Appendix D

WATER QUALITY MODELING REPORT FOR THE RICHMOND CSS FINAL PLAN

Prepared for: City of Richmond Department of Public Utilities

February 29, 2024

LimnoTech

Water Environment | Scientists Engineers

Page intentionally blank to facilitate double-sided printing.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

CFD: Cumulative Frequency Distribution

CFU: Colony Forming Units

CSO: Combined sewer overflow

CSS: Combined sewer system

CWA: Clean Water Act

EFDC: Environmental Fluid Dynamic Code

EMC: Event Mean Concentration

LTCP: Long Term Control Plan

MS4: Municipal separate storm sewer system

RIA: Richmond International Airport

RT-DSS: Real Time Decision Support System

SWMM: Storm Water Management Model

STV: Statistical Threshold Value

USGS: United States Geological Survey

WWTP: Wastewater Treatment Plants

1 Executive Summary

1.1 Introduction

In April of 2020, the Virginia General Assembly signed an Act requiring the City of Richmond to develop an Interim and Final Combined Sewer System (CSS) Plan to address the requirements of the consent special order (SO) issued by the State Water Control Board. The CSO Interim Plan Report was delivered to the Virginia Department of Environmental Quality (VA DEQ) on July 1, 2021 and included interim CSS projects to reduce CSS discharges. The intent of the Final Plan is to update the Interim Plan and describe additional actions and projects as required by the consent special order. The Final Plan must be submitted to VA DEQ by July 1, 2024, and will present an estimated timeline, an estimated cost, projected water quality improvements, and proposed funding sources for the plan.

To help understand and compare the projected bacteria water quality improvements of the potential CSS Final Plan projects, a bacteria water quality model was used and applied. The water quality model used herein is based on the water quality model that was developed to support the Clean Water Plan in 2017 (City of Richmond, 2017) and the Interim CSS Plan in 2021 (City of Richmond, 2021). The purpose of the water quality model is to quantify present day bacteria (*Escherichia coliform [E. coli]*) loads and concentrations in the James River and to predict future *E. coli* concentrations for the Final CSS Plan projects. The modeled bacteria concentrations are compared against applicable bacteria recreational water quality standards to assess projected water quality improvements.

The overall objectives of the water quality model were as follows:

- Use recently collected site data, literature, and professional judgment to update model parameters;
- Provide a reliable and reasonably complete accounting of *E. coli* sources to the James River and achieve a level of model accuracy adequate to support decision; and
- Evaluate and summarize model results to predict improvements in water quality conditions from alternative control projects and inform the selection of Final CSS Projects.

Section 2 of this report contains more detailed information on the history and objectives of the water quality model.

1.2 Water Quality Model Updates

The water quality model used to support the development of the Final CSS Plan is based on the water quality model that was developed for the City of Richmond to support the development of the Clean Water Plan in 2017 (City of Richmond, 2017). The 2017 model was originally calibrated to represent the conditions from calendar years 2011-2013. As part of the Final CSS Plan development, the 2017 water quality model was reviewed and updated to reflect current conditions in the CSS infrastructure and physical characteristics of the Richmond area and James River. For this report, current conditions are defined as the period from 2019-2021, which is also called the "Performance Evaluation Period."

Following updates to the receiving water quality model to reflect current conditions, the model was applied and results evaluated to confirm that the model can reasonably reproduce observed *E. coli* bacteria concentrations in the James River for the performance evaluation period. *E.coli* concentrations predicted by the updated water quality model were compared against the *E. coli* concentrations obtained from the monitoring program at five locations along the James River for 2019-2021. This comparison showed that the water quality model continues to:

- Capture the central tendencies of the monitoring data.
- Capture the variability of bacteria going from upstream to downstream within the City of Richmond limits.
- Capture the variability of bacteria due to seasonal or local weather patterns.
- Provide a slightly more conservative estimate of *E.coli* concentrations in the James River compared to the monitoring data (i.e.: in this context, more conservative means higher *E.coli* concentrations).

Section 3 of this report contains more detailed information on the water quality model updates and performance evaluation.

1.3 Model Application and Results

The updated water quality model was applied for the hydrologic period of 2011-2013 (the CSS Scenario Evaluation Period). The water quality model scenario results were evaluated relative to compliance with the geometric mean and the statistical threshold value (STV) water quality standards, on a 90-day rolling basis. These standards state that, "in freshwater, *E. coli* bacteria shall not exceed a geometric mean of 126 counts/100ml and shall not have greater than a 10% excursion frequency of a statistical threshold value (STV) of 410 counts/100 ml, both in an assessment period of up to 90 days." (VADEQ, 2019). Model results were also evaluated relative to the reduction in total *E.coli* load from the CSO component source.

For all scenarios, model results were evaluated at five locations along the James River that correspond to sampling locations: the Upstream City Boundary near Huguenot Bridge, CSO 06 near the Shockoe Retention Basin, CSO-40 near Manchester, Buoy 168 near Luck Stone Quarry, and Buoy 166 at the Downstream City Limit. The five CSS Final Plan project scenarios that were evaluated are shown in **Table 1-1** below.

Table 1-1: Summary of the CSS Final Plan Scenarios

Scenario #	Scenario Name	Description

1	Baseline	CSO baseline conditions, which represented the current CSS conditions, as well as the following.
		• Cleaning of the following Facilities/Pipelines:
		  ○ Shockoe Retention Basin
		  ○ Hampton/McCloy Retention Tunnel
		  ○ Shockoe 96-inch Interceptor / Twin 66-inch Siphons (1-ft of debris was assumed to remain in these sewers for the evaluation)
		• Construction and operation of all ten Interim Plan Projects

2	100% CSO In-Situ Disinfection	All CSO discharges are captured and fully treated (disinfected) at each CSO location.
3	Special Order Projects	Remaining CSO Projects included in the 2005 Special Order (LTCP) are implemented. These infrastructure projects include: • Conveyance sewer from Outfalls 004, 005, 034 and 035 to the WWTP (7-ft to 8-ft diameter) [SO #13] • High-Rate Disinfection Facility at the WWTP (160-MGD) to increase ability to handle additional wet weather flows [SO #15] • High-Rate Disinfection Facility on Chapel Island to control Outfall 006 (3,300-MGD) [SO #19]
4	Alternative Regulatory Compliance	Least expensive improvements that still meet the same regulatory requirements as the 2005 Special Order projects (Scenario 3) but with alternative and less expensive infrastructure projects, including: • Convert a portion of the SRB to a High-Rate Disinfection Facility (1,000 MGD) • Storage Tank at the WWTP to serve Outfall 021 (10 MG) • Hilton Street Separation of the combined sewer drainage • Dock Street Conveyance sewer from Outfalls 005, 034 and 035 to the SRB (5-ft diameter) • Gillies Creek Sewer Improvements
5	Preliminary CSS Final Plan Project Selection	Substitute several projects from scenario #4 to provide more bacteria reduction. This scenario includes the following infrastructure projects: • Convert a portion of the SRB to a High-Rate Disinfection Facility (1,000 MGD) • Hilton Street Separation of the combined sewer drainage • Storage Tank in Canoe Run Park (6 MG) to reduce overflows at CSO-40 • Storage Tank at Outfall 031 (1 MG)

The following observations were made about the baseline scenario:

- The baseline results show that the *E.coli* loads from upstream sources are the largest, followed by the CSO *E.coli* loads. One of the primary goals of the CSS Final Plan is to reduce the CSO *E.coli* loads. The CSO loads tend to dominate the overall *E.coli* load during the summer months when there is heavier and more intense local precipitation (summer storms) that causes the CSO's to discharge. The upstream loads tend to dominate the overall *E.coli* load during the winter and spring months.

- Under baseline conditions, the model predicts that the 90-day geomean standard of 126 CFU/100mL is not exceeded at any of the five key locations for the 2011-2013 Scenario Evaluation period. The highest geomean concentrations are observed at the CSO-40 and CSO-06 locations in the James River. These are the two areas that the CSS Final Plan is targeting for improvement.
- Under baseline conditions, the 90-day STV exceedance criterion of 10% is exceeded three times (December 2011, September 2012, and July 2013) at location CSO-40 and at the Downstream City Limit. Implementation of the CSS Final Plan projects, and particularly the reduction of CSO discharges at CSO-40 and CSO-06, are intended to reduce these exceedances.

Additional details about the modeled baseline conditions are provided in **Section 4.2**.

Upon application of the CSS Final Plan Scenarios in the water quality model, the following observations were made:

- The James River near CSO-40 shows the largest in-stream water quality improvements under scenario 2 (100% CSO In-Situ Disinfection) and scenario 5 (Preliminary CSS Final Plan Project). STV exceedance seen under baseline, scenario 3, and scenario 4 are no longer observed under scenarios 2 and 5 at this location.
- The James River near CSO-06 shows nearly similar in-stream water quality improvements under scenarios 2 through 5. This is because all those scenarios provide similar levels of control for the CSO-06 discharge.
- The James River at the downstream end of the city shows the largest in-stream water quality improvements under scenario 2 (100% CSO In-Situ Disinfection) and scenario 5 (Preliminary CSS Final Plan Project). STV exceedances seen under baseline conditions are no longer observed under scenarios 2 through 5 at this location.
- The CSS infrastructure improvements included in Scenario 5 result in a significant reduction of CSO *E.coli* load, turning this load from the second *biggest* overall load under the baseline conditions to the second *smallest* overall load under Scenario 5.

Additional details about the modeled Final CSS Plan Scenarios are provided in **Section 4.2**.

2 Introduction

In April of 2020, the Virginia General Assembly signed an Act requiring the City of Richmond to develop an Interim and Final Combined Sewer System (CSS) Plan to address the requirements of the consent special order (SO) issued by the State Water Control Board. The CSO Interim Plan Report was delivered to the Virginia Department of Environmental Quality (VA DEQ) on July 1, 2021 and included interim CSS projects to reduce CSS discharges. The intent of the Final Plan is to update the Interim Plan and describe additional actions and projects as required by the consent special order. The Final Plan must be submitted to VA DEQ by July 1, 2024, and will present an estimated timeline, an estimated cost, projected water quality improvements, and proposed funding sources for the plan.

A water quality model was applied to assess the water quality improvements of alternative control projects and inform the selection of proposed Final CSS Plan projects. This report describes the water quality model and the results from this modeling effort.

2.1 Model Background and Objectives

A water quality model that simulates bacteria levels in the James River was developed and applied to understand and compare the projected water quality improvements of the potential CSS Final Plan projects. The purpose of the water quality model is to quantify present day bacteria (*Escherichia coliform [E. coli]*) loads and concentrations in the James River and to predict future *E. coli* concentrations for the Final CSS Plan projects. *E. coli* concentrations simulated by the model can be compared against applicable water quality standards to assess projected water quality improvements.

The overall objectives of the modeling effort were as follows:

- Use recently collected site data, literature, and professional judgment to update model parameters (See section 3.2);
- Provide a reliable and reasonably complete accounting of *E. coli* sources to the James River and achieve a level of model accuracy adequate to support decision making (See sections 3.3); and
- Evaluate and summarize model results to predict improvements in water quality conditions from alternative control projects and inform the selection of Final CSS Projects.

2.2 Water Quality Model History

A water quality model was initially developed to inform the Clean Water Plan in 2017 (City of Richmond, 2017). This water quality model was presented to the RVAH2O Technical Stakeholder Group and used extensively to assess the predicted in-stream bacteria improvements for the Clean Water Plan strategies. Appendix A of the 2017 Clean Water Plan documents the development, calibration, and application of the water quality model.

The water quality model was subsequently used to support the development of the Interim CSS Plan in 2021 (City of Richmond, 2021) to predict in-stream bacteria improvements for the Interim CSS Plan strategies. Appendix C of the 2021 Interim CSS Plan Report documents the evaluation and application of the water quality model for that project.

The same water quality model was further developed for applications to inform the Final CSS Plan, as presented in this report.

2.3 Model Description

The receiving water quality model uses the EFDC modeling framework (Environmental Fluid Dynamics Code). EFDC has been applied to support numerous CSO water quality projects and is suitable for representing hydrodynamic conditions occurring in the James River, including the transition from riverine to estuarine conditions, and low head dam hydraulics. EFDC is a state-of-the-art finite difference model that can be used to simulate hydrodynamic and water quality behavior in one, two, or three dimensions in riverine, lacustrine, and estuarine environments (TetraTech 2007). The model was developed by John Hamrick at the Virginia Institute of Marine Science in the 1980s and 1990s, and it is currently maintained under support from the USEPA. The model has been applied to hundreds of water bodies, including the Chesapeake Bay. The EFDC model is both public domain and open source, meaning that the model can be used free of charge, and the original source code can be modified to tailor the model to the specific needs of a particular application. As a result, EFDC provides a powerful and highly flexible framework for simulating hydrodynamic behavior and water quality dynamics in the James River.

The water quality model is grounded in monitoring data, including flow, tide, and *E. coli* data. Section 3.1 describes the monitoring data that was used to evaluate the water quality model.

The water quality model also includes inputs that represent the flows and *E. coli* loads from combined sewer overflows. These flows and loads are provided by a model of the combined sewer system (CSS) developed by Brown and Caldwell to support the Final CSS Plan. The CSS model is based upon the EPA Storm Water Management Model (SWMM) framework and uses the SWMM engine version 5.1.015. The model is operated within the PCSWMM environment.

Lastly, the water quality model also includes inputs that represent the flows and *E. coli* loads from contributing areas of tributaries to the James River within the greater Richmond area, as well as from Richmond's Municipal Separate Storm Sewer System (MS4). These flows and loads are provided by a watershed model developed by LimnoTech. The watershed model also uses the EPA Storm Water Management Model (SWMM) framework and uses the SWMM engine version 5.1.015. The model is operated within the PCSWMM environment.

Figure 2-1 below shows how the various models and data are connected to each other.

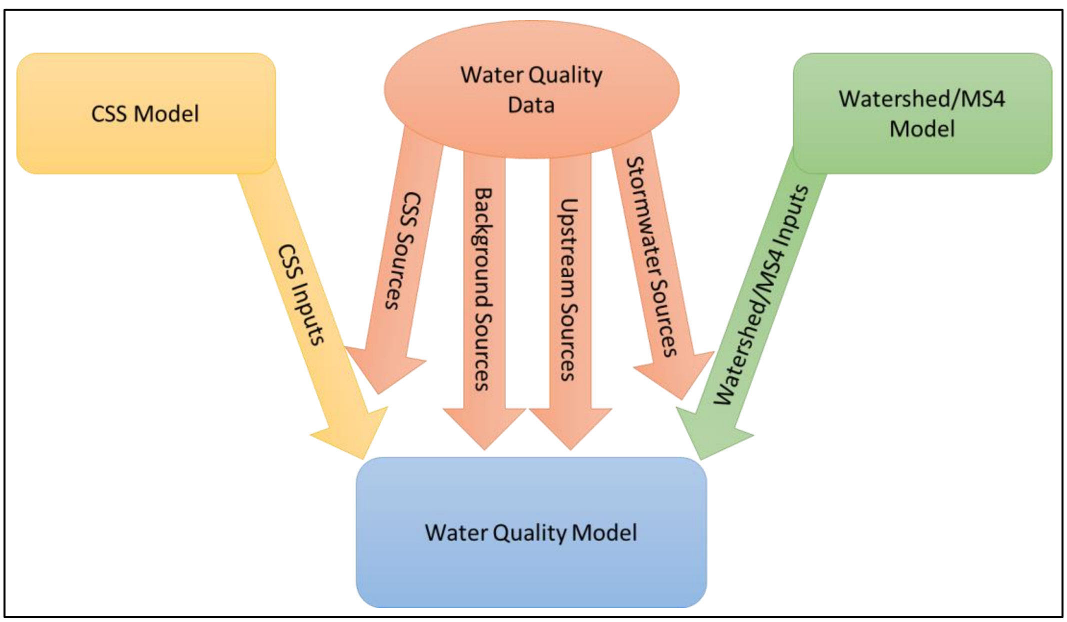


Figure 2-1: Modeling Framework Schematic

2.4 Model Extent

The model extent defines the spatial or geographic boundary to which the model applies. The James River receiving water quality model extends from South Gaskins Road upstream of the Richmond city boundary, to Osborne Park downstream of the Richmond city boundary. The upstream limit of the model was chosen to be just upstream of Richmond's city limits. The downstream limit was chosen to be downstream of Cornelius Creek and near a frequently sampled water quality station. Twenty-three miles of the James River are represented in the model with average grid cell dimensions of 140 feet wide and 340 feet long. Six cells typically span the width of the river. The depth of the river is captured within a single cell.

Key physical features included in the model are the James River low head dams and islands; the James River Falls near downtown Richmond; the CSO and WWTP discharge outfalls; and tributary streams. Also represented in the model are flow and *E. coli* loads from the James River upstream of Richmond; from tributary and MS4 base flow and runoff; from the City wastewater treatment plant; from the combined sewer system outfalls; and from the downstream tidal flows in the Lower James River. These features are shown in **Figure 2-2.**

The figure also shows the extent of the CSS and Watershed models. The CSS model provides flows for all currently active CSS outfalls and the WWTP outfall, to which *E. coli* loads are then assigned. The watershed model provides flows and *E. coli* loads for 23 tributaries of the James River that fall within the receiving water quality model extent.

2.5 Water Quality Standards

In 2019, Virginia adopted EPA's recommended recreation water quality criteria that are designed to protect the public from exposure to harmful levels of pathogens while participating in water-contact activities, such as swimming, wading, and surfing, in all water bodies designated for such recreational uses (EPA, 2012; VADEQ, 2019). The Virginia standards state that in freshwater, *E. coli* bacteria shall not exceed a geometric mean of 126 counts/100ml and shall not have greater than a 10% excursion frequency of a statistical threshold value (STV) of 410 counts/100 ml, both in an assessment period of up to 90 days.

These water quality criteria apply to the James River and all its tributaries within the limits of the City of Richmond.

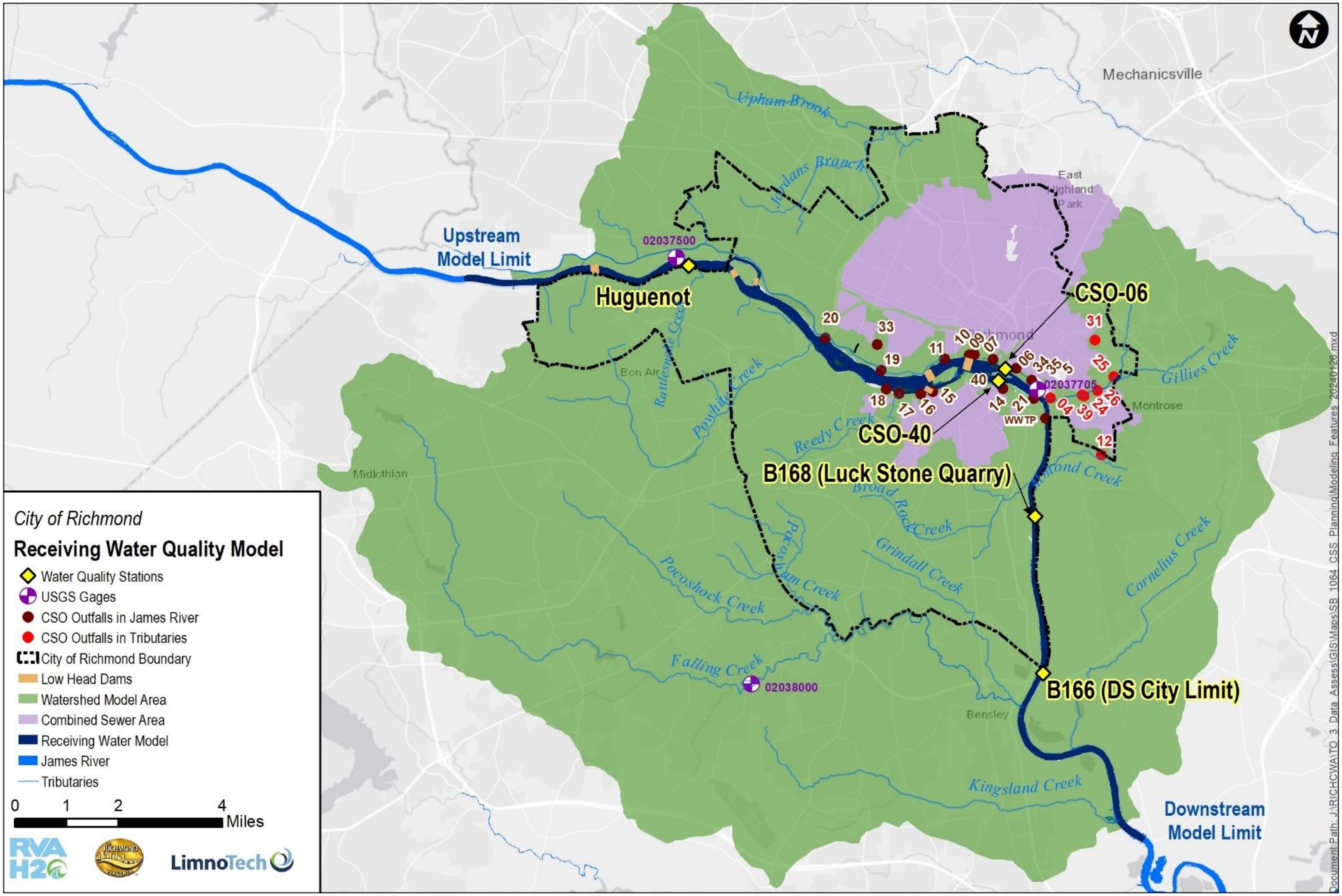


Figure 2-2: Extent and Key Features of the Receiving Water Quality Model

3 Water Quality Model Updates and Performance Evaluation

The James River water quality model described above was originally developed to support the Clean Water Plan in 2017 (City of Richmond, 2017) and the Interim CSS Plan in 2021 (City of Richmond, 2021). As part of the Final Plan development, the water quality model was reviewed and updated to reflect current conditions in the CSS infrastructure and physical characteristics of the Richmond area and James River. For this report, current conditions are defined as the period from 2019-2021, which is also called the "Performance Evaluation Period." Following updates to receiving water quality model to reflect current conditions, the model was applied and results evaluated to confirm that the model can reasonably reproduce observed *E. coli* bacteria concentrations in the James River for the performance evaluation period. The following sections describe the data used to inform model updates, the actual model updates, and the evaluations conducted to verify model performance.

3.1 System Monitoring Data

Various hydrologic and water quality data were obtained to update and apply the water quality model for the Performance Evaluation Period (2019-2021) and for the Scenario Evaluation Period (2011-2013). These data included rainfall, James River flow and tidal water level, event mean concentrations (EMCs) of *E. coli* in CSOs, and James River *E. coli* sampling data. Other data that were originally used to develop and calibrate the 2017 model, but have not changed since the initial calibration period, are not described in this report. Appendix A of the 2017 Clean Water Plan (City of Richmond, 2017) presents the original data used to inform the model. Appendix A includes, for example, descriptions of data sets such as land use, tributary flows, imperviousness, and slopes.

3.1.1 Rainfall Data

Rainfall data are used as a model input for the MS4 and the CSS models to predict stormwater and CSO discharges into the James River. The Richmond International Airport (RIA) rainfall gauge was used to obtain the rainfall data. **Figure 3-1** shows the total annual rainfall between the years 2004 and 2022 as blue bars, and the statistical thresholds for classifying individual years as dry, average, or wet as red lines across the bars. Both selected evaluation periods (highlighted in orange in the figure) include a dry, an average, and a wet year. The rainfall data shows significant variability during this 2004-2022 period.

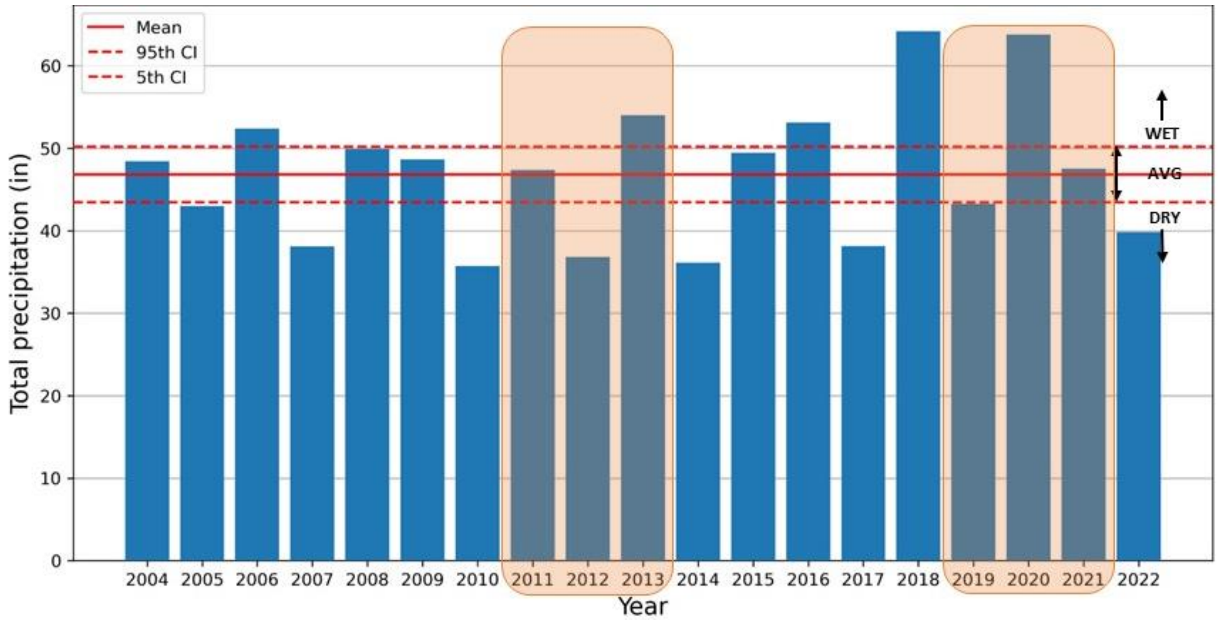


Figure 3-1. Annual Rainfall Data as Measured at the Richmond International Airport

3.1.2 James River Flow and Level Data

Data from two USGS stations supported the hydrodynamic model calibration: one in the riverine reach at Huguenot Bridge (Station 02037500, James River near Richmond, VA); and one in the estuarine reach (Station 02037705, James River at the City Locks at Richmond, VA). Data from the riverine USGS station quantify the change in stream depth and velocity with river flow. Data from the estuarine USGS station quantifies the amplitude and phasing of tidal water levels.

Upstream James River flows at Huguenot Bridge were directly applied at the upstream model boundary. Median flow at this location was 4,190 cubic feet per second (cfs) for the Scenario Evaluation Period of 2011 to 2013, and 6,310 cfs for the Performance Evaluation Period of 2019-2021. **Figure 3-2** is a plot of the James River flows from October 2010 through December 2021, with the Scenario and Performance Evaluation periods labeled.

Tidal water levels at City Locks were applied at the downstream boundary of the model but were adjusted to account for changes in water level between the gage and the model boundary, as described in Appendix A, Section 4.3.3, of the 2017 Clean Water Plan (City of Richmond, 2017).

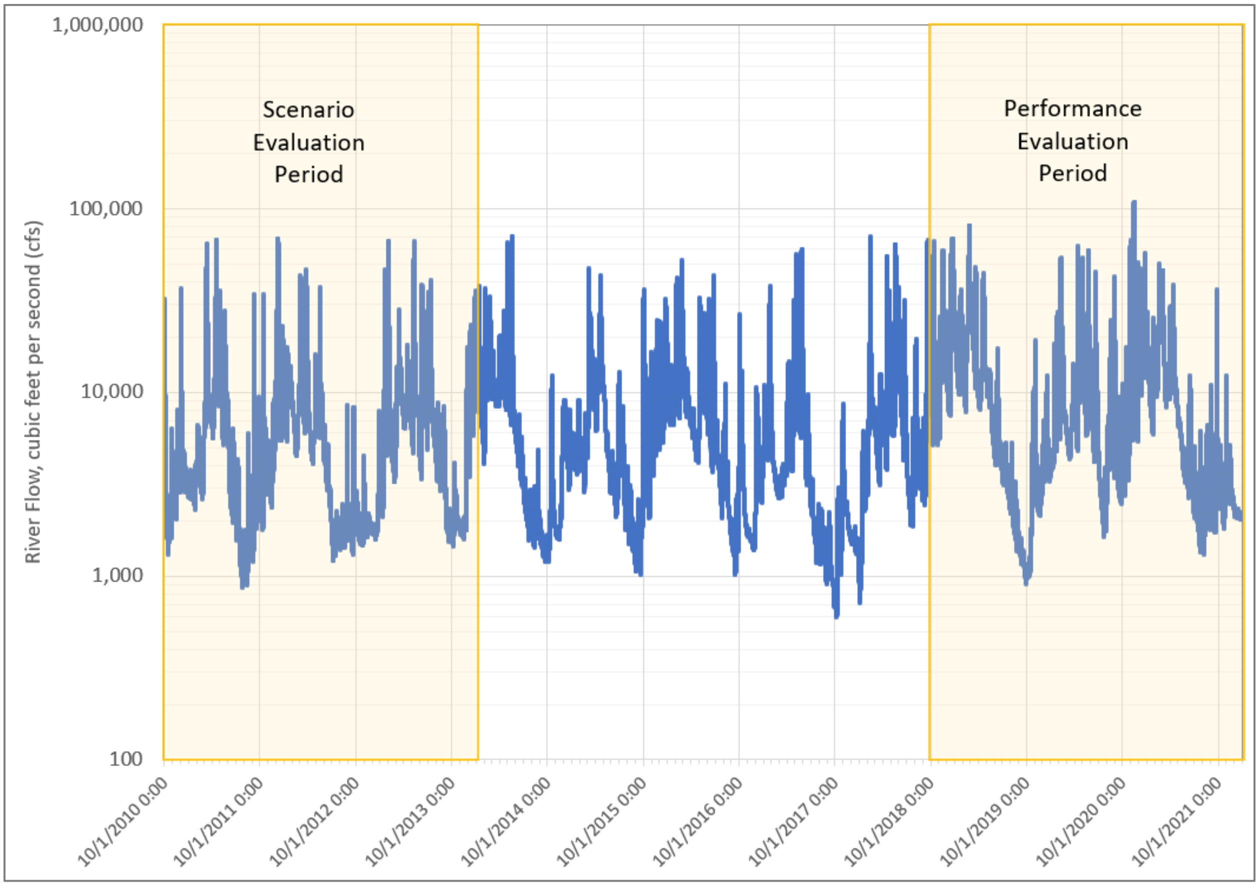


Figure 3-2. James River Flows Near Huguenot Bridge (USGS Station 0237500).

3.1.3 CSS EMC Data

CSO EMCs are the *E. coli* concentration values that are assigned to CSO model flow time series to calculate each CSO's *E. coli* load to the James River in the water quality model. The City of Richmond conducted sampling to inform CSO EMCs in 2022-2023 in order to update the previous EMCs that were used to develop the City's 2002 Long Term Control Plan. **Table 3-1** shows the previous 2002 and updated 2023 EMC values by CSO district.

EMCs were updated for four of the six CSO Districts including significant reductions for South Side James River Park and Gillies Creek CSOs and a significant increase for Shockoe Creek CSOs.

Table 3-1. CSO *E.coli* Event Mean Concentration (EMC) Comparison

CSO District	CSS Outfalls Included	2002 *E. Coli* EMC Value (CFU/100mL)	2023 *E. Coli* EMC Value (CFU/100mL)
South Side James River Park	15-18, 40	318,000	112,500
North Side James River Park	7-11, 36	150,000	150,000
Manchester Area (WWTP area)	13-14, 21	34,000	26,750
Gillies Creek	2-5, 23-28, 35, 39	205,000	81,600
Shockoe Creek	6, 34	111,000	164,000
Remote Locations	12, 19-20, 31, 33	215,000	215,000

3.1.4 Receiving Water Quality *E.coli* Data

Water from the James River is routinely sampled and tested for *E. coli* at key locations in the river by the City of Richmond. Samples have been collected either on a weekly or bi-monthly basis, year-round. Sampling locations are indicated in **Figure 2-2** in **Section 2.4** above. Sampling results are summarized using box-and-whisker plots, as shown in **Figure 3-3** below. These box and whisker plots show the minimum and maximum concentration within each data set (the whiskers) as well as the 25th percentile, median, and 75th percentile of each data set (the three lines comprising the blue box).

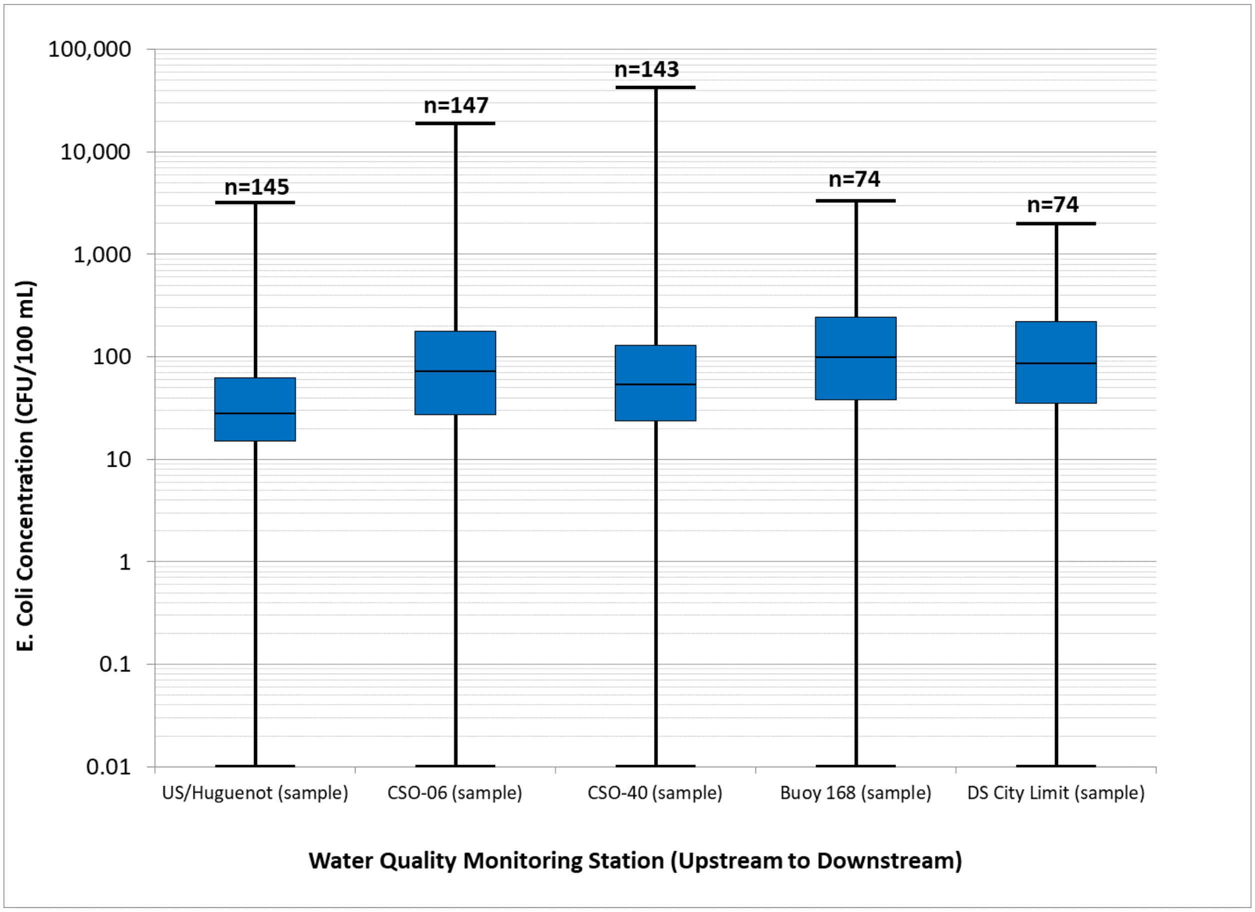


Figure 3-3. James River E.coli Sampling Data Results (2019-2021)

Several observations can be made from the water quality sampling data:

- *E.coli* concentrations in the James River at the upstream boundary of the city (Huguenot Bridge) sometimes cause exceedances of water quality criteria. This indicates that there are bacteria sources that originate outside of the City and are, therefore, outside of the City's control. If these upstream sources of bacteria are not reduced, the James River within the City of Richmond will experience exceedances of the water quality criteria no matter what investments the City may make through the CSS Final Plan.
- *E.coli* concentrations in the James River are highest in the downtown area of Richmond where the major CSO discharges occur (CSO-40 and CSO-06). These areas also show the most frequent exceedances of water quality criteria. The investments that the City will make through the CSS Final Plan will have a direct impact on the *E.coli* concentrations in these areas.
- *E.coli* concentrations are lower in the tidal section of the James River downstream of the CSO district, but elevated levels persist for longer periods of time due to the tidal action of the river in this area that slows the net downstream movement of water.

The 2019-2021 sampling data was also used to assess the performance of the updated water quality model by comparing model output with the sampling data. This performance evaluation is described in Section 3.3.

3.2 Receiving Water Quality Model Updates

The receiving water quality model was originally developed for the City to support the development of the Clean Water Plan in 2017 and was, at the time, specifically calibrated to represent the conditions from calendar years 2011-2013. As part of the CSS Final Plan development, this model was reviewed and updated to reflect current conditions in the CSS infrastructure and physical characteristics of the Richmond area and James River. The receiving water quality model was then evaluated for the Performance Evaluation Period (2019-2021) to confirm that the model can reasonably reproduce "current" observed bacteria concentrations in the James River. The following subsections describe the updates that were made.

3.2.1 Upstream Flow and Bacteria Concentrations (LOADEST)

The USGS LOADEST software package was used to provide a regression-based estimate of *E. coli* concentrations in the James River that enter at the upstream boundary of the model. This regression uses existing flow monitoring data from USGS Station 02037500 at Huguenot Bridge and bacteria sampling data collected at Huguenot Bridge to develop a relationship between flow and *E.coli* concentration. A more detailed discussion of LOADEST and its application can be found in Appendix C, Section 3.2.12 of the 2021 Interim Plan Water Quality Model Report (City of Richmond, 2021) as well as in Appendix A, Section 3.3 of the 2017 Clean Water Plan (City of Richmond, 2017). **Figure 3-4** shows the continuous upstream *E. coli* concentrations, as estimated by LOADEST, compared with the weekly upstream sampling data from the Huguenot Bridge station, from January 2011 through December 2021. **Figure 3-5**Figure 3-5 is a plot of the regression of flow and *E. coli* concentration at the Huguenot Bridge location for the same time period.

These figures show that the LOADEST regression captures the central tendency of the *E. coli* data but does not typically capture observed *E. coli* concentrations below 10-20#/100mL. For purposes of evaluating the CSS Final Plan scenarios and compliance with water quality standards, the LOADEST predictions of *E.coli* concentrations at the upstream boundary of the model were deemed satisfactory.

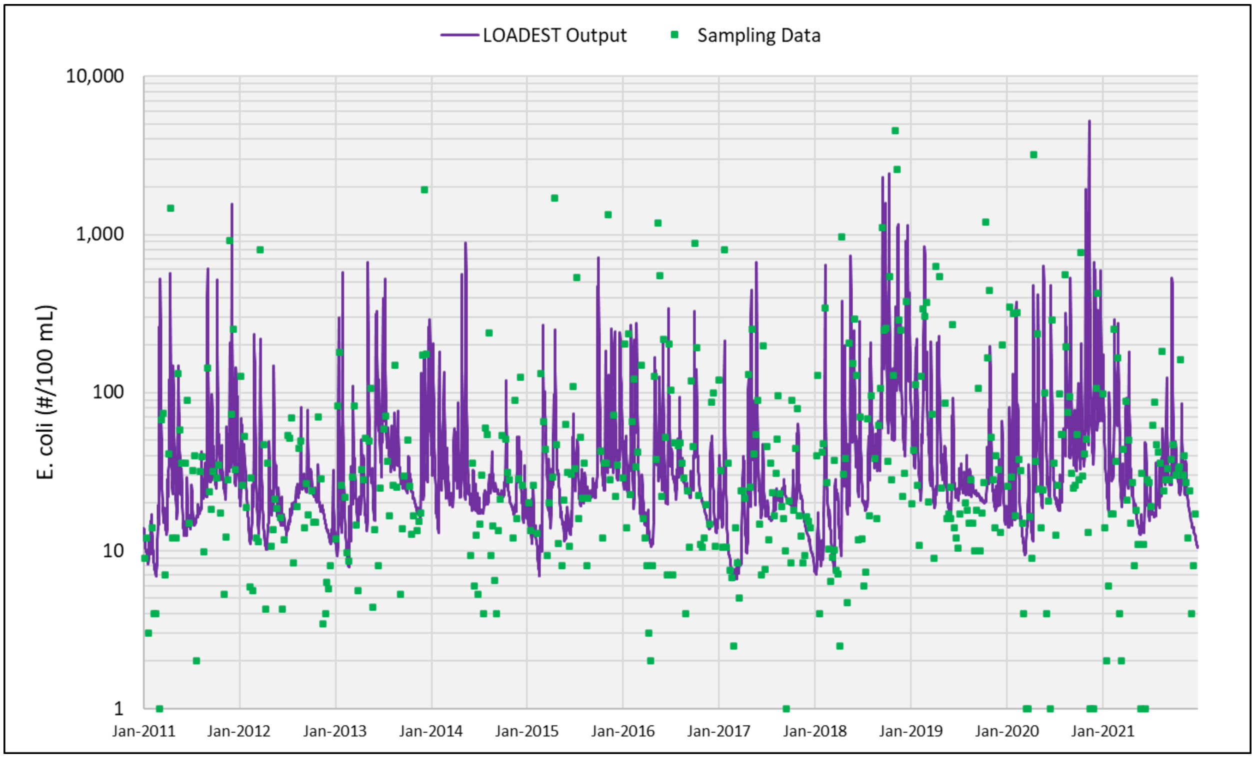


Figure 3-4. LOADEST Concentrations and Upstream Sampling Data

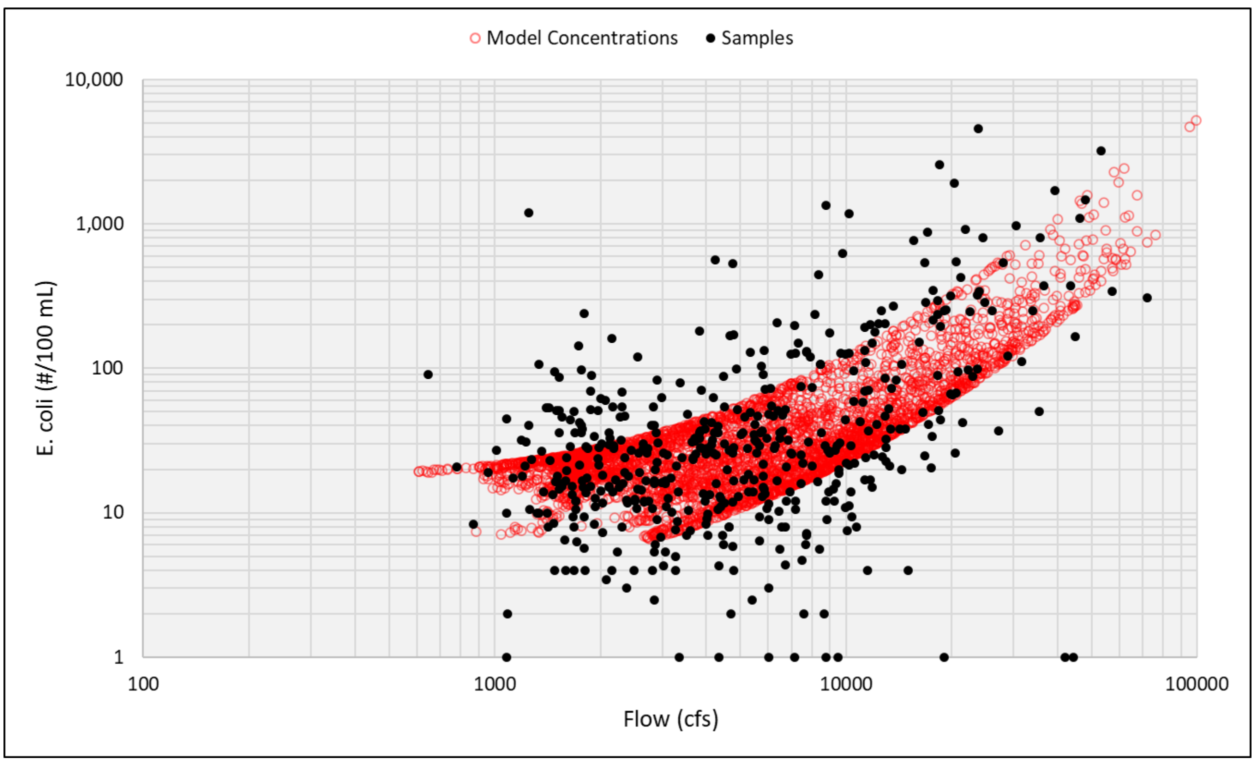


Figure 3-5. Regression of James River Flow and *E. coli* Concentration at Huguenot Station

3.2.2 Downstream Water Surface Elevation

The downstream water surface elevation boundary condition used in the model is based on the data obtained from USGS gauge # 0237705. These data were adjusted for location and time differences since the downstream model boundary is not at the exact same location as the gauge. A more detailed description of the process used to make this adjustment can be found in Appendix A, Section 4.3.3, of the 2017 Clean Water Plan (City of Richmond, 2017).

3.2.3 Background Source

The water quality model developed for the 2017 Clean Water Plan includes a background source that is introduced between the Huguenot Bridge and the 14th Street Bridge. This source was included to represent bacteria contributions from common background sources. However, the exact nature of the source is not well understood at this point. This source was introduced to the model at a constant rate of 3.2E+12 CFU/day just downstream of the Pony Pasture Park. This assumed loading rate is of the same order of magnitude as the loading rate estimated for failing septic systems and wildlife in the James River Richmond Bacteria TMDL (MapTech, 2010).

The sensitivity of the model to the introduction of this bacteria source was evaluated during the previous round of water quality modeling; that process is described in Appendix C, Section 3.2.3 of the 2021 Interim Plan Water Quality Model Report (City of Richmond, 2021).

The updated model included a change in how the background source is loaded to the James River. The load is now distributed over four model cell transects in the updated model rather than one transect in the previous model. **Figure 3-6** shows where the background source load is introduced in the updated model. Each of the purple cells receives the same load, with the sum of all loads being equal to the 3.2E+12 CFU/day that was used previously. The easternmost band of cells is where all of the loads had been assigned in the previous model. The reason for distributing this source over a larger area is to acknowledge that the exact location and distribution of the background source is currently unknown. However, it is believed to enter along that stretch of river. Distributing this source in this manner is intended to avoid potential misinterpretations that this source has a known location.

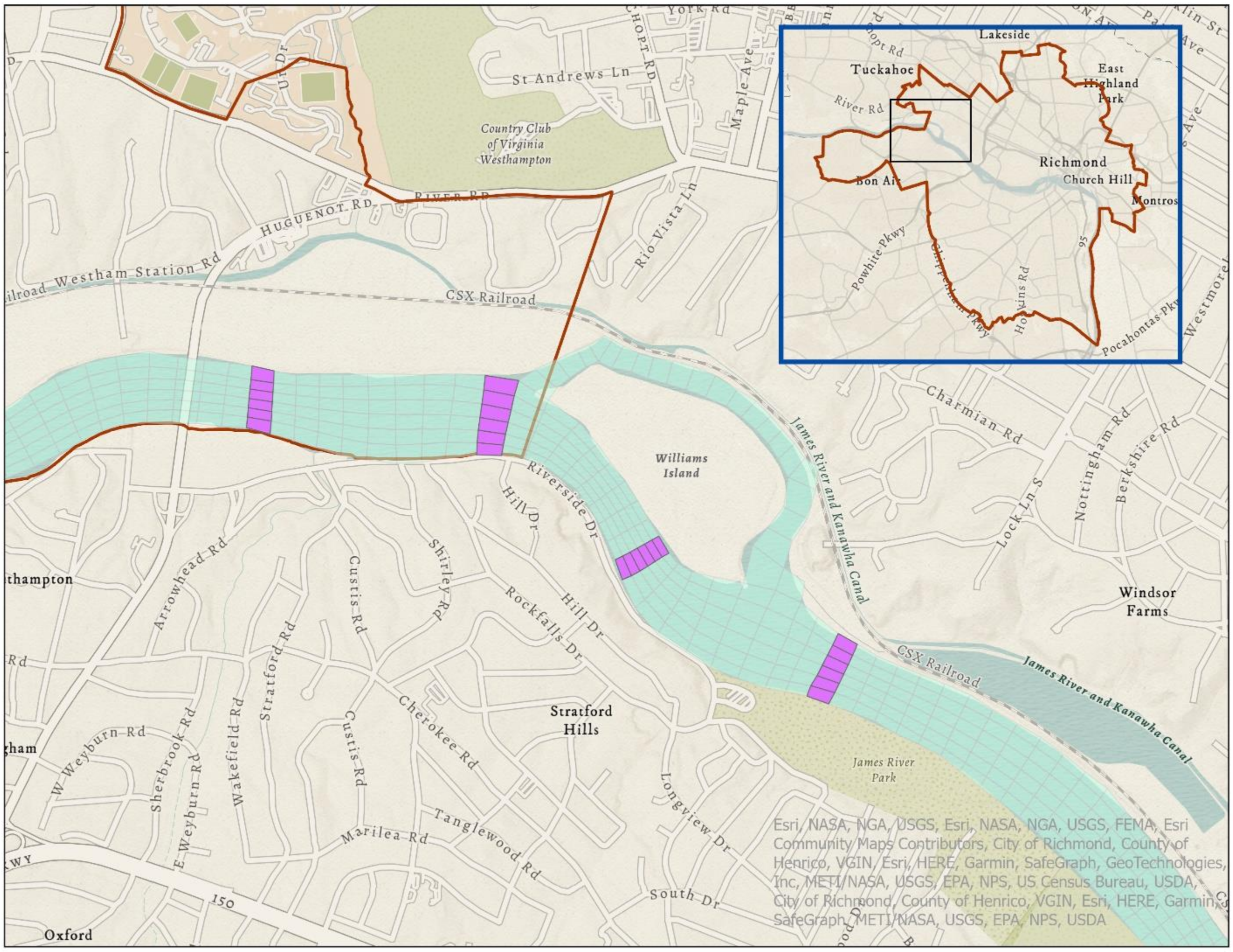


Figure 3-6. Background Source Model Input Locations

3.2.4 MS4/Tributary Model Inputs

The water quality model includes inputs that represent the flows and *E. coli* loads from tributaries to the James River within the greater Richmond area, as well as from Richmond's Municipal Separate Storm Sewer System (MS4). Note that the Gillies Creek and Almond Creek tributaries both receive CSO discharges. Estimates of the MS4 and tributary flows and loads are provided by application of a watershed model developed by LimnoTech. The watershed model is based upon the EPA Storm Water Management Model (SWMM) framework and uses the SWMM engine version 5.2.3. The model is operated within the PCSWMM environment.

3.2.5 CSS Model Inputs

The water quality model also incorporates inputs reflecting the flows and *E. coli* loads stemming from Richmond's CSOs as well as the wastewater treatment plant (WWTP). The flow inputs are calculated using the CSS Final Plan collection system model which was developed by Brown and Caldwell. The model is built on the EPA Storm Water Management Model (SWMM) framework and uses the SWMM engine version 5.1.015. The model is also operated within the PCSWMM environment. *E.coli* loads for each outfall are calculated based on the simulated flows and EMC values which are described in section 3.1.3.

3.2.6 Decay rate

The *E. coli* decay rate was evaluated during previous rounds of water quality modeling and is described in detail in Appendix C, Section 3.2.4 of the 2021 Interim CSS Plan Water Quality Model Report (City of Richmond, 2021) as well as in Appendix A, Section 3.1.4 of the 2017 Clean Water Plan (City of Richmond, 2017). The decay rate of 1/day that was used for both the 2017 Clean Water Plan and the 2021 Interim CSS Plan was maintained for the Final CSS Plan water quality modeling.

3.2.7 Bacteria Source Components Analysis

The water quality model was run in components analysis mode for all simulations. Running the water quality model in this mode allows for the tracking of each *E.coli* source separately. The model reports the share of *E.coli* that each source component contributes to the total *E.coli* load at any location and time step in the model. The five *E.coli* source types that are tracked are:

- Upstream: incoming James River *E.coli* load upstream of the City of Richmond.
- CSO: combined CSO *E.coli* loads
- WWTP: wastewater treatment plant effluent *E.coli* load. If the scenario includes high-rate disinfection (HRD) at the Shockoe Retention Basin, this source also includes that *E.coli* load.
- Stormwater / Tributaries: combined MS4 and James River tributaries *E.coli* loads that discharge to the James River within the City of Richmond boundary.
- Background Source: Background *E.coli* load, introduced between Huguenot Bridge and 14^{th} Street Bridge (see section 3.2.3).

3.3 Water Quality Model Performance Evaluation for 2019-2021 "Existing Conditions"

The primary objectives of the James River water quality model performance evaluation were to: 1) evaluate the reasonableness of modeled *E. coli* loads (i.e.: does the model capture the central tendencies of monitoring data) and 2) evaluate the completeness of modeled *E. coli* sources (i.e.: are all known sources represented adequately). These objectives were achieved by evaluating consistency between modeled and observed *E. coli* concentrations at different locations in the James River and identifying and resolving significant biases. The *E.coli* concentrations in the James River are largely controlled by estimates of *E. coli* concentrations from upstream of the study area and by estimates of *E. coli* concentrations from the CSS. Because of this, particular attention was given to evaluate water quality model performance at the following *E.coli* monitoring locations:

- Upstream/Huguenot Bridge: This sampling location reflects the *E.coli* contributions from all incoming James River *E.coli* loads upstream of the City of Richmond.
- CSO-06: This sampling location on the north shore of the river just downstream of the CSO-06 outfall reflects the *E.coli* contributions from upstream, background, and MS4/tributary sources. During wet weather events, this location primarily shows the impact of CSO-06 (Shockoe Retention Basin) discharge, which is the largest CSO within the City.
- CSO-040: This sampling location on the south shore of the river just downstream of the CSO-40 outfall reflects the *E.coli* contributions from upstream, background, and MS4/tributary sources. During wet weather events, this location primarily shows the impact of CSO-040 discharge, which is one of the largest CSO's within the City.
- Buoy 168: This sampling location reflects the cumulative *E.coli* contributions from all sources included in the model. In addition, it reflects the impact of tidal re-entrainment on *E.coli* concentrations in the James River. The location is near the Luck Stone Quarry property.
- Downstream (D/S) City Boundary: This sampling location, like Buoy 168, also reflects the cumulative *E.coli* contributions from all sources in the model and the impact of tidal re-entrainment. This sampling location is located where the James River exits the City of Richmond.

The water quality model was applied using the Performance Evaluation Period (2019-2021) to evaluate the model's performance under existing conditions. All sewer model inputs reflect as best as possible the condition and operation of the CSS, MS4, and the WWTP systems during the 2019-2021 period. The upstream load also reflects as best as possible the flows and loads of the 2019-2021 period, using flow data from the USGS and *E.coli* concentrations that were developed through application of the LOADEST tool (see also section 3.2.1). The background source model input is independent of the hydrologic period and so was not modified for purposes of the model performance evaluation (see also section 3.2.3).

3.3.1 Performance Evaluation at Key Locations

E.coli concentrations predicted by the water quality model were compared against the *E. coli* concentrations obtained from the monitoring program at five locations along the James River. The hourly model results for the entire evaluation period were plotted against the sampled data for each location, as shown in **Figure 3-7**. In addition, the modeling and monitoring data were summarized using box-and-whisker plots, as shown in **Figure 3-8**. These box and whisker plots show the minimum and maximum concentration within each data set (the whiskers) as well as the 25th percentile, median, and 75th

percentile of each data set (the three lines comprising the blue box). The goal for the water quality model is to capture the central tendencies of the monitoring data, so particular attention is given to comparing the boxes between the modeled and monitoring data. Several observations can be made from this evaluation:

- The model captures the variability of bacteria at the upstream end of the City well most of the time. The modeled *E. coli* concentrations tend to be higher than the observed *E. coli* concentrations during baseflow or dry weather conditions. This is because the LOADEST regression tends to overpredict the lower-end bacteria concentrations. Maximum modeled *E. coli* concentrations also tend to be higher than observed *E. coli* concentrations. This is because model results are computed for every hour of the evaluation period, while samples were only taken once a week, making it unlikely that the samples would capture the highest *E. coli* concentrations that actually occur in the river.
- At locations CSO-40 and CSO-06, the model results show higher and more frequent *E.coli* peaks than the monitoring data. These are due to the CSO discharge events. These overflow events are rarely captured by monitoring efforts due to their short duration but are captured by the water quality model. Although the model predicts higher peaks at these two locations, the model results are generally consistent with the monitoring data.
- Median model values are slightly lower than the median sample values for the Buoy 168 and D/S City Boundary locations. These two locations are more sparsely sampled (only twice a month instead of once a week) and may not reflect all the weather conditions that are captured by the model data.
- The model predicts higher maximum and higher minimum *E.coli* concentrations compared to the sampling data. This results in a conservative representation of *E.coli* concentrations in the James River (i.e.: in this context, more conservative means higher *E.coli* concentrations)
- The model adequately captures the central tendencies of the monitoring data (i.e.: results are within the same order of magnitude) at all locations.

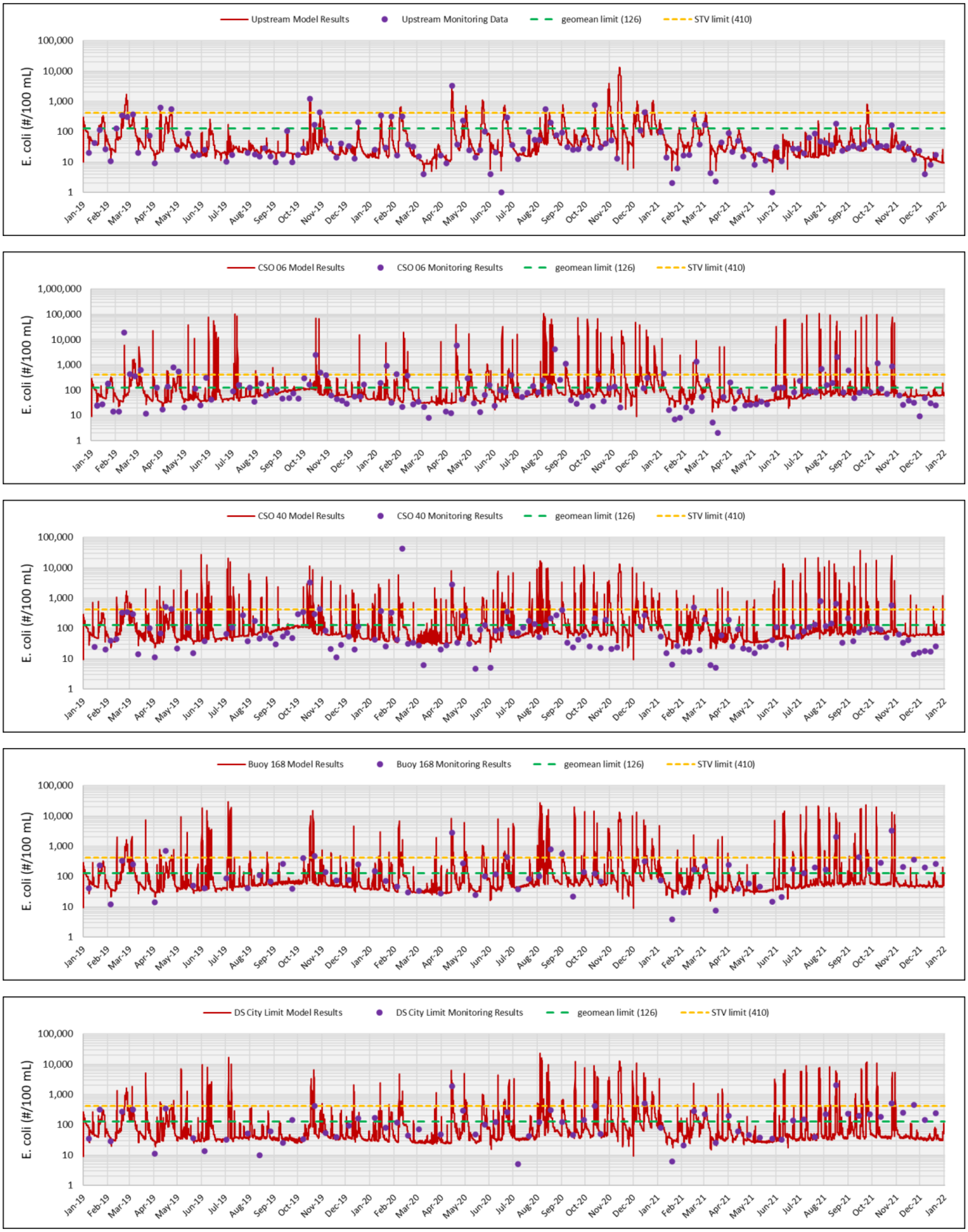


Figure 3-7. Comparison of Modeled and Sampled *E. coli* Time Series Concentrations at Select James River Locations (2019-2021).

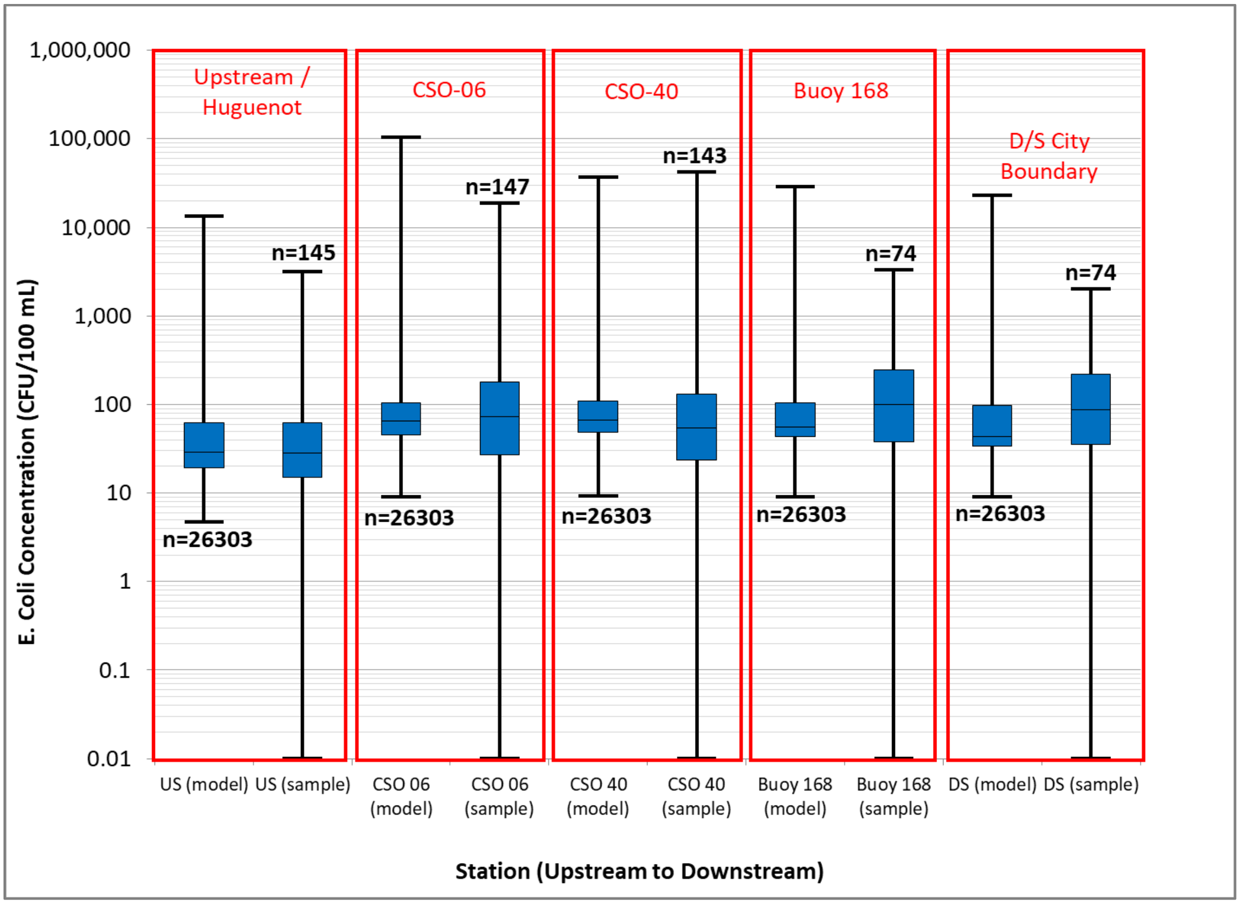


Figure 3-8. Comparison of Modeled and Sampled *E. coli* Concentrations Box and Whisker Plots at Select James River Locations (2019-2021).

4 Water Quality Model Application and Final CSS Plan Scenario Evaluation

The water quality model was used to evaluate the following scenarios:

- Scenario 1: CSO baseline conditions, which represented the CSS conditions existing circa 2019-2021, as well as CIP projects that are currently underway.
- Scenario 2: 100% CSO in-situ disinfection, which assumes that all CSO discharges are completely captured and fully treated (disinfected) at each CSO location.
- Scenario 3: 2005 Special Order Projects, which are the projects included in the 2005 Special Order / LTCP.
- Scenario 4: Alternative Regulatory Compliance, which includes slightly different CSS infrastructure projects as compared to Scenario 3, but these projects are the least expensive system improvements that meet the same regulatory requirements as Scenario 3.
- Scenario 5: Preliminary CSS Final Plan Project Selection, which are CSS infrastructure projects that provide more bacteria reductions as compared to Scenario 3 or 4

These projects are described in more detail in the next subsections, as well as in the main body of the CSS Final Plan. The water quality model was applied and results were evaluated for the Scenario Evaluation Period of 2011-2013.

The following process was followed when applying the water quality model to evaluate the various strategies:

1. Simulate improvements to the combined sewer system or treatment plant with the CSS model;
2. Relay CSS model results to the watershed model to simulate impacts of CSO's in Gillies Creek and Almond Creek;
3. Relay the watershed and CSS model results to the James River Receiving Water Quality Model; and
4. Summarize the results of the water quality model scenarios using the metrics described below.

The water quality model scenario results were evaluated relative to compliance with the geometric mean and the statistical threshold value (STV) water quality criteria, on a 90-day rolling basis. These criteria require that the geometric mean *E. coli* concentration does not exceed 126 cfu/100 mL and that no more than 10% of *E. coli* concentrations may exceed 410 cfu/100 mL in any given 90-day period for a water body to be in compliance with the recreational bacteria water quality standards. Model results were also evaluated relative to the reduction in total *E.coli* load from the CSO component source.

For all scenarios, model results were evaluated at five locations along the James River that highlight key locations in the system and also correspond to sampling locations: the Upstream City Boundary near Huguenot Bridge; near CSO 06 (Shockoe); near CSO 40; Buoy 168 near Luck Stone Quarry; and Buoy 166 at the Downstream City Limit.

4.1 Baseline Conditions

4.1.1 Overview

The baseline model includes several system improvements to the model applied to assess existing conditions, as described in **Table 4-1**.

Table 4-1: Summary of baseline model changes

Existing Conditions	Baseline Conditions
Shockoe Retention Basin, Hampton/McCloy Retention Tunnel, Shockoe 96" and Twin 66" Sewers not cleaned out	Shockoe Retention Basin, Hampton/McCloy Retention Tunnel, Shockoe 96" and Twin 66" Sewers cleaned out (1-ft of debris was assumed to remain in these sewers for the evaluation)
CSO 4, 5, 21 tide gates always open	CSO 4, 5, 21 tide gates operating as intended
CSS Interim Plan (10) projects are not included	CSS Interim Plan (10) projects are included

The baseline model assumes 75 MGD of full or complete treatment at the WWTP with an assumed effluent concentration of 4 CFU/100mL, which is consistent with WWTP long-term effluent monitoring results. The baseline model also assumes that wet weather flows up to 140 MGD are treated at the WWTP using the following log reduction function for UV-based primary treatment to estimate the effluent *E.coli* concentration:

$$Effluent\ E.coli\ concentration = \frac{influent\ concentration}{reduction\ factor}$$

$$Log\ reduction\ factor = 0.76 * 10^{2.57904-1.2563*\log(Q)}$$

Where: Q is the WWTP inflow in MGD (between 75 MGD and 140 MGD)

The reduction factor is large when wet weather flows are small due to increased contact time with the UV disinfection system. Therefore, a treatment floor of 21 cfu/100 mL was set, which is consistent with long-term wet weather treated effluent monitoring data.

In addition to WWTP upgrades, the baseline model was also modified to include cleaning of the Shockoe 96" and twin 66" sewers such that these two sewers can flow at full capacity, as well as upgrades to the tide gates that prevent inflow from the James River.

4.1.2 Results

The water quality model's *E. coli* load *inputs* per component source were summarized to assess the relative contribution of each source for the Scenario Evaluation Period (2011-2013). **Figure 4-1** shows the percent contribution of *E.coli* loads by component source for the baseline model inputs. This figure shows that the *E.coli* loads from upstream sources are the largest, followed by the CSO *E.coli* loads. One of the primary goals of the CSS Final Plan is to reduce the CSO *E.coli* loads.

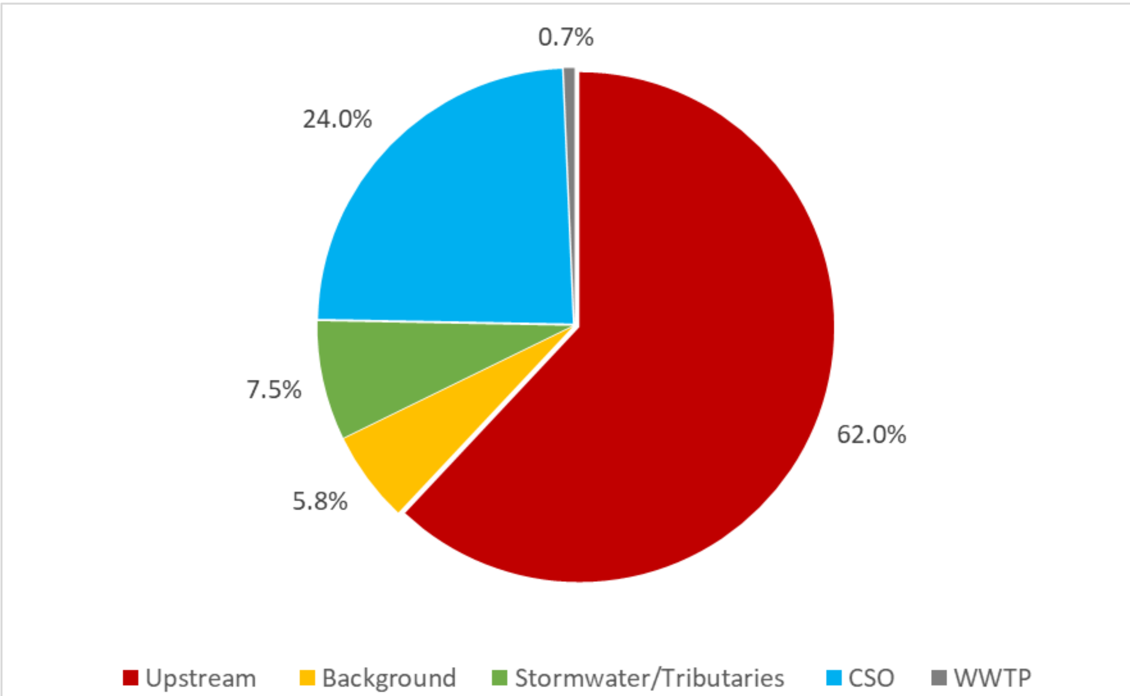


Figure 4-1. Percent Contribution of *E.coli* Loads by Source, Baseline Model Inputs

Figure 4-2 shows the baseline source component input loads summed by month, along with monthly precipitation totals for Richmond. This plot shows that in some months, the upstream loads dominate, while in other months, the CSO loads dominate. The CSO loads tend to dominate the overall *E.coli* load during the summer months when there is heavier and more intense local precipitation events (summer storms) that cause the CSOs to discharge. The upstream loads tend to dominate the overall *E.coli* load during the winter and spring months, when the precipitation in the upstream watershed causes the river flows to swell and carry more *E.coli* load towards Richmond.

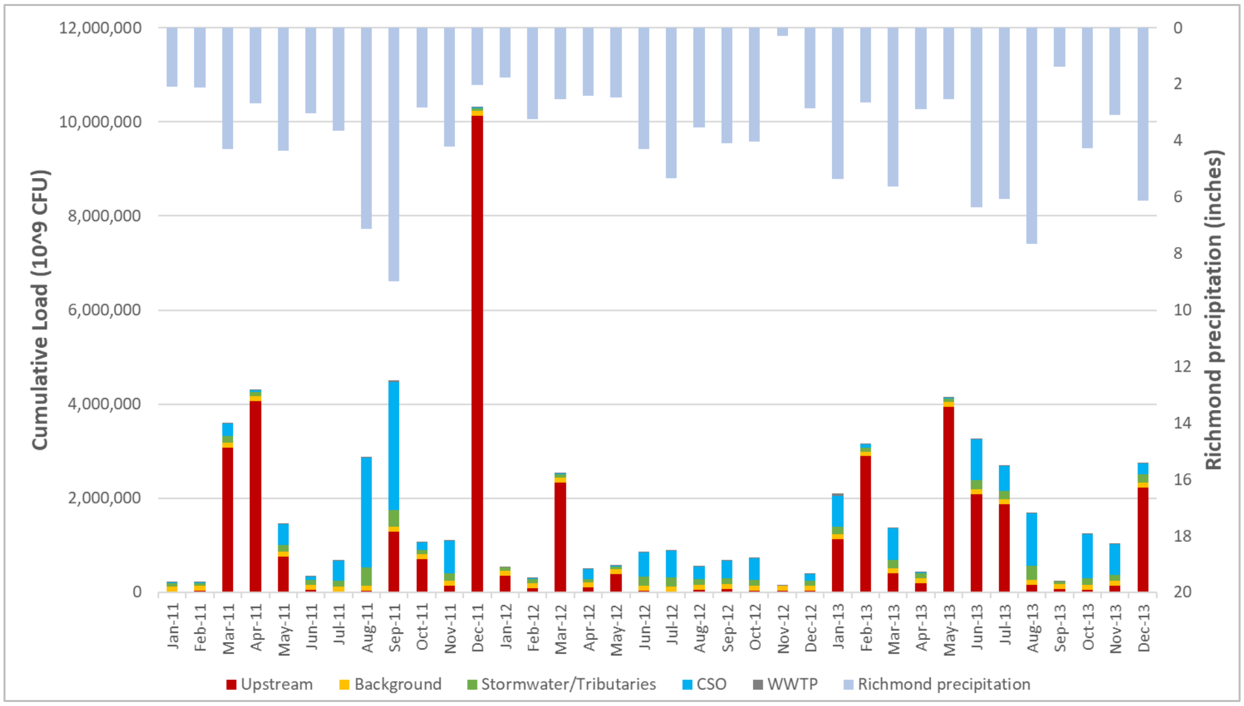


Figure 4-2. Contribution of *E.coli* Load by Source and Month, Baseline Model Inputs

The results shown in **Figure 4-3** and **Figure 4-4** are of the model-predicted 90-day geomean *E. coli* concentrations and the 90-day percent exceedance of the STV, respectively. Several observations can be made:

- The model predicts that the 90-day geomean standard of 126 CFU/100mL is not exceeded at any of the five key locations for the 2011-2013 hydrologic period under the baseline conditions.
- At two of the locations – CSO-40 and the Downstream City Limit – the 90-day percent STV exceedance limit of 10% is exceeded three times, in December 2011, September 2012, and July 2013.
- The highest geomean concentrations are observed at the CSO-40 and CSO-06 locations in the James River. These are the two areas that the CSS Final Plan is targeting for improvement.
- The highest percent exceedances of the STV limit are observed at the CSO-40 and DS City limit in the James River. Implementation of the CSS Final Plan, and particularly the reduction of CSO discharges at CSO-40 and CSO-06, will help reduce these exceedances.

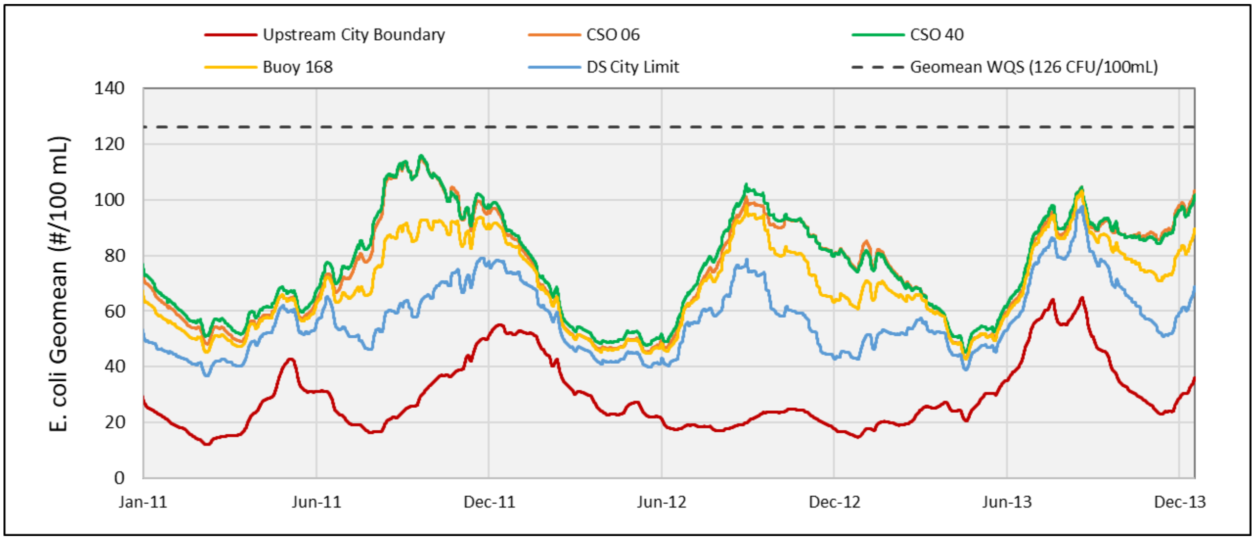


Figure 4-3. *E. coli* 90-day Geomean, Baseline Model

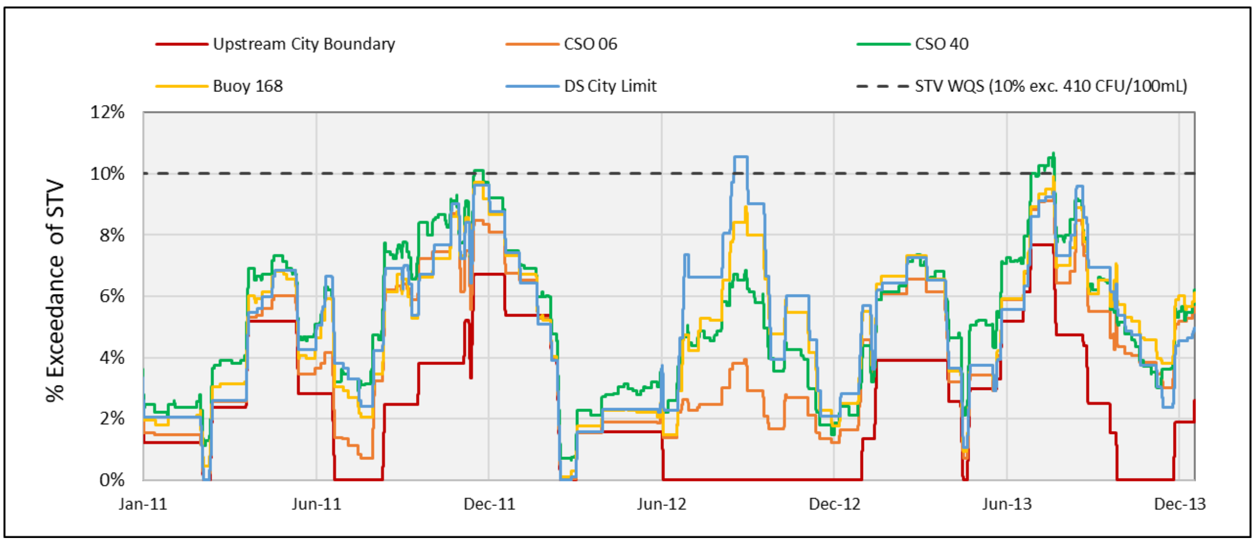


Figure 4-4. *E. coli* STV Exceedance Percentages, Baseline Model

4.2 Final CSS Plan Scenarios

4.2.1 Overview

The water quality model was applied to evaluate four different CSS Final Plan scenarios, in addition to the baseline scenario. Those were described briefly in the introduction to Section 4; **Table 4-2** provides details about the system configuration and operation for each scenario.

Table 4-2. Summary of Alternative Scenarios.

Scenario #	Scenario Name	Description
2	100% CSO In-Situ Disinfection	All CSO discharges are captured and fully treated (disinfected) at each CSO location.
3	Special Order Projects	Remaining CSO Projects included in the 2005 Special Order (LTCP) are implemented. These infrastructure projects include: • Conveyance sewer from Outfalls 004, 005, 034 and 035 to the WWTP (7-ft to 8-ft diameter) [SO #13] • High-Rate Disinfection Facility at the WWTP (160-MGD) to increase ability to handle additional wet weather flows [SO #15] • High-Rate Disinfection Facility on Chapel Island to control Outfall 006 (3,300-MGD) [SO #19]
4	Alternative Regulatory Compliance	Least expensive improvements that still meet the same regulatory requirements as the 2005 Special Order projects (Scenario 3) but with alternative and less expensive infrastructure projects, including: • Convert a portion of the SRB to a High-Rate Disinfection Facility (1,000 MGD) • Storage Tank at the WWTP to serve Outfall 021 (10 MG) • Hilton Street Separation of the combined sewer drainage • Dock Street Conveyance sewer from Outfalls 005, 034 and 035 to the SRB (5-ft diameter) • Gillies Creek Sewer Improvements
5	Preliminary CSS Final Plan Project Selection	Substitute several projects from scenario #4 to provide more bacteria reduction. This scenario includes the following infrastructure projects: • Convert a portion of the SRB to a High-Rate Disinfection Facility (1,000 MGD) • Hilton Street Separation of the combined sewer drainage • Storage Tank in Canoe Run Park (6 MG) to reduce overflows at CSO-40 • Storage Tank at Outfall 031 (1 MG)

For all scenarios, only the CSS and MS4/tributary model inputs to the water quality model varied. The CSS inputs changed according to the modeled improvements to the CSS infrastructure. The MS4/tributary model changed only for tributaries that have CSO discharges, which includes Gillies Creek and Almond Creek. The other inputs to the MS4/tributary model, like tributary stormwater and baseflow inputs, were identical across all scenarios. Other model inputs, such as the flow and *E.coli* load from upstream and from the background source were identical across all scenarios, as were the downstream tidal conditions.

4.2.2 Results

The model results for the 90-day geomean *E. coli* concentrations and for the 90-day percent exceedance of the STV criterion were compared at the five locations along the James River for all five scenarios. The magnitudes of differences between scenarios vary based on location, but generally the scenarios can be ordered as follows, in descending order of *E. coli* concentration:

1. Baseline [scenario #1, highest *E.coli* concentrations]
2. Special Order Projects [scenario #3]
3. Alternative Regulatory Compliance [scenario #4]
4. Preliminary CSS Final Plan Project Selection [scenario #5]
5. 100% CSO In-Situ Disinfection [scenario #2, lowest *E.coli* concentrations]

Figure 4-5 and **Figure 4-6** show the differences in geomeans and STV percent exceedance, respectively, at several key locations in the James River. Several observations can be made:

- The James River near CSO-40 shows the largest in-stream water quality improvements under scenario 2 (100% CSO In-Situ Disinfection) and scenario 5 (Preliminary CSS Final Plan Project). STV exceedances seen under baseline, scenario 3, and scenario 4 are no longer observed under scenarios 2 and 5 at this location.
- The James River near CSO-06 shows similar in-stream water quality improvements under scenarios 2 through 5 because those scenarios provide similar levels of control for the CSO-06 discharge.
- The James River at the downstream end of the City shows the largest in-stream water quality improvements under scenario 2 (100% CSO In-Situ Disinfection) and scenario 5 (Preliminary CSS Final Plan Project). STV exceedances seen under baseline conditions are no longer observed under scenarios 2 through 5 at this location.

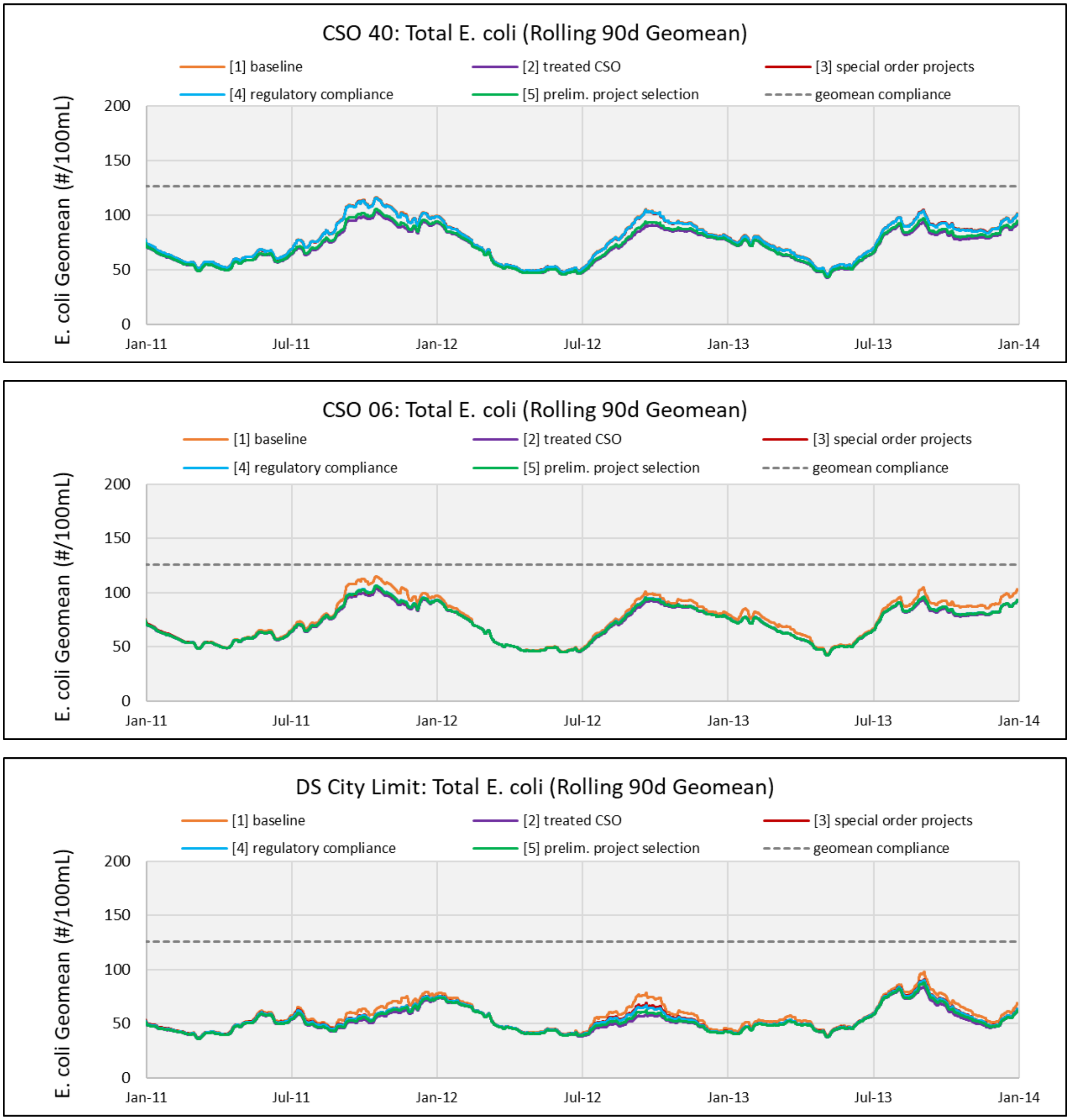


Figure 4-5. Model Scenario Comparison, 90-day Geomean

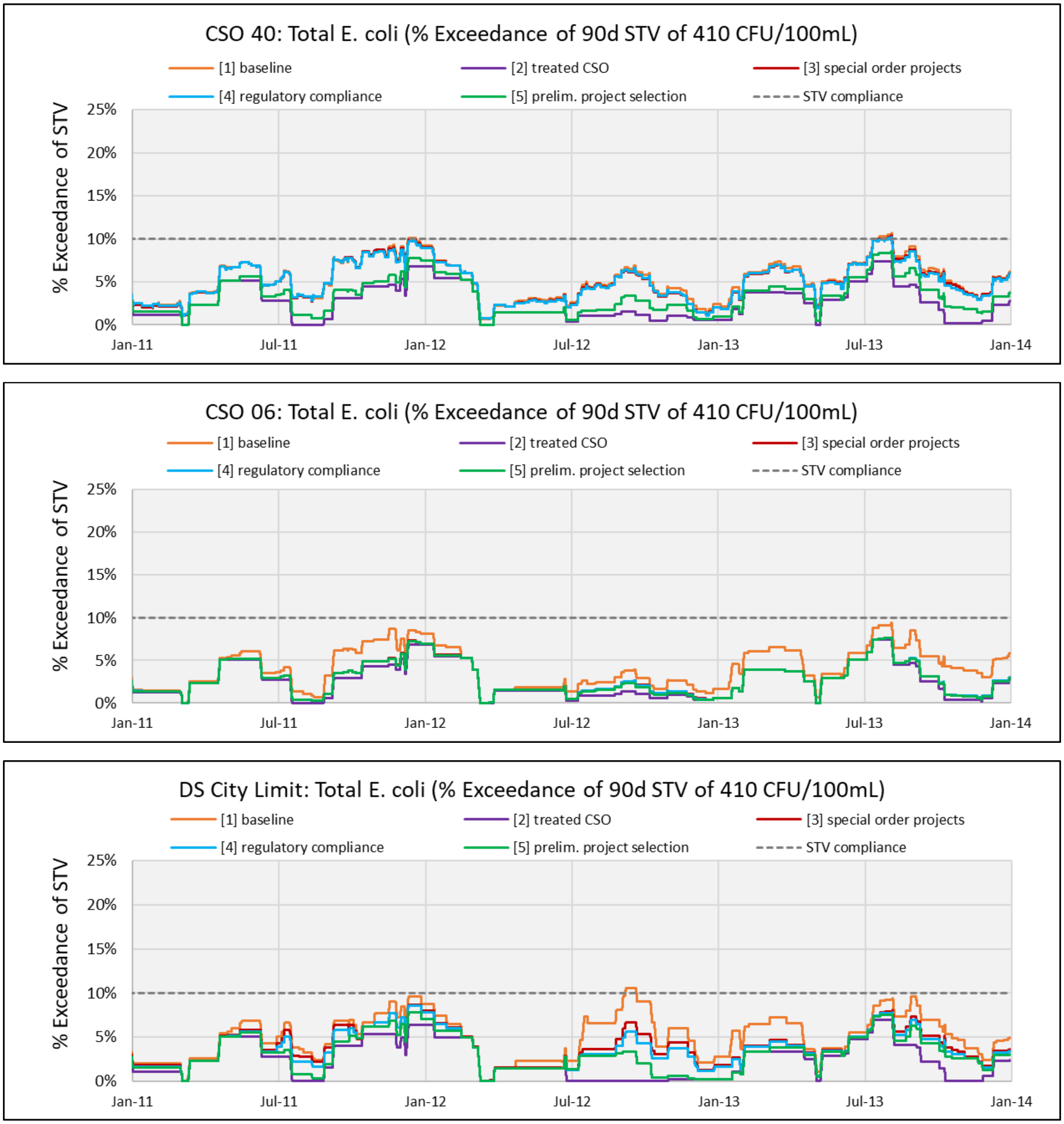


Figure 4-6. Model Scenario Comparison, 90-day Percent STV Exceedance

The total CSO *E.coli* load inputs per component source were computed and summarized for scenario 5 and compared to the baseline condition to assess the impact of the CSS infrastructure projects on CSO *E.coli* load. This comparison is shown in

Figure 4-7**.** The CSS infrastructure improvements included in Scenario 5 result in a significant reduction of CSO *E.coli* load, turning this load from the second *biggest* overall load under the baseline conditions to the second *smallest* overall load under Scenario 5.

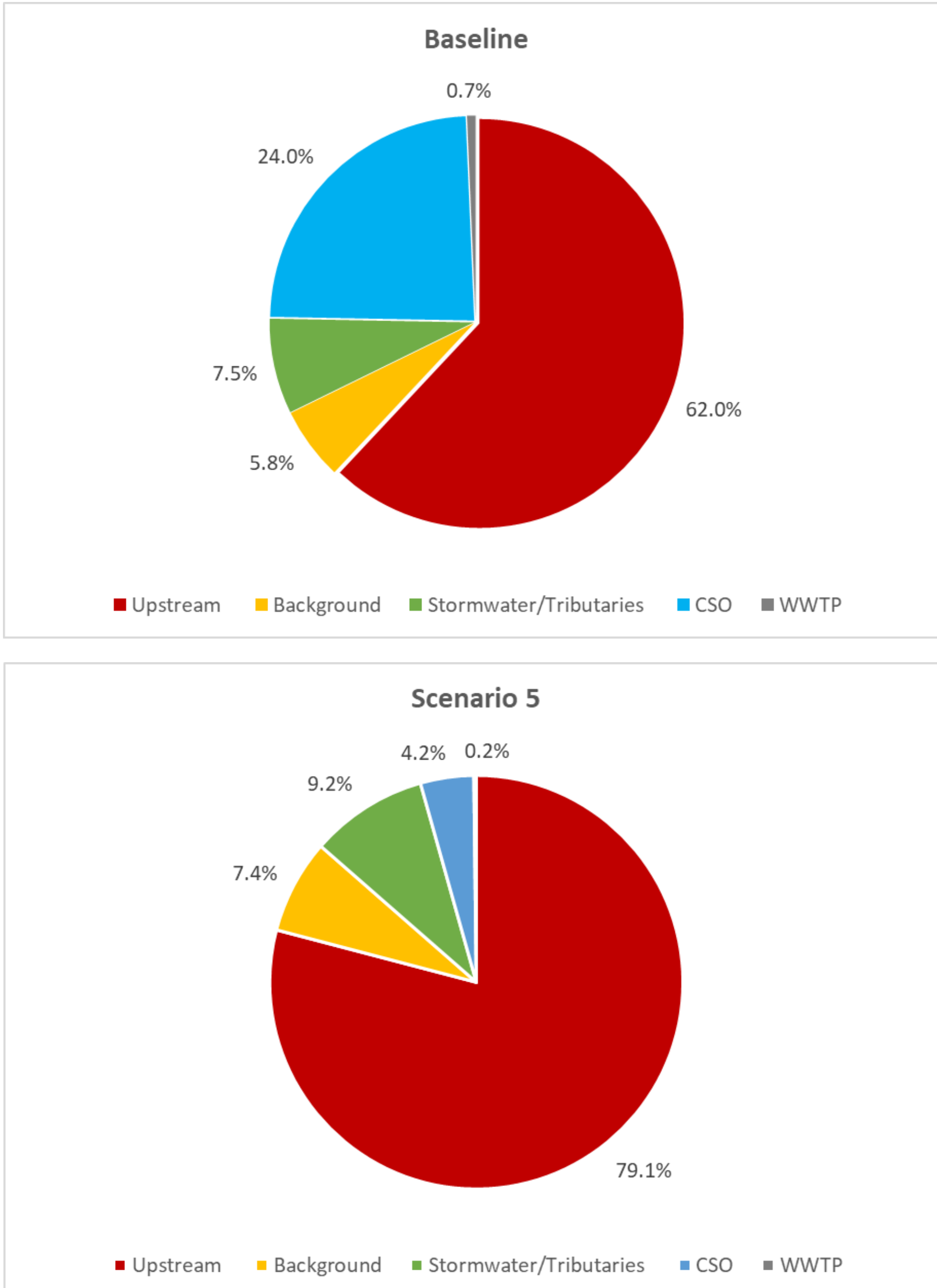
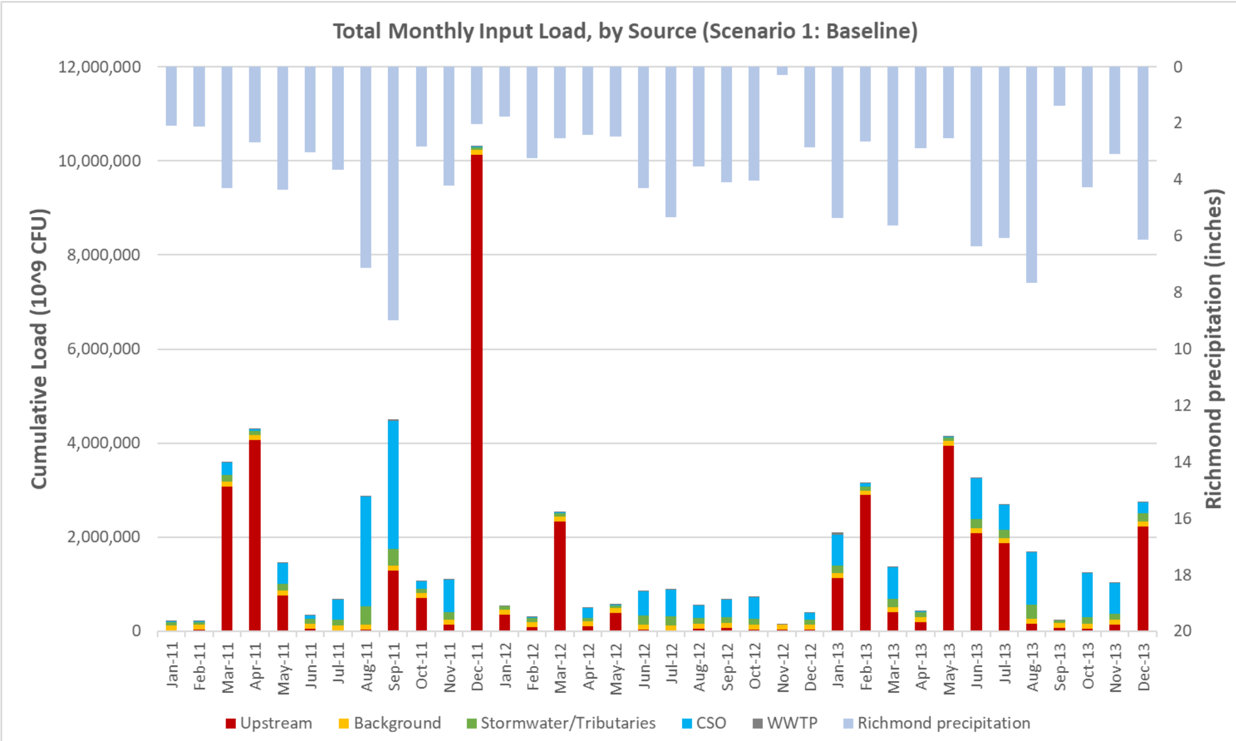


Figure 4-7. Percent Contribution of *E.coli* Loads by Source, Baseline vs Scenario 5 Model Inputs

Figure 4-8 below shows the source component input loads summed by month for both the baseline conditions and scenario 5. This figure illustrates the significant reduction in overall CSO *E.coli* load due to the CSS infrastructure improvements from scenario 5, as seen by comparing the size of the blue bars in the top figure with the bottom figure.



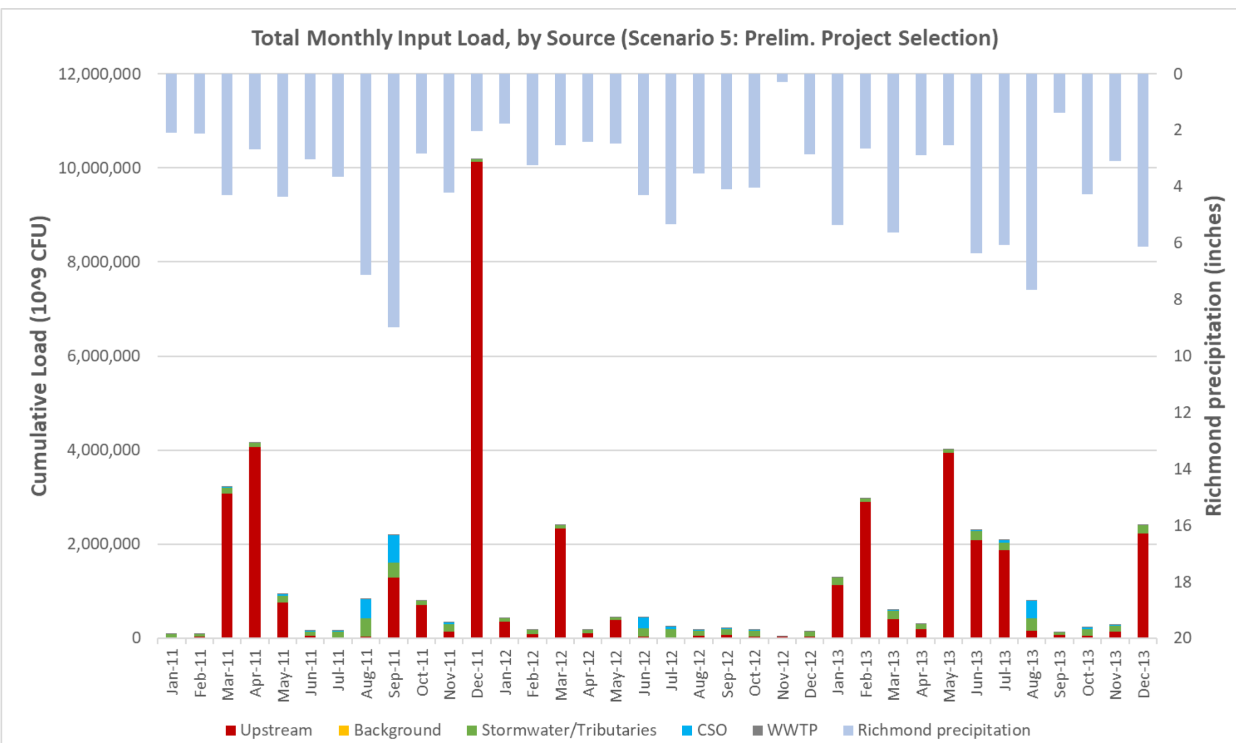


Figure 4-8. Contribution of *E.coli* Load by Source and Month, Baseline vs. Scenario 5 Model Inputs

4.3 Animations

Animations (videos) of the water quality model scenarios (baseline and scenario 5) are available for viewing and downloading from the RVAH2O website (https://rvah2o.org/).

5 References

City of Richmond. 2017. 2017 RVA Clean Water Plan. https://j3n7e4b9.stackpathcdn.com/wp-content/uploads/2020/02/Final_RVA_Clean_Water_Plan.pdf

City of Richmond. 2021. CSO Interim Plan Report. https://rvah2o.org/wp-content/uploads/2021/07/Interim-Plan-Report-2021-0617-1.pdf

MapTech, 2010. Bacterial Total Maximum Daily Load Development for the James River and Tributaries – City of Richmond. November 2010. McCuen, R. et al. 1996. Hydrology, FHWA-SA-96-067, Federal Highway Administration, Washington, DC

TetraTech, 2007. The Environmental Fluid Dynamics Code. User Manual. US EPA Version 1.01 https://www.epa.gov/sites/production/files/2016-01/documents/efdc_user_manual_epa_ver-101.pdf

USEPA, 2012. 2012 Recreation Water Quality Criteria Fact Sheet https://www.epa.gov/sites/production/files/2015-10/documents/rec-factsheet-2012.pdf

USGS, 2017. Load Estimator (LOADEST): A Program for Estimating Constituent Loads in Streams and River. Website accessed 2/13/2017. Page last modified: 12/12/2016.

VADEQ, 2019. Water Quality Standards. 9VAC25-260-170 https://law.lis.virginia.gov/admincode/title9/agency25/chapter260/section170/

VADEQ, 2024. Water Quality Assessment Guidance Manual https://townhall.virginia.gov/L/GetFile.cfm?File=C:\TownHall\docroot\GuidanceDocs\440\GDoc_DEQ_7624_v1.pdf