Urban	2.05E+07	2.05E+07	2.05E+07	3.07E+07	3.07E+07	3.07E+07
Open	3.40E+07	3.40E+07	3.40E+07	5.10E+07	5.10E+07	5.10E+07
Residential-Septic	5.49E+07	5.49E+07	5.49E+07	8.23E+07	8.23E+07	8.23E+07
Residential-sewer	7.68E+07	7.68E+07	7.68E+07	1.15E+08	1.15E+08	1.15E+08

Table 2-20. Estimated enterococci storage limits in New Castle County (cfu/ac)

Landuse	January	February	March	April	May	June
Agricultural-rowcrop	1.06E+09	1.06E+09	3.66E+09	1.26E+10	1.19E+10	2.57E+09
Agricultural-livestock	1.21E+11	1.21E+11	3.57E+11	2.34E+11	2.21E+11	2.03E+11
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	1.32E+06	1.32E+06	1.32E+06	6.59E+05	6.59E+05	6.59E+05
Urban	4.10E+07	4.10E+07	4.10E+07	2.05E+07	2.05E+07	2.05E+07
Open	6.81E+07	6.81E+07	6.81E+07	3.40E+07	3.40E+07	3.40E+07

Residential-Septic	1.10E+08	1.10E+08	1.10E+08	5.49E+07	5.49E+07	5.49E+07
Residential-sewer	1.54E+08	1.54E+08	1.54E+08	7.68E+07	7.68E+07	7.68E+07
Landuse	July	August	September	October	November	December
Agricultural-rowcrop	2.51E+09	2.51E+09	2.92E+09	7.84E+10	7.91E+10	1.05E+09
Agricultural-livestock	2.00E+11	2.00E+11	2.35E+11	3.88E+11	2.71E+11	1.21E+11
Forested	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Road	6.59E+05	6.59E+05	6.59E+05	1.32E+06	1.32E+06	1.32E+06
Urban	2.05E+07	2.05E+07	2.05E+07	4.10E+07	4.10E+07	4.10E+07
Open	3.40E+07	3.40E+07	3.40E+07	6.81E+07	6.81E+07	6.81E+07
Residential-Septic	5.49E+07	5.49E+07	5.49E+07	1.10E+08	1.10E+08	1.10E+08
Residential-sewer	7.68E+07	7.68E+07	7.68E+07	1.54E+08	1.54E+08	1.54E+08

2.4.3.2 Animal direct loading to stream due to grazing

Beef and milk cows may access a stream during grazing and directly deposit waste into the stream. Due to the different definitions in the USGS HSPF models and MRLC, the original BIT was modified to add grazing of beef cows only on agriculture-rowcrop land and grazing of milk cow only on agriculture-livestock land. In addition, horses and sheep also are able to directly enter streams. The BIT was modified to include the possible direct loading of manure from horses, sheep, and any other animals to streams from agriculture-rowcrop land. In this study, no detailed inventory of wildlife was available. Therefore, only contributions from cattle, horses, and sheep were estimated for direct loading of fecal coliform and enterococci bacteria to streams.

The original BIT estimated the total flow rates and load of bacteria in each subbasin. In Christina River Basin, only county level animal population numbers were available. Instead of allocating the animals to agriculture-rowcrop and agriculture-livestock land in each subbasin and calculating the flow rate and load of fecal coliform to each subbasin, the BIT was modified to calculate the bacteria load per unit area of agriculture-rowcrop and agriculture-livestock land.

To estimate the direct discharge of fecal coliform due to animal grazing, the time spent grazing was specified, and literature values were used in this study as shown in Table 2-21. The fraction of time spent standing in streams during grazing periods is listed in Table 2-22. The loading rate was estimated using the animal waste production rate and the density of the waste. The loading rate was calculated using the daily fecal coliform and enterococci production rates and the amount of grazing animals in streams. Using the fraction of time spent in the stream, the total numbers of beef cows, milk cows, horses, and sheep, the agriculture-rowcrop area, and the agriculture-livestock area, the unit area flow rate and the average animal fecal coliform and enterococci concentrations were calculated as shown in Tables 2-23, 2-24, 2-25, and 2-26 for Chester County and New Castle County.

Table 2-21. Fraction of time spent grazing

Month	BEEF CATTLE	DAIRY CATTLE	HORSES	SHEEP
January	0.60	0.25	0.35	1.00
February	0.60	0.25	0.35	1.00
March	1.00	0.60	0.75	1.00
April	1.00	0.70	0.75	1.00
May	1.00	0.70	0.75	1.00
June	1.00	0.70	0.75	1.00
July	1.00	0.70	0.75	1.00
August	1.00	0.70	0.75	1.00
September	1.00	0.70	0.75	1.00
October	1.00	0.70	0.75	1.00
November	1.00	0.60	0.75	1.00
December	0.60	0.25	0.35	1.00

Table 2-22. Fraction of time spent in stream during grazing

Month	BEEF CATTLE	DAIRY CATTLE	HORSES	SHEEP
January	0.000	0.000	0.000	0.000
February	0.000	0.000	0.000	0.000
March	0.000	0.010	0.100	0.100
April	0.013	0.060	0.100	0.100
May	0.019	0.060	0.200	0.200
June	0.044	0.180	0.200	0.200
July	0.044	0.180	0.200	0.200
August	0.044	0.180	0.200	0.200
September	0.019	0.060	0.100	0.100
October	0.013	0.060	0.100	0.100
November	0.013	0.070	0.000	0.000
December	0.010	0.000	0.000	0.000

Table 2-23. Animal direct discharge of fecal coliform in Chester County

Month	Cropland Flow(cfs/ac)	Cropland Concentration(cfu/100ml)	Pasture Land Flow(cfs/ac)	Pasture Land Concentration(cfu/100ml)
January	0.00E+00	0.00E+00	0.00E+00	0.00E+00
February	0.00E+00	0.00E+00	0.00E+00	0.00E+00
March	2.30E-08	3.42E+07	2.67E-08	1.83E+08
April	2.65E-08	9.48E+07	1.87E-07	1.83E+08
May	5.11E-08	8.01E+07	1.87E-07	1.83E+08
June	5.79E-08	1.28E+08	5.61E-07	1.83E+08
July	5.79E-08	1.28E+08	5.61E-07	1.83E+08
August	5.79E-08	1.28E+08	5.61E-07	1.83E+08
September	2.81E-08	1.18E+08	1.87E-07	1.83E+08
October	2.65E-08	9.48E+07	1.87E-07	1.83E+08
November	3.52E-09	4.91E+08	1.87E-07	1.83E+08
December	1.62E-09	4.91E+08	0.00E+00	0.00E+00

Table 2-24. Animal direct discharge of fecal coliform in New Castle County

Month	Cropland Flow(cfs/ac)	Cropland Concentration(cfu/100ml)	Pasture Land Flow(cfs/ac)	Pasture Land Concentration(cfu/100ml)
January	0.00E+00	0.00E+00	0.00E+00	0.00E+00
February	0.00E+00	0.00E+00	0.00E+00	0.00E+00
March	1.33E-09	1.54E+08	1.93E-07	1.83E+08
April	2.67E-09	3.22E+08	1.35E-06	1.83E+08
May	4.61E-09	2.96E+08	1.35E-06	1.83E+08
June	7.18E-09	3.66E+08	4.04E-06	1.83E+08
July	7.18E-09	3.66E+08	4.04E-06	1.83E+08
August	7.18E-09	3.66E+08	4.04E-06	1.83E+08
September	3.28E-09	3.54E+08	1.35E-06	1.83E+08
October	2.67E-09	3.22E+08	1.35E-06	1.83E+08
November	1.33E-09	4.91E+08	1.35E-06	1.83E+08
December	6.15E-10	4.91E+08	0.00E+00	0.00E+00

Table 2-25. Animal direct discharge of enterococci in Chester County

Month	Cropland Flow(cfs/ac)	Cropland Concentration(cfu/100ml)	Pasture Land Flow(cfs/ac)	Pasture Land Concentration(cfu/100ml)
January	0.00E+00	0.00E+00	0.00E+00	0.00E+00
February	0.00E+00	0.00E+00	0.00E+00	0.00E+00
March	2.30E-08	4.14E+07	2.67E-08	3.09E+07
April	2.65E-08	4.00E+07	1.87E-07	3.09E+07
May	5.11E-08	4.03E+07	1.87E-07	3.09E+07
June	5.79E-08	3.93E+07	5.61E-07	3.09E+07
July	5.79E-08	3.93E+07	5.61E-07	3.09E+07
August	5.79E-08	3.93E+07	5.61E-07	3.09E+07
September	2.81E-08	3.95E+07	1.87E-07	3.09E+07
October	2.65E-08	4.00E+07	1.87E-07	3.09E+07
November	3.52E-09	3.11E+07	1.87E-07	3.09E+07
December	1.62E-09	3.11E+07	0.00E+00	0.00E+00

Table 2-26 Animal direct discharge of enterococci in New Castle County

Month	Cropland Flow(cfs/ac)	Cropland Concentration(cfu/100ml)	Pasture Land Flow(cfs/ac)	Pasture Land Concentration(cfu/100ml)
January	0.00E+00	0.00E+00	0.00E+00	0.00E+00
February	0.00E+00	0.00E+00	0.00E+00	0.00E+00
March	1.33E-09	3.88E+07	1.93E-07	3.09E+07
April	2.67E-09	3.49E+07	1.35E-06	3.09E+07
May	4.61E-09	3.55E+07	1.35E-06	3.09E+07
June	7.18E-09	3.40E+07	4.04E-06	3.09E+07
July	7.18E-09	3.40E+07	4.04E-06	3.09E+07
August	7.18E-09	3.40E+07	4.04E-06	3.09E+07
September	3.28E-09	3.42E+07	1.35E-06	3.09E+07
October	2.67E-09	3.49E+07	1.35E-06	3.09E+07
November	1.33E-09	3.11E+07	1.35E-06	3.09E+07
December	6.15E-10	3.11E+07	0.00E+00	0.00E+00

2.4.3.3 Septic tank failure

Failing septic systems are potential sources of fecal coliform and enterococci. To estimate the fecal coliform and enterococci loading rates from failed septic tanks, the number of septic tanks, the failure rate, and the concentrations of fecal coliform and enterococci in the discharge of failed septic tanks are required. The number of septic tanks in Chester County and New Castle County were downloaded from http://factfinder.census.gov/. The model calibration period is from 1994 to 1998. However, only 1990 data are available. Therefore, the number of septic tanks in existence during the calibration period was estimated according to the following methodology.

After examining the housing units in rural areas in the two counties reported in the 1990 U.S. Census, it was found that approximately each rural housing unit has a septic tank or cesspool (see Table 2-27). Since the number of rural housing units in New Castle County was similar in 1990 and 2000, the 1990 septic tank data was used as the basis to calculate the average septic tank load during the model calibration period. In Chester County, approximately 1,500 permits issued every year of which about 600 of are for repair work and 1,100 are for new permits (CCHD, 2005). The total number of septic systems during the calibration period in Chester County was then calculated assuming an annual increase of 1,100 systems since 1990, resulting an average of about 60,000 septic systems from 1994 to 1998. Thus, for the model calibration period, the average numbers of septic systems were estimated as 12,142 and 60,000 for New Castle County and Chester County, respectively.

Table 2-27. Census data related to septic tank estimation

Census Category	United States	New Castle County	Chester County
1990 Number of rural housing units	26,063,380	10,335	50,396
1990 Number septic tanks or cesspools	24,670,877	12,142	52,493
1990 Rural population	61,658,330	29,468	146,612
2000 Number of rural housing units	25,938,086	10,094	29,594
2000 Rural population	59,063,597	27,810	82,433

The failure rate directly controls the amount of septic load contributing fecal coliform and enterococci bacteria to streams. No surveys of failure rates in Chester County and New Castle County were available. According to CCHD (2005), 600 permits are issued for repair work, which is approximately 1% of the total septic tanks in Chester County. However, a permit issued for repair work does not necessarily mean the septic system is leaking. In order to estimate loads from malfunctioning septic systems, it was assumed that 20% of the repaired systems leak.

The original BIT was designed for subbasins and it assumes that septic contribution is evenly distributed on all the land areas within a subbasin. For the same reason as estimating the direct discharge from grazing animals, the BIT was modified to estimate the septic contribution as flow rate per unit area of residential-septic since septic tanks are only associated with residential-septic land use. As mentioned in the previous section, the

1995 land use was developed by the USGS only for the Christina River Basin HSPF model, and no county level land uses with the USGS HSPF definitions are available for 1995. The residential-septic areas in the Christina River Basin were obtained by overlaying sewer pipe with residential areas according to the USGS reports (Senior and Koerkel, 2003). To estimate the county level residential-septic areas, it was assumed that the ratio between residential-septic areas in the Christina River Basin inside the two counties and the areas in the two counties do not vary significantly from 1992 to 2001. The MRLC land use data are then used to obtain the ratios. A comparison of the low intensity residential land in 1992, low intensity residential land in 2001, and residential-septic is shown in Figure 2-3. Although the definitions among the three years are different, the areas are in the same magnitude except in Christina River watershed, where two tidally affected areas were not included in the USGS land use. The average ratios in 1992 and 2001 were used to estimate the county-level residential-septic areas. The ratios and the estimates areas are listed in Table 2-28.

Table 2-28. Estimated county-level residential-septic areas

County	Ratio of 1992 Low Intensity Residential	Ratio of 2001 Low Intensity Residential	Estimated Residential Septic Area (acres)
Chester	0.44	0.46	60,762
New Castle*	0.35	0.32	15,337

* Christina watershed was not included in estimate of area in New Castle County.

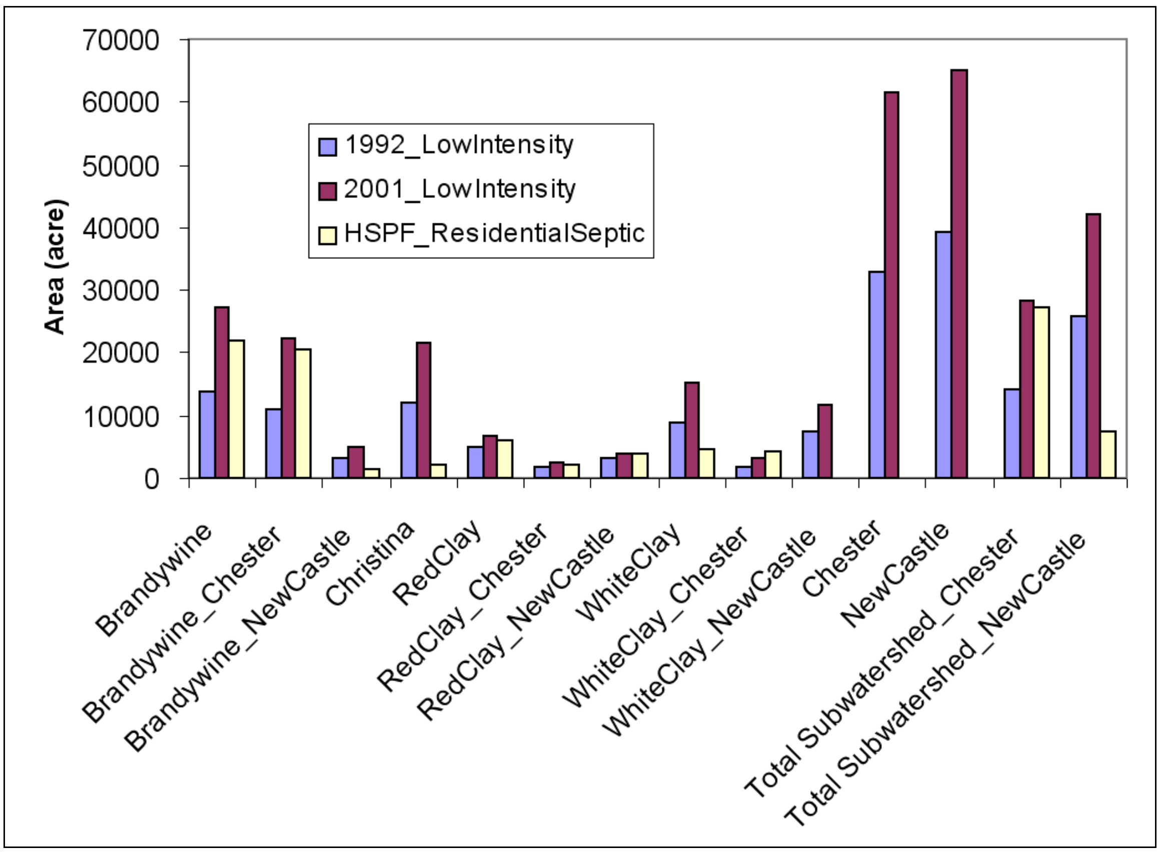

Figure 2-3. Comparison of MRLC and USGS HSPF Land Use

Using the estimated number of septic tanks, the failure rate, and the persons served per septic tank, the contribution of septic tanks were calculated using the modified BIT. The estimated flow rates are 6.10×10^{-7} cfs/ac and 4.16×10^{-7} cfs/ac in Chester County and New Castle County, respectively. The fecal coliform concentration in septic flow was assumed as the default value in BIT, i.e., 1.0×10^{7} cfu/100mL.The enterococci concentration in the septic discharge was assumed as 8.0×10^{5} cfu/100mL (from http://www.unc.edu).

2.4.3.4 Municipal wastewater treatment plant discharge

Raw municipal wastewater usually carries very high fecal coliform and enterococci concentrations. After treatment, the fecal coliform and enterococci concentrations in the discharge should be able to meet the environmental standard. Although the instantaneous fecal coliform and enterococci concentration in the discharge varies, no violation is considered to occur if the geometric means of fecal coliform and enterococci meet the standard. Therefore, in this study, the contribution of fecal coliform and enterococci from the municipal wastewater treatment plants was estimated using the geometric mean standards of 200 cfu/100ml for fecal coliform and 100 cfu/100ml for enterococci.

2.4.3.5 Combined sewer overflows

In urban areas, rainfall runoff enters the receiving waters via either storm sewer or combined sewer overflow pipes. The impacts of bacteria from storm water runoff were implicitly considered in HSPF models using the impervious land module. The potential contributions from combined sewer overflow (CSO) was not included in the seven HSPF models since CSOs are mainly located around the city of Wilmington inside the Christina River watershed and discharge into tidally impacted water bodies, which were modeled using the EFDC framework The indicator bacteria standard uses enterococci in the state of Delaware. Hence, only the load of enterococci was estimated for the modeling period.

There are 38 CSOs included in the City of Wilmington's XP-SWMM model. The locations of the CSOs are shown the Figure 2-4. The flow rates from the CSOs were estimated by running XP-SWMM model for the city of Wilmington for the 1994 to 1998 calibration period. Ideally, the CSO loads would be estimated using the CSO flow rates calculated by the XP-SWMM model and enterococci concentrations at each CSO outfall for each overflow event. However, such an ideal scenario was not possible due to the high cost of field monitoring. Therefore, the enterococci loads were estimated using event mean concentrations measured at CSO4b, CSO25, and 11th St Pump Station for storm events monitored on 10/27/2003, 12/27/2003, 11/4/2004, and 10/8/2005. The storm-event monitoring data and EMC values for the Wilmington CSO sampling sites are shown in Table 2-29.

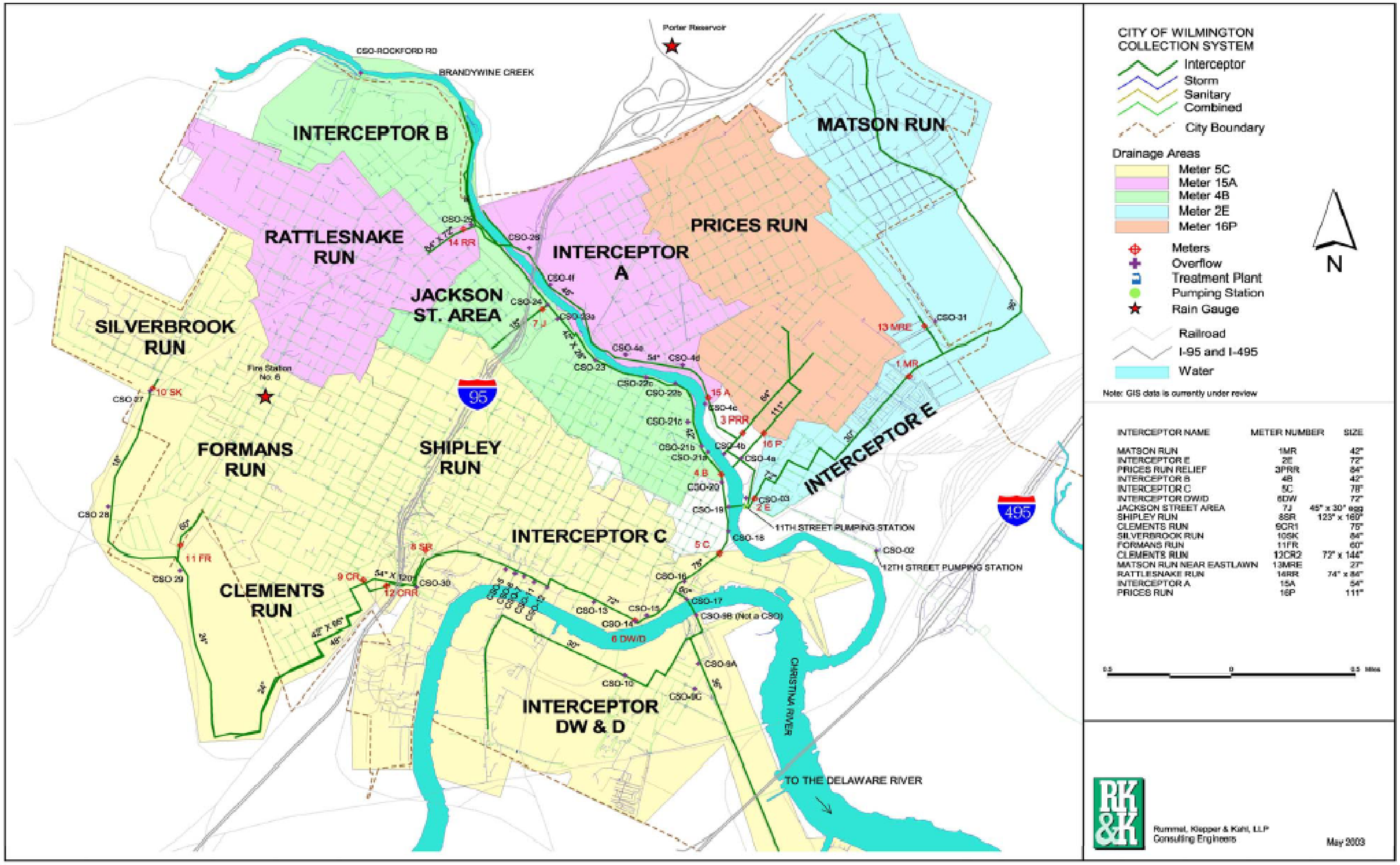

Figure 2-4. CSO locations (courtesy of RK&K Consulting Engineers, LLP)

Table 2-29. CSO Storm Monitoring Enterococci Data and Even Mean Concentrations (EMCs)

CSO 4b		CSO 25		CSO 3 (11th St Pumping Station)	
Date and Time	Enterococci cfu/100mL	Date and Time	Enterococci cfu/100mL	Date and Time	Enterococci cfu/100mL
Storm Event #1					
10/27/2003 11:40	90,000	10/27/2003 11:00	230,000	10/27/2003 11:20	280,000
10/27/2003 12:10	90,000	10/27/2003 11:30	70,000	10/27/2003 11:50	400,000
10/27/2003 12:40	110,000	10/27/2003 12:00	40,000	10/27/2003 12:10	130,000
10/27/2003 13:10	110,000	10/27/2003 12:30	80,000	10/27/2003 12:50	140,000
10/27/2003 13:40	130,000	10/27/2003 13:30	30,000	10/27/2003 13:20	130,000
10/27/2003 14:10	50,000	10/27/2003 14:00	50,000	10/27/2003 13:50	110,000
Storm Event #2					
12/17/2003 09:00	25,000	12/17/2003 08:45	18,000	12/17/2003 08:50	36,000
12/17/2003 09:30	18,000	12/17/2003 09:15	1,500,000	12/17/2003 09:20	32,000
12/17/2003 10:00	20,000	12/17/2003 09:45	100,000	12/17/2003 09:50	24,000
12/17/2003 10:30	15,000			12/17/2003 10:20	27,000
12/17/2003 11:00	11,000			12/17/2003 10:50	23,000
12/17/2003 11:30	4,400			12/17/2003 11:20	34,000
Storm Event #3					
11/04/2004 13:33	33,000	11/04/2004 13:20	27,000	11/04/2004 13:25	370,000
11/04/2004 14:03	26,000	11/04/2004 13:50	27,000	11/04/2004 13:55	360,000
11/04/2004 14:33	39,000	11/04/2004 14:20	25,000	11/04/2004 14:25	380,000
11/04/2004 15:03	36,000	11/04/2004 14:50	42,000	11/04/2004 14:55	290,000
11/04/2004 15:33	34,000			11/04/2004 15:25	400,000
				11/04/2004 15:55	340,000
Storm Event #4					
		10/08/2005 07:55	70,000		
		10/08/2005 08:25	218,182		
		10/08/2005 08:55	96,396		
		10/08/2005 09:25	101,802		
		10/08/2005 09:55	61,818		
		10/08/2005 10:15	510		
		10/08/2005 10:25	236,364		
Event Mean Concentration (EMC)					
EMC	34,917		57,885		121,635
	EMC other CSOs	45,888			

2.4.3.6 Municipal Separate Storm Sewer Systems (MS4)

As part of the 1987 amendments to the Clean Water Act (CWA), Congress added Section 402(p) to the Act to cover discharges composed entirely of storm water. Section 402(p)(2) of the CWA requires permit coverage for discharges associated with industrial activity and discharges from large and medium municipal separate storm sewer systems (MS4). Large MS4s serve populations over 250,000 and medium MS4s serve populations between 100,000 and 250,000. These discharges are referred to as Phase I MS4 discharges. EPA issued regulations on December 8, 1999 (64 FR 68722), expanding the NPDES storm water program to include discharges from smaller MS4s, including all systems within urbanized areas and other systems serving populations less than 100,000 as well as storm water discharges from construction sites that disturb one to five acres, with opportunities for area-specific exclusions. This expansion is referred to as Phase II of the MS4 program.

Storm water discharges that are regulated under Phase I and Phase II of the NPDES MS4 program are considered point sources that must be included in the WLA portion of a TMDL. Storm water discharges that are not currently subject to Phase I or Phase II of the MS4 program are not required to obtain NPDES permits and, therefore, for regulatory purposes, are analogous to nonpoint sources and may be included in the LA portion of a TMDL.

Essentially all townships and boroughs within the Christina River Basin in Chester County are covered by the Phase II MS4 program regulations. The delineation of the storm water collection system contributing areas within each municipality has not been completed at the present time. Therefore, it is not possible to assign a WLA specific to the storm sewer collection areas within each MS4 municipality. Instead, the TMDL will be presented as a WLA for the entire land area of the township or borough. In the future, when the storm sewer collection systems have been delineated, the TMDL will be revised to reflect the appropriate WLA and LA components.

Runoff from urban areas may carry significant loads of bacteria and sediment that reaches surface waters, and increased storm runoff flows may cause streambed and bank erosion. To assess the relative loads of bacteria and sediment from different land uses within municipal boundaries, it was important to have an inventory of municipal land use data as a proportion of the HSPF subbasins in which the municipality resides. Since the 1995 land use data available for assessing the municipalities is different than the land use in the HSPF model, an aggregated land use was developed for this purpose as shown in Table 2-30. The land use areas for each MS4 municipality are provided in Appendix L.

Table 2-30. Aggregated Land Uses for MS4 Assessments

Aggregated Land Use for MS4 Assessments	HSPF Land Use	1995 Land Use
Residential	Residential-septic Residential-sewer	Single family Multi-family
Agricultural	Agricultural-cows Agricultural-crops Agricultural-mushroom	Agriculture
Open Land	Open land	Public/private open space
Forest	Forest	Wooded
Water	Wetlands, water	Water
Urban	Commercial/industry Undesignated use Roads, building-resid Roads, building-urban	Vacant Transportation/utility Unknown Institutional Industrial Commercial Mining

2.4.4 Time Step and Simulation Duration

The HSPF models were executed on a 1-hour time step. The duration of the calibration runs was from 10/1/1994 to 10/1/1998, a period of 4 years.

2.5 Model Testing and Calibration

2.5.1 Bacteria Model Testing and Calibration

The HSPF models developed by USGS were updated to simulate fecal coliform and enterococci for the four major watersheds of the Christina River Basin. Since the state of Delaware uses enterococci as indicator bacteria criteria and the Christina River watershed is almost entirely within the state of Delaware, fecal coliform was not modeled for this watershed. Therefore, fecal coliform and enterococci were modeled using a total of seven HSPF models, including Brandywine Creek watershed fecal coliform model, Red Clay Creek watershed fecal coliform model, White Clay Creek watershed fecal coliform model, Brandywine Creek watershed enterococci model, Red Clay Creek watershed enterococci model, White Clay Creek watershed enterococci model, and Christina River watershed enterococci model.

The indicator bacteria fecal coliform and enterococci were modeled as dissolved constituents without attaching to sediments. Fecal coliform and enterococci accumulate on land surfaces due to manure application and during animal grazing in dry weather days. The accumulation rates and storage limit were obtained using EPA’s Bacteria Indicator Tool as discussed in Section 2.4.3. The monthly accumulation rates MON-ACCUM and storage limit MON-SQOLIM were added to the HSPF user control input (uci) files for the seven models. In addition to these two parameters, interflow and groundwater concentrations of fecal coliform and enterococci were added to MON-IFLW-CONC and MON-GRND-CONC for pervious land uses in the uci files.

For the impervious land uses, the bacteria accumulation rates and storage limits were assumed to be constant throughout the year without seasonal variation. The ACQOP and SQOLIM values are also obtained from the EPA bacteria indicator tool.

During wet weather conditions, the accumulated fecal coliform and enterococci on the land surfaces are washed into channels. The wash off rate is determined by the parameter WSQOP, which is the rate of surface runoff that will remove 90 percent of stored bacteria per hour. These parameter values were adjusted during calibration period.

In addition to the contributions from land surfaces, septic tank failure was considered as direct discharge to streams. In the models, these effects were included as point sources. The discharge rates of failed septic tanks were estimated as discussed in Section 2.4.3. The generated monthly discharge rates were input to WDM file and were matched to each subbasin in the External Source group in the uci files. The loading rates were calculated by multiplying the discharge rate and the fecal coliform concentration. Both the discharge rates and loading rates were read in by specifying the WDM time series IDs in the External-Source blocks in the HSPF uci files.

Another type of point source is the direct discharge of waste by animals such as beef cows and milk cows when they access streams during grazing. The direct discharge was modeled as point sources in the same way as septic tank failure. The monthly discharge rates and loading rates were estimated as discussed in Section 2.4.3. The time series were input to WDM files and read in by specifying the WDM time series IDs in the External-Source blocks in the uci files.

A significant number of municipal wastewater treatment plants are located in the four watersheds. No bacteria violations have been reported in the facilities discharge monitoring records (DMRs). Therefore, the geometric mean standard of 200 cfu/100mL for fecal coliform and 100 cfu/100mL for enterococci were assigned to the effluents of wastewater treatment plants. The loads from these plants were specified in the External-Source blocks EXT SOURCES in the uci files.

Since the majority of CSOs are in the city of Wilmington, the HSPF models do not include any CSOs. Instead, the CSOs were simulated in the EFDC model.

After fecal coliform and enterococci enter receiving water via the pathways mentioned above, these bacteria are assumed to be dissolved material in the water column in the HSPF models. The fecal coliform and enterococci concentrations in the receiving water depend on not only the loading rates from the watersheds, but also the die-off kinetics in the water column. The die-off of bacteria is calculated using the DDECAY subroutine in the HSPF models. In general, temperature and solar radiation are the most important factors that determine the net die-off rate. Temperature can be modeled with relatively high accuracy in HSPF. The impact of solar radiation on bacteria decay rate is assumed to be negligible in this study because the solar radiation reaching the water surface is greatly reduced by the shade from the trees along the banks of the narrow streams. Furthermore, suspended solids and other dissolved materials are able to attenuate the solar radiation quickly. Therefore, the net die-off rates of fecal coliform and enterococci are calculated using

$$k = k_{20}\theta^{(T-20)}$$

Where k is the die-off rate; k_{20} is the die-off rate at 20^{o}C; θ is a temperature dependency constant; T is the water temperature. The constant θ was set to 1.02 for both fecal coliform and enterococci, which is within the range of literature values. Water temperature was simulated using HSPF. The values of k_{20} were set to 2.0d^{-1} for fecal coliform and 1.0d^{-1} for enterococci after model-data comparison (calibration).

The advective transport of fecal coliform and enterococci bacteria is calculated using the ADVECT subroutine in the HSPF models. ADVECT computes the bacteria concentrations in the reaches and the total amount of bacteria that leave the reaches due to advection through the exits of the reaches. Two assumptions were made in the ADVECT subroutine:

1. The bacteria are uniformly dispersed throughout the water columns of the reaches, that is, they are evenly mixed in each reach;
2. The bacteria move at the same velocity as the water.

The parameters on land surfaces and in streams together with linkages from land to stream and stream-to-stream connections were prepared in the seven HSPF uci files. The hydrology simulations are the same as the original USGS configurations. The HSPF models ran at hourly time step. The model results of enterococci are shown in Appendices A, B, C, and D as time-series graphics with model-data comparisons for Brandywine Creek, White Clay Creek, Red Clay Creek, and Christina River watersheds. The model-data time-series comparisons of fecal coliform are shown in Appendix E for three stations in the Brandywine Creek watershed. Model-data comparisons of the cumulative probability distribution of enterococci concentrations are presented in Appendix K. Model-data time-series comparisons with daily rainfall superimposed on the graph are presented in Appendix J. Representative stations in each of the four main watersheds were selected for the model-data comparison graphs based on the quantity of available field data.

2.5.2 Sediment Model Testing and Calibration

The HSPF models were also used to simulate suspended solids for the Brandywine Creek, Red Clay Creek, and White Clay Creek watershed mainly using the original USGS configurations.

The suspended solids or sediment concentrations in streams are determined by various factors such as the load from land surface and settling and erosion rate in the streams. On the land surface, the soil detaches during rainfall events and is washed off by the runoff. At the same time, the runoff is able to erode the attached soil and carry the sediments into receiving water. HSPF model computes the soil detachment by rainfall using the following equation:

$$DET=DELT60\times(1.0-CR)\times SMPF\times KRER\times(RAIN/DELT60)^{JRER}$$

where:

DET	= sediment detached from the soil matrix by rainfall (tons/ac/interval)
DELT60	= number of hours/interval
CR	= fraction of the land covered by snow and other cover
SMPF	= supporting management practice factor
KRER	= detachment coefficient dependant on soil properties
RAIN	= rainfall (in/interval)
JRER	= detachment exponent dependent on soil properties

The detached sediments are washed off by surface runoff. The runoff is also able to scour the soil matrix directly. HSPF provides two methods to determine the carrying and scour capabilities of the surface runoff. In this project, the first method was selected as described below from the HSPF user's manual. The transport capacity is calculated by the equation:

$$STCAP = DELT60\times KSER\times((SURS + SURO)/DELT60)^{JSER}$$

where:

STCAP	= capacity for removing detached sediment (tons/ac/interval)
DELT60	= hr/interval
KSER	= coefficient for transport of detached sediment
SURS	= surface water storage (inches)
SURO	= surface outflow of water (in/interval)
JSER	= exponent for transport of detached sediment

When STCAP is greater than the amount of detached sediment in storage, washoff is calculated by:

$$WSSD = DETS \times SURO/(SURS + SURO)$$

If the storage is sufficient to fulfill the transport capacity, then the following relationship is used:

$$WSSD = STCAP \times SURO/(SURS + SURO)$$

where:

WSSD = washoff of detached sediment (tons/ac/interval)
DETS = detached sediment storage (tons/ac)

WSSD is then subtracted from DETS.

Transport and detachment of soil particles from the soil matrix is simulated with the following equation:

$$SCRSD = SURO/(SURS + SURO) \times DELT60 \times KGER \times ((SURS + SURO)/DELT6O)^{JGER}$$

where:

SCRSD = scour of matrix soil (tons/ac/interval)
KGER = coefficient for scour of the matrix soil
JGER = exponent for scour of the matrix soil

The sum of the two fluxes, WSSD and SCRSD, represents the total sediment outflow from the land segment.

HSPF model uses three classes of sediments: sand, silt, and clay. The ratios of the three classes were specified in the uci files as 0.10 for sand, 0.40 for silt, and 0.50 for clay. After the sediment enters receiving water, sand settles quickly in the water column and may move as both the bed load and suspended load. Silt and clay settle with a lower velocity and only move as suspended load. The sediment on the bottom can be eroded (resuspended) back the water column under high shear stress conditions. Due to the complex characteristics of sediment particle, such as size and component, the critical shear stresses for resuspension for the sediments from different subbasins may different. Therefore, the critical shear stresses for resuspension for the reaches were adjusted during calibration.

The results of suspended solids are shown in Appendices F, G, and H with time-series graphics model-data comparisons for the Brandywine Creek, White Clay Creek, and Red Clay Creek watersheds.

3.0 Hydrodynamic Fate and Transport Model

3.1 EFDC Model Overview

EFDC is a general-purpose modeling package for simulating one- or multi-dimensional flow, transport, and bio-geochemical processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. The EFDC model was originally developed by Hamrick (1992) at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software. This model is now being supported by U.S. Environmental Protection Agency (EPA) and has been used extensively to support TMDL development throughout the country. In addition to hydrodynamic, salinity, and temperature transport simulation capabilities, EFDC is capable of simulating cohesive and non-cohesive sediment transport, near field and far field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish. Special enhancements to the hydrodynamic portion of the code, including vegetation resistance, drying and wetting, hydraulic structure representation, wave-current boundary layer interaction, and wave-induced currents, allow refined modeling of wetland marsh systems, controlled flow systems, and near-shore wave induced currents and sediment transport. The EFDC model has been extensively tested, documented, and applied to environmental studies worldwide by universities, governmental agencies, and environmental consulting firms.

The structure of the EFDC model includes four major modules: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model. The hydrodynamic, water quality, and sediment transport models were used for this study. The EFDC hydrodynamic model is composed of six transport modules including dynamics, dye, temperature, salinity, near field plume, and a tracer module, which simulates the movement of neutrally buoyant drifters released in each three-dimensional model cell at specified time sequences (see Figure 3-1). A more complete description of the EFDC model can be found in the low-flow model report (USEPA, 2000).

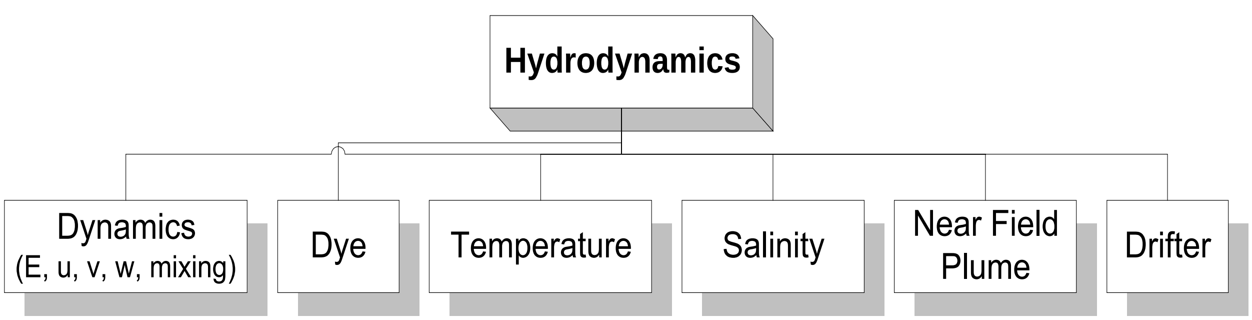

Figure 3-1. EFDC hydrodynamic model structure.

3.2 Description of Solution Methods

The computational schemes in the EFDC model are equivalent to the widely used Blumberg-Mellor model (Blumberg and Mellor, 1987) in many aspects. The EFDC model uses a stretched or sigma vertical coordinate and Cartesian, or curvilinear, orthogonal horizontal coordinates. It employs second order accurate spatial finite differencing on a staggered or C grid to solve the equations of momentum, while time integration is implemented using a second order accurate three-time level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear or baroclinic mode from the external free surface gravity wave or barotropic mode. The external mode solution is semi-implicit and simultaneously computes the two-dimensional (2-D) surface elevation field by a preconditioned conjugate gradient procedure. The external solution is completed by the calculation of the depth-averaged barotropic velocities using the new surface elevation field. The model's semi-implicit external solution allows large time steps that are constrained only by the stability criteria of the explicit central difference or higher order upwind advection scheme (Smolarkiewicz and Margolin, 1993) used for the nonlinear accelerations. Horizontal boundary conditions for the external mode solution include options for simultaneously specifying the surface elevation only, the characteristics of an incoming wave (Bennett and McIntosh, 1982), free radiation of an outgoing wave (Bennett 1976; Blumberg and Kantha, 1985), or the normal volumetric flux on arbitrary portions of the boundary. The EFDC model's internal momentum equation solution, at the same time step as the external solution, is implicit with respect to vertical diffusion. The internal solution of the momentum equations is in terms of the vertical profile of shear stress and velocity shear, which results in the simplest and most accurate form of the baroclinic pressure gradients and eliminates the over-determined character of alternate internal mode formulations. Time splitting inherent in the three-time-level scheme is controlled by periodic insertion of a second-order accurate two-time-level trapezoidal step.

The EFDC model implements a second-order, accurate in space and time, mass conservation, fractional step solution scheme for the Eulerian transport equations for salinity, temperature, and other constituents. The transport equations are temporally integrated at the same time step or twice the time step of the momentum equation solution. The advective step of the transport solution uses either the central difference scheme used in the Blumberg-Mellor model or a hierarchy of positive definite upwind difference schemes. The highest accuracy upwind scheme, second order accurate in space and time, is based on a flux-corrected transport version of Smolarkiewicz's multidimensional positive-definite advection transport algorithm (Smolarkiewicz and Clark, 1986; Smolarkiewicz and Grabowski, 1990), which is monotonic and minimizes numerical diffusion. The horizontal diffusion step is explicit in time, whereas the vertical diffusion step is implicit. Horizontal boundary conditions include material inflow concentrations, upwind outflow, and a damping relaxation specification of climatological boundary concentration.

3.3 Modeling Assumptions

The main objective of applying the EFDC model was to develop hydrodynamic information for the primary tidal river channels in the lower Christina River Basin to simulate fate and transport of bacteria. Specifically, it was necessary to accurately understand the variability of the system hydrodynamics under variable flow conditions. Major assumptions included:

- The waterbody was well mixed laterally and vertically, therefore a longitudinal one-dimensional configuration was appropriate for the tidal river channels.

- Thermal stratification was not likely due to the shallow and narrow characteristics of the creek, thus temperature is not an important driving force for flow and transport.

- Wind effects on flow and transport were not a critical factor due to the one-dimensional flow pattern.

The impact of groundwater interaction on flow and transport was minimal during low flow conditions, thus flow distribution can be obtained through directly balancing upstream and downstream flow rates.

3.4 Model Configuration

The general procedure for application of the EFDC model to the Christina River Basin followed a sequence of steps beginning with model configuration and continued through model execution of the calibration time period. Model configuration involved the construction of the horizontal grid for the waterbodies in the basin, interpolation of bathymetric data to the grid, construction of EFDC input files, and compilation of the Fortran source code with appropriate parameter specification of array dimensions. The model included 120 point-source discharges and 28 consumptive use water withdrawals.

3.4.1 Segmentation

The numerical model domain includes the tidal Delaware River from Reedy Point on the south to Chester on the north. Both the tidal and nontidal Christina River reaches are included in the model. The lower Christina River is directly connected to the Delaware River. The nontidal Christina River is connected to the tidal portion by a dam control structure at Smalley’s Pond at the outlet of subbasin C08. The tidal Brandywine Creek is connected to the tidal Christina River by means of a pseudo tidal inlet control structure. The tidal White Clay Creek is also connected to the tidal Christina River via a pseudo tidal inlet control structure. The pseudo tidal inlet control structure is a numerical technique in the hydrodynamic model to allow flow from a large grid cell (e.g., in Christina River) to exchange with a small tributary grid cell since a direct connection between adjacent faces of large and small grid cells is not physically possible.

The basic equations in EFDC were solved using the finite-difference method. The grid was designed to resolve velocity shears both axially and laterally, and at the same time allow a time step suitable for efficient computation. Solutions to the hydrodynamics were obtained using a 60-second time step. The spatial domain of the study area was divided into a grid of discrete cells. To achieve close conformance of the grid to the estuary geometry, the cells in the Delaware River were represented using curvilinear horizontal grid cells constructed using an orthogonal mapping procedure (Ryskin and Leal 1983) to form a 2-D grid domain. The cells in the narrow tidal and nontidal streams were represented in a 1-D Cartesian coordinate system. To obtain adequate resolution in the streams, longitudinal cells were configured according to lengths ranging from 500 to approximately 1,000 meters. Cell widths were adjusted according to estimated stream channel widths under low-flow conditions. Velocities were computed on the boundaries between cells, and temperature, salinity, and density were computed at the center of each cell. The numerical grid for the bacteria modeling consisted of a subset of the 406-cell grid developed for the low-flow model. Only the tidal portion of the Christina River model was simulated for the bacteria study.

3.4.2 Streamflow Estimation

Variable streamflow discharge was estimated using output from the HSPF models for the calibration period 1994-1998.

3.4.3 Atmospheric and Tidal Boundary Conditions

Unlike nutrients, there are no atmospheric bacteria loads. Meteorological information (i.e., atmospheric pressure, temperature, relative humidity, wind speed and direction, rainfall, cloud cover, and solar radiation) was obtained from the NOAA National Climatic Data Center weather station (WBAN 13781) at the New Castle County Airport near Wilmington, Delaware.

Tides were specified at the north and south boundaries in the Delaware River based on the astronomical harmonic constants for the NOAA subordinate tide stations at Reedy Point, Delaware (south boundary) and Chester, Pennsylvania (north boundary). The predicted tides from the harmonic constants will not include any low-frequency influences due to storms or regional low-pressure conditions. The enterococci bacteria concentrations at the tidal boundaries were set to the marine water quality standard of 10 cfu/100mL.

3.4.4 Initial Conditions

Initial enterococci bacteria concentration conditions in the tidal Delaware River and tidal Christina River were estimated using the geometric mean marine water quality standard of 10 cfu/100mL. These initial conditions allow the model to begin its simulation at a stable numeric state. Due to bacteria decay, advection, and dispersion, the impacts of initial conditions diminish quickly with time.

3.4.5 Point and Nonpoint Source Representation

Nonpoint sources of bacteria were estimated by the delineation of subbasins and land use categories in the HSPF watershed model. The nonpoint source loads generated by the watershed model provided predictive bacteria loads to the receiving waters reflective of variable meteorological (rainfall-runoff) characteristics.

CSO flows were estimated using XP-SWMM and were provided by the City of Wilmington. Bacteria loads from CSO outfalls were estimated using the XP-SWMM flow rates and event mean concentrations based on storm event monitoring conducted by the City of Wilmington and Delaware DNREC.

3.4.6 Time Step and Simulation Duration

The EFDC model was executed at a time step of 60 seconds and the calibration simulated the period from October 1, 1994 to October 1, 1998, a period of 4 years.

3.5 Model Testing and Calibration

3.5.1 Re-configuration of the low-flow EFDC model

EFDC framework was used to model the enterococci bacteria concentrations in the tidally impacted portions of the Christina River and Brandywine Creek. The HSPF model was used to simulate enterococci bacteria in the non-tidal streams in the Christina River Basin. The EFDC model developed for the low-flow condition nutrient TMDL in the Christina River Basin (USEPA, 2000) was re-configured for modeling enterococci bacteria. The original EFDC channel network was reduced to include only the portion of the Christina River below USGS station 01478000 and the portion of Brandywine Creek below USGS station 01481500.

In addition to the modification of the grid, the weather data was expanded to cover the modeling period from 10/01/1994 to 10/29/1998. The original low-flow EFDC model has been calibrated for hydrodynamics using observed water surface elevations and temperature (USEPA, 2000). Therefore, no additional hydrodynamic calibration was performed and the model was used to directly simulate enterococci bacteria.

The original EFDC model includes a bacteria module that only uses temperature to calculate the die-off rate. In narrow streams with trees on bank and with high level of suspended and dissolved materials, this assumption is valid. However, for the tidally impacted portion of the Christina River, the channel is relatively wide and solar radiation can reach to the water surface. Therefore, the solar radiation was considered as a potential cause of enterococci die-off. In addition, sediment impact on bacteria levels in receiving waters has been widely observed (Crabill et al., 1999; Gannon and Schillinger, 1983; Irvine et al., 1995; Milne et al., 1986; Muirhead et al., 2004; Wilkinson et al., 1995). The original bacteria module considers bacteria as a dissolved material. To include the sediment impact on bacteria for future study and to consider the solar radiation impact, the TOXIC module in the EFDC model was modified to simulate enterococci bacteria instead of using the bacteria module. The parameters in the TOXIC module were modified to compute the die-off rate of enteric bacteria based on previous studies (Bai, 2004).

3.5.2 Enterococci sources to EFDC model

The enterococci sources for the EFDC model include the watershed contributions from Brandywine Creek watershed, Red Clay Creek watershed, White Clay Creek watershed, and the Christina River watershed. The HSPF model directly computed the inflow rates and enterococci load from the Brandywine Creek at the entrance to the EFDC modeling domain (cell number 54, 22). The enterococci load from Red Clay Creek watershed enters White Clay Creek first. The combined flow rates and enterococci loads from Red Clay Creek and White Clay Creek then enter the EFDC modeling domain (cell number 43,13).

Inside the Christina River watershed, the enterococci loads generated from the land surfaces in HSPF subbasin C08 and C09 were modeled and distributed uniformly to the EFDC model cells inside each of those subbasins. In addition, loads from subbasin C03 (upper Christina River) enter the tidal Christina River EFDC modeling domain at grid cell 24,13; loads from subbasin C06 (Muddy Run) and subbasin C07 (Belltown Run) enter the EFDC modeling domain at cell 29,13; loads from subbasin C04 (Little Mill Creek) enter the EFDC model at cell 40,55 and loads from subbasin C05 were distributed to the EFDC grid cells in that subbasin.

In addition to the watershed contributions, wastewater treatment plant effluents may carry enterococci bacteria into the receiving waters. Since no facility violation for bacteria has been reported in DMRs of wastewater treatment plants in the Christina River Basin, the enterococci concentrations were set to the geometric mean standard of 100 cfu/100mL for model calibration.

CSOs are potential sources of enterococci around the city of Wilmington. Section 2.4.3 discussed the method to derive the loading rates and flow rates for the EFDC model. The CSO enterococci bacteria loads were included as volumetric sources in the EFDC model.

No measurements were available for enterococci bacteria at the open boundaries in the Delaware River. The water at the open boundaries may impact the enterococci concentrations in the Christina River due to tidal transport. The enterococci bacteria levels at the open boundaries were set to the marine geometric mean standard of 10 cfu/100mL.

3.5.3 Transport of enterococci in receiving water

After enterococci enter the receiving water via various pathways, the bacteria can be carried by flow in the same manner as dissolved materials. Advection and diffusion are the main transport mechanisms. The governing equation of the transport of enterococci is an advection-diffusion equation and is solved in the EFDC model using the MPDATA scheme to minimize numerical diffusion, which is same numerical scheme used for dye, salt, heat, and other dissolved materials.

Since the model consisted of only one layer, the water column was considered well mixed in the vertical direction.

3.5.4 Die-off of enterococci in receiving water

Enterococci is a type of enteric bacteria that usually exhibit a net decrease of concentration after leaving the original living environment, i.e., the intestine of warm blooded animals, including humans. Therefore, the die-off rate of enterococci can be expressed as first-order decay as

$$\frac{dC}{dt} = -kC$$

where:

C = enterococci concentration

k = die-off rate

The die-off of enterococci is governed by the first-order decay rate. A variety of environmental factors such as temperature, solar radiation, salinity, pH, nutrients, bacteriophage, and algae may affect the die-off of enterococci. Among these factors, temperature and solar radiation are considered the most important factors. In addition, temperature and solar radiation can be modeled using EFDC with high accuracy. Hence, the enterococci die-off rate in the receiving water column is calculated as

$$k = \alpha I + k_{20}\theta^{(T-20)}$$

Where:

k = die-off rate (per day)

k_{20} = die-off rate at 20^{o}C (per day)

θ = temperature dependency constant (unitless)

T = water temperature (^{o}C)

α = solar radiation proportional constant

I = layer-averaged solar radiation intensity (Langley/day).

Since no observation data were available, these parameters k_{20}, θ, and α were estimated during the calibration process.

3.5.6 Enterococci model results

The input time-series data, including streamflow loads, point source loads, and meteorological parameters, were prepared into EFDC formatted files, and the model simulated the calibration period from 10/01/1994 to 10/01/1998. The model time step was set to 60 second to satisfy stability criteria. Other parameters such as the tidal harmonic components were the same as the low-flow EFDC model. Data for comparison to EFDC model results were available at five monitoring locations in the tidal Christina River and Brandywine Creek (see Table 3-1 and Figure 3-2). The model-data time-series comparison graphics for enterococci concentrations are shown in Appendix I. EFDC model-data results for station 106011 are presented in Appendix J (time series with daily rainfall hyetograph) and Appendix K (cumulative probability distribution).

Table 3-1. Enterococci bacteria monitoring stations

Station ID	EFDC cell	Description
106291	55,13	Christina River at Conrail bridge
106011	53,13	Christina River at Rt 13/Rt 9 bridge
106021	45,13	Christina River at Rt 141 bridge, Newport
106031	34,13	Christina River at Smalley's Dam spillway
104011	54,20	Brandywine Creek at Brandywine Park footbridge

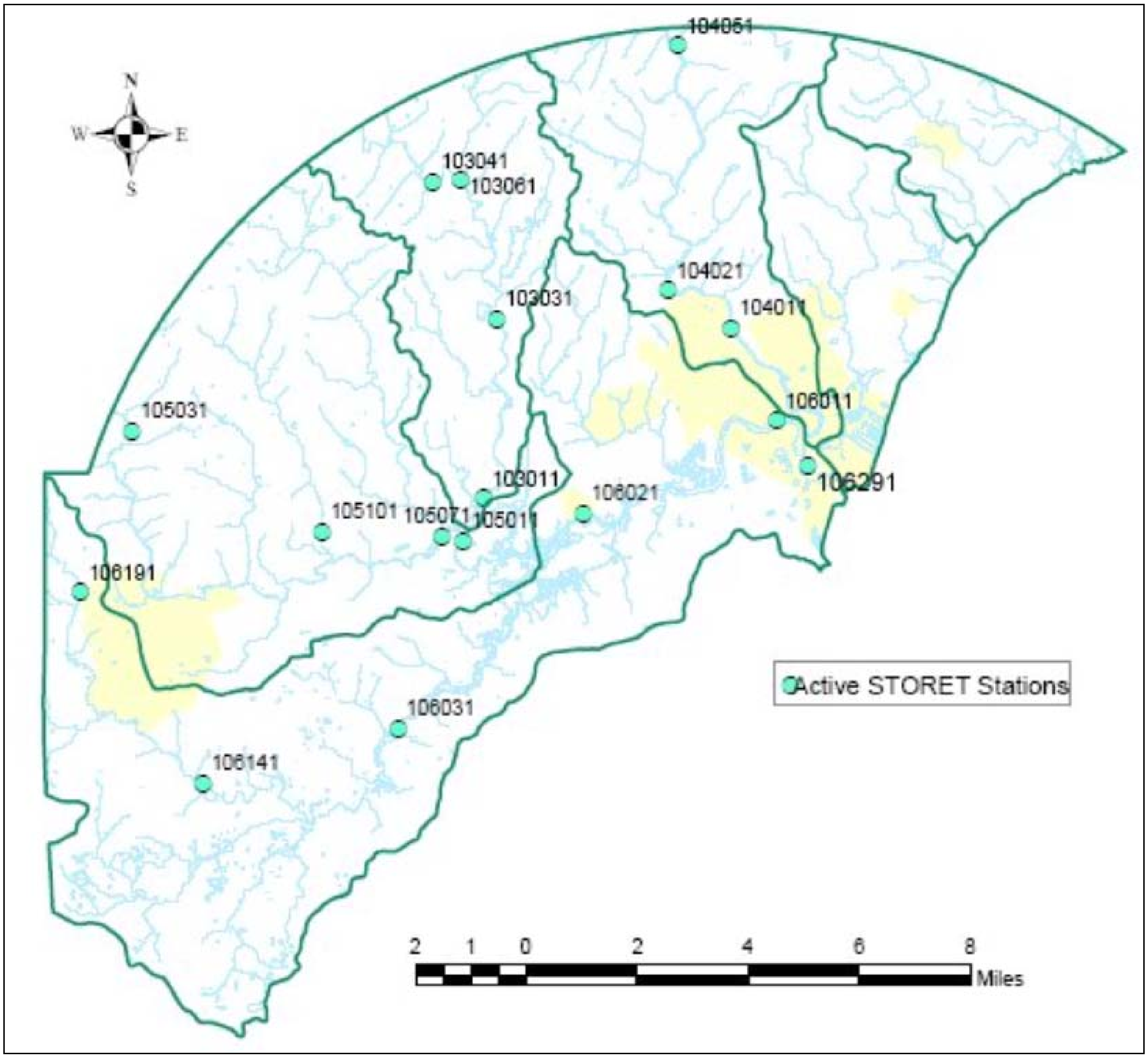

Figure 3-2 Locations of ambient water quality monitoring stations

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5.0 Acronyms

BIT	Bacteria Indicator Tool
BMP	Best management practice
cfu	Colony-forming unit
CSO	Combined sewer overflow
CWA	Clean Water Act
DNREC	Delaware Department of Natural Resources and Environmental Control
EFDC	Environmental Fluid Dynamics Code
EMC	Event mean concentration
EPA	Environmental Protection Agency
F R	Federal Register
GIS	Geographic Information System
HSPF	Hydrologic Simulation Program-Fortran
LA	Load allocation (for nonpoint sources in TMDLs)
MOS	Margin of safety (an element in the TMDL equation)
MRLC	Multi-resolution land classification
MS4	Municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
PADEP	Pennsylvania Department of Environmental Protection
TMDL	Total maximum daily load
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WLA	Waste load allocation (for point sources in TMDLs)
WQS	Water quality standard
WWTP	Waste Water Treatment Plant
XP-SWMM	Storm Water Management Model

HSPF Model Terms:

ACQOP	Constant bacteria accumulation rate on land surface
ADVECT	Subroutine to calculate bacteria transport in streams
CR	Fraction of the land covered by snow
DDECAY	Subroutine to calculate bacteria die-off in streams
DELT60	Number of hours/interval
DET	Sediment detached from the soil matrix by rainfall
DETS	Detached sediment storage
EXT SOURCES	External source block
IMPLND	Impervious Land
JGER	Sediment scour exponent
JRER	Soil detachment exponent
JSER	Exponent for transport of detached sediment
KGER	Sediment scour coefficient
KRER	Sediment detachment coefficient
KSER	Coefficient for transport of detached sediment

MON-ACCUM	Monthly accumulation rate of bacteria on land surface
MON-IFLW-CONC	Monthly bacteria concentration in interflow
MON-GRND-CONC	Monthly bacteria concentration in groundwater
MON_SQOLIM	Monthly storage limit of bacteria on land surface
PERLND	Pervious Land
RAIN	Rainfall intensity
SCRSD	Scour rate of sediment
SMPF	Supporting management practice factor
SQOLIM	Constant bacteria storage limit on land surface
STCAP	Capacity for removing detached sediment
SURO	Land surface outflow rate
SURS	Land surface water storage
WDM	Watershed data management (database file used by HSPF)
WSQOP	Wash off coefficient of bacteria from land surface
WSSD	Wash off rate of detached sediment