Green City, Clean Waters

Tributary Water Quality Model for Bacteria

Consent Order & Agreement

Deliverable VI

City of Philadelphia Combined Sewer Overflow Long Term Control Plan Update

Submitted to

The Commonwealth of Pennsylvania

Department of Environmental Protection

By The Philadelphia Water Department

June 1, 2013

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Glossary of Acronyms

ALCOSAN	Allegheny County Sanitary Authority
CCR	Comprehensive Characterization Report
CFU	Colony Forming Units
COA	Consent Order and Agreement
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
DCIA	Directly Connected Impervious Area
DEM	Digital Elevation Model
EMC	Event Mean Concentration
FEMA	Federal Emergency Management Agency
FGM	Fluvial Geomorphology
FIS	Flood Insurance Study
GIS	Geographic Information Systems
H&H	Hydrologic and Hydraulic
IQR	Interquartile Range
LTCPU	Long Term Control Plan Update
NEXRAD	Next-Generation Radar
PADEP	Pennsylvania Department of Environmental Protection
PASDA	Pennsylvania Spatial Data Access
SWMM	Storm Water Management Model
SWMM4	Storm Water Management Model version 4
SWMM5	Storm Water Management Model version 5
TTF	Tookany-Tacony/Frankford
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WASP	Water Quality Analysis Simulation Program

1.0 Introduction

This report focuses on Deliverable Item 6 of the 2011 Consent Order and Agreement (COA) between the Pennsylvania Department of Environmental Protection (PADEP) and the Philadelphia Water Department (Water Department), the Tributary Water Quality Model for Bacteria. For the purposes of this report, "bacteria" refer to fecal coliform and *E. coli* unless otherwise noted. Fecal coliform are pathogen indicator microorganisms for which PADEP has established surface water quality standards. *E. coli* are alternative pathogen indicator microorganisms for which there is no PADEP standard, but are the subject of United States Environmental Protection Agency (US EPA) recommended criteria. *E. coli* are included in this report in the event PADEP adopts a related water quality standard in the future.

Bacteria water quality models were developed for the nontidal extents of two tributaries that receive combined sewer overflow (CSO) discharges, Tookany/Tacony-Frankford (TTF) Creek and Cobbs Creek (Figures 1-1 and 1-2). The highly developed degree of land use in each watershed is depicted in Figures 1-3 and 1-4.

The Cobbs Creek Watershed and Tookany/Tacony-Frankford Creek Watershed have been extensively described in their 2004 and 2005 Comprehensive Characterization Reports (CCRs), respectively (Philadelphia Water Department, 2004 and 2005). These documents can be referenced for more detailed information on watershed characteristics and for summaries of physical, chemical, and biological water quality monitoring results.

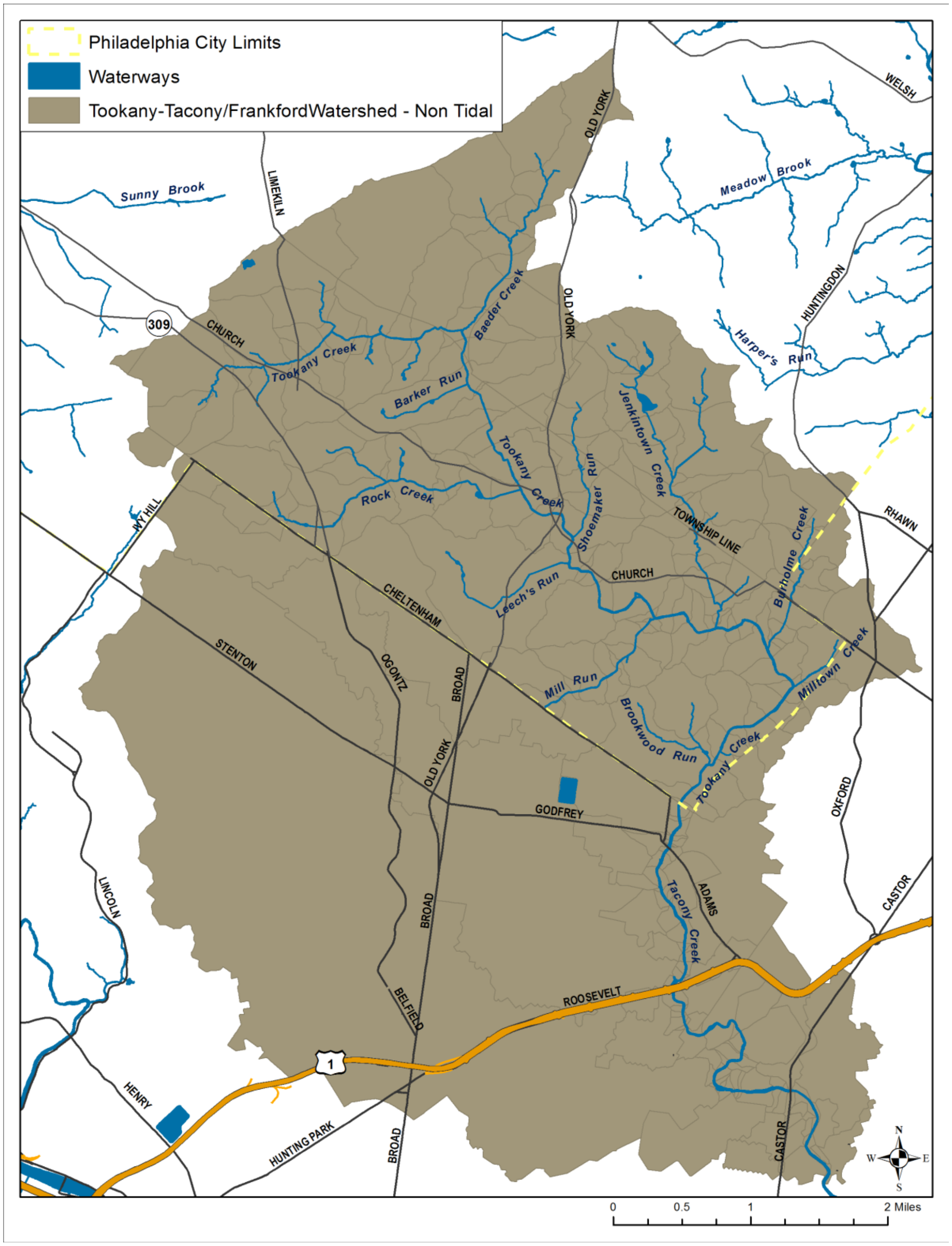

Figure 1-1: Nontidal TTF Creek Watershed

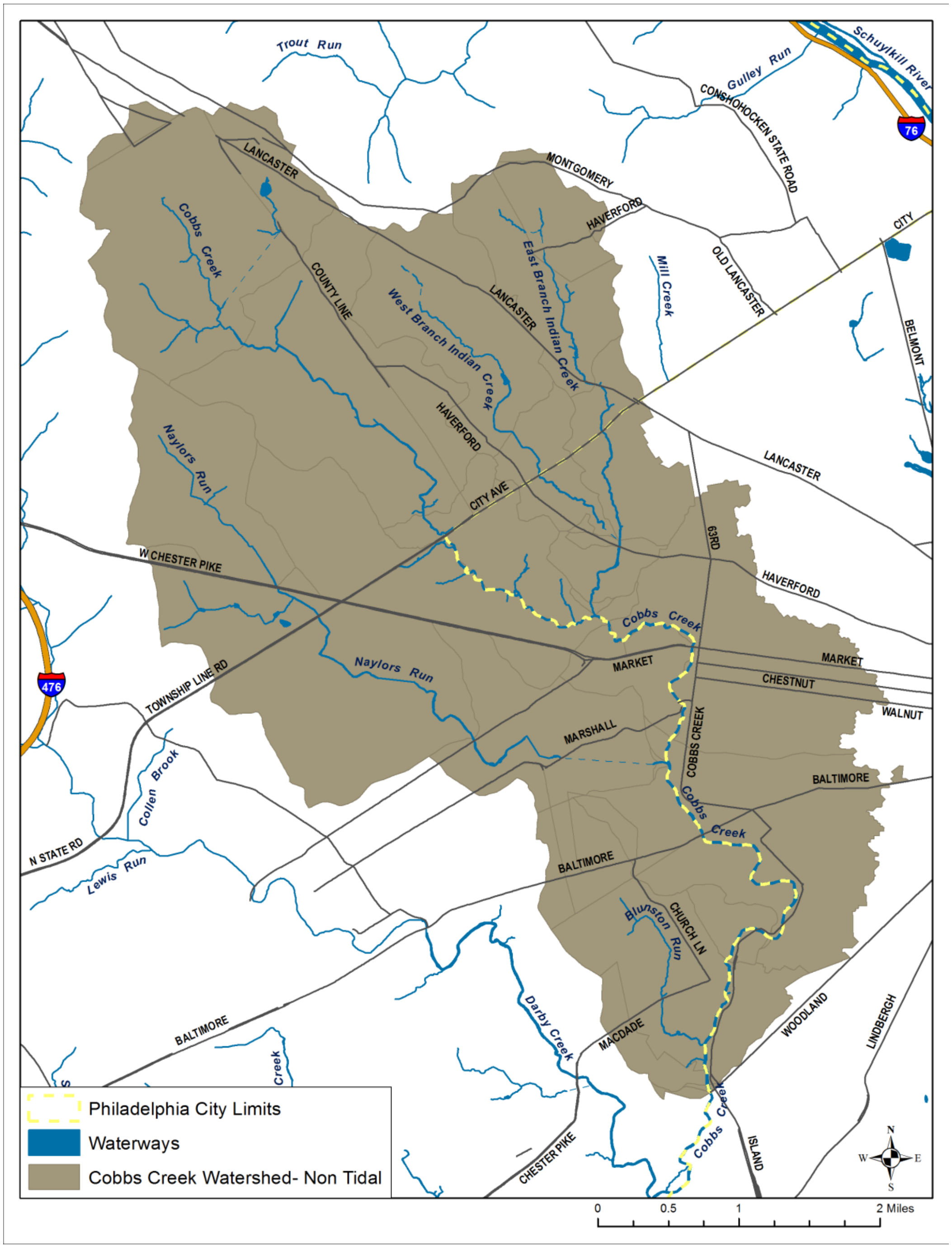

Figure 1-2: Nontidal Cobbs Creek Watershed

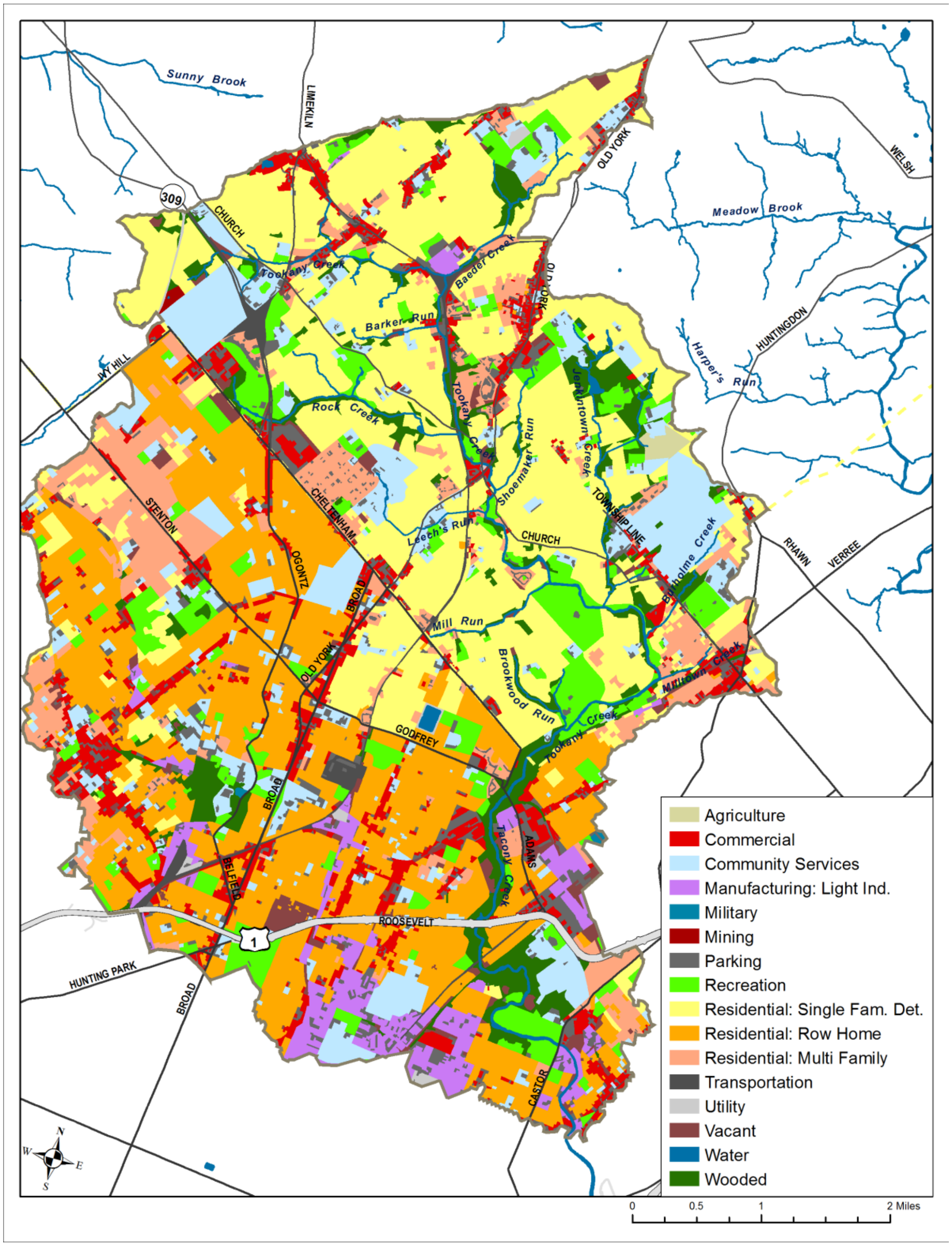

Figure 1-3: Land Use in Nontidal TTF Creek Watershed

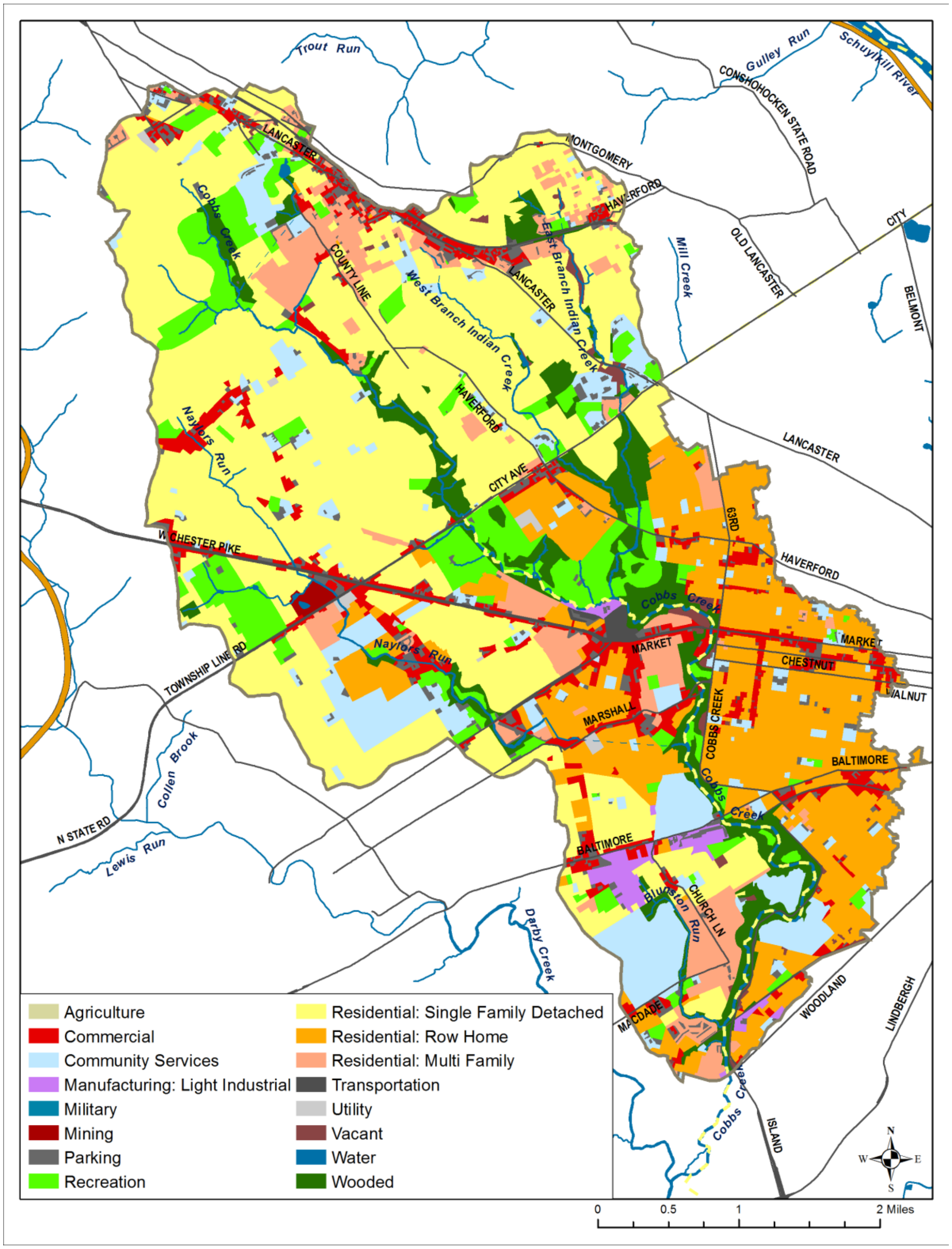

Figure 1-4: Land Use in Nontidal Cobbs Creek Watershed

1.1 TTF Creek Water Quality Model Extent

The TTF Creek water quality model explicitly simulates in-stream bacteria conditions in the nontidal reaches affected by City discharges. In the TTF Creek water quality model extent, there are 21 outfalls that release combined stormwater and sanitary wastewater during storms that exceed the Northeast Water Pollution Control Plant treatment capacity (Figure 1-5). Based on model simulations for the typical year precipitation record, the outfalls in the TTF Creek water quality model extent discharge a total volume of 3.95 billion gallons (Table 1-1).

Table 1-1: Outfall Statistics in the TTF Creek Water Quality Model Extent Based on Typical Year Rainfall

Outfall Number	Frequency (Times/ Year)	Duration (Hours/ Incident)	Volume (Gallons/ Incident)
T-01	64	3.7	745,735
T-03	58	2.2	426,790
T-04	57.5	2	292,345
T-05	41	1.2	208,717
T-06	37	1.5	1,622,474
T-07	9	0.7	130,164
T-08	69.5	5.5	10,143,848
T-09	41	1.2	156,119
T-10	63	3.2	337,804
T-11	54	1.8	188,744
T-12	8	0.7	49,457
T-13	61.5	2.8	601,959
T-14	60.5	3.9	19,989,405
T-15	55	2.6	889,724
F-03	32	1.5	606,465
F-04	63	3.4	1,064,214
F-05	68	3.7	123,639
F-06	18.5	1.5	300,016
F-07	41.5	1.8	480,139
R-15	21	1.5	2,163,800
R-18	71	7.7	22,283,609

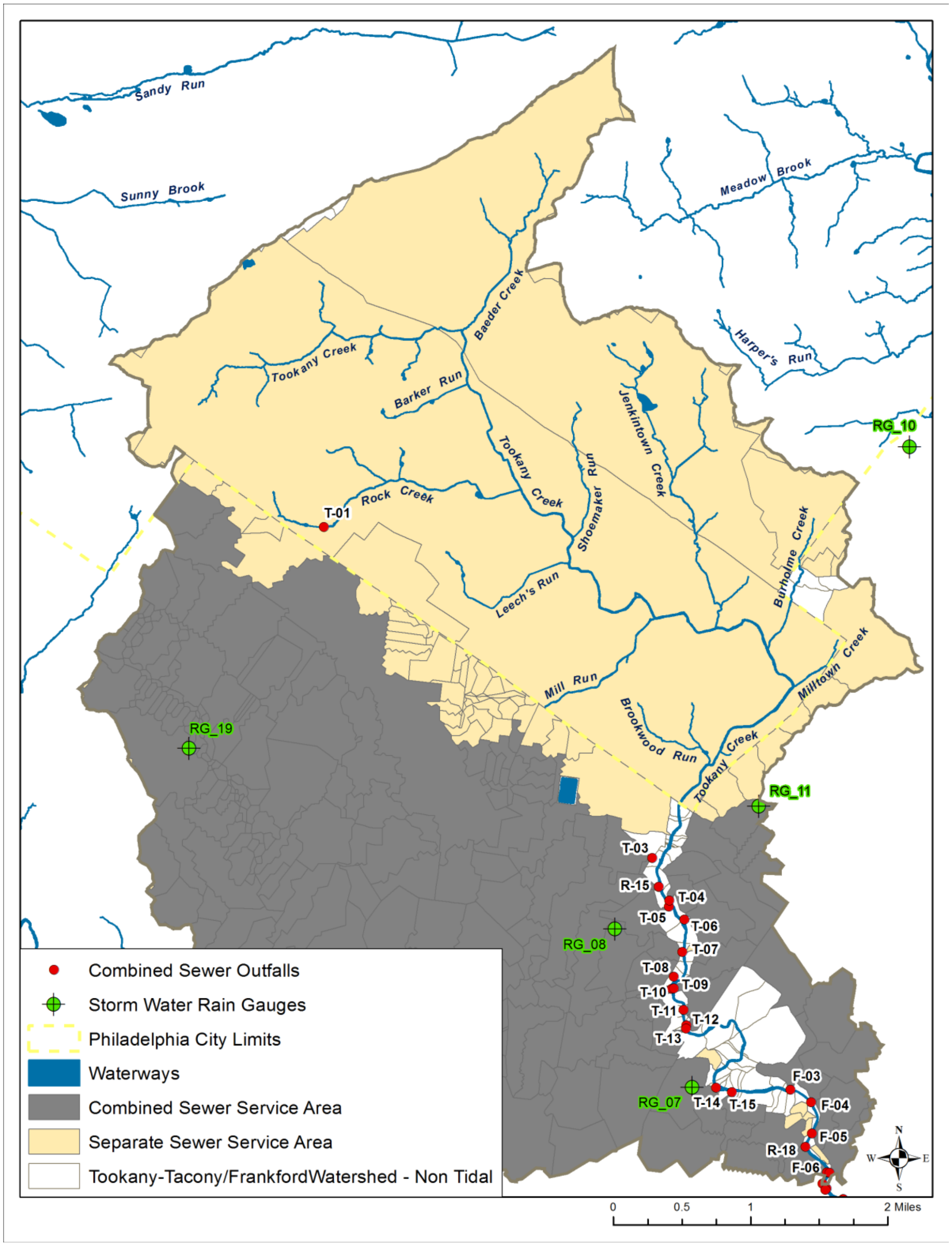

Figure 1-5: CSO Outfalls in the Nontidal TTF Creek Watershed

The upstream boundary of the water quality model extent is at River Mile 11.48 in Montgomery County. This was done to capture the influence of City outfall T01 which discharges to Rock Creek, a tributary that enters the Tookany Creek at River Mile 10.88. The downstream boundary of the water quality model is at River Mile 1.77, the Torresdale Avenue weir dam, assumed to be the head of tide. The water quality model extent covers the entire nontidal zone of City discharge influence on the creek and also receives loading from 7 tributaries, all of which enter the mainstem in Montgomery County. The tidal reach of Frankford Creek will be included in the Year 4 (June 1, 2015) deliverable for water quality models of tidal receiving waters.

1.2 Cobbs Creek Water Quality Model Extent

The Cobbs Creek water quality model explicitly simulates in-stream bacteria conditions in the nontidal reaches of Cobbs, East Indian, and West Indian Creeks affected by City discharges. In the Cobbs Creek water quality model extent, there are 30 outfalls that release combined stormwater and sanitary wastewater during storms that exceed the Southwest Water Pollution Control Plant treatment capacity (Figure 1-6). During a typical year, the outfalls in the Cobbs Creek water quality model extent discharge a total volume of 719 million gallons (Table 1-2). The water quality model extends upstream on Cobbs Creek to the boundaries of Philadelphia and Delaware Counties, and upstream on East Indian and West Indian Creeks to the boundaries of Philadelphia and Montgomery Counties. The downstream boundary of the water quality model is at River Mile 1.10, the Woodland Avenue dam, assumed to be the head of tide. The Cobbs Creek water quality model extent covers the entire nontidal zone of City discharge influence on the Cobbs, East Indian, and West Indian Creeks. The Cobbs Creek water quality model also receives loading from the Naylors Run tributary, which enters Cobbs Creek at River Mile 4.40. The tidal reach of Cobbs Creek will be included in the Year 4 (June 1, 2015) deliverable for water quality models of tidal receiving waters.

Table 1-2: Typical Year Outfall Statistics in the Cobbs Creek Water Quality Model Extent

Outfall Number	Frequency (Times/ Year)	Duration (Hours/ Incident)	Volume (Gallons/ Incident)
C01	15.5	0.7	130,504
C02	5.5	0.5	33,528
C04A	20.5	1.1	140,481
C05	14.5	1	219,411
C06	60.5	2.7	709,114
C07	20.5	1.7	558,388
C09	32	1.7	448,895
C10	15.5	2.1	108,490
C11	41.5	2.7	2,469,046
C12	39.5	2.3	456,852
C13	29.5	2	402,150
C14	30.5	2.4	754,592
C15	18.5	1.8	152,954
C16	5	0.6	41,587
C17	54.5	4.4	5,295,500
C18	28.5	1.9	744,971
C19	19	0.8	267,911
C20	15	1.2	190,576
C21	18	1.3	218,592
C22	35.5	1.9	440,852
C23	10.5	1.9	164,864
C31	38.5	2.1	289,224
C32	31	1.5	348,038
C33	19.5	0.9	183,354
C34	13	0.7	170,268
C35	11	0.9	77,737
C36	9.5	0.7	79,298
C37	15	0.8	73,167
CFRTR	75	5.9	1,406,370
CFRA	12	0.6	555,935

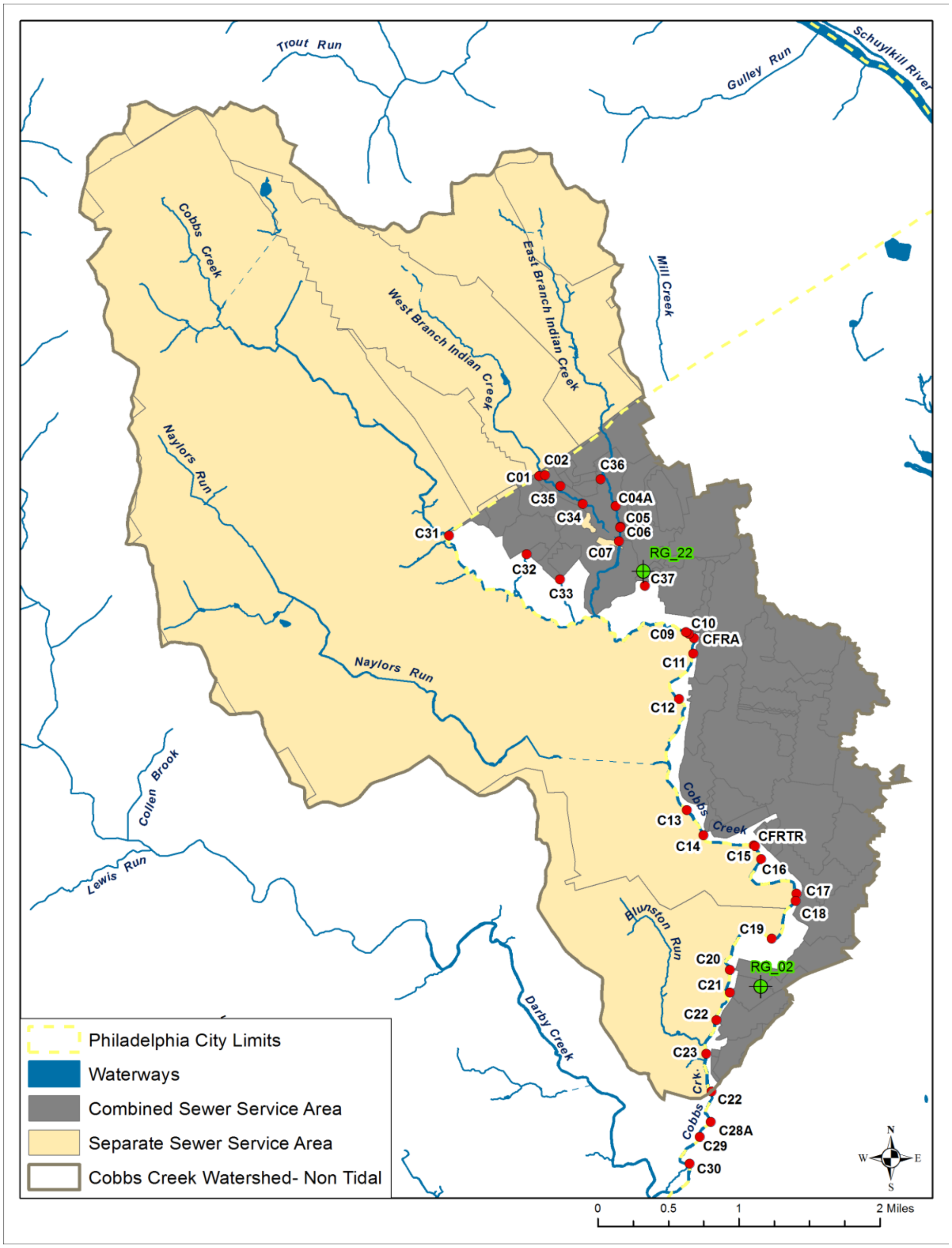

Figure 1-6: CSO Outfalls in the Nontidal Cobbs Creek Watershed

1.3 Applicable Surface Water Quality Standards

PADEP has established a maximum limit for fecal coliform bacteria of 200 colony forming units (CFU) per 100mL sample during the period May 1 - September 30, the "swimming season", and a less stringent limit of 2000 CFU/100mL for all other times. It should be noted that state criteria are based on the geometric mean of a minimum of five consecutive samples with each sample collected on different days during a 30-day period. For the swimming season, no more than 10% of the total samples taken during a 30-day period may exceed 400 CFU/100mL (Commonwealth of Pennsylvania, 2001).

PADEP has not established a standard for *E. coli*, however US EPA (1986) recommended limits of 409 and 4096 CFU/100mL in swimming and non-swimming seasons, respectively. US EPA (2012) recently recommended updated recreational water quality criteria for Enterococci and *E. coli* comprised of a magnitude, duration, and frequency of excursion for both a geometric mean and a statistical threshold value.

1.4 Problem Definition

Extensive sampling of the Cobbs and TTF Creek Watersheds since 1999 indicates exceedance of the fecal coliform water quality standard, particularly during wet weather and during the recreational season when the limit is more stringent. As per the Compliance Requirements listed in Section 3a of the COA, the Department must submit a water quality model that simulates bacteria in TTF Creek and Cobbs Creek by June 1, 2013. The water quality model and assessment tools will aid in the process of better understanding bacteria fate and transport in these waterbodies.

1.5 Model Objectives

The objectives of the model were to represent bacteria conditions in the receiving waters through comparison of predicted and observed fecal coliform and *E. coli* concentrations during past wet weather events. Dry weather grab samples and wet weather data collected via grab and automated samples were used to validate the model for fecal coliform and *E. coli*.

1.6 Modeling Approach

The Consent Order and Agreement requires the Water Department to develop a bacteria model appropriate for characterizing flow and water quality in the receiving waters which are defined as Tookany/Tacony-Frankford Creek and Cobbs Creek.

Flow and pollutants can enter the receiving waters through:

- Overflows from sewer systems
- Runoff (direct and through stormwater collection systems)
- Secondary tributaries
- Baseflow (groundwater)

The Water Department Tributary Hydrologic and Hydraulic (H&H) Models were developed and validated to provide reasonable estimates of combined sewer overflows resulting from precipitation events. The H&H Models simulate and couple the sewer system, contributing watershed area, and open channel (*i.e.*, mainstem creek and tributaries). These models were developed using the US EPA Storm Water Management Model version 5 (SWMM5), which has the capability to simulate surface runoff pollutant loadings through a variety of buildup-washoff functions and assign pollutant concentrations directly to a flow time series. Stormwater and sanitary wastewater pollutants are carried through the collection system and discharge through the outfalls to the receiving waters during an overflow event. The Water Department Tributary H&H Models were used to generate pollutant loading time series from the collection systems, secondary tributaries, and baseflow to the receiving waters.

A one dimensional water quality model was considered appropriate for the receiving waters. A one-dimensional model does not take into account cross sectional differences in flow or concentration, but instead provides a uniform cross sectional average. The US EPA Water Quality Analysis Simulation Program (WASP) version 7.5 was selected to model pollutant fate, with a linkage to the SWMM5 transport model. WASP7.5 routes and transforms pollutants by assuming completely mixed modeling segments. More detail on WASP is provided in Section 3.4.

Figure 1-7 presents a flow chart of the Water Department Water Quality Modeling approach, the major elements of which are described below.

The Tributary H&H Models included the following model domains:

- **Combined Sewer System (CSS) Models**. This model domain included:
    - The combined service area within the City borders, which drains to the Water Department Water Pollution Control Plants.
    - The sanitary portion of the separate sewered area, within and outside the City, which drains to the Water Department Water Pollution Control Plants. A simplified version of the sanitary collection system is modeled inside the City, and indirectly modeled outside the City.
    - The combined sewer overflow and interceptor relief outfall pipes within the City, which discharge into receiving waters.
- **Watershed Models.** This model domain included:
    - Open channel representations of the receiving waters and major tributaries within the watershed.
    - The stormwater and direct runoff areas within and outside of the City borders. Stormwater collection system conduits are not explicitly modeled.

The models developed for the Act 167 Stormwater Management Plans served as the starting point for the water quality model development. The Act 167 Models were created by merging the CSS Models with the Watershed Models, and hydraulically connecting the CSS Models' CSO outfall conduits to the Watershed Models' receiving waters. The resulting models after updates and modifications to incorporate water quality are the Tributary H&H Models.

The predicted flows and loads from the Tributary H&H Models drive the Tributary Water Quality Models, which simulate bacteria fate and transport in the receiving waters affected by City discharges. Additional details about these modeling elements are provided throughout this report.

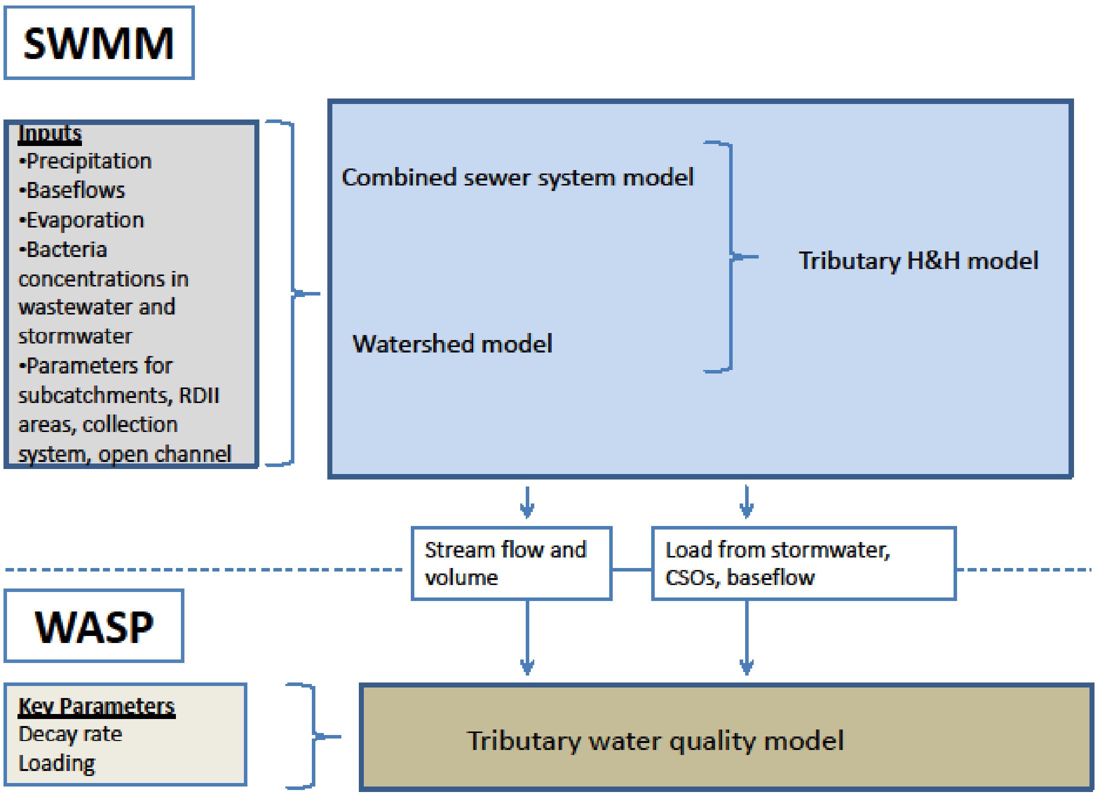

Figure 1-7: Modeling Approach for Bacteria in Tributaries

2.0 Tributary H&H Models

2.1 SWMM and Model Development Overview

The Tributary H&H Models were developed in SWMM5 to provide the hydrologic and bacteria loadings to the WASP models. The Tookany/Tacony-Frankford Creek and Cobbs Creek receiving waters are collectively referred to as the major tributaries and discharge into the Delaware River. Since these waterways are smaller in size and typical of urban streams, they are expected to have short residence times following a storm or overflow event. A one-dimensional transport model was appropriate to represent these waterways. A one-dimensional model does not take into account cross sectional differences in flow or concentration, but instead provides a uniform cross sectional average. SWMM5 utilizes full dynamic wave routing of flow and routes pollutants by assuming completely mixed modeling segments. SWMM5 was primarily used to simulate the hydrologic and hydraulic flow routing to and through the open channel system of the tributaries. SWMM5 was also used to simulate pollutant loads and routing to the major tributaries and determine bacteria loadings at the outfalls, but was not used to simulate pollutant routing within the major tributaries. Water quality routing and processes within the major tributaries were simulated by the Tributary Water Quality Models in WASP.

The Water Department Combined Sewer System (CSS) models were a primary part of the modeling effort. These models were developed for the Long Term Control Plan Update (LTCPU) and validated to provide reasonable estimates of combined and sanitary sewer overflows during precipitation events. These models were originally developed using the US EPA Storm Water Management Model version 4 (SWMM4) and later converted to version 5. The CSS Models were adapted to perform the hydrologic and hydraulic flow routing and water quality routing for the combined and sanitary sewer area collection systems.

The Watershed Models were also developed in SWMM5, and included the open channel representations of the receiving waters and major tributaries within the watershed, and the stormwater and direct runoff areas within and outside of the City borders. These runoff areas were primarily comprised of the neighboring communities to the north and west of the City. These areas contribute runoff and associated pollutant loads to the receiving waters either through stormwater collection systems, direct runoff, or through minor tributary waterways.

The CSS Models were developed by drainage district to the three Water Pollution Control Plants. The Northeast and Southwest District CSS Models were integrated into the Tookany/Tacony-Frankford Creek and Cobbs Creek Watershed Models independently. As described in Section 1.5, the Tributary H&H Models were created by merging the CSS Models with the Watershed Models, and hydraulically connecting the CSO outfall conduits of the CSS Models to the receiving waters of the Watershed Models. The Tributary H&H Models were validated to streamflow at USGS gaging sites along the major tributaries.

2.2 Tributary H&H Model Validation

Details on the tributary H&H model development and validation in the Tookany/Tacony-Frankford Creek and Cobbs Creek are given in Appendix A and Appendix B, respectively. A summary of the approach and results is provided in this section.

Tributary H&H model validation was accomplished by adjusting initial estimates of the selected variables, within a specified range, until a satisfactory correlation between simulated and measured runoff values, over a range of storm events, was obtained. The selected adjustment parameters were impractical to measure precisely (*e.g.*, percent routed, soil infiltration parameters, etc.), and had the greatest effect on the accuracy of the results. The validation parameters were prioritized according to their influence on the model results, which vary from one drainage system to another over a range of hydrologic and operating conditions.

2.2.1 Model Domain and Validation Parameters

Model Domain

The Tributary H&H Models were validated to USGS flow monitoring gages in the Tookany/Tacony-Frankford Creek and Cobbs Creek. While the Tributary H&H Models were built by merging the CSS Models and the Watershed Models, the CSS Models underwent a separate validation based on flow monitoring within the collection system. Therefore the CSS Model domain elements were not adjusted. The hydrologic parameters within the Watershed Model were exclusively adjusted to accomplish the Tributary H&H Model validation.

Validation Parameters

The adjustment parameters selected for the watershed models included:

- Percent Routed / DCIA
- Saturated Hydraulic Conductivity
- Initial Soil Moisture Deficit
- Soil Capillary Suction Head
- Subcatchment Width
- Impervious and Pervious Depression Storage

2.2.2 Validation Data

USGS Data

Streamflow estimates, measured within the City of Philadelphia and published by USGS, were used in the validation of H&H models. USGS gaging stations recorded water surface elevation at continuous 15 minute increments. Low streamflows were estimated through the use of depth to flow rating curves established at the gaging stations. These rating curves were populated through direct field measurements of velocity taken with acoustic Doppler profilers. For flows greater than the maximum rate measured in the field, a separate depth to flow rating curve was used, which was developed through the use of a HEC-RAS model or detailed hydraulic calculations. Published flow data from USGS gage stations were estimated to be ± 30% accurate (Matt Gyves (USGS), personal communication, 4/3/2013).

The modeled volumes, peak flows, and hydrograph shapes were validated to two USGS gages on each tributary. The gage locations are shown in Figures 3-3 for Tookany/Tacony-Frankford Creek and Figure 3-5 for Cobbs Creek in Section 3. The model results were compared to 15-minute interval streamflow data. A summary of USGS gage information is provided in Table 2-1. Presently there are two gages along the Tookany/Tacony-Frankford Creek, USGS gage 01467086 and USGS gage 01467087. Gage 01467086, located near the Adams Avenue bridge, is the more upstream gage and near where the stream passes through the City border. Gage 01467087 at the Castor Avenue bridge is the more downstream gage. The Castor Avenue gage is approximately 2.8 miles upstream of the mouth of the stream at the Delaware River and above the influence of tide.

There are also two gages currently in service along the Cobbs Creek. USGS Gage 01475530 (Rt. 1) is located near the intersection of Cobbs Creek with the City border. USGS Gage 01475548 (Mt. Moriah) is located approximately two-thirds the river mile distance downstream of Rt. 1 gage to the mouth of the Cobbs Creek Watershed (confluence with Darby Creek).

Table 2-1: Available USGS 15-Minute Flow Data

Gauge ID	Location	Data Range	
		Start	End
01467086	Tacony Creek above Adams Avenue	10/1/2005	present
01467087	Frankford Creek at Castor Avenue	7/1/1982	present
01475530	Cobbs Creek at US Highway No. 1 at Phila, PA (Rt. 1)	09/07/2004	present
01475548	Cobbs Creek at Mt. Moriah Cemetery at Phila. PA (Mt. Moriah)	10/17/2005	present

Baseflow

In order to approximate baseflow during the validation time period, baseflow separation was performed on the USGS data sets. Area weighted baseflow was loaded into the modeled stream channel to maintain flow during dry weather periods. Baseflow was also needed during model validation to isolate the rainfall response of stormwater runoff from the complete stream hydrograph. Baseflow separation involved disaggregation of monitored flow time series into its wet-weather and dry-weather components based upon expected hydrological response times. The baseflow in the tributaries is mostly comprised of groundwater inflow to the stream.

Precipitation

Gage adjusted radar rainfall was obtained from Vieux & Associates, Inc. (Norman, OK) and processed to be used for the hydrologic validation period and the water quality validation events. The radar data is produced by the National Weather Service Next Generation Radar (NEXRAD) system. NEXRAD Level II radar data are often referred to as Base Data and contain the full spatial/temporal/data resolution data from the radar. Level II radar data measures reflectivity in decibels of reflectance (dBZ), and at a spatial resolution of 0.5-degree by 0.25-km every 4 – 10 minutes with a data resolution of 0.5 dBZ amounting to 256 data levels of data. Level III Q0 radar data have the same data and temporal resolution, but a reduced spatial resolution of 1-degree by 1-km. The primary radar data source was Level II NEXRAD data from KDIX located near Mt. Holly, NJ.

The radar grid was calibrated to the existing Water Department rain gage network, which consists of 24 tipping bucket gages within the City limits, and a network of public domain gages surrounding the City. The City rain gage network is field verified once month with a test volume of water and a redundant rain gage deployment occurs on a rotating schedule as a second verification of rain gage accuracy. The radar rainfall coverage represents an improvement beyond the existing rain gage network in providing a clear representation of precipitation over the entire Tookany/Tacony-Frankford Creek and Cobbs Creek Watersheds. Because radar data has the potential to better represent the spatial distribution of rainfall between gages within the City and for locations outside the rain gage network, precipitation estimates derived from radar rainfall provided a better model input toward estimating streamflow than extrapolated point rain gage estimates.

Events

The monitored and predicted hydrographs were split into discrete wet weather events over time, so comparisons could be made on an event by event basis. Events were defined not by continuous rainfall, but by continuous wet-weather response. Additionally, since snowmelt was not simulated, snowfall and all potential snow-melt events were removed from the validation data set. This determination was based on precipitation and temperature data obtained from the Philadelphia International Airport. The observed and simulated hydrographs were compared for their general response magnitude, shape, and timing. During the validation process, the model hydrologic parameters were adjusted to provide a better fit between the simulated and monitored flows. Events that appeared to be non-representative outliers were removed.

For the Tookany/Tacony-Frankford Creek, 146 wet-weather events were defined at both USGS Gage 01467086 (Adams Avenue) and USGS Gage 01467087 (Castor Avenue) over the years 2010 through 2012. The events defined for the two gages were similar with respect to hydrograph shape and duration, and exhibited a lag of wet weather flow travel time from the upstream gage (Adams Avenue) to the downstream gage (Castor Avenue). Due to less impervious area in the headwaters of the Tookany/Tacony-Frankford Creek, the events at the Adams Avenue gage were less flashy than at the Castor Avenue gage.

For the Cobbs Creek, 110 wet-weather events at USGS Gage 01475530 (Rt. 1), and 109 wet-weather events at USGS Gage 01475548 (Mt. Moriah) were defined over the years 2011 and 2012. The defined events were similar with respect to hydrograph shape and duration. Events typically began one to two hours earlier at the upstream gage (Rt. 1). Also, there was a higher percentage of pervious cover contributing to the Rt. 1 gage, so event measurements there exhibited slower response times and more prolonged wet-weather tails. Consequently, a few of the events at Rt. 1 were merged based on timing and extended wet-weather tails, as compared to the Mt. Moriah events.

2.2.3 Validation Results

The first phase of validation utilized the aforementioned hydrologic parameters that control event hydrograph volume, namely:

- Percent Routed / DCIA
- Saturated Hydraulic Conductivity
- Initial Soil Moisture Deficit
- Soil Capillary Suction Head

The second phase of validation utilized the aforementioned hydrologic parameters that control event hydrograph timing and peak, namely:

- Subcatchment Width
- Impervious and Pervious Depression Storage

Scatter plots of observed and simulated event volumes at each of the Tookany/Tacony-Frankford Creek gages are shown in Figures 2-1 and 2-2. A least squares regression line is plotted in solid black on each scatter plot. The validated model has a fitted line slope of 1.086 and R-Square value of 0.9444 at Gage 01467086 (Adams Avenue) (Figure 2-1), and a fitted line slope of 0.9362 and an R-Square value of 0.9706 at Gage 01467087 (Castor Avenue) (Figure 2-2).

Scatter plots of observed and simulated event volumes at each of the Cobbs Creek gages are shown in Figures 2-3 and 2-4. A least squares regression line is plotted in solid black on each scatter plot. The validated model has a fitted line slope of 0.9515 and R-Square value of 0.9137 at Gage 01475530 (Rt. 1) (Figure 2-3), and a fitted line slope of 0.9928 and an R-Square value 0.9001 at Gage 01475548 (Mt. Moriah) (Figure 2-4).

These results suggest that the Tributary H&H Models developed in SWMM adequately predict the runoff response and streamflow during wet weather events and are appropriate to use to generate hydrologic loading for the Tributary Water Quality Models.

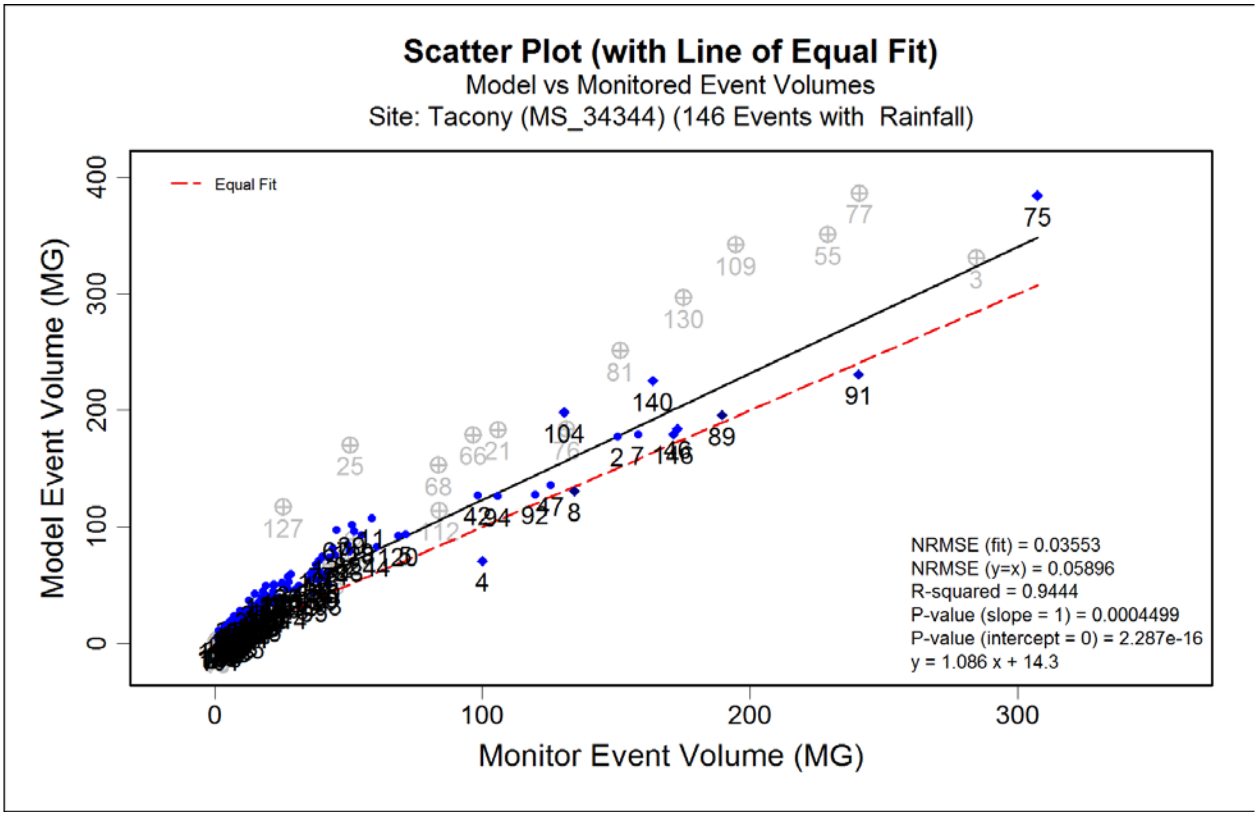

Figure 2-1: Tookany/Tacony-Frankford Creek Volume Validation at Gage 01467086 (Adams Avenue)

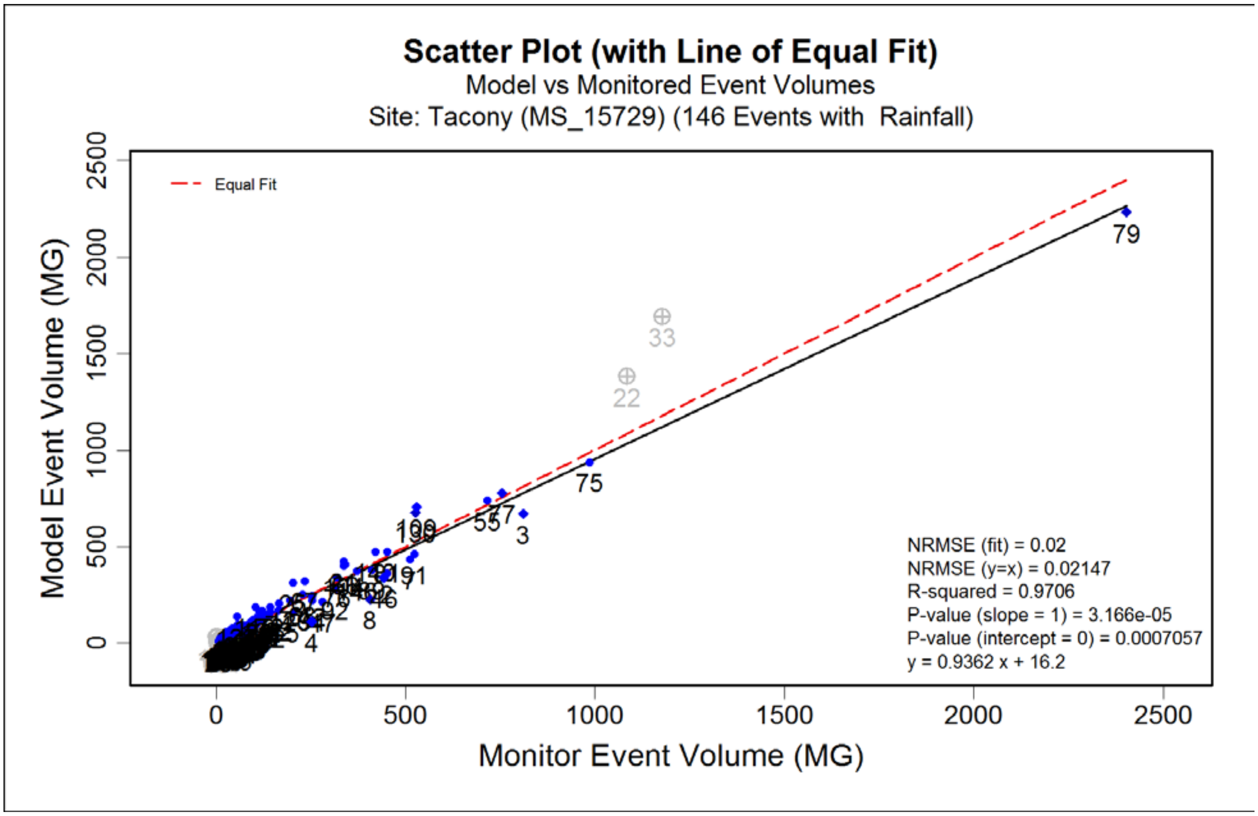

Figure 2-2: Tookany/Tacony-Frankford Creek Volume Validation at Gage 01467087 (Castor Avenue)

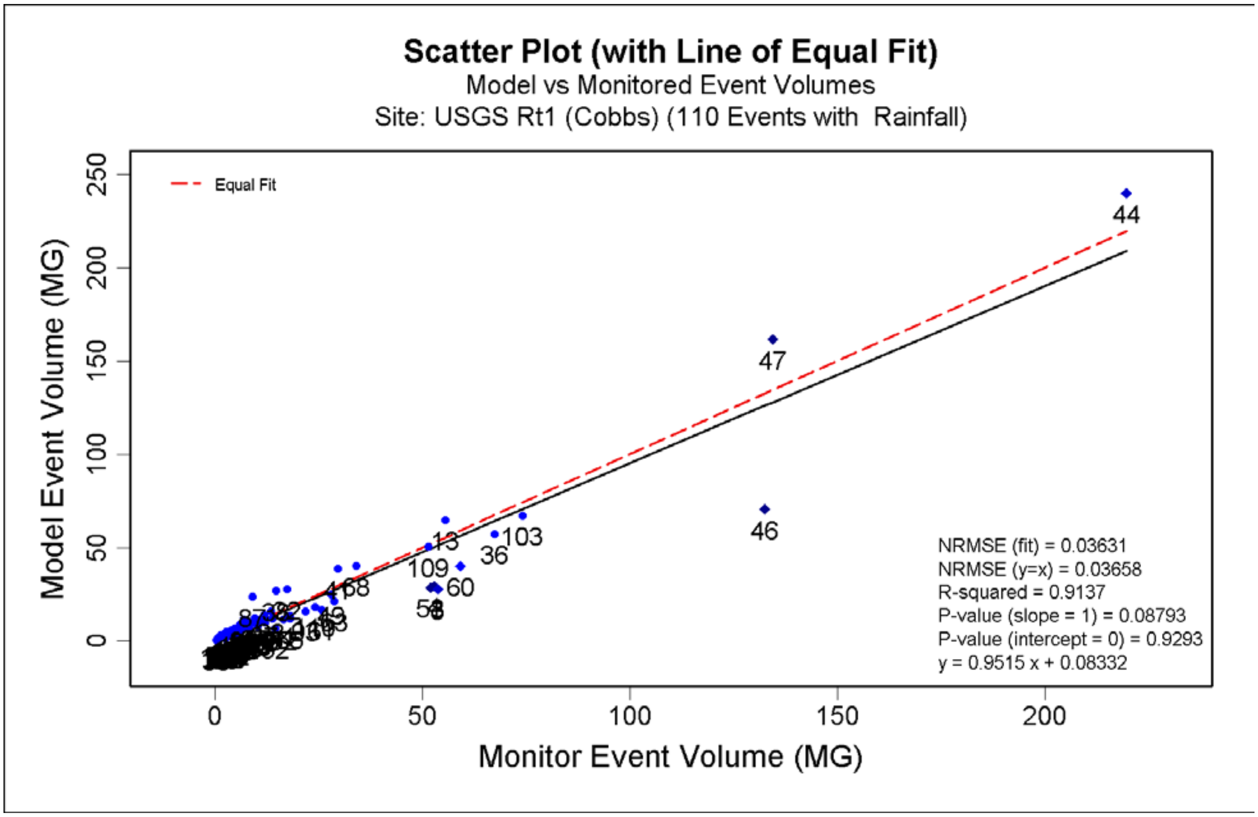

Figure 2-3: Cobbs Creek Volume Validation at Gage 01475530 (Rt. 1)

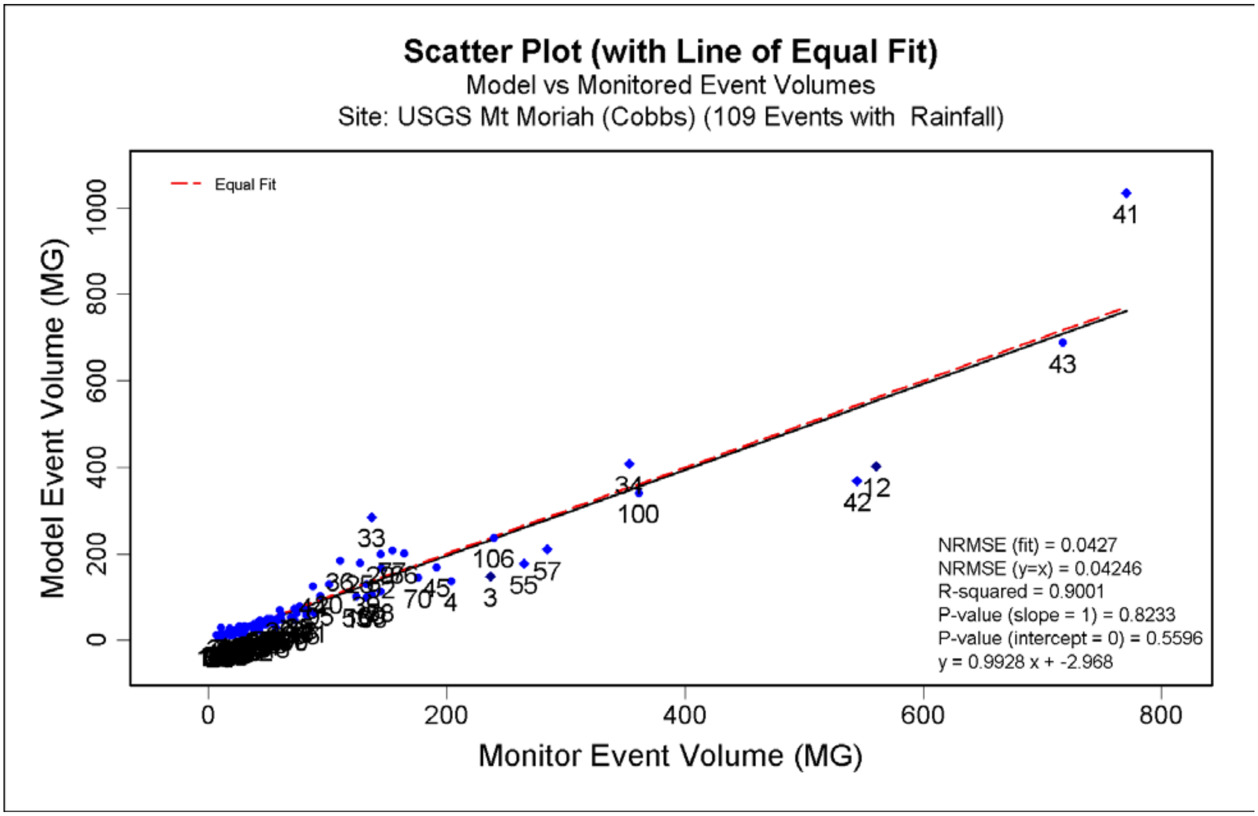

Figure 2-4: Cobbs Creek Volume Validation at Gage 01475548 (Mt. Moriah)

3.0 Water Quality Model

3.1 Literature Review of Urban Stream Bacteria Models

Related literature on urban stream bacteria models were compiled from peer-reviewed journal articles and reports authored by agencies and consultant firms. Four of the models were based on linked SWMM-WASP models, in which SWMM was used to simulate hydrology and hydraulics and WASP was used to simulate water quality, the same approach employed in the TTF and Cobbs Creeks water quality models. Although the body of literature cited is not large, it is reflective of the work to date in the field of urban stream bacteria modeling. The models and their salient features are summarized in Table 3-1.

With respect to pathogen indicator, three of the seven models (*i.e.*, Butler Creek, Buffalo River, Chicago River) exclusively simulated fecal coliform, two models (*i.e.*, Indianapolis LTCP and Columbus River) exclusively simulated *E. coli*, one model simulated both fecal coliform and *E. coli* (ALCOSAN), and one model (*i.e.*, Merrimack River) simulated fecal coliform, *E. coli* and enterococcus. WASP was the most common water quality model used, applied in four of the seven cases. The other cases applied DUFLOW, RMA4, SWMM5 and a simple spreadsheet model. The ALCOSAN case applied two water quality models, RMA4 for the Main Rivers and SWMM5 for tributaries.

The bacteria decay process was described for four of the models. In all four cases a first order process was applied. First order decay rates ranged from 0.1 d^{-1} to 1.6 d^{-1}. Decay rate was a primary calibration parameter and was generally derived from references such as Bowie *et al.* (1985) and US EPA (2001). The decay rate was constant across the spatial extent in all models except the Chicago River model, which applied a spatially varying rate derived from a novel comparison of frequency distributions of historic data from neighboring sites, and the Buffalo River spreadsheet model which did not apply decay. None of the models attempted to simulate complex processes such as bacterial regrowth or resuspension. A straightforward first order decay model was the norm. In-stream temperature time series was also included in some models (*e.g.*, Columbus River), since the first order decay model can be configured to account for faster decay at greater water temperatures.

Among cases which reported water quality model time step, it varied from 15 seconds to 1 hour. With respect to reported segment length, the Butler Creek WASP model divided 10 miles into 16 segments, or an average 3300 feet per segment. The Chicago River DUFLOW model divided 76.3 miles into 36 segments, or an average 2.1 miles per segment.

Besides the decay rate, bacteria loading was the other main calibration parameter. Sources of loading include CSOs, other point sources, direct watershed runoff, and headwaters. Four models—Indianapolis LTCP, Buffalo River, Columbus River, and ALCOSAN—measured actual time series of bacteria loading from a few discrete outfalls to help inform CSO loading in the model. A typical approach was to apply flow-weighted concentrations from several outfalls lumped into one discharge point per segment (Figure 3-1) during wet weather events, and adjust the discharge concentrations through calibration. Other models applied a time varying concentration from CSOs to mimic a first flush effect (*e.g.*, Indianapolis LTCP) based on data from other CSO systems which were adjusted through calibration. For fecal coliform modeling, the maximum reported simulated concentration from a single outfall loading was 1.89 million CFU/100 mL in the Merrimack River model. More typical simulated discharge concentrations for fecal coliform ranged from 140,000 to 1 million CFU/100 mL. For watershed runoff, either a buildup-washoff function (*e.g.*, Merrimack River) or event mean concentration (EMC) (*e.g.*, ALCOSAN) was applied. Of the articles reviewed, the ALCOSAN model featured the most extensive efforts to calibrate EMCs.

The amount of in-stream observed data used for model validation varied greatly, ranging from none (*e.g*, Butler Creek) to observations at 30 minute intervals during storm events (*e.g.*, Chicago River). Some models (*e.g.*, Indianapolis LTCP) used historical data to supplement a sparse set of actual event data for model validation. Observed in-stream data on the order of one to three observations per storm event was also found in the review (*e.g.*, ALCOSAN).

Validation of bacteria water quality models is generally limited in objectivity due to the scarcity of observed data in most models, and the uncertainties inherent to both observed (Gronewold and Borsuk, 2009) and simulated concentrations. Absolute thresholds or statistical criteria for model performance are not in place to evaluate bacteria water quality models. Instead, as was the case with the cited literature, model validation is generally conducted through visual comparison of simulated and observed time series plots for periods of wet and/or dry weather until a determination is made that the model adequately represents the system of interest.

Table 3-1: Features of Reviewed Urban Stream Bacteria Models

Waterbody/ Project	Hydrology model	Hydraulic model	Water quality model (WQM)	WQM time step	WQM stream miles	WQM n segments	WQM n outfalls	Pathogen indicator	decay rate [d^{-1}]	Simulation of regrowth/ resuspension
Indianapolis LTCP (White River plus tributaries)	SWMM4	SWMM4	WASP	Not given	miles not given; SWMM CSO area = 37.4 sq mi	not given; each segment at least 2 miles on average	94 in SWMM; no more than 1 per segment in WASP	*E. coli*	1	None
Butler Creek	SWMM4	SWMM4	WASP5	Not given	10 mi.	16	109 consolidated into 5	Fecal coliform	1	None
Merrimack River	HSPF	SWMM4	WASP5	Not given	Miles not given; overall basin is ~5000 sq mi	140	Not given; output from 5 separate City CSO models used	Fecal col., *E. coli*, entero-coccus	Not given	None
Buffalo River	HSPF	XP-SWMM	Spread-sheet	1hr	Not given	Not given	Not given	Fecal coliform	None	None
Chicago River	DUFLOW	DUFLOW	DUFLOW EUTROF2 (based on WASP)	15 mins	76.3 mi.	36	35 (includes nearly 200 CSOs represented by 28 points)	Fecal coliform	spatial varying 0.1-1.6	None
Columbus River	SWMM4	SWMM4	WASP	Not given	Not given	Not given	Not given	*E. coli*	Not given	None
ALCOSAN (Ohio, Allegheny, Monongahela Rivers plus tributaries)	SWMM5	SWMM5 (collection system, watershed, tributaries) and RMA2 (Main Rivers)	RMA4 (2D finite element) for Main Rivers; SWMM5 for tributaries	RMA4: 15mins; SWMM5: 15 secs	SWMM5 tributaries: 22 mi	trib: several hundred channel cross sections; RMA4 results spatially averaged in segments of 0.5-1.0 river mi	Not given	Tributaries: Fecal coliform , *E. coli*; RMA4: Fecal coliform	0.58 (Main Rivers and Tributary models, both Fecal coliform and *E. coli*)	None

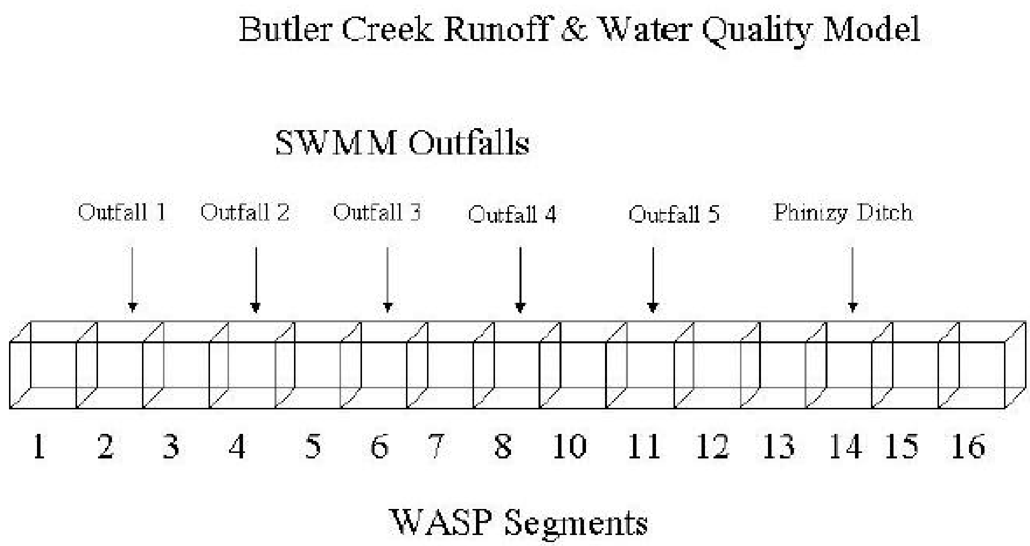

Figure 3-1: Example of SWMM-WASP linkage in Butler Creek model. 109 SWMM outfalls were consolidated into 5 discharge points into WASP (Georgia Environmental Protection Division, 2000).

3.2 Key Processes in Urban Stream Bacteria Modeling

Fecal coliform and *E. coli* bacteria enter TTF and Cobbs Creeks primarily via stormwater runoff, combined sewer overflow discharges, and tributaries. Neither waterbody receives discharge from any wastewater treatment plants. Direct deposition from wildlife occurs but is not accounted for explicitly in the model.

In the environment, bacteria is partitioned into dissolved and particulate fractions. Regrowth and resuspension are phenomena that have been described in the literature (Uchrin and Weber, 1981; Crabill *et al.*, 1999; Davies *et al.*, 1999; Steets and Holden, 2003; Muirhead *et al.*, 2004; Characklis *et al.*, 2005; Jeng *et al.*, 2005; Bai and Lung, 2005; Jamieson *et al.*, 2005), however, as noted in the literature review, the common practice in bacteria water quality modeling is to represent bacteria entirely as dissolved, and not account for regrowth or resuspension. Although multiple processes affect the decay rate, such as temperature, salinity, predation, photolysis, predation, settling, resuspension, and regrowth (US EPA, 2001), in this project bacteria is modeled through a first order decay term applied in a spatially uniform manner.

As urban streams, TTF and Cobbs Creeks are typical in terms of the rapid rate at which stream discharge and pollutant concentrations can change. This context is important to understanding the fate and transport of bacteria in these tributaries. During wet weather events, the rate of change in stage and discharge in TTF and Cobbs Creeks is extreme, unlike a natural stream (Appendix A, Figure A-4). The flashiness of the urban stream environment results in large loadings of pollutants that are rapidly transported through the system. Observed pollutographs from TTF and Cobbs Creeks demonstrate increases of bacteria of 3 to 4 orders of magnitude that occur in a matter of minutes to hours. The applied H&H and water quality model must be able to compute numerical solutions of this highly dynamic environment. Model selection is described in Section 3.5.

3.3 Summary of Available In-Stream Bacteria Data

Extensive sampling and monitoring programs were conducted from 2000-2004 to inform development of the TTF Creek Watershed Comprehensive Characterization Report (CCR), and from 1999-2003 for the Cobbs Creek Watershed CCR. The programs included hydrologic, water quality, biological, habitat, and fluvial geomorphological aspects.

Fecal coliform and *E. coli* samples were collected in dry weather and wet weather conditions via grab samples and automated samplers (Isco, Inc.) in recreational and non-recreational seasons. During wet weather sampling, several discrete samples were collected just before and during the course of a wet weather event. Automated samplers were configured to collect samples throughout the wet weather event, at intervals ranging from 20 to 90 minutes. The data allowed characterization of water quality responses to stormwater runoff and combined sewer overflows.

The CCR data offered the main set of observations used to validate the water quality model for eight specific wet weather events in TTF Creek, and four wet weather events in Cobbs Creek. The water quality model validation events for TTF Creek are described in Table 3-2, and Table 3-3 for Cobbs Creek. They encompass a broad range of storms in terms of rainfall, peak flow, maximum bacteria concentration, geometric mean bacteria concentration, and bacteria load. Additional summary statistics on each water quality model validation event are tabulated in Tables 3-2 and 4-2 of Appendix C, and Tables 2-2 and 3-2 of Appendix D.

Table 3-2: TTF Creek Water Quality Model Validation Events

Storm	Rainfall (in)	Peak Flow (cfs)	Site	n bacteria samples	Max. fecal coliform concentration	Max. *E. coli* concentration	Event geometric mean, fecal coliform	Event geometric mean, *E. coli*	Event load, fecal coliform	Event load, *E. coli*
					CFU/100ml				CFU	
5/6/2003	0.16	637	TF280	9	177000	177000	43252	34948	6.7E11	6.1E11
			TF680	4	48000	36000	24701	8870	2.0E11	1.4E11
			TF975	4	33000	31000	18337	7521	9E10	7.6E10
5/7/2003	0.71	3280	TF280	5	31000	23000	7397	5698	4.7E11	3.4E11
			TF680	9	34000	25000	17106	10079	6.4E11	4.3E11
			TF975	7	42000	22000	7486	3666	3.3E11	2.0E11
5/16/2003	0.31	59	TF280	11	104000	42000	7796	4556	4.8E11	2.4E11
			TF680	9	21000	12000	7558	6142	1.1E11	8.8E10
			TF975	11	8000	7100	5821	4610	4.9E10	4.0E10
7/10/2003	0.19	179	TF280	9	180000	175000	75321	69232	9.7E11	9.3E11
			TF680	9	85000	80000	19601	16247	1.8E11	1.5E11
			TF975	8	29000	17000	9437	6826	5.2E10	3.5E10
9/23/2003	0.71	1710	TF280	6	182000	182000	45607	41766	5.8E12	5.6E12

Storm	Rainfall (in)	Peak Flow (cfs)	Site	n bacteria samples	Max. fecal coliform concentration	Max. *E. coli* concentration	Event geometric mean, fecal coliform	Event geometric mean, *E. coli*	Event load, fecal coliform	Event load, *E. coli*
			TF680	10	66000	46000	41454	22681	1.2E12	7.7E11
			TF975	8	54000	38000	31805	20652	6.7E11	4.3E11
10/14/2003	1.28	3460	TF280	7	61000	56000	27380	22831	3.6E12	3.7E12
			TF680	0	na	na	na	na	na	na
			TF975	6	42000	40000	20262	14150	1.1E12	8.9E11
7/7/2004	0.20	198	TF280	8	na	na	na	na	na	na
			TF680	8	11400	11400	4520	3799	4.7E10	4.1E10
			TF975	8	14300	14300	6596	5366	5.7E10	5.1E10
8/30/2004	0.43	866	TF280	9	780000	620000	249144	188243	1.1E13	8.3E12
			TF680	0	na	na	na	na	na	na
			TF975	8	430000	230000	89287	61618	8.2E11	5.3E11

Table 3-3: Cobbs Creek Water Quality Model Validation Events

Storm	Rainfall (in)	Peak Flow (cfs)	Site	n bacteria samples	Max. fecal coliform concentration	Max. *E. coli* concentration	Event geometric mean, fecal coliform	Event geometric mean, *E. coli*	Event load, fecal coliform	Event load, *E. coli*
					CFU/100ml				CFU	
7/26/2000	2.68	2600	DCC110	3	129000	20000	44670	12500	6.6E12	1.5E12
7/23/2003	0.28	720	DCC208	8	182000	182000	99000	99000	5.9E11	6.0E11
			DCC455	8	200000	200000	54000	37500	2.4E11	2.6E11
7/24/2003	0.46	100	DCC208	6	131000	98000	70000	52500	1.1E12	1.0E12
			DCC455	7	> 200000	> 200000	71000	58000	8.4E11	1.0E12
9/13/2003	0.55	140	DCC208	10	166000	166000	28000	22000	6.0E11	6.6E11
			DCC455	10	215000	215000	33000	22500	4.1E11	3.5E11

Bacteria data has also been collected quarterly since 2009 at each USGS gage site on the TTF Creek (01467086 and 01467087) and Cobbs Creek (01475530 and 01475548). Along with quarterly data from the USGS gages, other data collected in the TTF Creek and Cobbs Creek watersheds through separate monitoring programs were added to the CCR data set to enable a more complete analysis of bacteria concentration statistics by recreation season, weather condition and site.

Water quality model validation sites, and sites used to characterize dry weather bacteria concentrations are mapped in Figures 3-2 to 3-5.

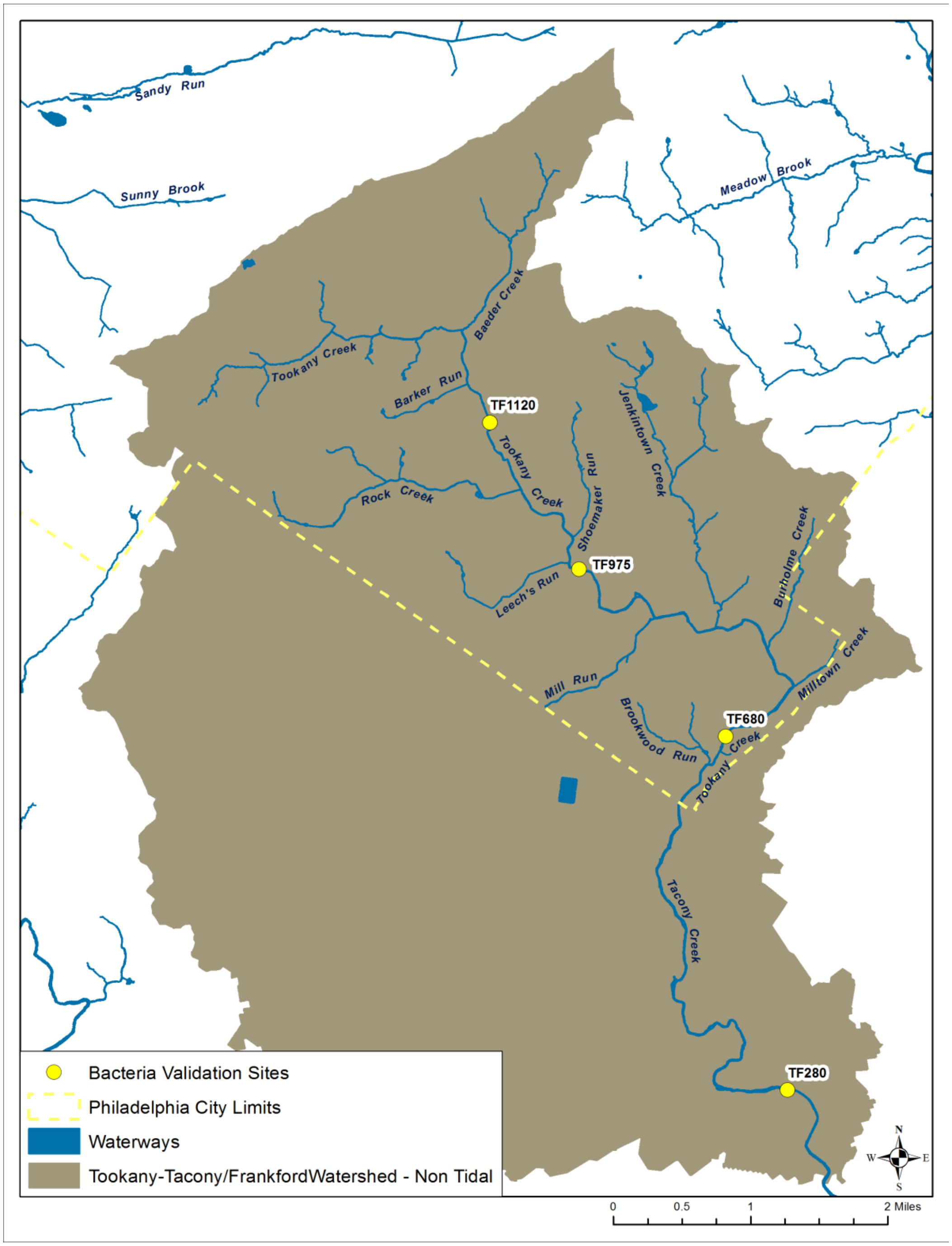

Figure 3-2: TTF Creek Bacteria Model Validation Sites

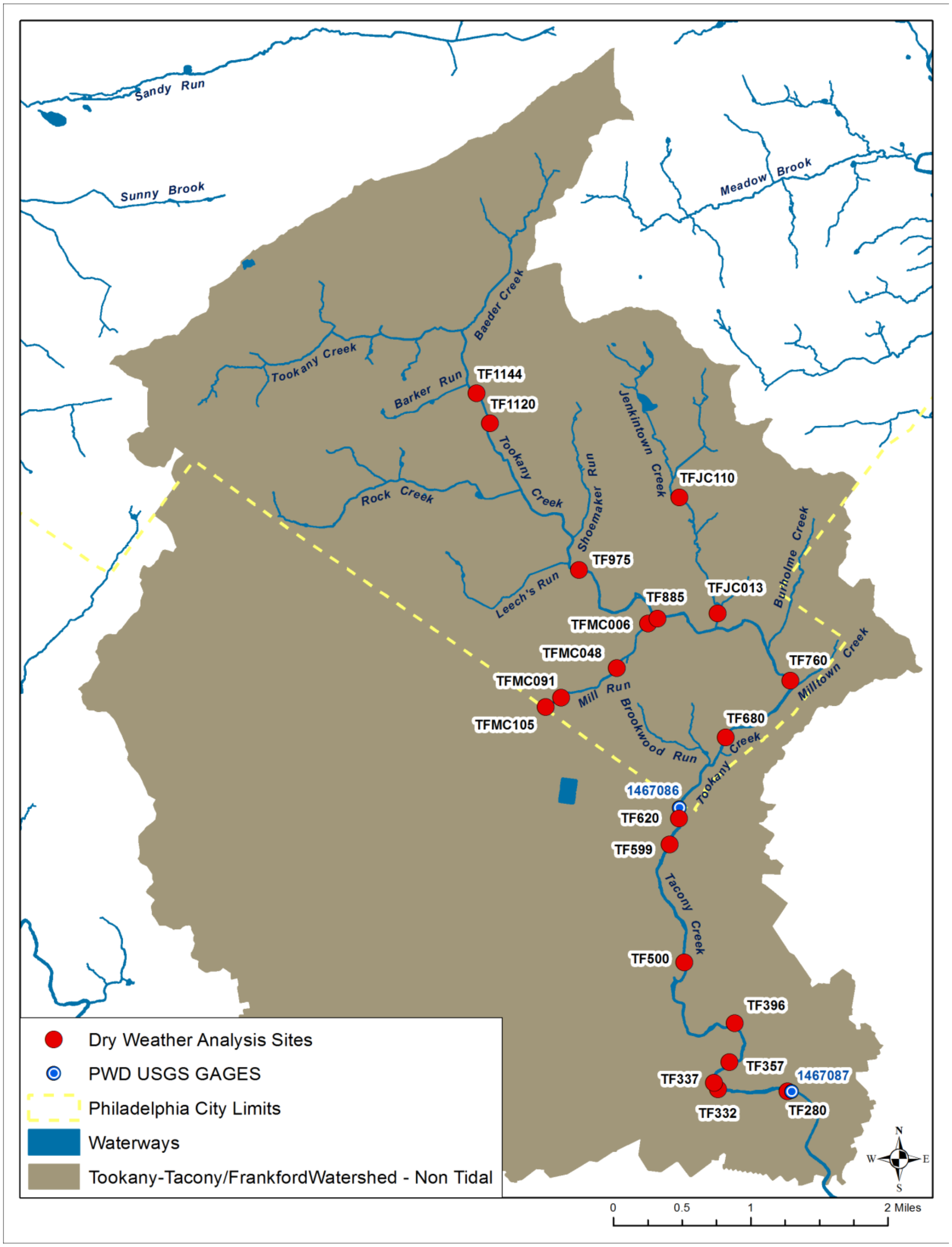

Figure 3-3: TTF Creek Bacteria Model Dry Weather Analysis Sites

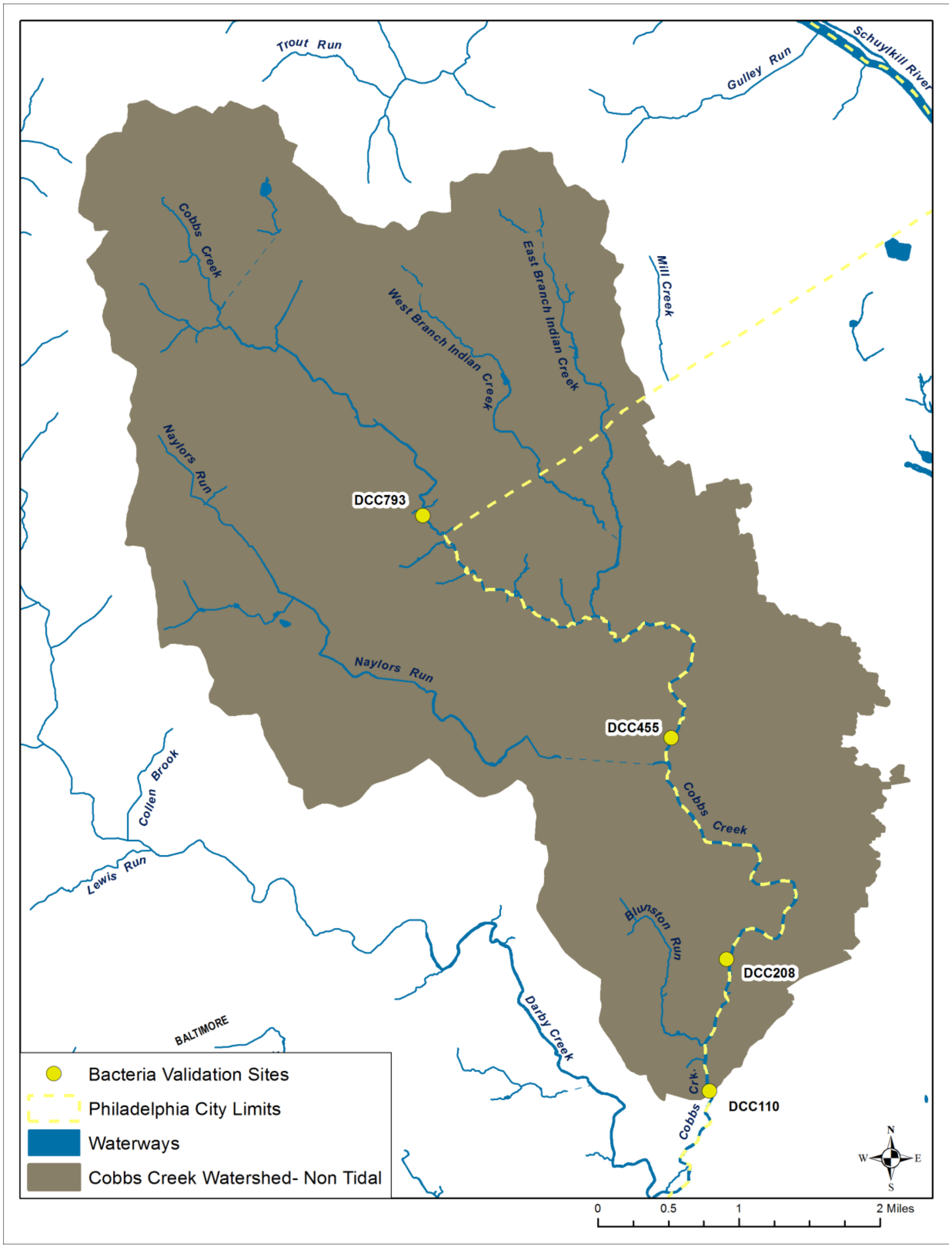

Figure 3-4: Cobbs Creek Bacteria Model Validation Sites

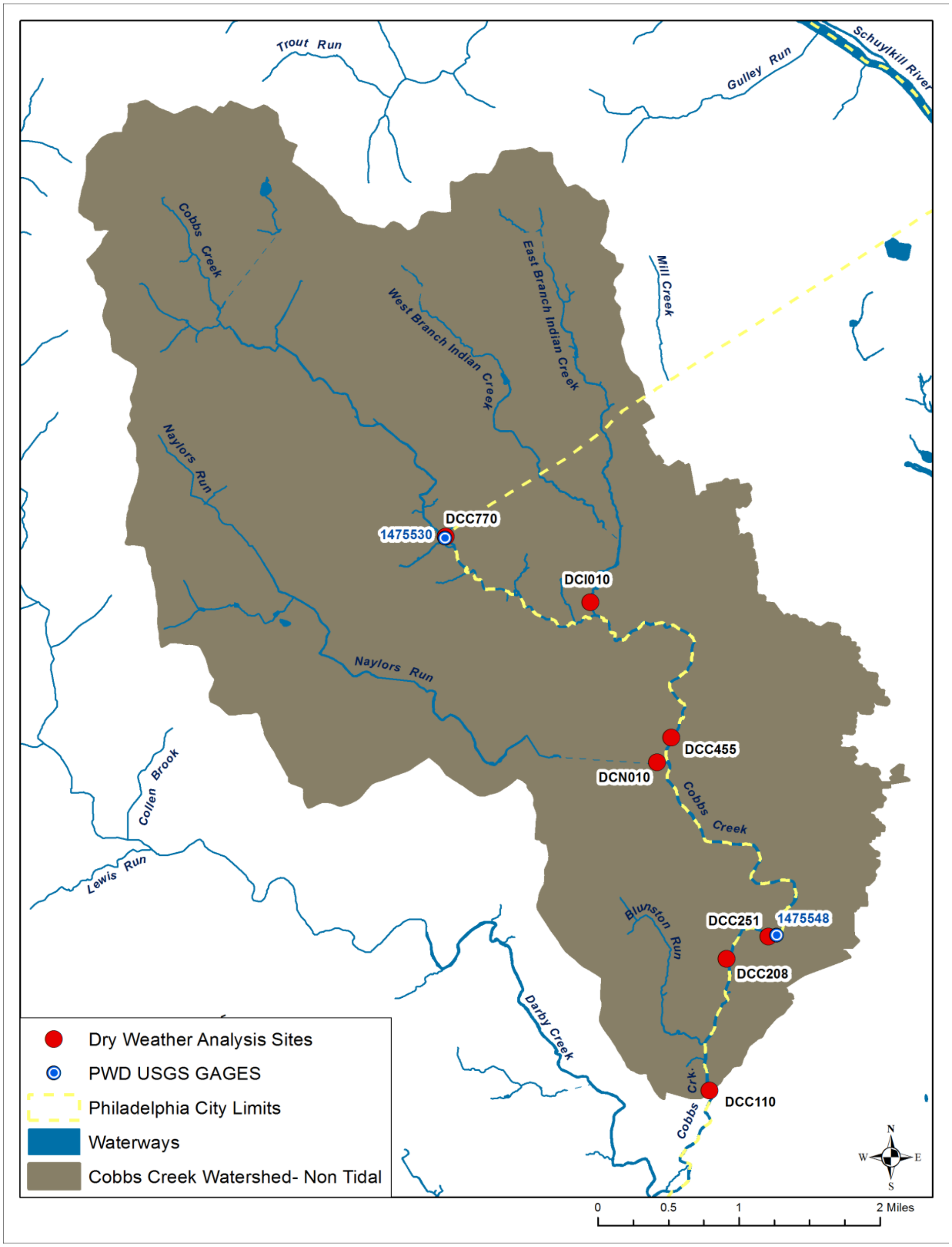

Figure 3-5: Cobbs Creek Bacteria Model Dry Weather Analysis Sites

3.4 Water Quality Model Selection

Key criteria in water quality model selection were:

- Ability to simulate bacteria with first order decay
- Ability to handle rapid temporal changes in concentration common in urban stream environment
- Capability to receive output from US EPA SWMM5
- Model platform that is accepted by modeling community and regulators
- Affordable for public entity

Based on the above criteria, the Water Quality Analysis Simulation Program (WASP) Version 7.5 was selected for this project (Wool *et al.*, 2003). WASP is a publicly available model administered by the US EPA Watershed and Water Quality Modeling Technical Support Center; Version 7.5 was released in 2011. WASP, originally released in 1983, is a dynamic compartment-modeling program for aquatic systems that simulates pollutants in a river network. WASP 7.5 simulates bacteria via its Heat Module (US EPA, 2008). Reaction kinetics are limited to first order decay, which is a common approach for bacteria modeling. The first order decay term lumps all degradation processes (*e.g.*, photolysis, predation, etc.), according to a global (*i.e.*, spatially constant) rate.

The first order decay equation used to simulate bacteria in WASP is:

$C(t)/C(t0) = e^{-k(\Delta t)}$

$C(t)$ = bacteria count at the present time

$C(to)$ = bacteria count at the previous time

K = decay coefficient [1/day]

Δt = change in time

WASP is a widely accepted model that has been used in numerous studies and TMDLs, as described in Section 3.2. It has been coupled with SWMM output for LTPCU models of the Rouge River (Detroit), the White River (Indianapolis), the Merrimack River (Massachusetts), and Butler Creek (Georgia).

WASP can incorporate hydrodynamic output from other models, using a hydrodynamic linkage option. Since SWMM5 is not yet configured to generate the required ".hyd file", extensive work was done by the Water Department and CDM Smith to create software that generates the linkage file from SWMM5 output, as detailed in the next section. Stress testing was also performed to ensure that WASP7.5 could compute stable bacteria output during the types of flashy wet weather events used for water quality model validation, also detailed in the next section.

WASP7.5 CPU run times of the validation events are very fast. A typical event run at a 30 second time step requires 6 seconds on a 3.06 GHz system with 12.0 GB RAM.

3.5 Linkage of Water Quality Model to H&H Model

SWMM4 had a built-in feature to export output to WASP. SWMM5 does not yet have such a feature, so the Water Department and CDM Smith developed an innovative software tool that could accomplish this in SWMM5. The program is based on a user defined segmentation scheme which matches SWMM open channel conduits and boundary inflows to WASP segments. Initial volumes are established for each WASP segment based on flow rate, mean velocity at baseflow conditions, and segment length. Segment volume is then updated in subsequent timesteps according to the continuity equation, such that changes in segment volume reflect the difference between flow in and out of the segment over the timestep. SWMM5 output was printed at a 30 second interval to allow execution of WASP at a 30 second time step.

The water quality model segmentations were designed to avoid large differences between segments in maximum instantaneous volume, to prevent instabilities. Consideration was also given to locations of monitoring sites, tributaries, and CSOs. Since WASP is limited to one boundary per segment, a composite flow-weighted concentration approach was used for each segment receiving multiple boundary inputs.

The TTF Creek water quality model was divided into 22 segments, with an average segment length of 2369 feet. The Cobbs Creek water quality model was divided into 19 segments, including 2 segments each for East and West Indian Creeks. Its average segment length is 3170 feet. Segmentation of each model is shown in Tables 3-4 and 3-5.

Table 3-4: TTF Creek Water Quality Model Segmentation

Segment	Length (ft)	Tributary	Outfall	Validation Monitoring Site
1	3160			TF1120*
2	4477	Rock Creek, Shoemaker Run	T-01 (enters Rock Creek)	
3	5804			TF975
4	3306	Mill Run, Jenkintown Creek		
5	3637	Burholme Creek		
6	2551	Milltown Creek		
7	1896			TF680
8	1769	Brookwood Run		
9	2436			
10	1786			
11	1615		T-03	
12	2341		R-15, T-04, T-05, T-06	
13	1956		T-07, T-08, T-09, T-10	
14	2304		T-11, T-12, T-13	
15	3618			
16	1101			
17	500		T-14	
18	1085			
19	1060		T-15	
20	663		F-03	TF280
21	2857		F-04, F-05, R-18	
22	2195		F-06, F-07	

*TF1120 is directly upstream of Segment 1 and was used for headwater loading.

Table 3-5: Cobbs Creek Water Quality Model Segmentation

	Segment	Length (ft)	Tributary	Outfall	Validation Monitoring Site
East Indian Creek	1	10966		C36,C06, C05, C04A	
	2	3294	West Indian Creek	C07	
West Indian Creek	3	9307			
	4	2907		C02, C01,C35,C34	
Cobbs Creek	5	4190		C31	DCC793*
	6	4202		C32,C33	
	7	3412	East Indian Creek	C37	
	8	3462		C09,C10,R24,C11	
	9	4347		C12	DCC455
	10	2979	Naylors Run	C13	
	11	3306		C14,R01,C15,C16	
	12	2250			
	13	2060		C17,C18	
	14	1631		C19	
	15	1506			
	16	1312			DCC208
	17	1628		C20,C21	
	18	2435		C22	
	19	917		C23	DCC110

*DCC793 is directly upstream of Segment 5 and was used for headwater loading.

The software tool to link SWMM5 and WASP was tested by running a range of loading scenarios with a conservative tracer (*i.e.*, bacteria without decay) in WASP at unsteady flow conditions. Steady inputs and spike inputs of a wide range of concentrations were tested for design storms and the validation storms, to ensure the linkage method yielded stable results during flashy wet weather events. The stable model result of a steady input of 100,000 CFU/100 ml without decay during the 10/14/03 storm is shown in Figure 3-6.

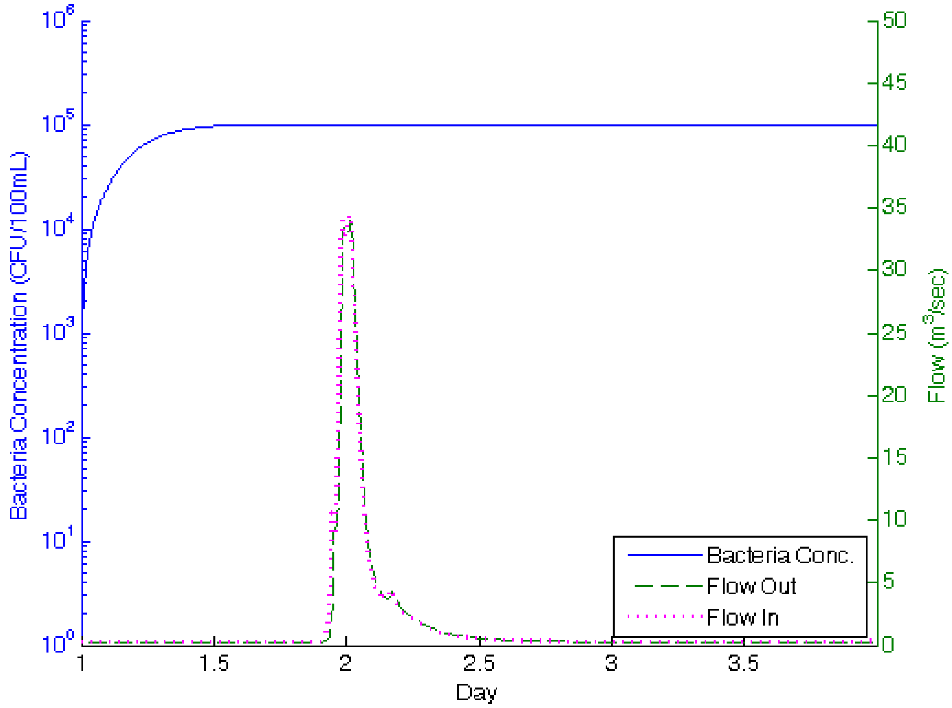

Figure 3-6: Example Output From Stability Test of Steady Input Without Decay During Storm

3.6 Water Quality Model Input Data

3.6.1 Boundary Conditions

The water quality model was designed so that a single WASP segment could receive up to five types of boundary inflows:

- Subcatchment runoff
- CSO
- Baseflow
- Headwaters
- Connecting tributary

Subcatchment runoff concentrations were initially assigned a constant EMC value of 3821 CFU/100mL for fecal coliform and 3298 CFU/100mL for *E. coli*, based on analyses of the Nationwide Urban Runoff Program, USGS, and National Stormwater Quality Database datasets. Through model validation, these concentration values were adjusted upward 25%, which is within an acceptable margin of uncertainty.

Time series of CSO concentrations were based on a flow weighted composite concentration of wastewater and stormwater runoff. Extensive dry weather sampling data from regulators throughout the Water Department combined sewer system indicated a mean fecal coliform concentration of 1,965,114 CFU/100mL in wastewater, with a 91% coefficient of variation. Through model validation, the wastewater component was set to a constant concentration of 3,000,000 CFU/100mL for fecal coliform and 2,610,000 CFU/100mL for *E. coli*. The stormwater component was assigned the adjusted EMC value described above. The partitioning between stormwater and wastewater discharged by the outfall varied throughout the storm. The time varying partitioning was analyzed in SWMM5 to develop the flow weighted composite concentration of wastewater and stormwater runoff that described the overall CSO concentration.

Baseflow was represented as "dry weather flow" in SWMM5. To represent water quality loads, the dry weather flow was assigned a constant bacteria concentration based on analyses of dry weather data from each watershed (Tables 3-6 - 3-9). Data below the detection limit were assumed to equal half the detection limit. The dry weather data was subsetted by recreation season, and further divided between mainstem and tributary sites. The median concentrations determined through these analyses were then applied to the mainstem and tributary segments in the model. Recreation season results were applied to the eleven validation events that occurred between May 1 - Sep 30; the twelfth event (10/14/03) was subject to the results from the non-recreation season analysis.

For the TTF Creek water quality model, monitoring data was available for each validation event at a site (TF1120) located 0.3 miles above the uppermost segment. Event data from TF1120 was used directly as the headwater boundary condition time series.

For the Cobbs Creek water quality model, monitoring data was available at site DCC793 for the three events in 2003. DCC793 is located 0.2 miles above the uppermost Cobbs Creek segment. Event data from DCC793 was used directly as the headwater boundary condition time series for Cobbs, East Indian, and West Indian Creeks. For the July 2000 event which did not have the benefit of data at DCC793, simulated bacteria time series from Naylors Run was applied to the headwater boundaries of Cobbs, East Indian, and West Indian Creeks.

In most cases, connecting tributaries were assigned the headwater site boundary condition time series, under the assumption that the wet weather concentrations observed in the mainstem headwaters would be similar to that of its tributaries. For the TTF Creek water quality model, monitoring data from Events 7 and 8 for Mill Run and Event 8 for Jenkintown Creek were applied directly in the model for those tributaries. Rock Creek, which receives discharge from the T-01 outfall, was simulated for bacteria in SWMM5 without decay as a conservative measure.

Table 3-6: Summary Statistics of Dry Weather Bacteria Samples in Mainstem TTF Creek, 2000-2011

		n sites	n samples	Median	Min.	Max.	10th percentile	90th percentile	Geo. Mean
				CFU/100mL					
Fecal coliform	Recreation season	11	87	730	190	31000	308	3640	927
	Non-recreation season	12	76	210	10	3000	41	880	203
E. coli	Recreation season	8	70	455	20	6000	195	2350	546
	Non-recreation season	9	67	180	10	1800	42	540	165

Table 3-7: Summary Statistics of Dry Weather Bacteria Samples in Tributaries to TTF Creek, 2000-2011

		n sites	n samples	Median	Min.	Max.	10th percentile	90th percentile	Geo. Mean
				CFU/100mL					
Fecal coliform	Recreation season	4	22	515	90	47000	121	25500	936
	Non-recreation season	5	14	95	5	3200	10	905	100
E. coli	Recreation season	3	16	220	80	36000	101	23474	418
	Non-recreation season	9	67	180	10	1800	42	540	165

Table 3-8: Summary Statistics of Dry Weather Recreation Season Fecal Coliform Samples in Mainstem Cobbs Creek, 1999-2011

	n sites	n samples	Median	Min.	Max.	10th percentile	90th percentile	Geo. Mean
			CFU/100mL					
Cobbs Creek	5	46	430	90	4700	183	1276	454
East Indian Creek	1	9	420	110	20000	126	12312	535
Naylors Run	1	8	850	150	2100	261	1860	754

Table 3-9: Summary Statistics of Dry Weather Recreation Season E. coli Samples in Mainstem Cobbs Creek, 1999-2011

	n sites	n samples	Median	Min.	Max.	10th percentile	90th percentile	Geo. Mean
			CFU/100mL					
Cobbs Creek	5	43	300	5	3600	132	1000	340
East Indian Creek	1	9	370	120	16000	152	9980	490
Naylors Run	1	7	700	300	1300	320	1242	677

3.6.2 Parameterization

The main parameter in the WASP bacteria model is the first-order decay rate. Based on values from the literature, a range of 0 to 1 per day was experimented with, as described in the next section.

The effect of loading can also be analyzed in WASP through adjusting the "boundary scale factor". This diagnostic parameter was helpful in comparing the relative sensitivity of the model to decay rate and loading.

3.7 Water Quality Model Sensitivity Analysis

A sensitivity analysis was performed to determine the effect of decay rate and loading on model output. The entire set of twelve validation events for TTF Creek and Cobbs Creek were uniformly exercised with a range of decay rates (0 to 1 d^{-1}) and boundary scale factors (100 to 150%).

Overall, the water quality model was more sensitive to loading than decay rate (Figures 3-7 and 3-8). As expected, decay rate had an inverse effect on peak concentration and duration of recession, while load scaling and output concentration were positively related.

For fecal coliform and *E. coli*, decay rates and load scaling were specified and adjusted to match observed water quality samples. Based on the sensitivity analysis, the decay rate was set to k = 0.5 per day, or 90% decay over 4.6 days, and EMC and wastewater concentrations were each increased above their initial values.

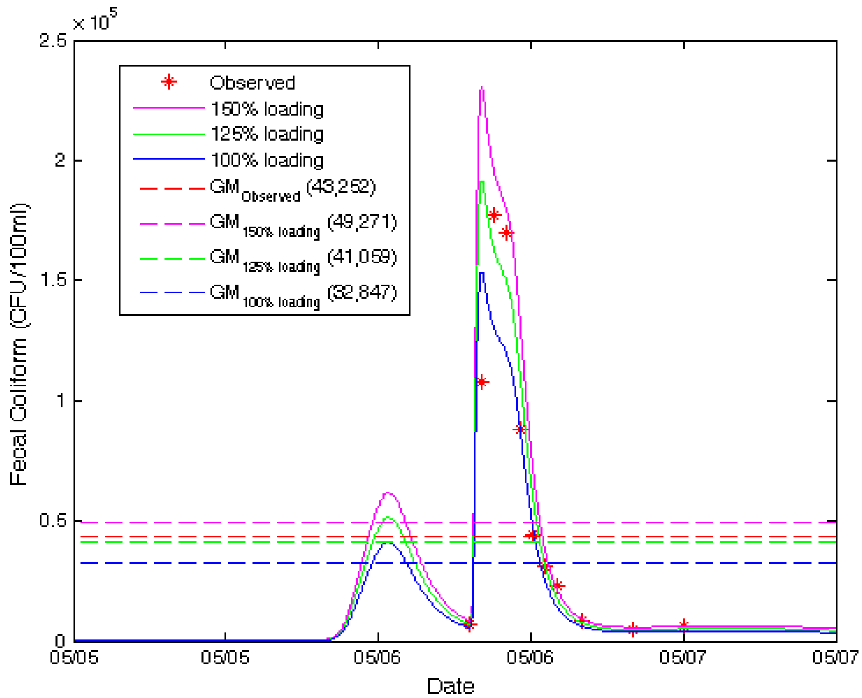

Figure 3-7: Sensitivity of Simulated Bacteria Output to Different Scale Factors for Loading

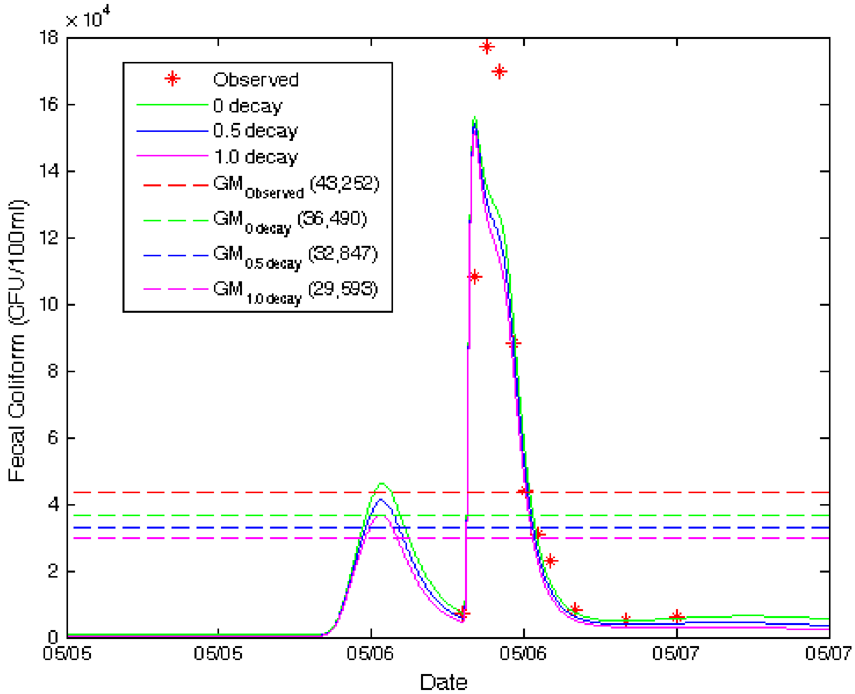

Figure 3-8: Sensitivity of Simulated Bacteria Output to Different Decay Rates

3.8 Water Quality Model Validation

Observed and simulated results were compared for individual events and sites, and at the aggregate level of all sites and events. Thus the model could be comprehensively assessed across a range of event magnitudes and locations, and in aggregate so as to evaluate system-wide performance across the entire time period.

A suite of three plot types were used to evaluate model performance - time series plot, box plot, and scatter plot. The function of each plot type in water quality model evaluation is briefly provided below.

For a given event and site, time series of observed and predicted bacteria were plotted. Time series plots are useful for evaluating model performance in terms of peak concentration, and timing and shape of the ascending and descending limbs of the pollutograph. The effect of the decay rate is apparent on the peak concentration and descending limb.

Time series plots were overlaid with a solid and dashed horizontal line representing observed and predicted event geometric mean, respectively. This offers another way to evaluate model performance at the individual site/event level.

Time series plots are convenient for assessing peak concentrations, but to assess the overall distribution of concentrations throughout a single or multiple events, box plots are more useful. Box plots allow for evaluation of model performance at key percentiles, such as the median, 25th and 75th percentiles. A common convention used here is to depict "whiskers" that extend from the 25th and 75 percentiles to the data nearest to 1.5*Interquartile Range (or IQR) (McGill *et al.*, 1978). Data beyond the whiskers are not necessarily statistical outliers. A few events were such that the IQR was very small, thus yielding short whiskers and numerous data beyond the whiskers.

Box plots were generated for all events at a single site, as well as all events at all sites. Thus the model could be comprehensively assessed at a range of scales.

Scatter plots of event load were developed to compare predicted and observed data. Each scatter plot displays the range of all event loads at a single site. This tool enables quick identification of underprediction or overprediction for event load at the site level. Predicted and observed bacteria loads at each site were calculated for each storm. Observed loads were calculated based on interpolation between measurements, then multiplying the interpolated data by the concurrent predicted flow rate, and then integrating over the event duration to determine the total load.

In addition, key summary statistics of observed and predicted data were tabulated for each event.

3.8.1 TTF Creek

The observed data from the 8 events in 2003-2004 were used to validate the water quality model. A total of 173 samples at 3 sites were used to compare predicted and observed data. In addition, a total of 96 samples at site TF1120 were used to load the uppermost segment of the water quality model for validation events, with linear interpolated time series based on observed data. Based on results of the sensitivity analysis, a first-order decay coefficient of 0.5 day^{-1} was applied to the bacteria concentrations in TTF Creek for all validation events. EMC and wastewater concentrations of fecal coliform were assumed to be 4776 and 3,000,000 CFU/100mL, respectively. EMC and wastewater concentrations of *E. coli* were assumed to be 4123 and 2,610,000 CFU/100mL, respectively.

Wet weather fecal coliform and *E.coli* observed data were highly correlated ($r^2 = 0.95$), and any given fecal coliform validation plot appeared similar to the corresponding *E. coli* plot. Therefore plots of fecal coliform are referred to in this section with the understanding the same pattern occurred for *E. coli* unless otherwise noted. All *E. coli* plots are shown in Appendix C.

Water quality model validation sites

Observed wet weather data from three monitoring were used to validate the TTF Creek water quality model (Figure 3-2). TF975 is located in Montgomery County, downstream of the Rock Creek tributary which receives discharge from the T-01 outfall. TF680 is located in Montgomery County, downstream of the Milltown Creek tributary. TF280 is located in Philadelphia at Castor Avenue, downstream of several CSOs and therefore bacteria concentrations at TF280 are more impacted by CSOs than stormwater runoff. The opposite trend applies to TF975 and TF680.

Results and discussion

Event scale

Time series plots indicated the water quality model was sometimes highly capable of matching observed data at upstream and downstream locations. The results displayed in Figures 3-9 and 3-10 show excellent replication of the timing of the pollutograph. Although the peak concentrations were not exactly simulated, the predicted event geometric means were very similar to observed values.

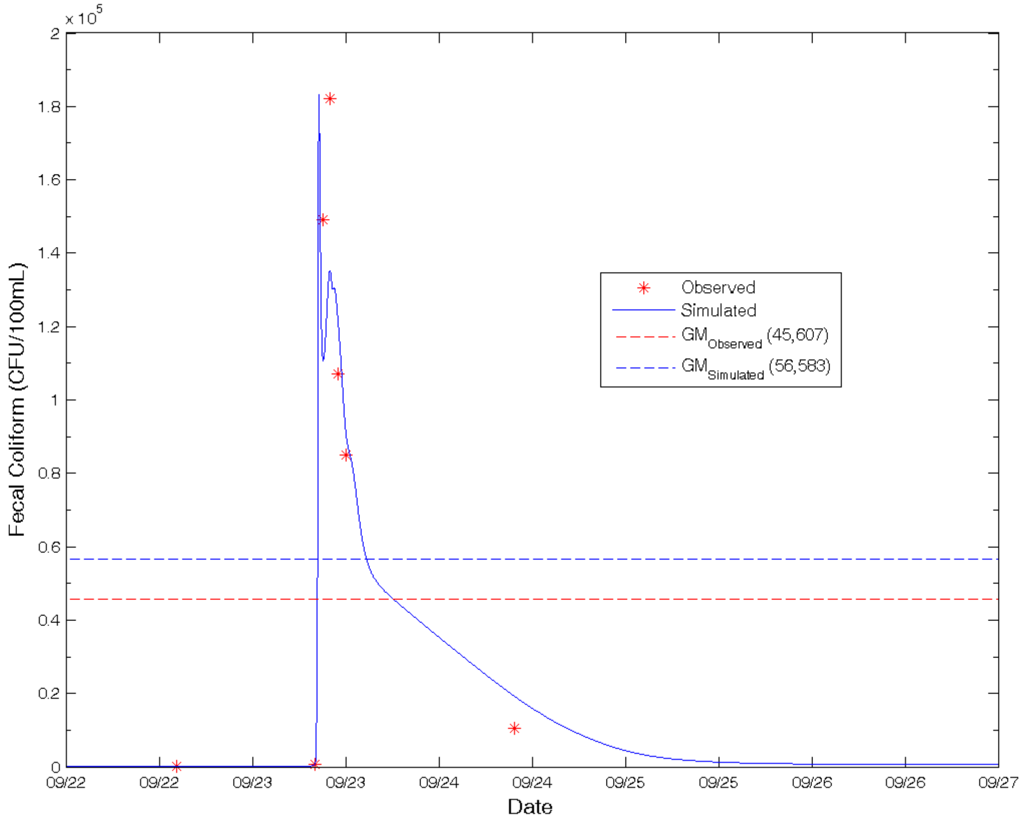

Figure 3-9: Observed and Simulated Fecal Coliform Concentration at Site TF280 During 9/23/03 Storm

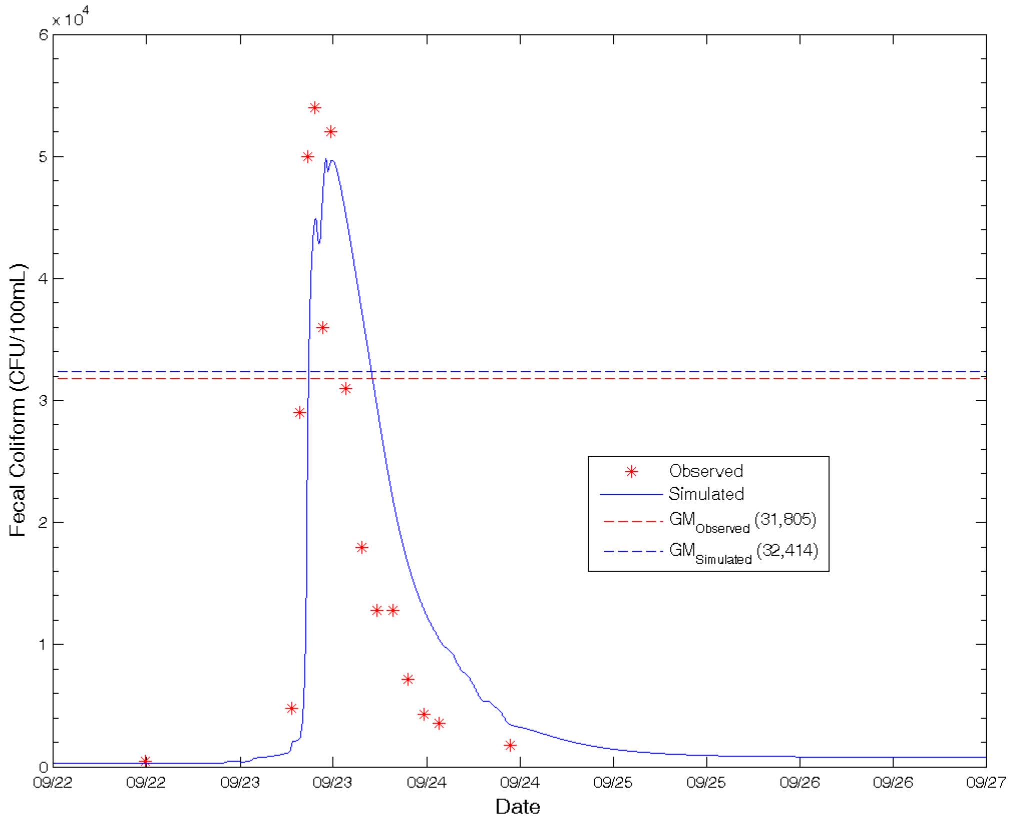

Figure 3-10: Observed and Simulated Fecal Coliform Concentration at Site TF975 During 9/23/03 Storm

In certain cases where the timing of the predicted pollutograph was not quite as good, there was still good to excellent agreement between observed and predicted event geometric means (Figures 3-11, 3-12, 3-13). In other instances, the timing of the pollutograph was good however the model underpredicted peak concentrations by ~50% (Figure 3-14). Examples of the poorest results can be seen in Figures 3-15 and 3-16, with three to fourfold underpredictions of peak concentration.

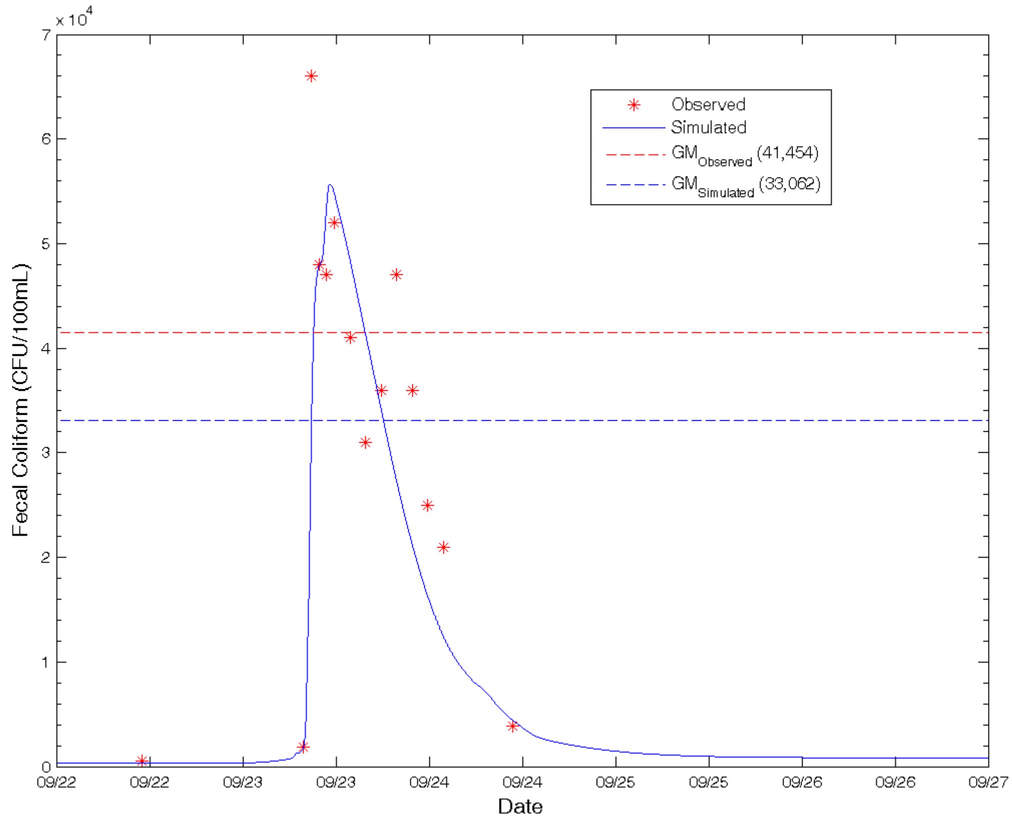

Figure 3-11: Observed and Simulated Fecal Coliform Concentration at Site TF680 During 9/23/03 Storm

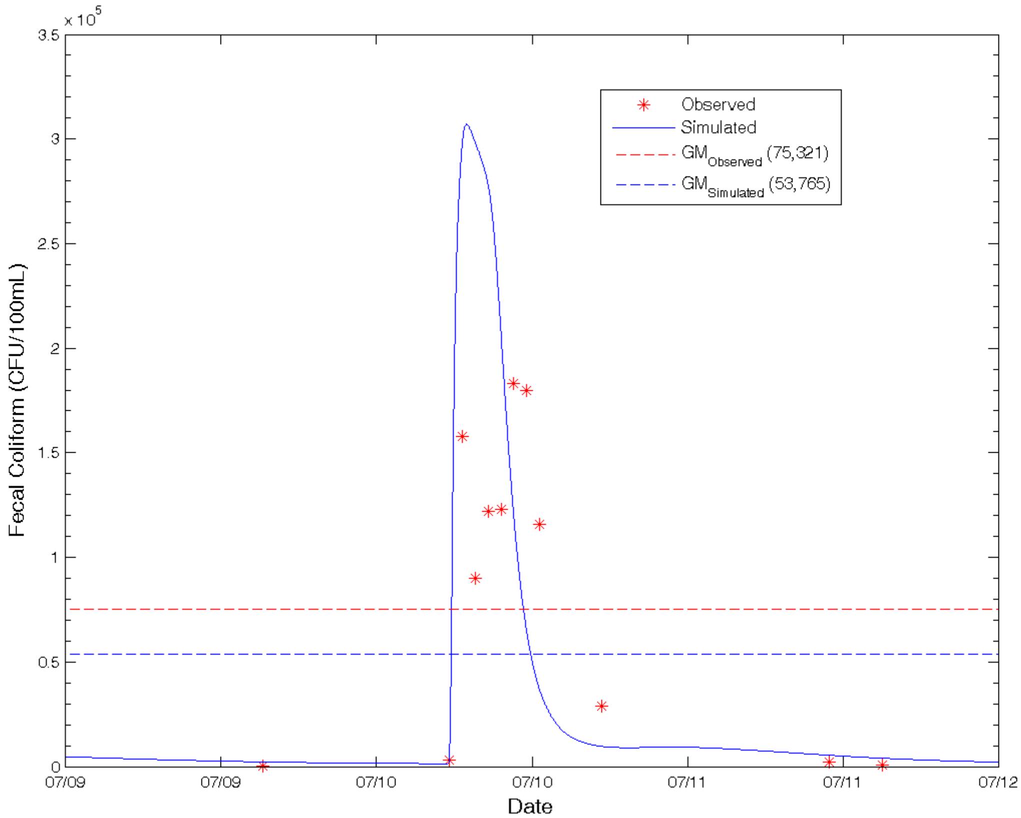

Figure 3-12: Observed and Simulated Fecal Coliform Concentration at Site TF280 During 7/10/03 Storm

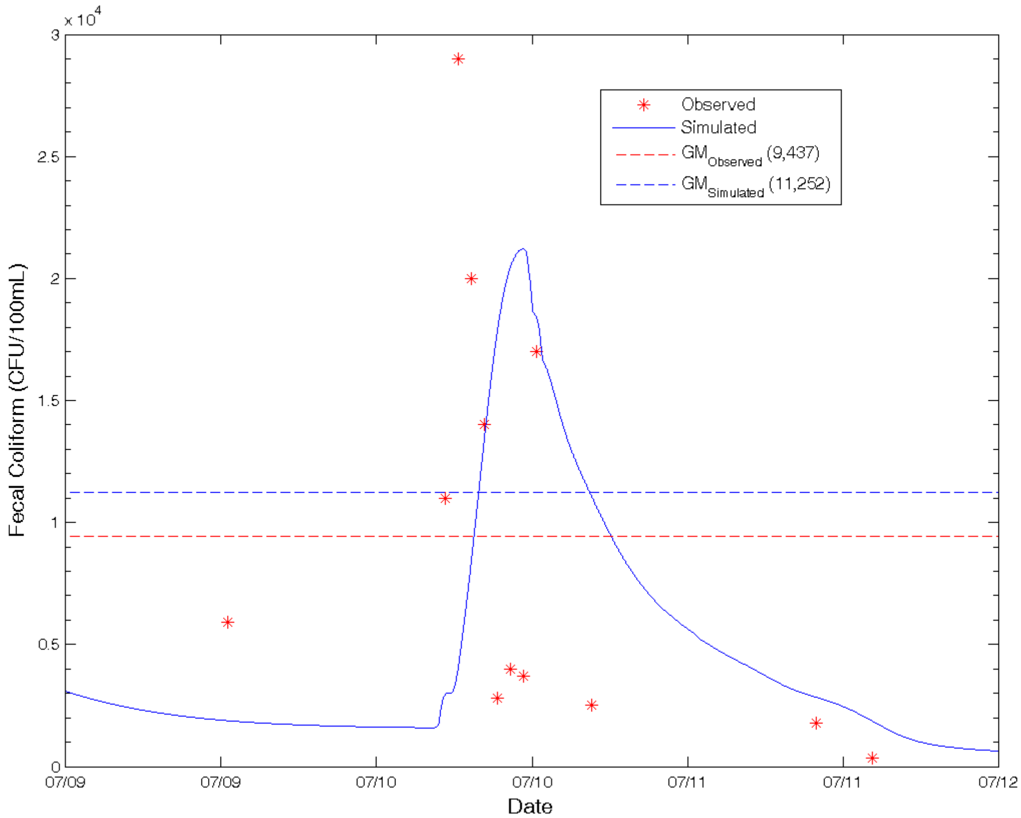

Figure 3-13: Observed and Simulated Fecal Coliform Concentration at Site TF975 During 7/10/03 Storm

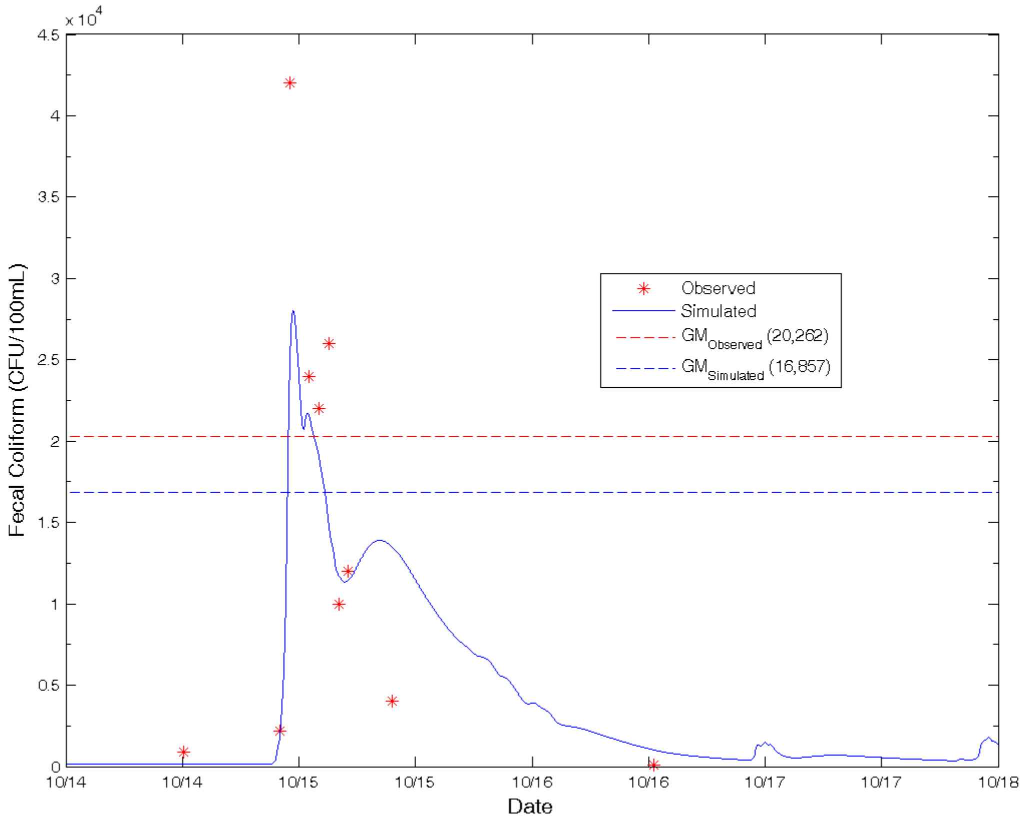

Figure 3-14: Observed and Simulated Fecal Coliform Concentration at Site TF975 During 10/14/03 Storm

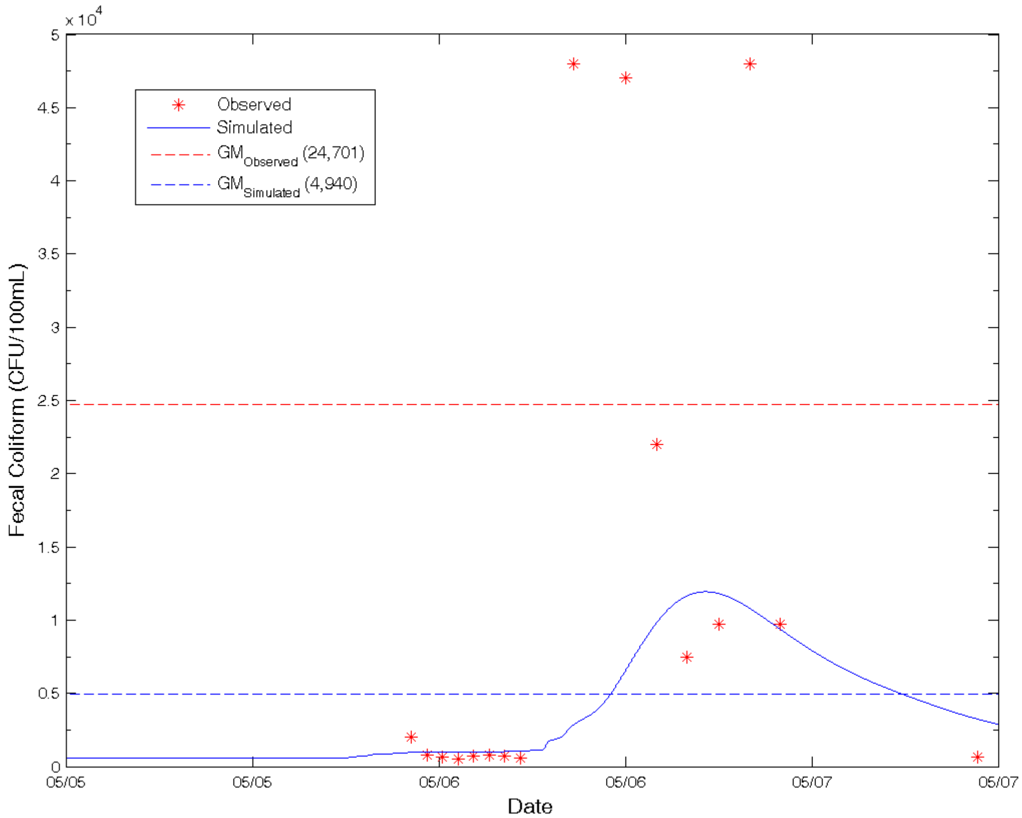

Figure 3-15: Observed and Simulated Fecal Coliform Concentration at Site TF680 During 5/6/03 Storm

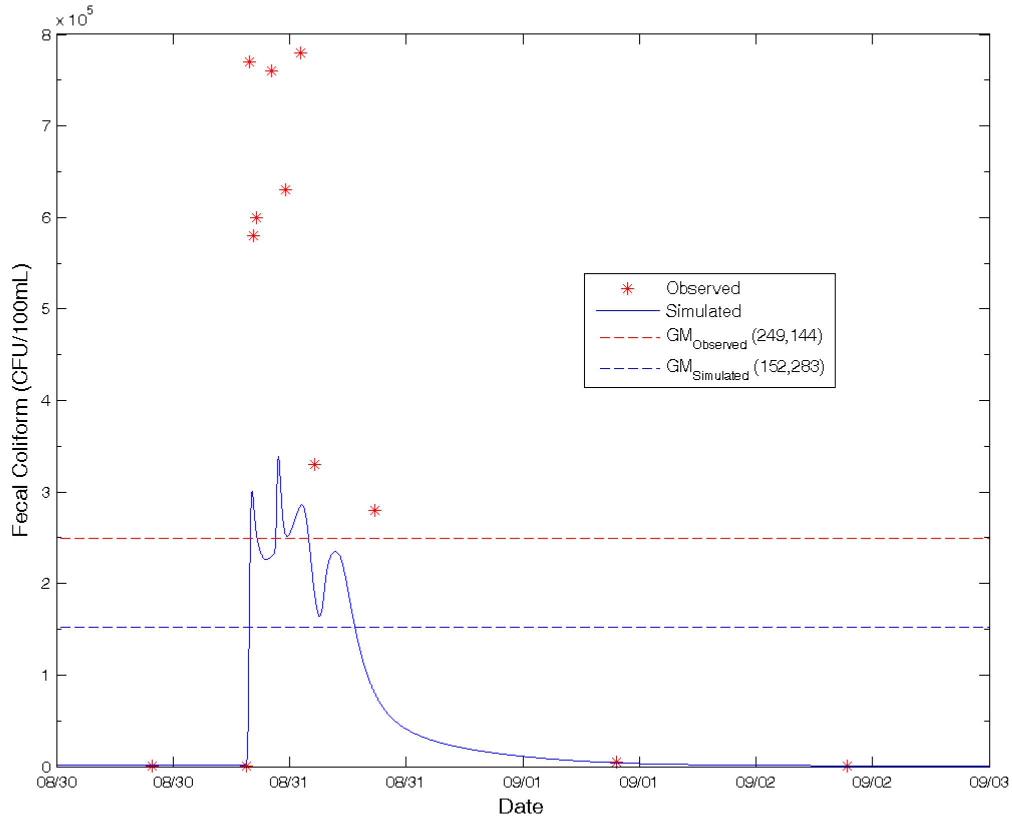

Figure 3-16: Observed and Simulated Fecal Coliform Concentration at Site TF280 During 8/30/04 Storm

Results for the two largest validation events in terms of rainfall (5/7/03 and 10/14/03) indicate adequate model performance at each site (Figures 3-17 - 3-21; 3-14) and represent the midlevel range of performance for the overall set of TTF water quality model time series plots.

There are several sources of uncertainty that could impact model results. Incomplete knowledge regarding the pervious and impervious areas of the contributing watershed, stream bathymetry, and precipitation data could affect the underlying H&H model. Water quality predictions can be affected by uncertainty in the assumed stormwater runoff and wastewater concentrations. Observed data regarding flow rate at the USGS gages, particularly at high flow rates, and bacteria data collected from automated samplers are subject to uncertainty in terms of magnitude and precise timestamp. When all of these sources of uncertainty are combined, the magnitude of under or overprediction seen in the time series plots would likely yield an overlap between predicted and observed margins of uncertainty.

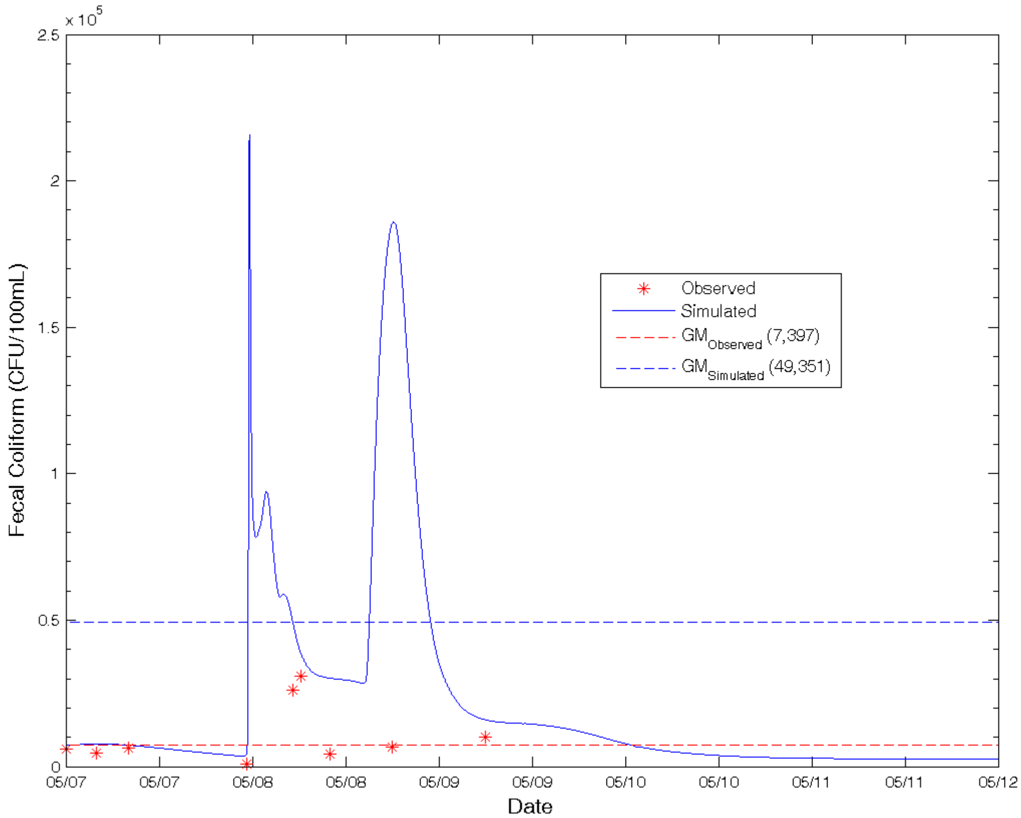

Figure 3-17: Observed and Simulated Fecal Coliform Concentration at Site TF280 During 5/7/03 Storm

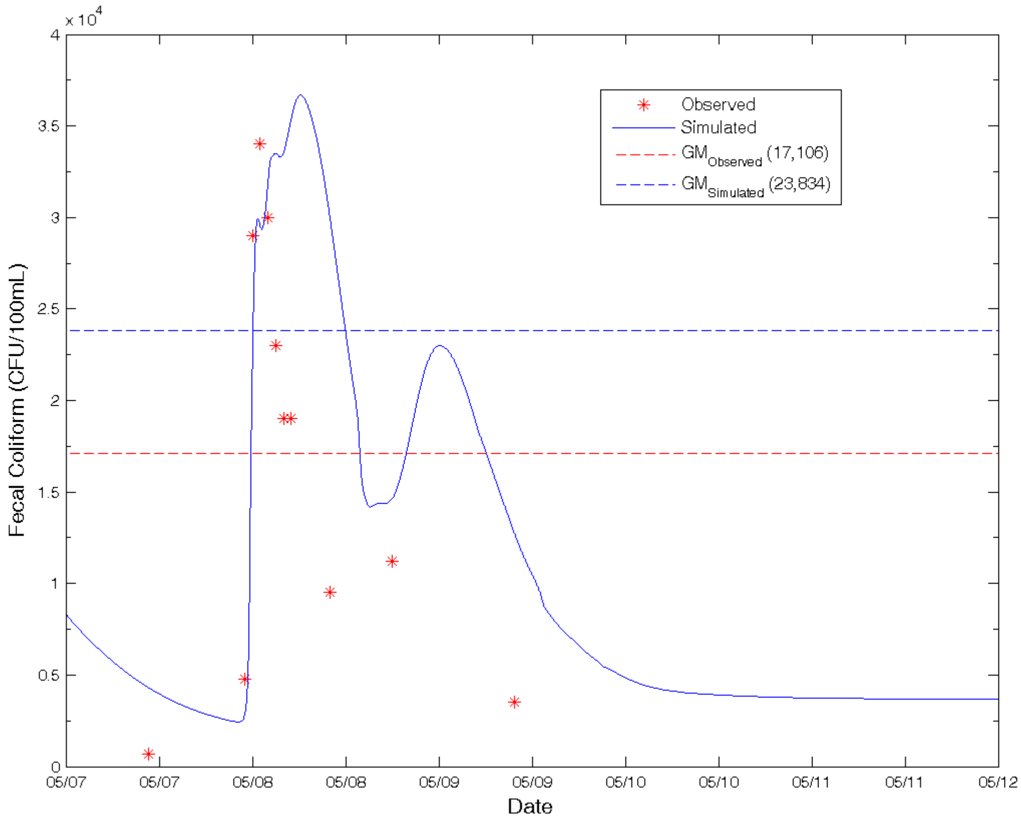

Figure 3-18: Observed and Simulated Fecal Coliform Concentration at Site TF680 During 5/7/03 Storm

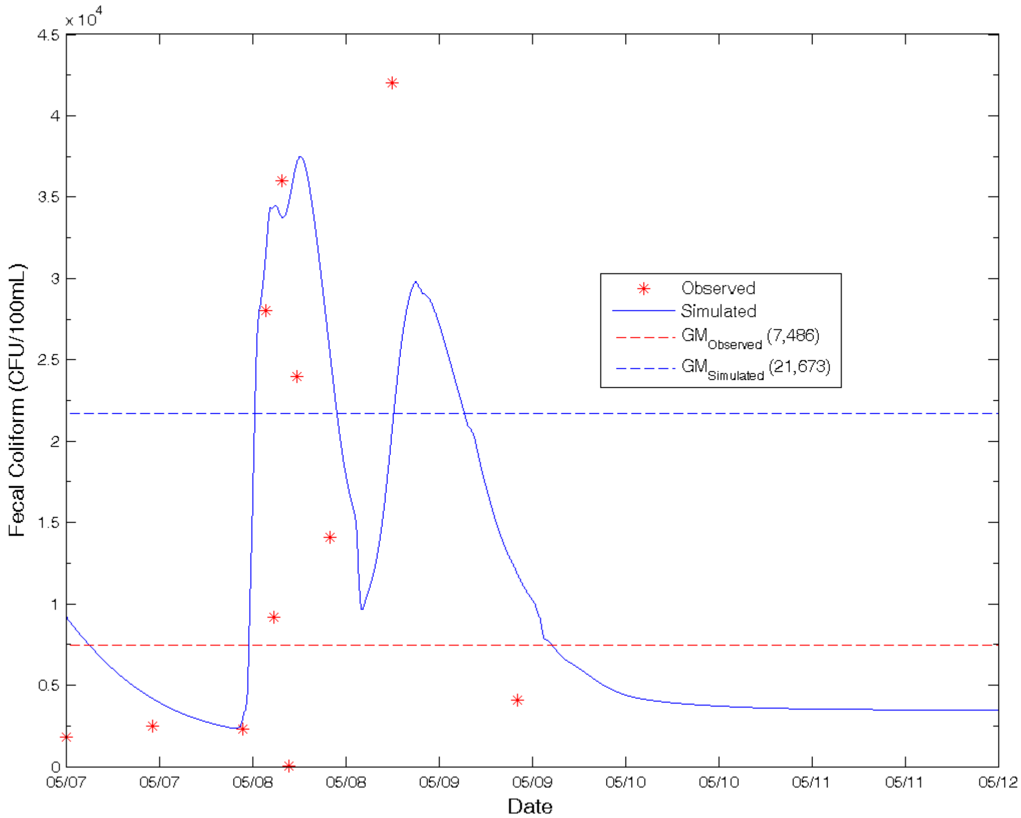

Figure 3-19: Observed and Simulated Fecal Coliform Concentration at Site TF975 During 5/7/03 Storm

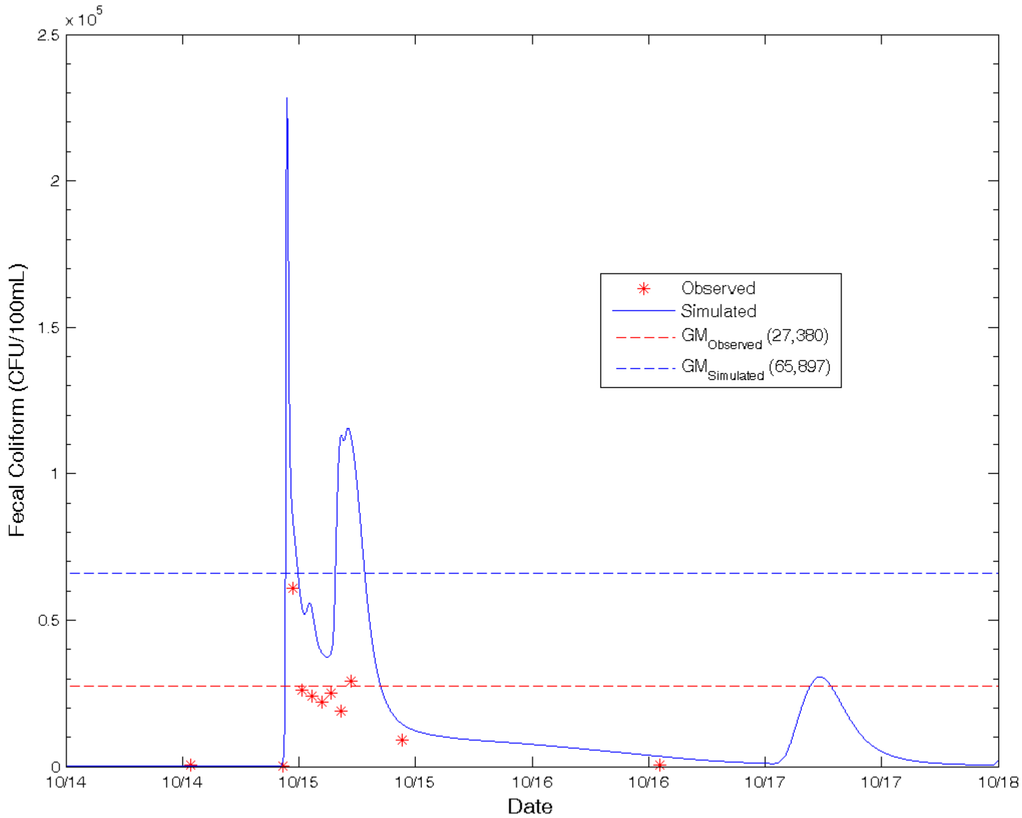

Figure 3-20: Observed and Simulated Fecal Coliform Concentration at Site TF280 During 10/14/03 Storm

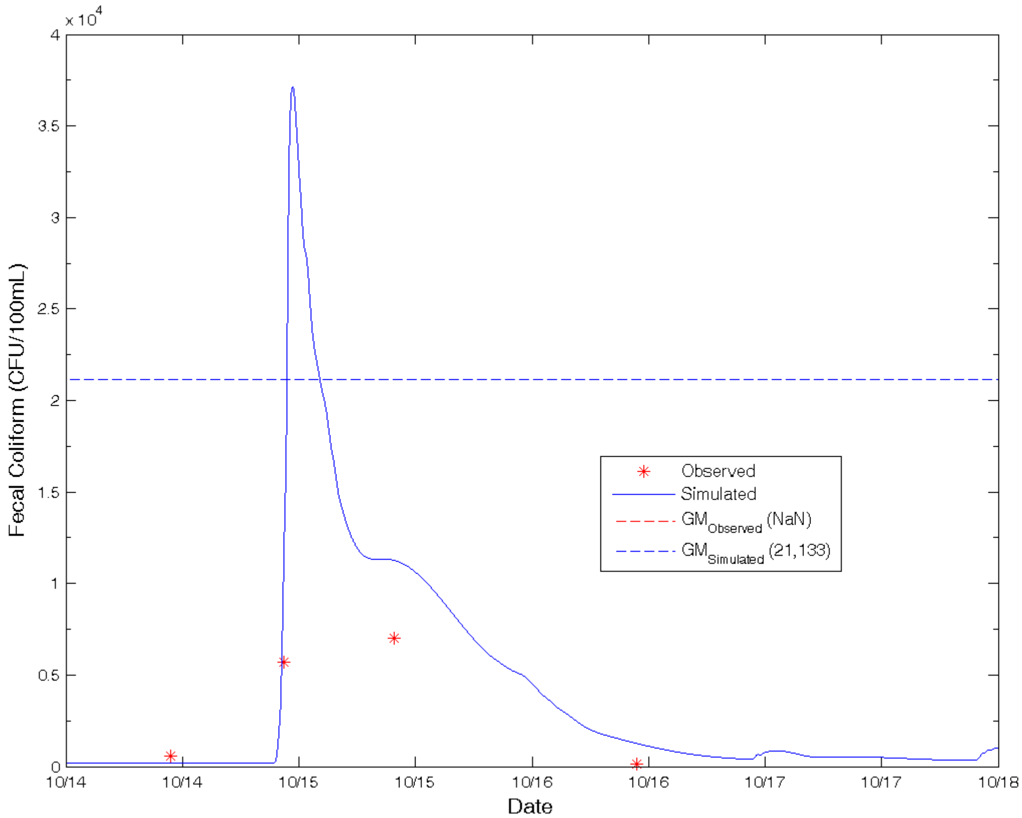

Figure 3-21: Observed and Simulated Fecal Coliform Concentration at Site TF680 During 10/14/03 Storm

Aggregate scale

An aggregate scale is more appropriate than an event scale to evaluate bacteria model performance. Uncertainties present at the event scale - in both predicted and observed data - might skew interpretation of a single event at a single site, but have less potential to bias model evaluation at the aggregate scale. Furthermore, the bacteria water quality standard emphasizes an entire season over a single storm, lending support to model evaluation at the aggregate scale.

Box plots indicate that when all events are aggregated for a single site (Figures 3-22, 3-23,3-24), the water quality model performed well matching observed data across a range of storm sizes and instream concentrations. That this pattern was seen in TF280, TF680 and TF975 suggests the water quality model can adequately represent impacts in both the combined and separate sewer service areas of TTF Creek Watershed.

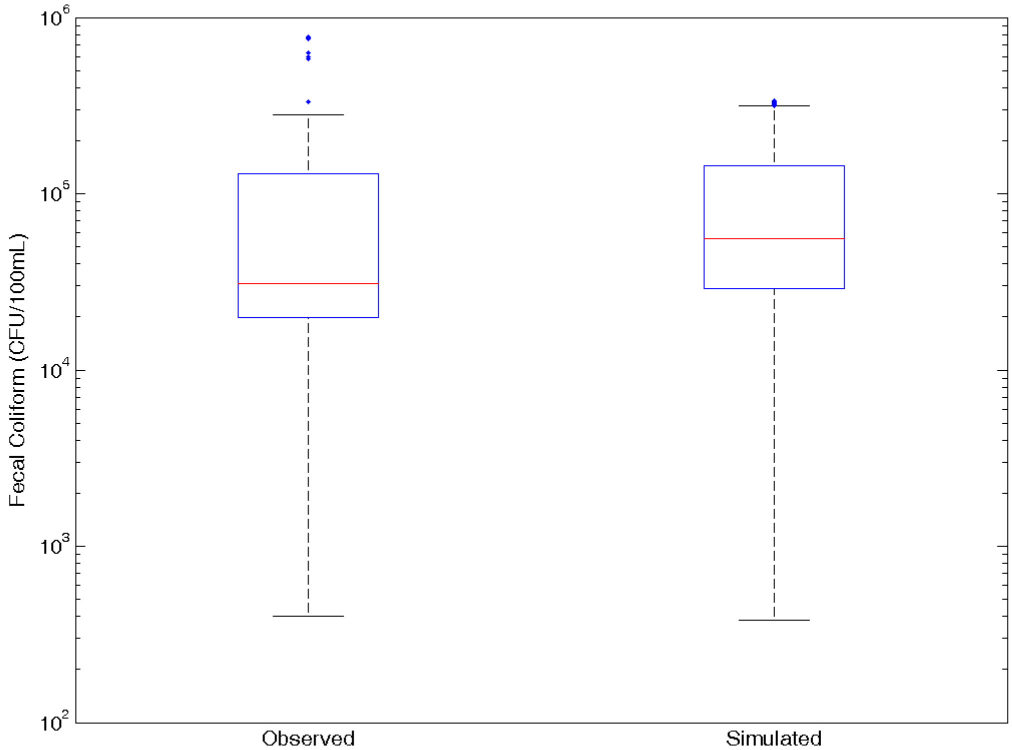

Figure 3-22: Box Plot of Observed and Simulated Fecal Coliform Concentration Data From All Water Quality Model Validation Storms at Site TF280

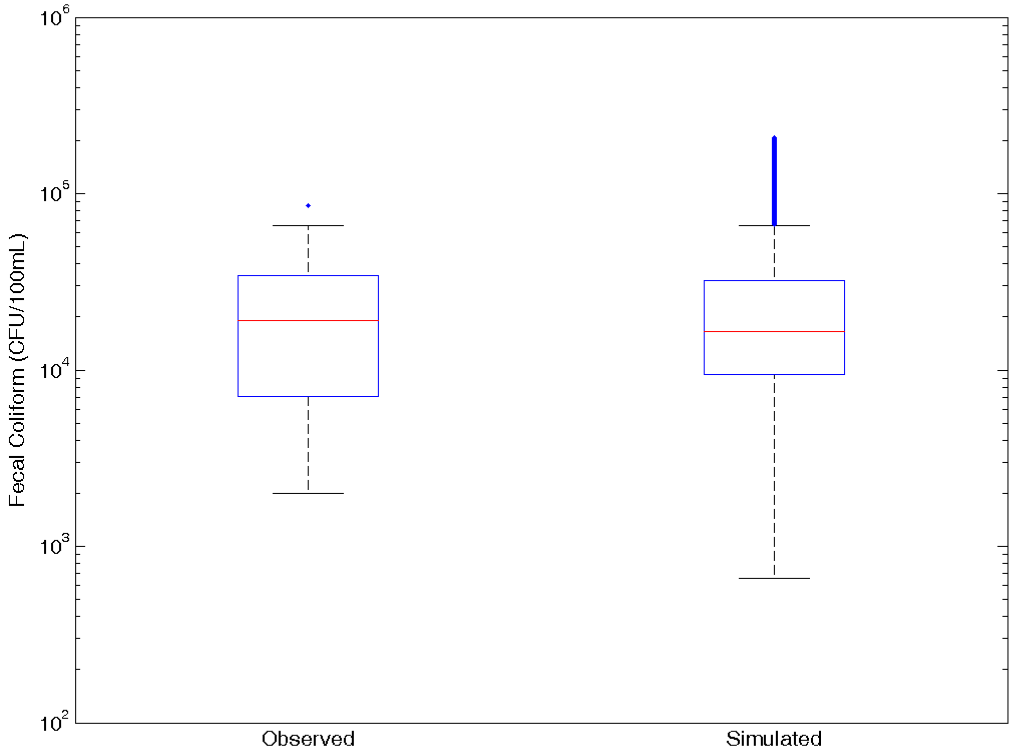

Figure 3-23: Box plot of Observed and Simulated Fecal Coliform Concentration Data From All Water Quality Model Validation Storms at Site TF680

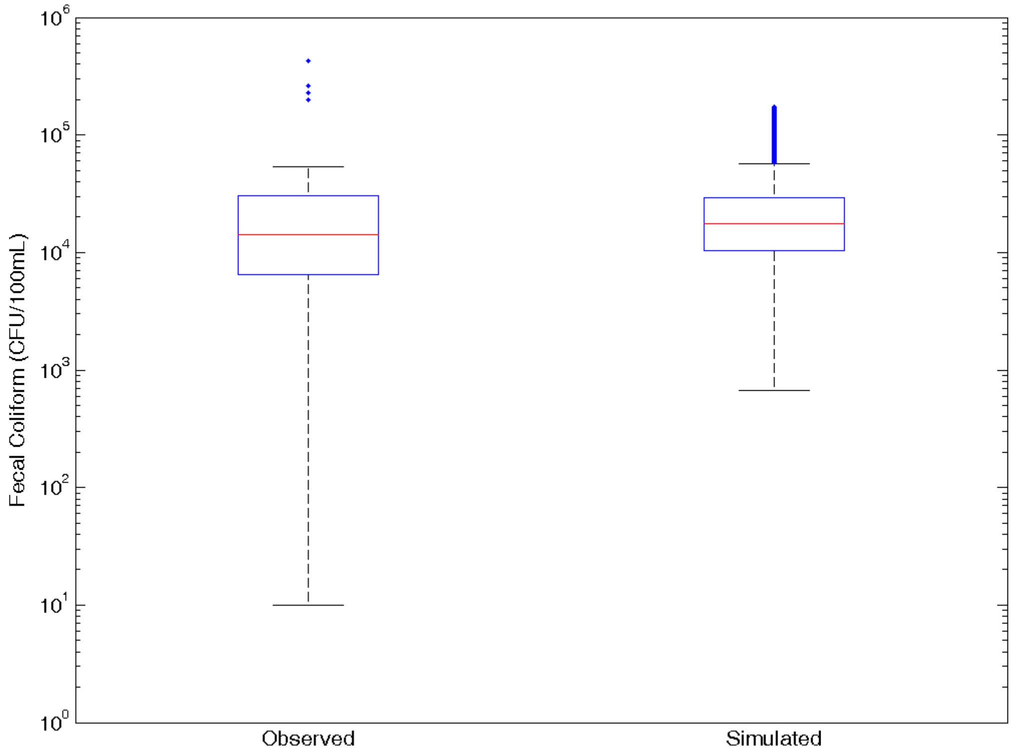

Figure 3-24: Box Plot of Observed and Simulated Fecal Coliform Concentration Data From All Water Quality Model Validation Storms at Site TF975

A box plot of all events aggregated for all sites (Figure 3-25) indicates the water quality model performed very well on a system-wide basis in simulating in-stream concentration.

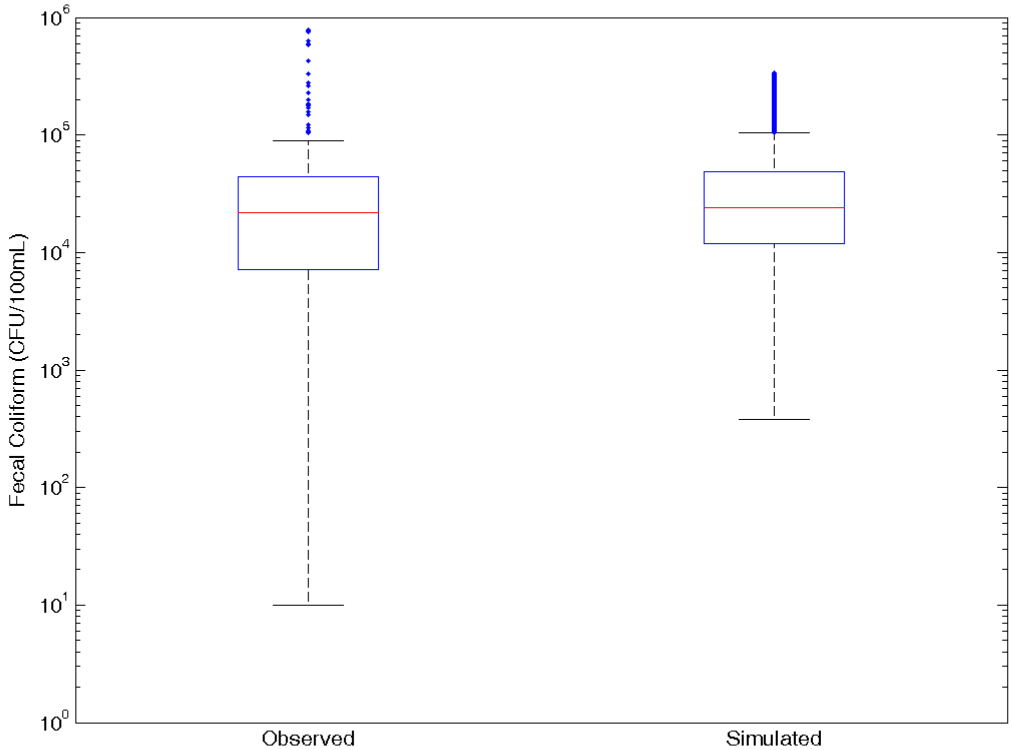

Figure 3-25: Box Plot of Observed and Simulated Fecal Coliform Concentration Data From All Water Quality Model Validation Storms at All Wet Weather Monitoring Sites (TF280, TF680, and TF975)

Scatter plots of predicted and observed event loads at each site show strong agreement at sites TF680 and TF975 (Figures 3-26, 3-27, 3-28). At site TF280, the variability is greater, with twofold overprediction of the 10/14/03 event load, and twofold underprediction of the 8/30/04 event load. The discrepancy at site TF280 for the 10/14/03 event load is due to a simulated peak concentration which was not observed (Figure 3-20); it is possible a peak did occur that was not sampled in the duration between automated collection times. The discrepancy at site TF280 for the 8/30/04 event load is most likely due to underprediction of peak flow in the Tributary H&H Model (Appendix C, Section 2). Four of the seven events plotted for site TF280 fall near the 1:1 line. The TF280 7/7/04 event load is not plotted because most of the observed data was right censored. Note that observed event loads are based on limited and interpolated data.

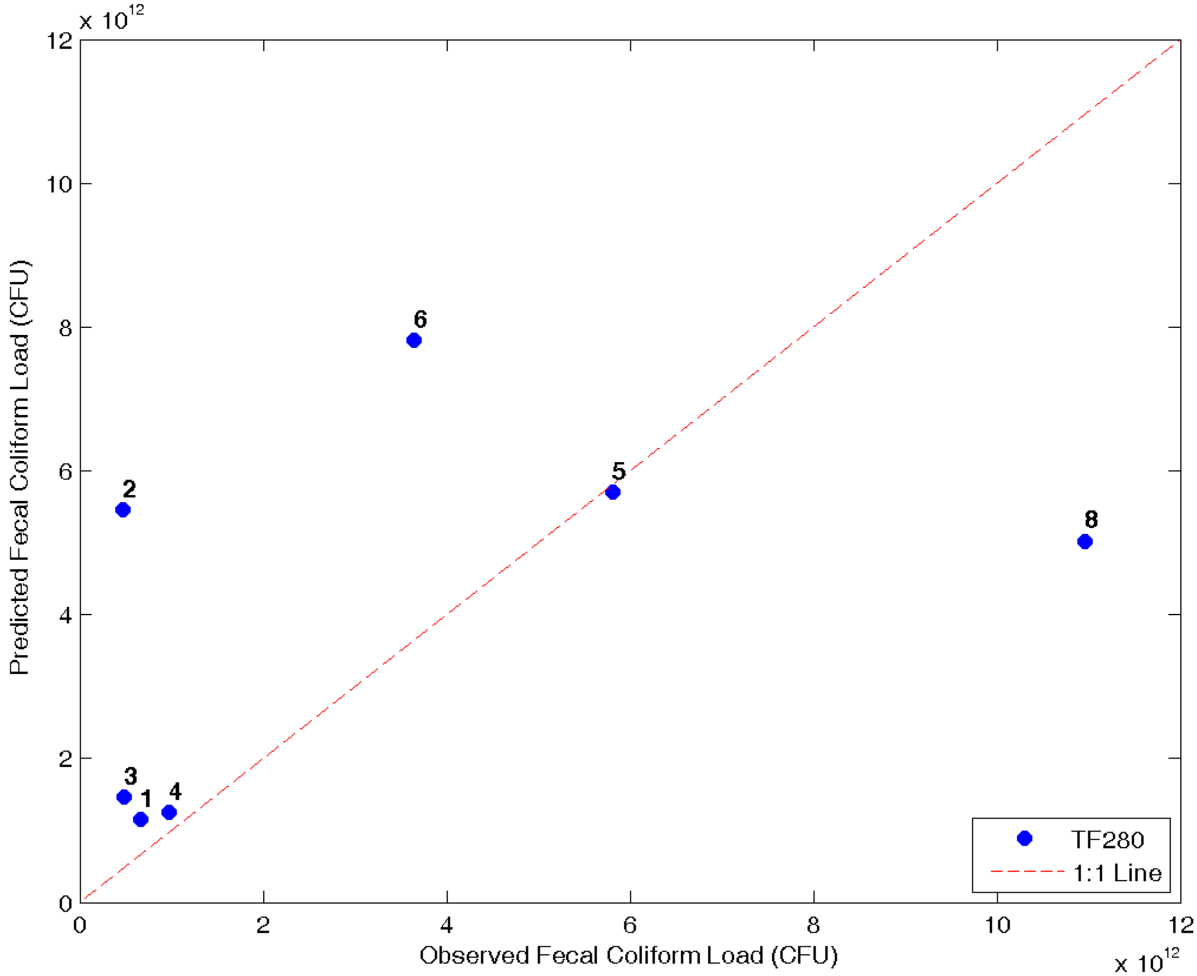

Figure 3-26: Scatter plot of Predicted and Observed Fecal Coliform Event Load at Site TF280

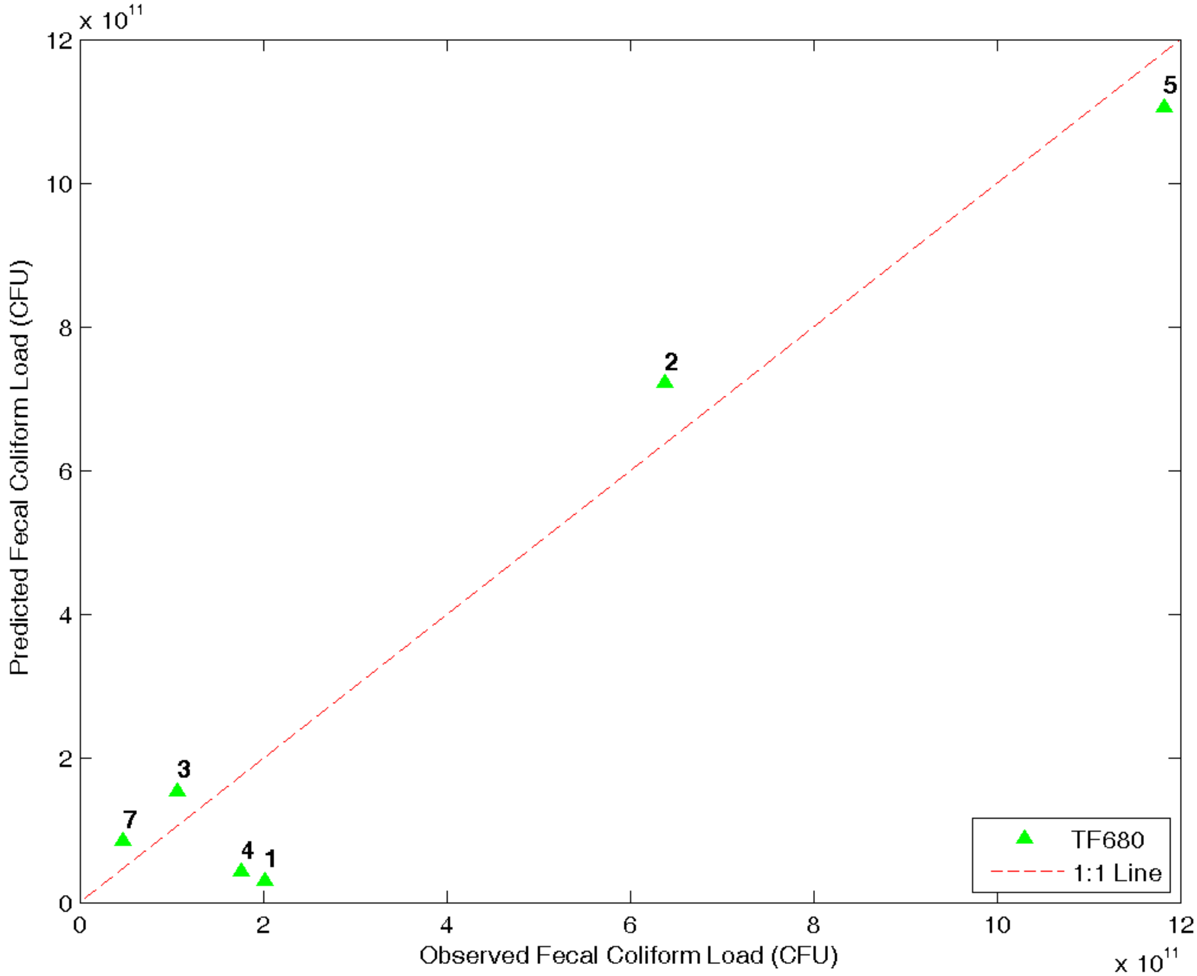

Figure 3-27: Scatter Plot of Predicted and Observed Fecal Coliform Event Load at Site TF680

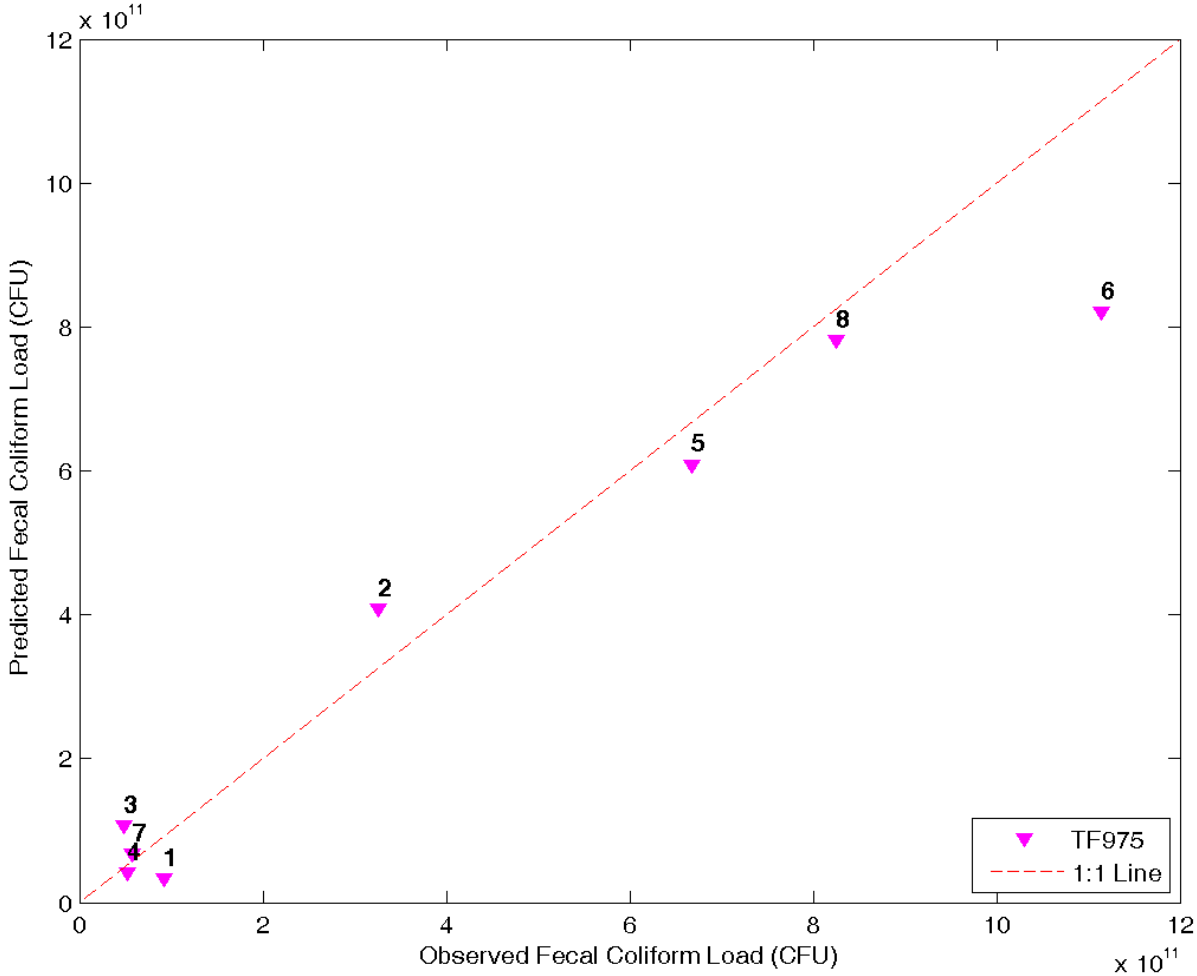

Figure 3-28: Scatter Plot of Predicted and Observed Fecal Coliform Event Load at Site TF975

3.8.2 Cobbs Creek

The observed data from the 4 events in 2000 and 2003 were used to validate the water quality model. A total of 52 samples at 3 sites were used to compare predicted and observed data. In addition, a total of 34 samples in 2003 at site DCC793 were used to load the uppermost segments (for Cobbs, East Indian and West Indian Creeks) of the water quality model for the 2003 validation events, with linear interpolated time series based on observed data. The first order decay rate, EMC and wastewater concentration values were kept consistent with the TTF Creek water quality model.

As with TTF Creek, wet weather fecal coliform and *E. coli* observed data were highly correlated (r^2=0.94), therefore plots of fecal coliform are referred to with the understanding the same pattern occurred for *E. coli* unless otherwise noted. All *E. coli* plots are shown in Appendix D.

Water quality model validation sites

Observed wet weather data from three monitoring sites, all located on Cobbs Creek in Philadelphia, were used to validate the Cobbs Creek water quality model (Figure 3-4).

DCC455 is located in the middle of the water quality model extent, just upstream of the confluence with Naylors Run. DCC208 is located 0.4 miles downstream of the Mt. Moriah USGS gage 01475548. DCC110 is located at the Woodland Avenue dam at the downstream end of the water quality model extent.

Results and discussion

Event scale

Overall, the Cobbs Creek bacteria model did not perform as well as the Tacony Creek bacteria model. This is primarily due to the lack of an operating USGS gage during the period of the water quality model validation events, which hindered the SWMM effort and left uncertainty as to the accuracy of the Tributary H&H Model for these events. The Cobbs Creek bacteria model was also challenged by being exercised against a smaller number of validation events and wet weather monitoring sites, compared to the Tacony Creek bacteria model.

Nevertheless, time series plots indicated the bacteria model performed adequately at the downstream locations DCC208 and DCC110 in most cases (Figures 3-29 through 3-31). It tended to underpredict observed concentrations at the upstream site DCC455 (Figure 3-32), notwithstanding the numerous sources of uncertainty described in Section 3.9.

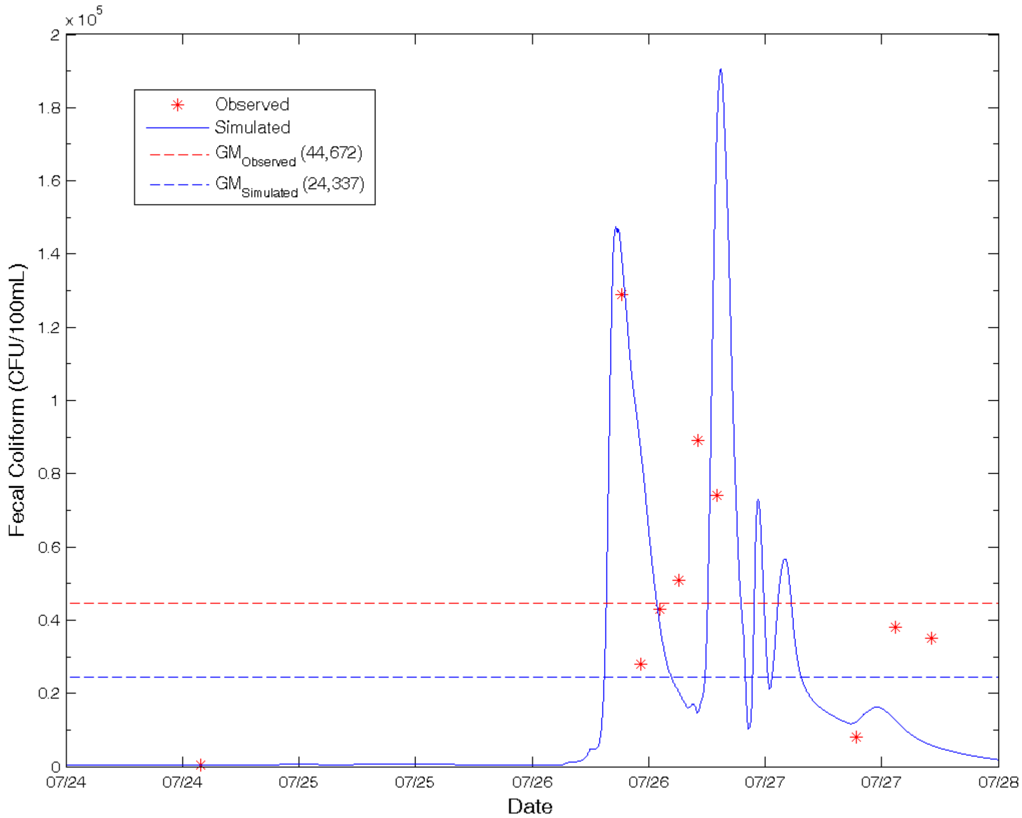

Figure 3-29: Observed and Simulated Fecal Coliform Concentration at Site DCC110 During 7/26/00 Storm

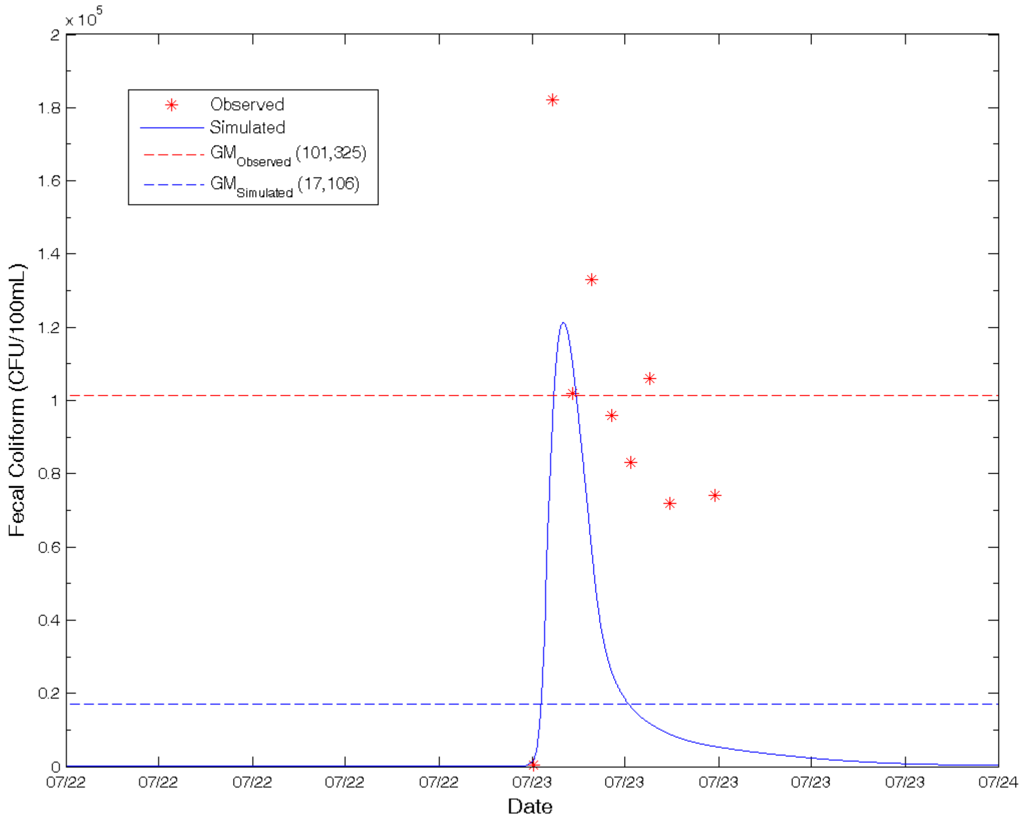

Figure 3-30: Observed and Simulated Fecal Coliform Concentration at Site DCC208 During 7/23/03 Storm

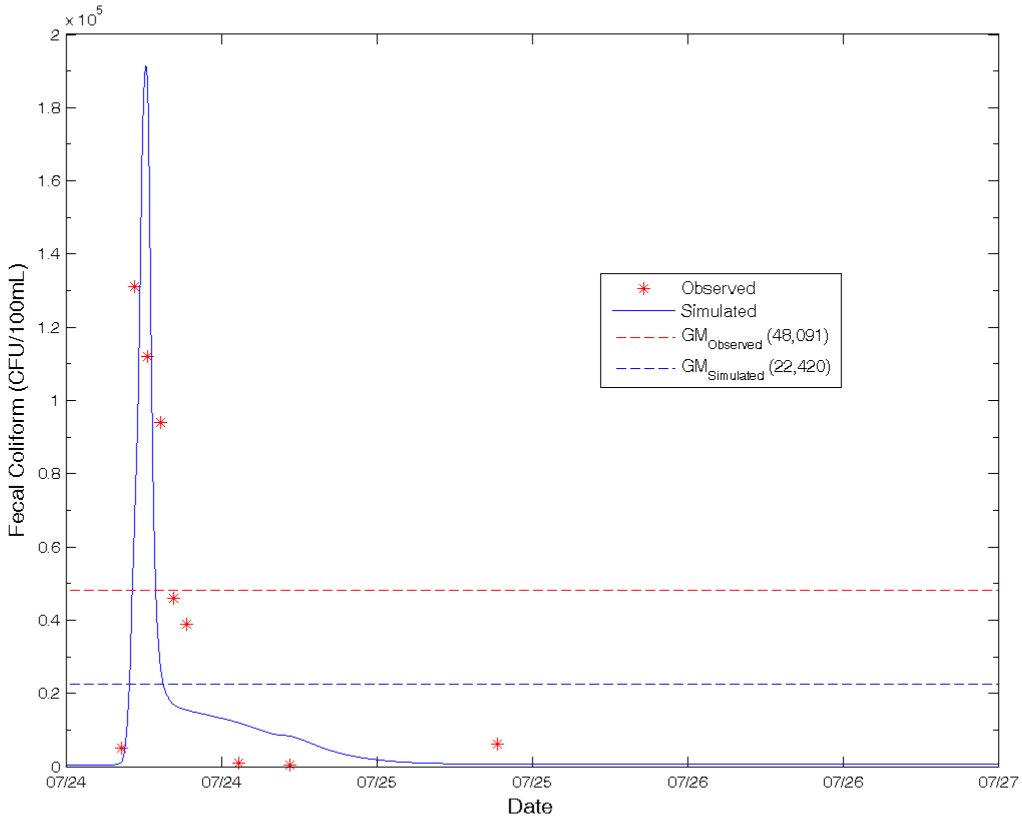

Figure 3-31: Observed and Simulated Fecal Coliform Concentration at Site DCC208 During 7/24/03 Storm

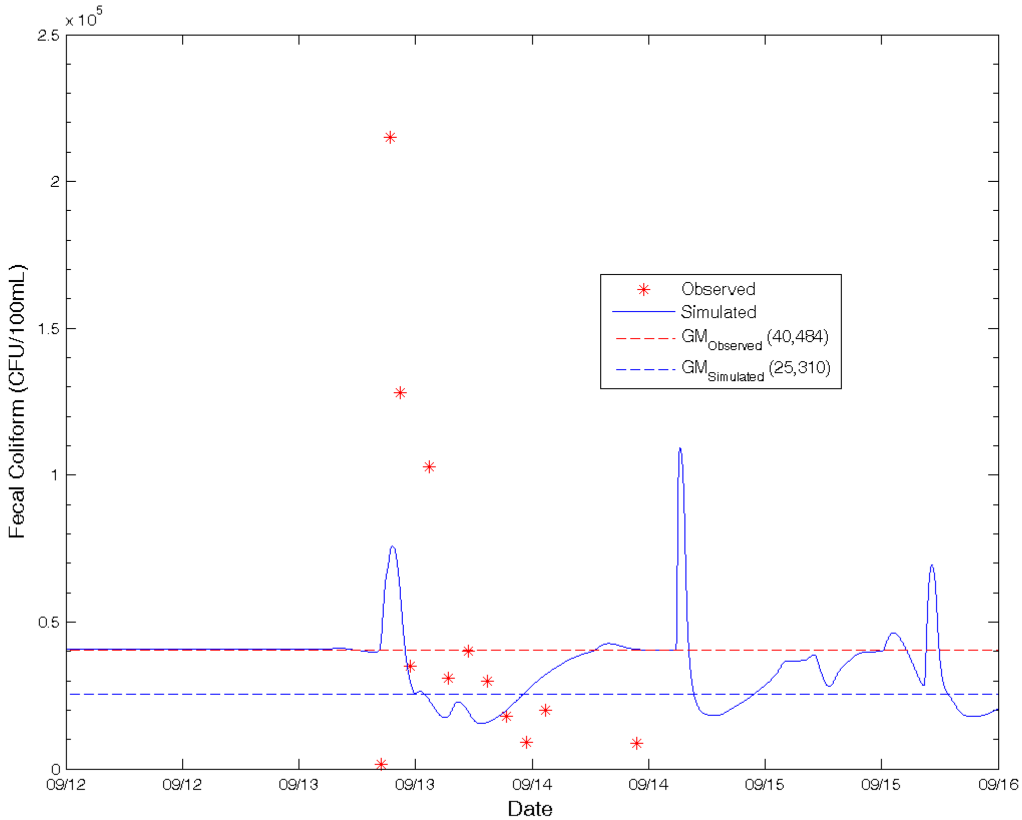

Figure 3-32: Observed and Simulated Fecal Coliform Concentration at Site DCC455 During 9/13/03 Storm

Aggregate scale

Box plots indicate that when all events are aggregated for a single site (Figures 3-33 and 3-34), the water quality model matched the overall range of observed concentrations, though not the quartiles, at the more critical site DCC208. The water quality model underpredicted observed concentrations at DCC455.

Scatter plots of predicted and observed event loads at each site illustrate underprediction at sites DCC208 and DCC455 (Figures 3-35 and 3-36). The magnitude of underprediction is lesser at the downstream site DCC208 where loads are greater than at DCC455.

The Cobbs Creek water quality model is adequate for simulating bacteria concentrations near the downstream USGS gage 1475548 at Mt. Moriah. The model is accurate to within an order of magnitude in the upper half of the model extent, a scale considered adequate in many bacteria modeling reports (Camp Dresser & Mckee, 2004 and 2011; Manache and Melching, 2005).

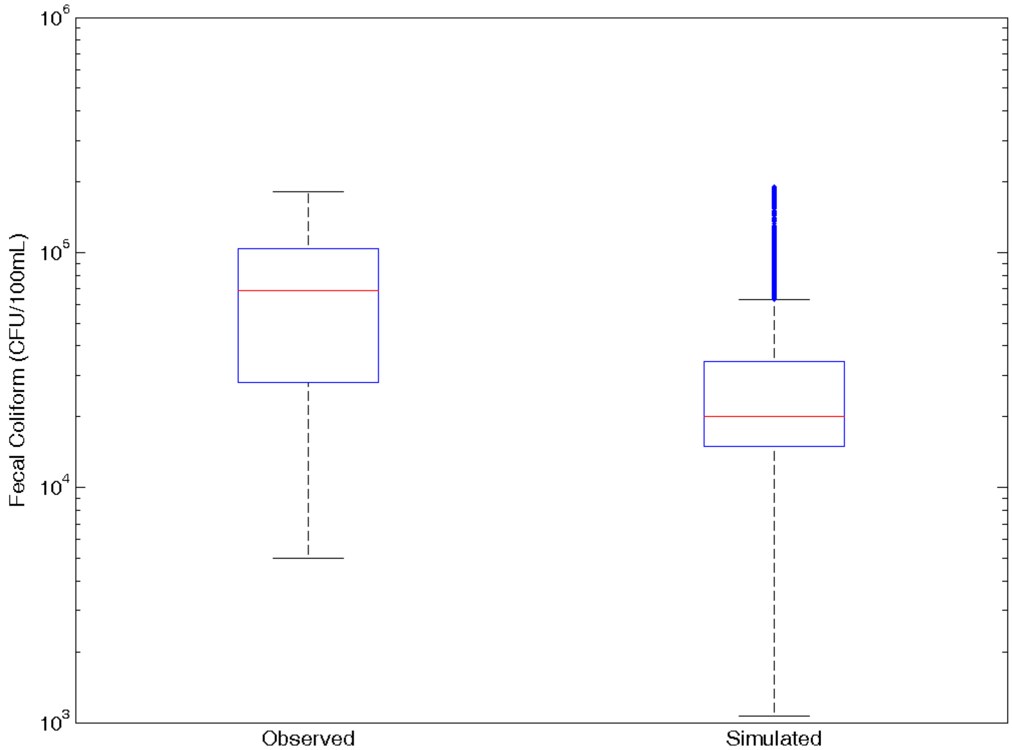

Figure 3-33: Box Plot of Observed and Simulated Fecal Coliform Concentration Data From All 2003 Validation Storms at Site DCC208

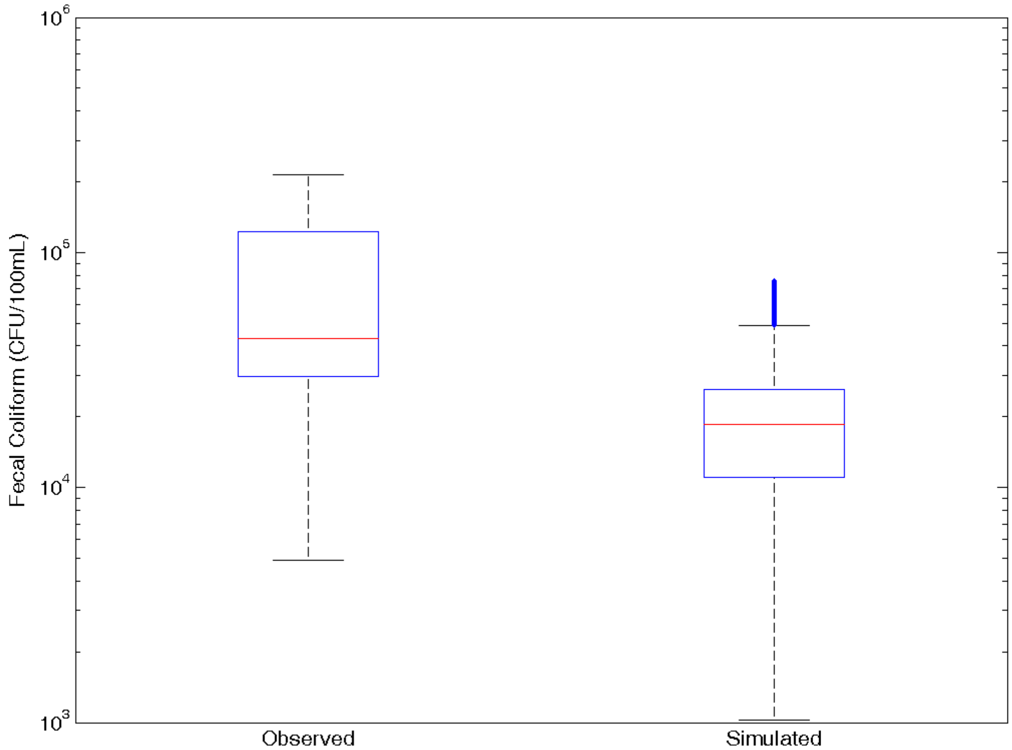

Figure 3-34: Box Plot of Observed and Simulated Fecal Coliform Concentration Data From All 2003 Validation Storms at Site DCC455

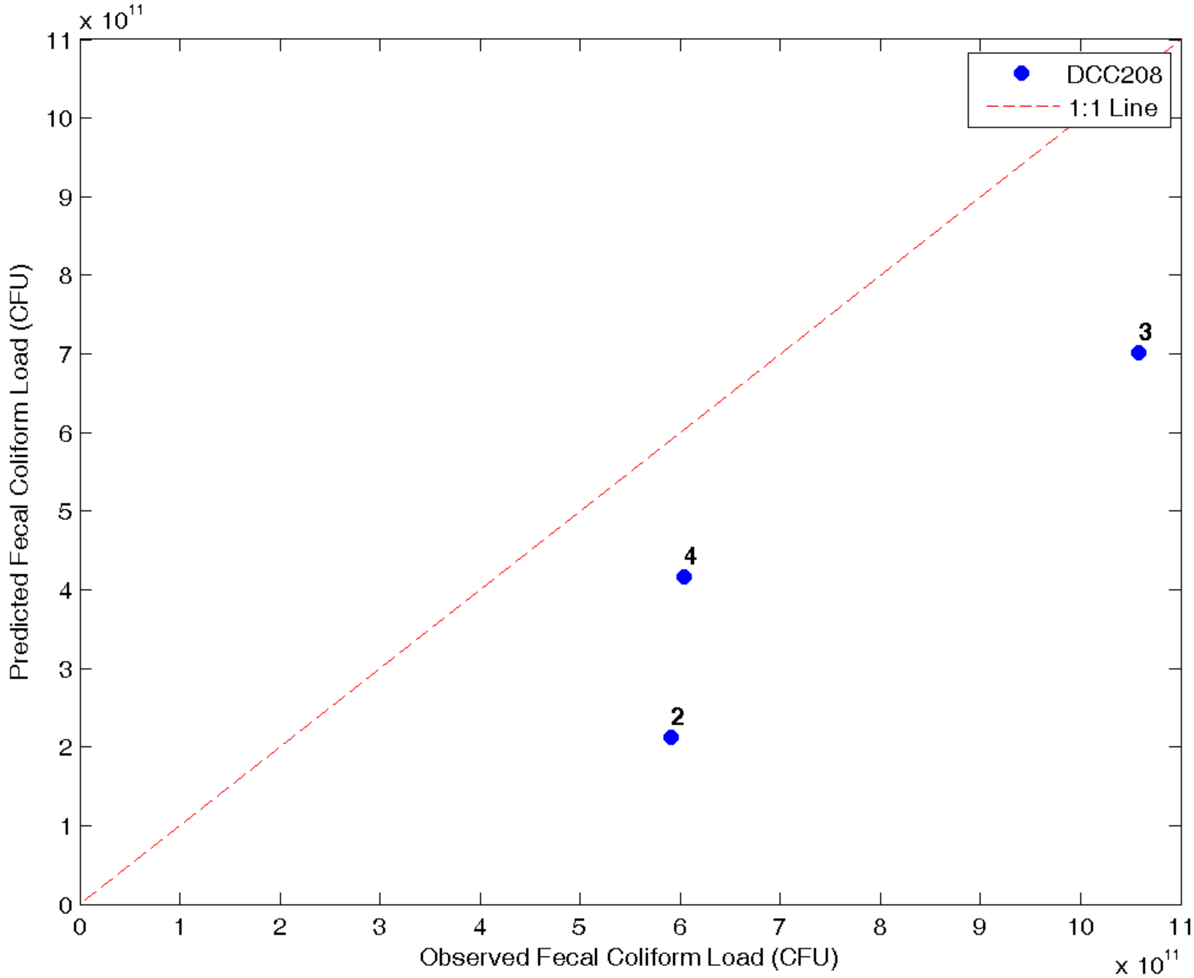

Figure 3-35: Scatter Plot of Predicted and Observed Fecal Coliform Event Load at Site DCC208

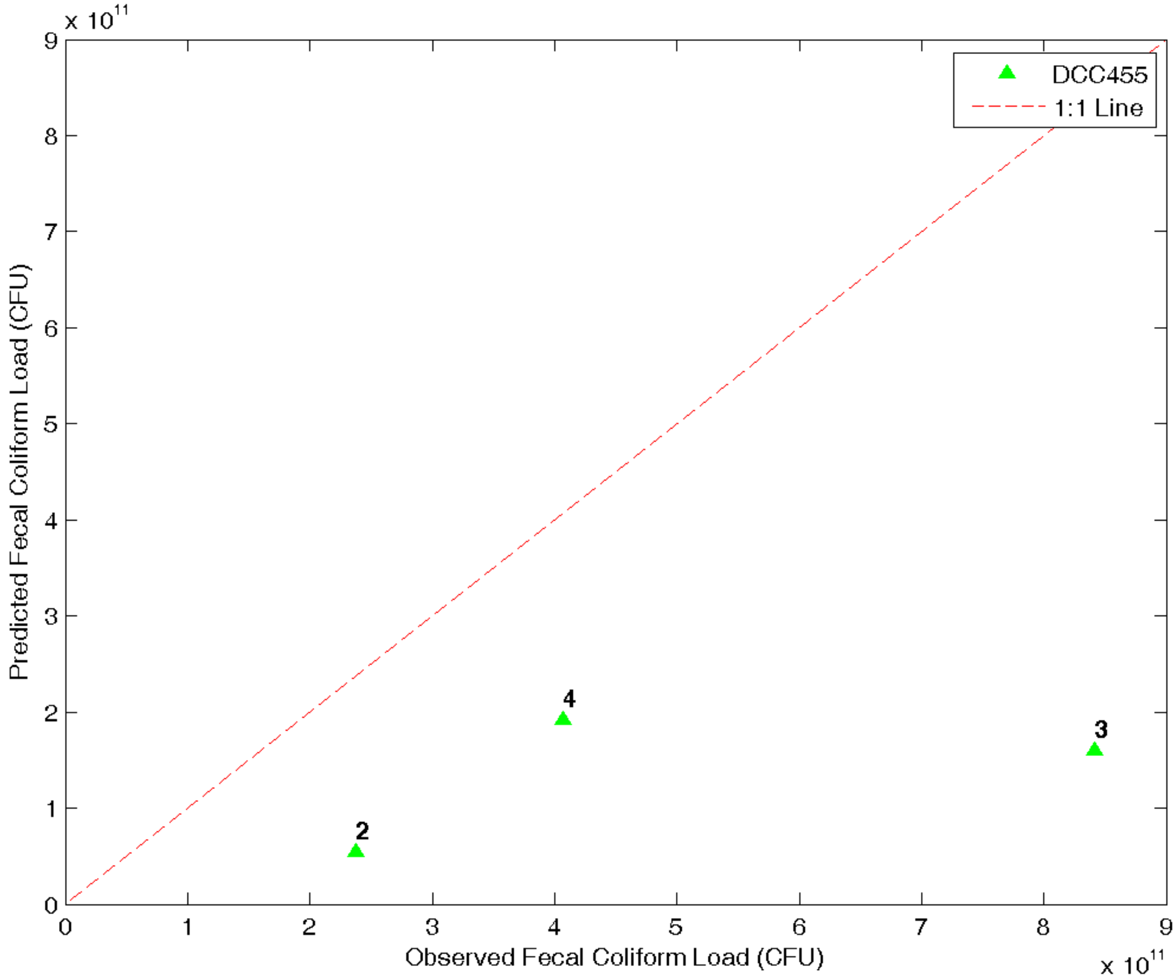

Figure 3-36: Scatter Plot of Predicted and Observed Fecal Coliform Event Load at Site DCC455

3.9 Water Quality Model Limitations

The TTF and Cobbs Creeks bacteria models were developed to provide a reasonable estimate of pollutant flow and load during wet weather over a wide range of storm magnitudes. They do not intend to predict actual concentrations at any given time, but rather to provide a range of flows and concentrations that may be found in the tributaries that receive CSO discharges.

3.10 Potential Areas for Improvement

The development of the Tributary Models followed an approach of continuous improvement and validation. The selected versions of the models presented in this report represent a snapshot in time, and does not limit the development of future updates, which may include more detailed and accurate information, additional simplifications, changes to a different model platform version, or even the selection of a different model platform. Model development flexibility is paramount to achieving models that best fit a variety of applications and analysis goals.

As with all models, the TTF and Cobbs Creeks bacteria models are limited by the quality of the monitored validation data, both flow and water quality, as well as the accuracy of the information used to construct the models. While an effort was made to use the best available data, future improvements to GIS coverage, additional bathymetry data, additional flow monitoring data, and additional water quality monitoring data could be used to improve the predictive ability of these models.

3.11 Conclusions

The tributary bacteria water quality models were developed and validated in compliance with the Consent Order and Agreement. Flow and water quality validations were performed on the Tookany/Tacony-Frankford and Cobbs Creeks. A total of twelve storms ranging from 0.16 to 2.68 inches of rainfall were used as water quality model validation events. Loading of fecal coliform and *E. coli* from stormwater runoff, combined sewer system outfalls, secondary tributaries and baseflow were each considered in model development. A sensitivity analysis was applied to identify the optimal decay rate, and adjust stormwater runoff and wastewater concentrations within accepted margins of uncertainty of observed data.

Time series plots, box plots, load scatter plots, and statistical summaries were used to evaluate water quality model performance. Analyses at the event and aggregate scales of the twelve validation storms indicate adequate water quality model performance, particularly for Tookany/Tacony-Frankford Creek. Future areas of improvement have been identified and can be pursued to enhance model performance for both Tookany/Tacony-Frankford and Cobbs Creeks. The validated water quality models can be used to provide a reasonable tool to assess the water quality impacts of combined sewer overflows to Tookany/Tacony-Frankford and Cobbs Creeks.

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