Task 5.2 Receiving Water Quality Model Development and Calibration

CSO Post Construction Monitoring and Performance Assessment

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1. Introduction

1.1 Water Quality Modeling Objectives

MWRA's Combined Sewer Overflow (CSO) performance assessment is the last scheduled milestone in the nearly 35-year-old Federal District Court Order in the Boston Harbor Case (U.S. v. M.D.C., et al, No. 85-0489 MA). MWRA has addressed 183 CSO-related court schedule milestones, including completion of the thirty-five (35) wastewater system projects that comprise the Long Term Control Plan (LTCP) by December 2015 and commencement of the CSO performance assessment by January 2018 (which MWRA met in November 2017). The last court milestone requires MWRA to submit the results of its performance assessment to the U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (DEP) by December 2021. This assessment, which is also required by the Water Quality Variances currently in place for the Charles River and Alewife Brook/Upper Mystic River, will demonstrate whether the levels of CSO control and water quality goals specified in the LTCP have been achieved.

An extensive flow metering and hydraulic collection system modeling effort has been undertaken to establish the level of attainment of the targets established in the LTCP for average annual CSO activations and volumes, based on the Typical Year rainfall. The Typical Year was developed during the CSO LTCP project based on comparison with 40-year rainfall records (Kubaska and Brocard, 1993). Year 1992 was selected as the basis of the typical year because it was the only year for which 15-minute rainfall data were available and modeling had shown that this data frequency was needed to provide accurate CSO predictions. Changes were made to the 1992 rainfall data to better match the long-term record. Eight storms between 0.25 and 0.50 inches of total rainfall were removed from the 1992 rainfall series, and two storms between one and two inches of total rainfall were added. The storms removed and added were selected to bring the month-by-month distribution of storms closer to the long-term average. It should be noted that the project 1-year design storm is one of the storms that was added to the Typical Year. This on-going effort has been documented in Semiannual CSO Discharge Reports 1 (November 2018) through 5 (October 2020) and will be further documented in subsequent reports until October 2021. Receiving water quality monitoring data to date demonstrate water quality improvements that are in line with the Authority's CSO planning projections.

This report describes the development and calibration of hydrodynamic and water quality models of the Charles River and Alewife Brook/Upper Mystic River. Looking ahead, the receiving water model simulations to be performed with these models will be critical in demonstrating whether the objectives of the LTCP have been satisfied for the CSO variance waters. The Authority expects that the results of the water quality assessment will demonstrate that the relative impact of the remaining CSO discharges is small. To quantify the water quality improvements, and to specifically identify CSO versus non-CSO contributions, these water quality models have been developed for the receiving waters currently covered by Water Quality Variances (Charles River and Alewife Brook/Upper Mystic River).

The specific water quality issues to be addressed by the models are to:

- Assess the relative impact of CSO on water quality in the Charles River and Alewife Brook/Mystic River.
- Provide information about impacts of stormwater and boundary conditions.
- Predict resulting *Enterococcus* and *E. coli* counts during the 3-month and 1-year storms as well as the Typical Year.

These models will be used to assess the benefits to water quality in these receiving waters resulting from the improvements made by implementing the MWRA CSO Long Term Control Plan over the last 30 years. Further model predictions will influence consideration given to whether further investments in CSO mitigation will result in meaningful water quality improvements and whether emphasis on non-CSO contributions of pollution would be more cost-effective. Regulatory options going forward must acknowledge that even though a LTCP has been completed consistent with court ordered requirements, state water quality standards may not be met as a result of stormwater or other non-CSO contributions, regardless of whether CSO discharges remain.

1.2 Description of the Models

The models that are used and the data sampling plans used to populate the model are described in a stipulated joint agreement submitted to the Court on July 18, 2019 by the Authority, the Department of Justice, and the Massachusetts Office of Attorney General, and are also referenced in MassDEP's water quality standards variances. The model and their coverages are as follows:

- The Charles River model is being implemented with the Delft3D software in two-dimensional mode. The model extends from the New Charles River Dam and Locks to the Watertown Dam (see Figure 1-1).

- The Alewife Brook/Upper Mystic River model is being implemented with the one-dimensional InfoWorks ICM software. The model extends from the Amelia Earhart Dam to the Lower Mystic Lake outlet and it includes the entirety of Alewife Brook (see Figure 1-1).

The models calculate time-varying distributions of *Enterococcus* and *E. coli* counts as a function of rainfall hyetographs (rainfall as a function of time) and other inputs. As an intermediate step, the rainfall data are input to other models to assess the CSO, stormwater, and stream boundary flowrates as a function of time.

The two models are "water quality models", inasmuch as their most important outputs are water quality parameters. However, they include hydrologic and hydrodynamic components that assess rain-derived inflows to the streams and the flow of water in the streams, both of which are essential elements of the water quality predictions.

This report describes the development and calibration of the two models. The calibrated models will then be used to assess the impacts of CSOs, stormwater and upstream inflows on stream water quality for the 3-month and 1-year design storms (historical storms with specific return periods that have been used in previous MWRA CSO planning activities) as well as the Typical Year used in the CSO LTCP process. This assessment will be presented in a later report.

The data used in the model development are summarized in Section 2. The calibration process and data used for the calibration are described in Section 3. The Charles River model and the Alewife Brook/Upper Mystic River models are described in Sections 4 and 5 respectively. Section 6 provides a summary and next steps for the use of the models.

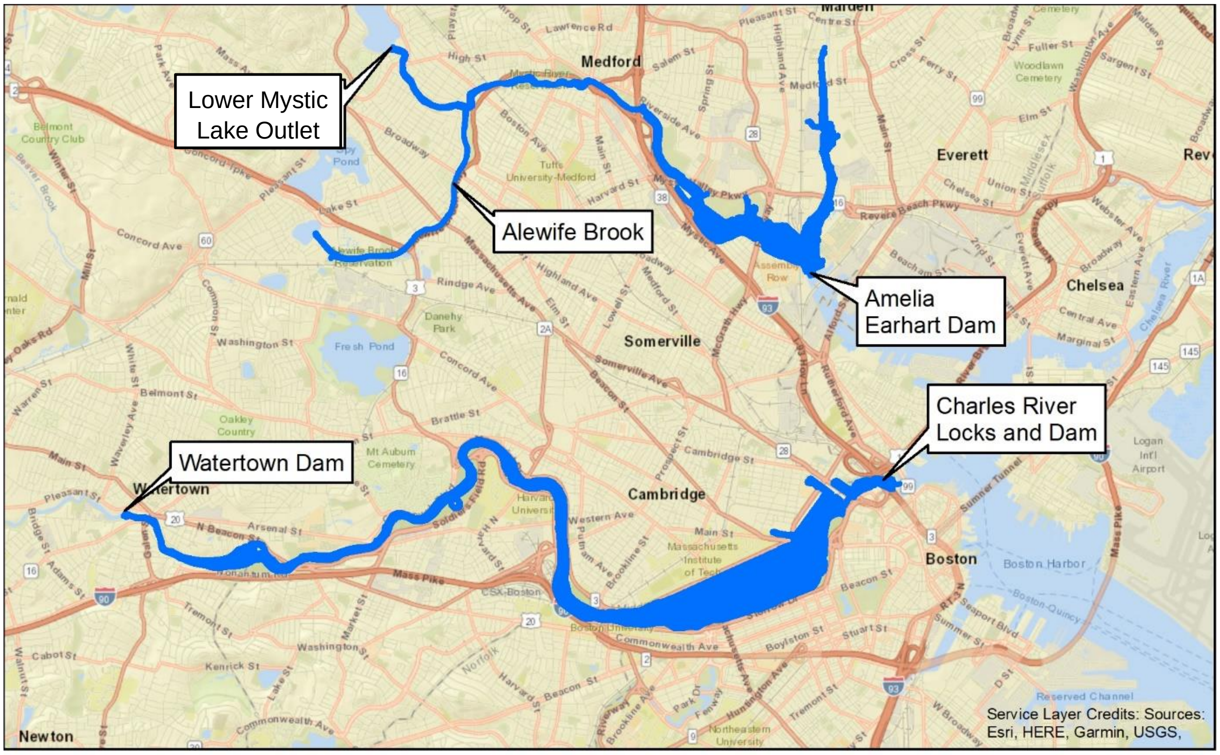


Figure 1-1. Extent of the Charles River and Alewife Brook/Upper Mystic River Models

2. Model Configuration and Input Data

2.1 Overview

The receiving water models compute time and spatially-varying *Enterococcus* and *E. coli* counts within the rivers based on the physical shape of the rivers as configured in the models, the various sources of flow that are input into the models, and the loadings from the identified sources of *Enterococcus* and *E. coli* that are input into the model. The sources for these various inputs are summarized for each model in Table 2-1. Site-specific details on the bathymetry, upstream boundary flows and quality, CSO flows and stormwater flows are provided for the Charles River and Alewife Brook/Upper Mystic River models in Sections 4 and 5, respectively. BWSC is conducting a stormwater quality monitoring program in 2020 and 2021, however the data are not yet available. When these data are available they could be used as a reasonableness check for the numbers being used in the model. For the *Enterococcus* and *E. coli* counts to be applied to the CSO and stormwater inputs, a key question was whether to apply constant, site-specific and/or time-varying values. This decision required analysis (presented below in section 2.4) of measured counts of *Enterococcus* and *E. coli* in CSO and stormwater from both the Charles River and Alewife Brook/Upper Mystic River systems. There may be other sources of bacteria including sediment resuspension, however, these are beyond the scope of this modeling study. The analyses conducted and conclusions on the approach are presented in the subsections below.

Table 2-1. Model Input Sources

Parameter	Charles River	Alewife Brook/Upper Mystic
Bathymetry	- MIT surveys (2015-17)	- FEMA measurements (2003)
CSO flows	- MWRA collection system hydraulic/hydrologic model (2019)	
Untreated CSO quality	- Cottage Farm and Prison Point CSO Facility influent monitoring (2017-19)	- MWRA monitoring at CSO outfalls CAM401A and SOM001A (2019)
Treated CSO quality	- Cottage Farm effluent monitoring (2018 to 2019)	- Somerville Marginal CSO Facility effluent monitoring (2018)
Stormwater Flows	- BWSC Drain model - USGS Charles River Stormwater Model - Cambridge ICM Model	- InfoWorks ICM Mystic River Basin Model
Stormwater Quality	- BWSC stormwater model (2012-16) - USGS Monitoring (1999-2000)	- MWRA monitoring (2019) - Cambridge and Somerville Monitoring (2019-2020)
Upstream Boundary flow	- Waltham USGS Gauge	- InfoWorks ICM Mystic River Basin Model
Upstream Boundary quality	- Calibrated buildup/washoff model	- MWRA Monitoring (2017-2018)

2.2 Untreated CSO Quality Assessment

The following subsections describe the sampling measurements, analysis, and resulting approach selected for representing *Enterococcus* and *E. coli* counts in untreated CSO for the Charles River and Alewife Brook/Upper Mystic River water quality models.

2.2.1 Charles River

For the Charles River, the initial intent was to base the untreated CSO bacteria counts on an evaluation of measurements of influent counts at the MWRA's Cottage Farm and Prison Point CSO Facilities. Influent and effluent *Enterococcus* and *E. coli* counts have been measured by the MWRA since 2016 at its CSO treatment facilities during facility activations. While these facilities are designed and operated to treat CSO flows, samples from the influent (before treatment) were collected to represent untreated CSO bacterial quality. This information was used in the development of the receiving water model.

Influent bacterial counts from grab samples collected at Cottage Farm and Prison Point are summarized in Table 2-2. The Cottage Farm data were collected between October 2017 and August 2019, and the Prison Point data were collected between January 2018 and December 2019.

Table 2-2. Cottage Farm and Prison Point Influent Bacterial Counts

		Cottage Farm(1)	Prison Point(2)
	Number of Measurements	31	18
	Number of Storms	7	9
Enterococcus (MPN(3)/100 mL)	Arithmetic Average of all samples	206,000	48,000
	Geometric Mean of all samples	171,000	39,000
	Standard Deviation of all samples	159,000	35,000
E. coli (MPN(3)/100 mL)	Arithmetic Average of all samples	1,306,000	169,000
	Geometric Mean of all samples	865,000	134,000
	Standard Deviation of all samples	1,434,000	115,000

(1) Data collected between October 2017 and August 2019
(2) Data collected between January 2018 and December 2019
(3) MPN = Most Probable Number

For Cottage Farm, the samples were collected over the course of seven storm events, with the number of samples per event ranging from two to seven. For Prison Point, the samples were collected over the course of nine rain events, with two samples taken per event. The sampled counts did not exhibit a consistent pattern with regard to timing relative to the CSO activation. At Cottage Farm, some storms had the highest counts measured at the initial samples, some had the highest counts measured at the last sample taken, and some had the highest count in the middle samples. For Prison Point, some storms had the higher count measured at the first of the two samples taken, and some had the higher count measured in the second sample taken.

The results of the sampling data collected at Cottage Farm and Prison point presented in Table 2-2 show that the influent bacterial counts are much higher at Cottage Farm than at Prison Point. This difference is due to the different sources of flow to each facility. Cottage Farm receives flow diverted from the South Charles Relief Sewer, the North Charles Metropolitan Sewer, and the North Charles Relief Sewer, which are all major interceptors. The South Charles Relief Sewer extends far west into separately sewered towns (Watertown, etc.), while the North Charles systems serve primarily combined sewer areas.

For Prison Point, the main contributors of flow are the Old Stony Brook Conduit, and a few overflow lines in Cambridge/Charlestown. The amount of dry weather sanitary sewage in the conduits tributary to Prison Point is relatively low (there is a small dry weather pump station at Prison Point). Therefore, it can be expected that the flow to Prison Point would have a higher percentage of stormwater, and a lower percentage of direct sanitary flow, than the flow to Cottage Farm. This difference in relative stormwater versus sanitary flow fractions would explain the differences in the bacteria counts measured at the influents to Cottage Farm and Prison Point.

Given these distinct measured differences in bacteria counts, which could be tied to differences in the sanitary and stormwater fractions in the influent combined sewage, it did not seem appropriate to assign a single, average value of bacteria count to untreated CSO. Rather, it would be more appropriate to compute time-varying CSO counts based on the relative fraction of stormwater and sanitary flow in the CSO.

The fraction of sanitary and stormwater flow in the influents to the CSO facilities can be calculated by the collection system hydraulic/hydrologic model by assigning a tracer concentration of 1.0 to the sanitary flow and 0 to stormwater. The model can then calculate the tracer concentration in the combined sewage flow, and that concentration would equal the sanitary fraction in the flow. This approach is well-established, and has been utilized in water quality modeling of CSO impacts by a number of municipalities and agencies, including New York City and San Francisco. The mass-balance calculations include the sanitary component of flow originating from the interceptor system that backed up through the regulator. The interceptor system is a system of typically larger-diameter pipes that collect flow from local combined sewers, and convey the flow to a wastewater treatment plant. A CSO regulator controls flow by directing normal dry weather flow and a portion of wet weather flow to an interceptor for conveyance to treatment. Excess wet weather flow is directed to an overflow conduit. By assigning bacterial counts to the sanitary and stormwater components, the bacterial count of the mixed flow can be estimated using the following equation:

$$C_{total}(t) = F_s(t) * C_{san} + [1 - F_s(t)] * C_{sw}$$

where $C_{total}(t)$ is the time-varying total count/unit volume, $F_s(t)$ is the time-varying sanitary fraction calculated by the collection system hydraulic/hydrologic model, C_{san} is a constant count/unit volume representative of sanitary flow, and C_{sw} is a constant count/unit volume representative of the non-sanitary fraction (stormwater and infiltration). The sanitary and non-sanitary bacterial counts are to be selected such that the mixed count best matches the MWRA measured influent counts at both Cottage Farm and Prison Point.

This approach was applied to the November 10, 2018 storm, which had flows to both facilities as well as influent monitoring bacteria results. Figure 2-1 shows the calculated sanitary fraction in the influent flow to Cottage Farm and Prison Point versus time for the November 10, 2018 storm. As indicated in Figure 2-1, the Cottage Farm influent flow had a much higher sanitary fraction than the Prison Point influent flow, which is consistent with the differences in measured influent bacteria counts.

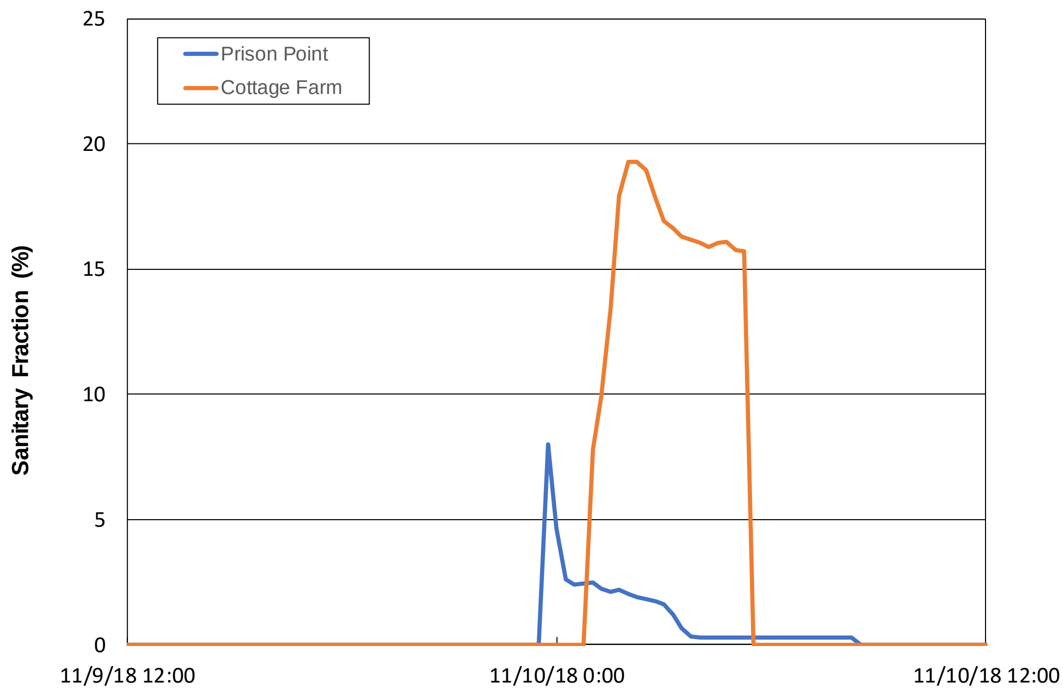


Figure 2-1. Calculated Sanitary Fractions at Cottage Farm and Prison Point for the November 10, 2018 Storm

One of the key considerations in using the sanitary fraction approach to estimating untreated CSO counts is the selection of the *Enterococcus* and *E. coli* counts to apply to the sanitary and non-sanitary fractions of the flow. Figure 2-2 presents the results of sampling of influent flow from the MWRA's North System at Deer Island from July 2015 through June 2020, representing a total of 60 samples taken under a range of flow conditions. Focusing on samples taken with flows less than about 220 MGD (North System average daily flow for 2019, from the MWRA Annual Infiltration and Inflow [I/I] Reduction Report for Fiscal Year 2020), which would tend to be consistent with dry days, the influent *Enterococcus* counts generally ranged from about 80,000 to 800,000 MPN/100mL. *E. coli* counts generally ranged from about 1,000,000 MPN/100mL to greater than 10,000,000 MPN/100mL. Given this range of measured counts in the North System influent at Deer Island, a reasonable question to ask would be whether a single count could be selected to represent the sanitary fraction in the upstream combined sewer systems.

To investigate this question, model runs were conducted to assess whether specified constant values for counts of *Enterococcus* and *E. coli* in sanitary and non-sanitary fractions could replicate measured influent counts at Cottage Farm and Prison Point over a range of storm events.

As starting point for this assessment, the model was run for the November 10, 2018 storm, with the non-sanitary fraction assigned the overall average of the *Enterococcus* and *E. coli* counts in stormwater samples collected in Arlington, Cambridge, Medford and Somerville as presented below in Table 2-4 (5,500 MPN/100 mL for *Enterococcus*, 13,400 MPN/100 mL for *E. coli*). Assigning the average stormwater counts to the non-sanitary fraction was a reasonable estimation, since in wet weather the non-sanitary fraction is mostly stormwater. The *Enterococcus* and *E. coli* counts in the sanitary fraction were then adjusted by trial-and-error until the modeled counts at Cottage Farm and Prison Point matched the measured values for that storm.

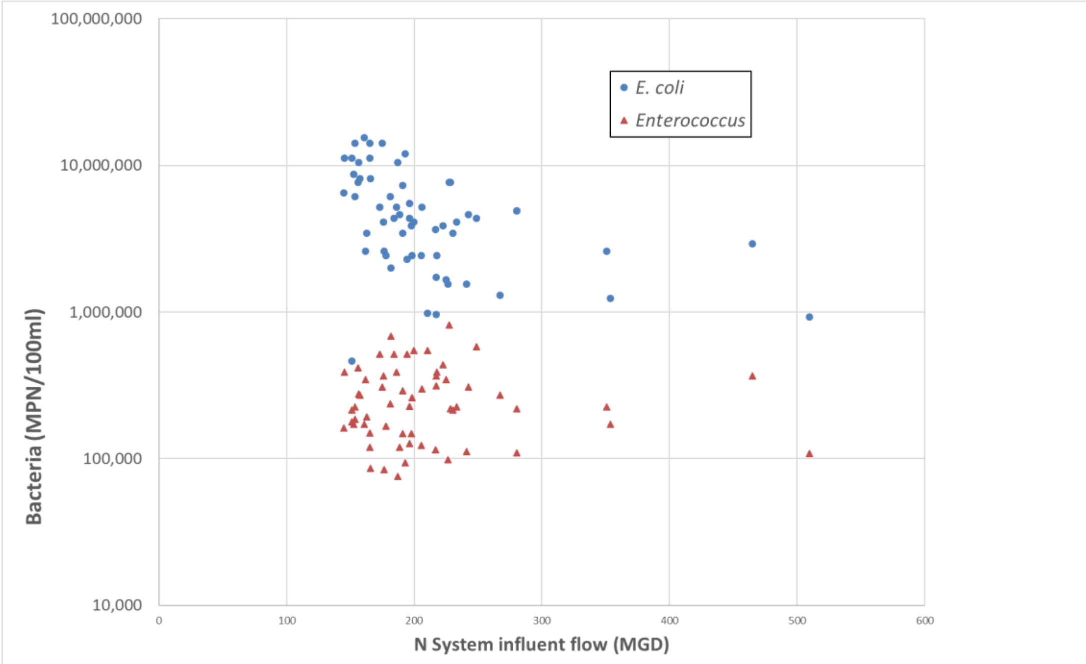


Figure 2-2. Deer Island North System Influent Measured Bacteria Counts

Figure 2-3 shows modeled versus measured influent *Enterococcus* counts versus time at Cottage Farm and Prison Point for the November 10, 2018 storm. The modeled values were based on the sanitary fractions shown in Figure 2-1, and *Enterococcus* counts of C_{san} = 1,000,000 MPN/100 mL for sanitary and C_{sw} = 5,500 MPN/100 mL for the non-sanitary fraction. The *Enterococcus* count that was arrived at for the sanitary component was above the range of sampled measurements for the North System at Deer Island. However, the sampled flow at Deer Island included both sanitary flow and infiltration, while in the model, the sanitary fraction does not include infiltration, which is a separate input value. Combining the modeled sanitary fraction and the modeled infiltration brings the resulting count back into the range measured at Deer Island.

Figure 2-4 shows the modeled versus measured influent *E. coli* counts versus time for the November 10, 2018 storm. The modeled values were based on the sanitary fractions shown in Figure 2-1, and *E. coli* counts of C_{san} = 7,000,000 MPN/100 mL for sanitary and C_{sw} = 13,400 MPN/100 mL for the non-sanitary fraction. The sanitary count was in the high end of the range of measured values from the North System at Deer Island, but as described above for *Enterococcus*, accounting for the infiltration flow in the model, the resulting count of sanitary plus infiltration flow brings these more in the mid-range of the measured values at Deer Island.

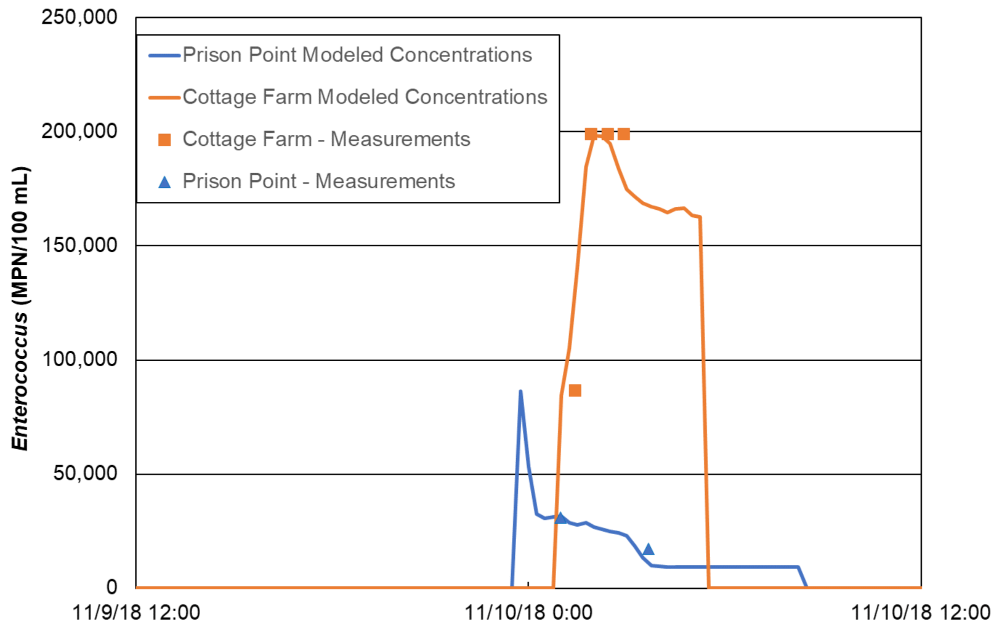


Figure 2-3. Measured and Calculated Influent *Enterococcus* Counts at Cottage Farm and Prison Point for the November 10, 2018 Storm

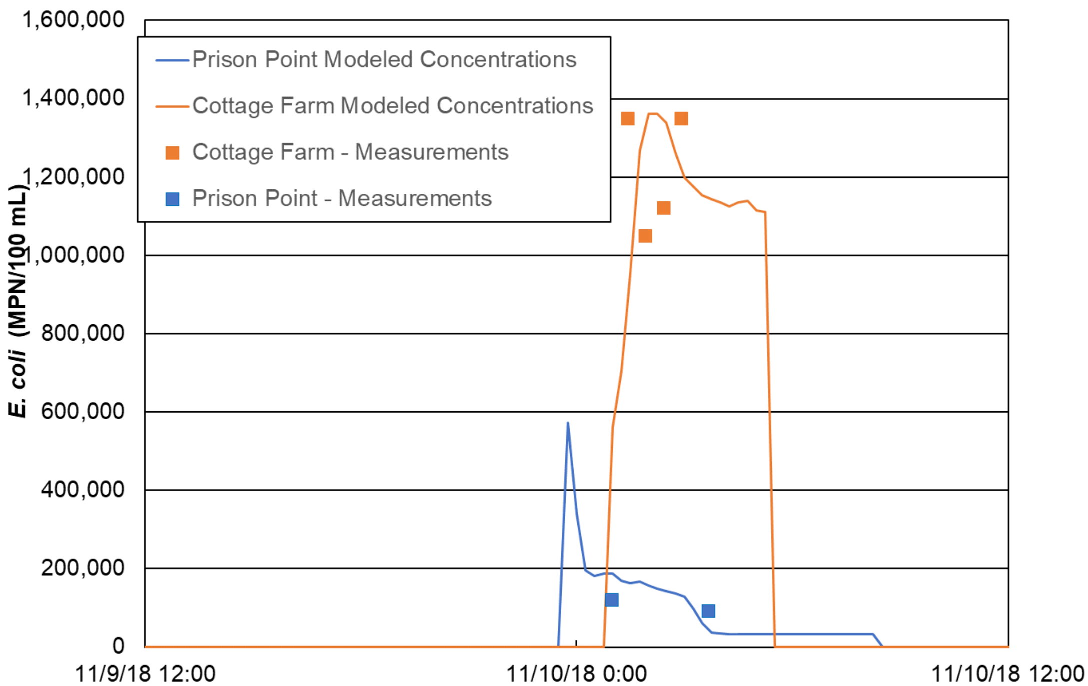


Figure 2-4. Measured and Calculated Influent *E. coli* Counts at Cottage Farm and Prison Point for the November 10, 2018 Storm

As indicated in Figures 2-3 and 2-4, the calculated influent counts of *E. coli* and *Enterococcus* closely matched the measured influent counts at Cottage Farm and Prison Point for the November 10, 2018 storm. The computational approach to modeling the influent bacterial counts based on the sanitary fractions was validated with measurements for the April 22, 2019 and August 8, 2019 storms at Cottage Farm (Figures 2-5 to 2-8), and the November 24 and December 14 storms at Prison Point (Figures 2-9 to 2-12). The measured values from those storms show the high degree of variability of the influent bacteria counts, with the Cottage Farm counts consistently higher than the Prison Point counts. The plots show that the model was able to replicate the relative orders of magnitude of the influent counts. Therefore, as a starting point for the water quality calibration, for all untreated CSOs discharging to the Charles River, the sanitary fraction was assigned an *Enterococcus* count of 1,000,000 MPN/100 mL and an *E. coli* count of 7,000,000 MPN/100 mL. Non-sanitary fractions were assigned an *Enterococcus* count of 5,500 MPN/100mL, and an *E. coli* count of 13,400 MPN/100mL.

In summary, the influent sampling data at Cottage Farm and Prison Point showed a substantial difference in the average influent bacteria counts at the two facilities. This finding indicated that selecting a single average value for CSO bacteria counts would not accurately represent the loadings from the various CSOs throughout the Charles River. Calculating CSO bacterial counts based on the sanitary fraction in the flow was demonstrated to reasonably match the widely-varying influent counts at Cottage Farm and Prison Point. Therefore, this approach was applied to generate the bacterial loadings from the untreated CSOs discharging to the Charles River. Additional details on the application of this approach to the CSOs in the Charles River are presented below in Section 4.3.4.

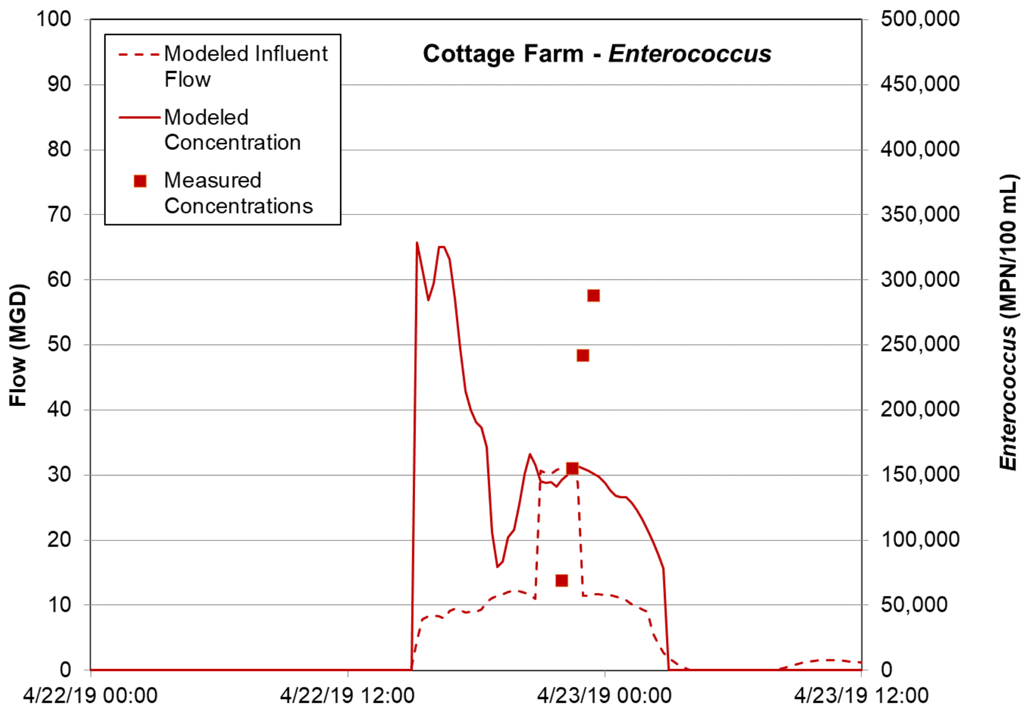


Figure 2-5. Measured and Calculated Influent *Enterococcus* Counts at Cottage Farm for the April 22, 2019 Storm

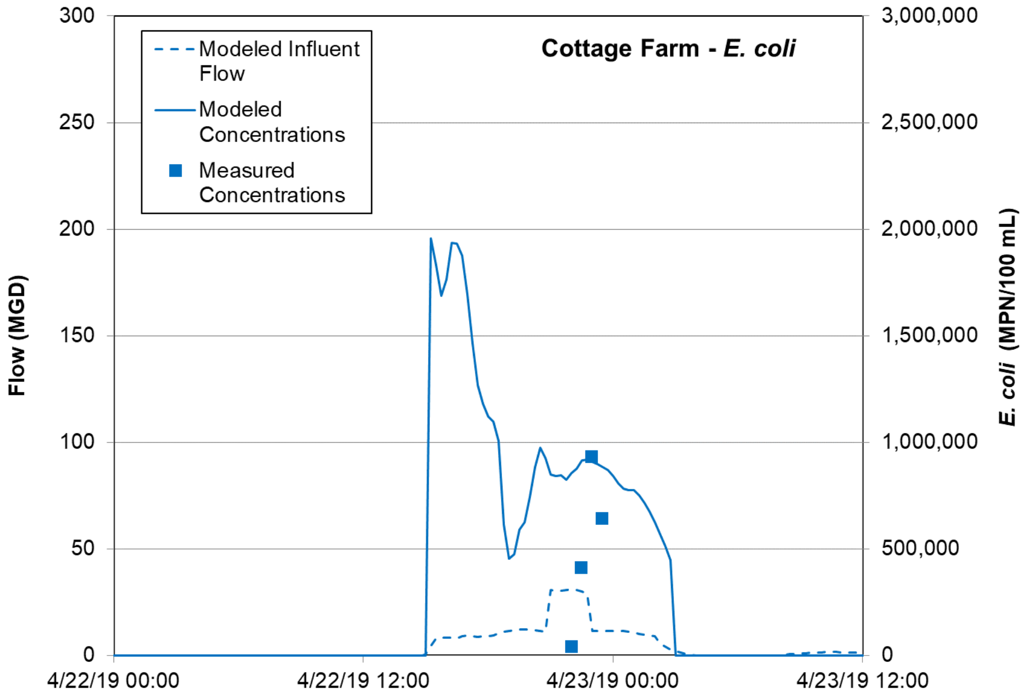


Figure 2-6. Measured and Calculated Influent *E. coli* Counts at Cottage Farm for the April 22, 2019 Storm

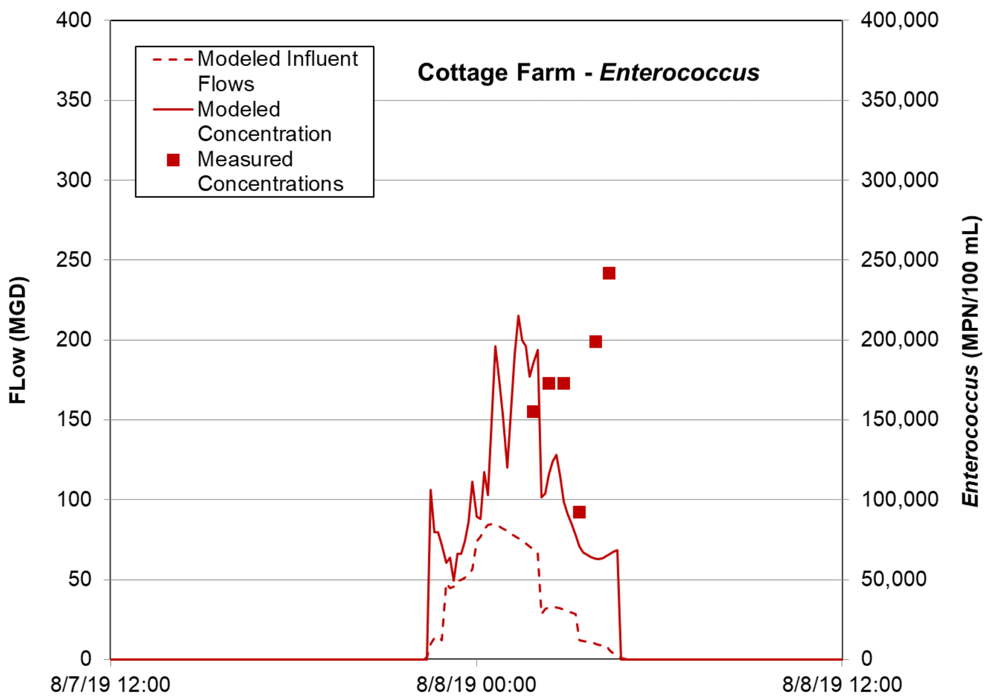


Figure 2-7. Measured and Calculated Influent *Enterococcus* Counts at Cottage Farm for the August 8, 2019 Storm

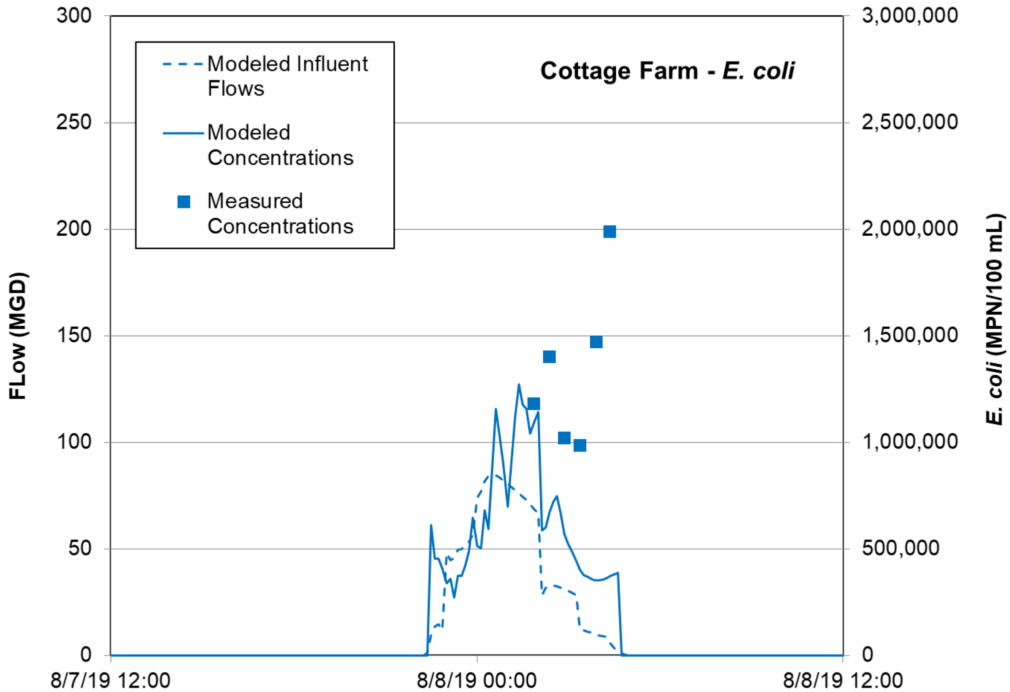


Figure 2-8. Measured and Calculated Influent *E. coli* Counts at Cottage Farm for the August 8, 2019 Storm

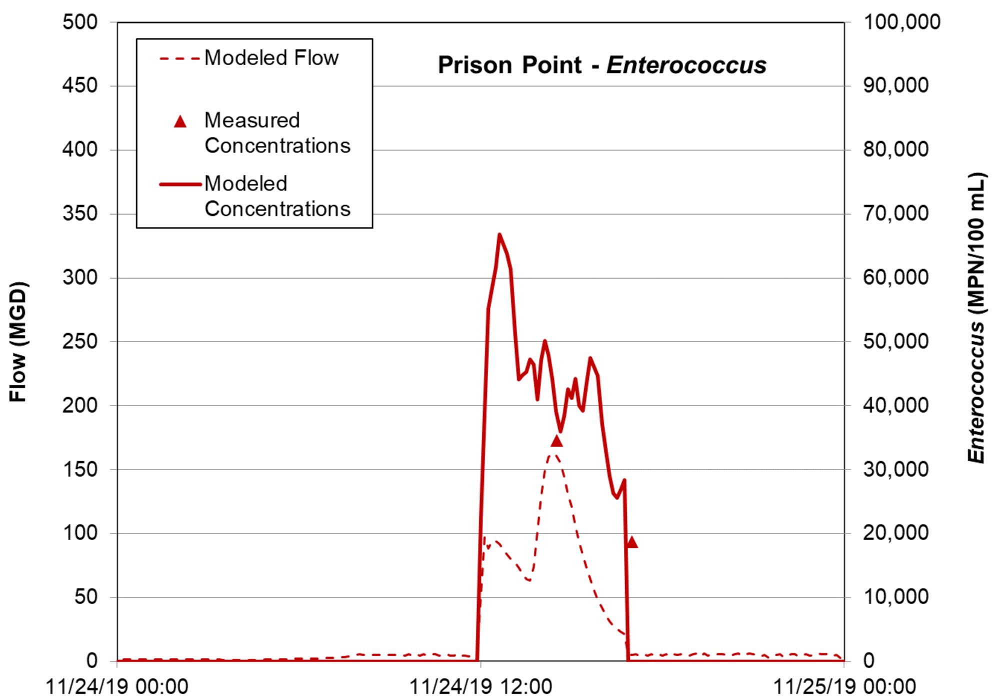


Figure 2-9. Measured and Calculated Influent *Enterococcus* Counts at Prison Point for the November 24, 2019 Storm

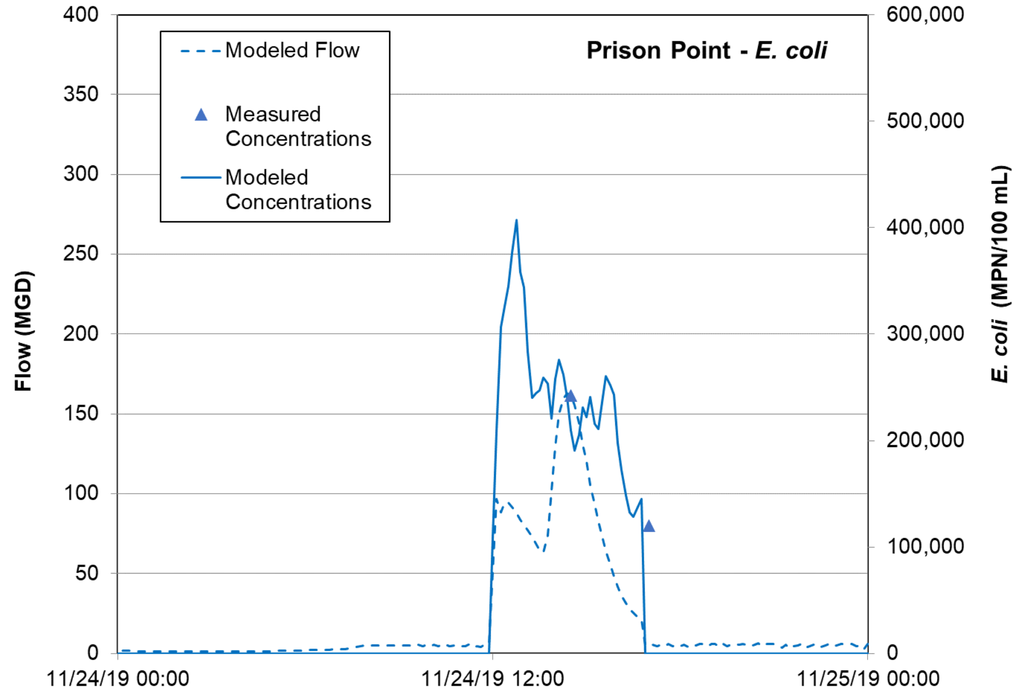


Figure 2-10. Measured and Calculated Influent *E. coli* Counts at Prison Point for the November 24, 2019 Storm

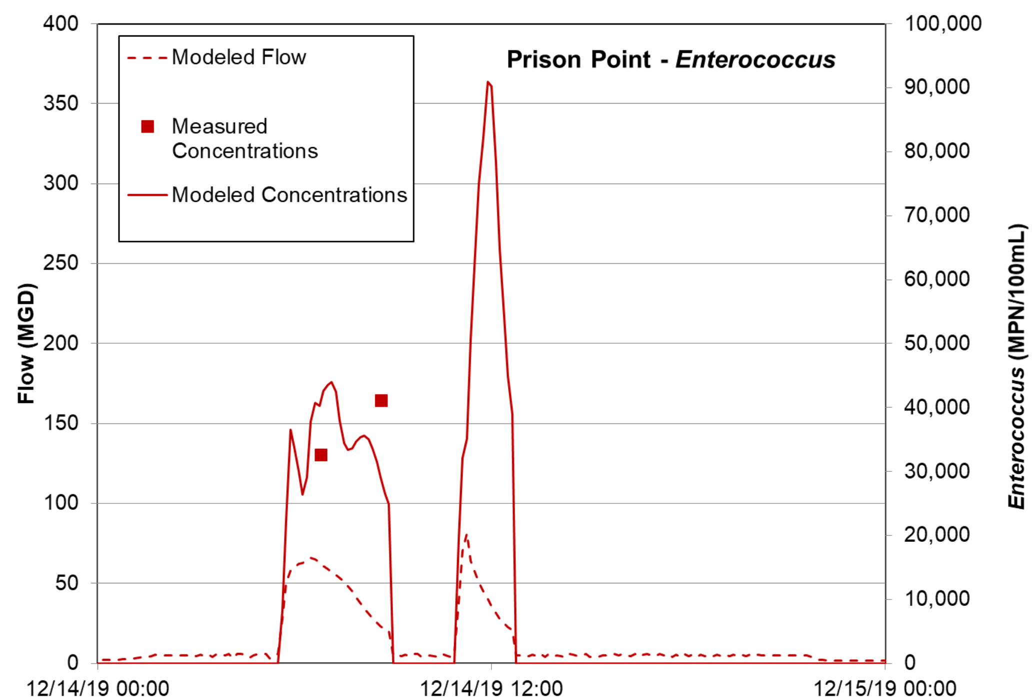


Figure 2-11. Measured and Calculated Influent *Enterococcus* Counts at Prison Point for the December 14, 2019 Storm

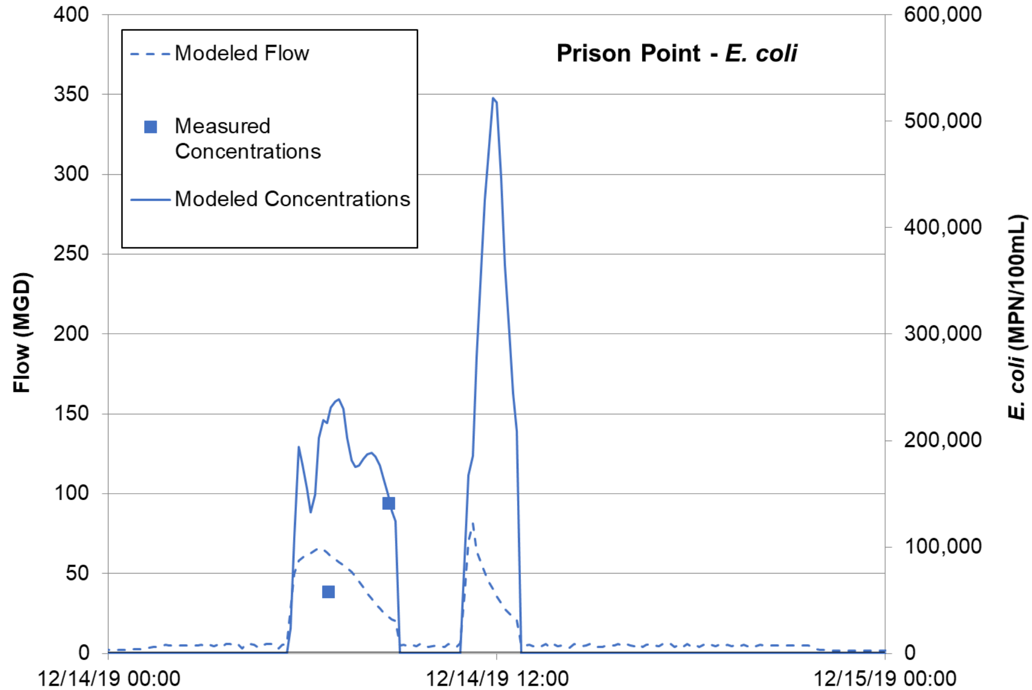


Figure 2-12. Measured and Calculated Influent *E. coli* Counts at Prison Point for the December 14, 2019 Storm

2.2.2 Alewife Brook/Upper Mystic River

Bacterial counts of the untreated CSOs discharging to the Alewife Brook and Upper Mystic River were specified using the same general approach as described above in Section 2.2.1 for the Charles River Model. In this approach, bacterial counts were assigned to the sanitary and non-sanitary components of combined sewage, and the bacterial counts in the CSO were calculated based on time-dependent sanitary fractions calculated by the collection system hydraulic/hydrologic model. As for the Charles River, the sanitary and non-sanitary bacterial counts in the CSO were calibrated based on measurements. For the Alewife Brook/Upper Mystic River, the modeled counts were compared to measurements from samples collected by the MWRA at CSO outfalls SOM001A and CAM401A.

The *Enterococcus* and *E. coli* counts measured in CSO outfalls CAM 401A and SOM001A in 2019 are summarized in Table 2-3. As indicated in Table 2-3, the measured values were relatively consistent when comparing the individual arithmetic means at outfalls CAM401A and SOM001A with the overall arithmetic means of all values.

As part of the initial efforts to calibrate the predicted CSO counts to the measurements shown in Table 2-3, it was discovered that the regulator associated with outfall CAM401A had no tributary sanitary flow in the model. The CSO monitoring data shown in Table 2-3 for samples collected immediately downstream of the weir indicate bacteria counts in the CSO that exceed the values expected for stormwater alone, indicating the presence of sanitary sewage. Consultations with the City of Cambridge indicated that much of the area upstream of outfall CAM401A had been separated, but the City agreed that the model should show some remaining sanitary flow tributary to the regulator. Therefore, a sanitary flow component was added to the model upstream of the regulator, adjusted to yield the measured sanitary fractions for the two 2019 storms when samples were collected. A constant sanitary inflow of 0.28 MGD was found suitable to match the measured counts immediately downstream of the weir.

Table 2-3. CSO Monitoring Data for Outfalls CAM401A and SOM001A Discharging to Alewife Brook

Outfall	Sample Time	*Enterococcus* MPN/100 mL	*E. coli* MPN/100 mL
CAM401A	8/29/19 0:20	36,500	54,800
CAM401A	8/29/19 0:40	61,300	86,600
CAM401A	8/29/19 1:20	54,800	86,600
CAM401A	10/17/20 0:31	54,800	130,000
CAM401A	10/17/20 0:46	22,500	36,500
CAM401A	10/17/20 1:01	17,900	21,900
CAM401A	10/17/20 1:16	30,800	13,100
CAM401A	10/17/20 1:31	16,100	17,200
CAM401A Arithmetic Mean		**36,838**	**55,838**
SOM001A	8/29/19 0:52	38,700	72,700
SOM001A	8/29/19 1:09	22,500	81,600
SOM001A	10/17/20 2:18	13,700	61,300
SOM001A	10/17/20 3:06	13,300	43,500
SOM001A Arithmetic Mean		**22,050**	**64,775**
Overall Arithmetic Mean		**31,908**	**58,817**
Overall Standard Deviation		**17,271**	**34,723**

Similarly, at outfall SOM001A, the collection system hydraulic/hydrologic model initially predicted an extremely low sanitary fraction in the overflow. To match the measured counts, a constant sanitary inflow of 0.94 MGD was added upstream of the regulator.

With these adjustments in place, following a similar trial-and-error process as used for the Charles River, the values for *Enterococcus* counts in the sanitary and non-sanitary fractions that best matched the measurements were 1,000,000 MPN/100 mL and 5,500 MPN/100 mL, respectively (same as those used for the Charles River model), while the *E. coli* counts in the sanitary and non-sanitary fractions that best matched the measurements were 2,500,000 MPN/100 mL and 13,400 MPN/100 mL, respectively (compared to 7,000,000/100 mL and 13,400/100mL for the Charles River). Figures 2-13 and 2-14 show the measured versus modeled *Enterococcus* counts at outfall CAM401A for the 8/29/19 and 10/17/19 storms, while Figures 2-15 and 2-16 show the measured versus modeled *E. coli* counts at CAM401A for those two storms. Figures 2-17 and 2-18 show the measured versus modeled *Enterococcu*s counts at outfall SOM001A for the 8/29/19 and 10/17/19 storms, while Figures 2-19 and 2-20 show the measured versus modeled *E. coli* counts at SOM001A for those two storms. As indicated in these figures, the model compared reasonably well with the measured values.

At outfall CAM401A, the sanitary fraction for the 8/29/19 storm ranged from 1.6 to 6.4 percent, and the sanitary fraction for the 10/17/19 storm ranged from 1.4 to 6.0 percent. At outfall SOM001A, the sanitary fraction for the 8/29/19 storm ranged from 1.9 to 2.8 percent, and the sanitary fraction for the 10/17/19 storm ranged from 1.4 to 2.0 percent.

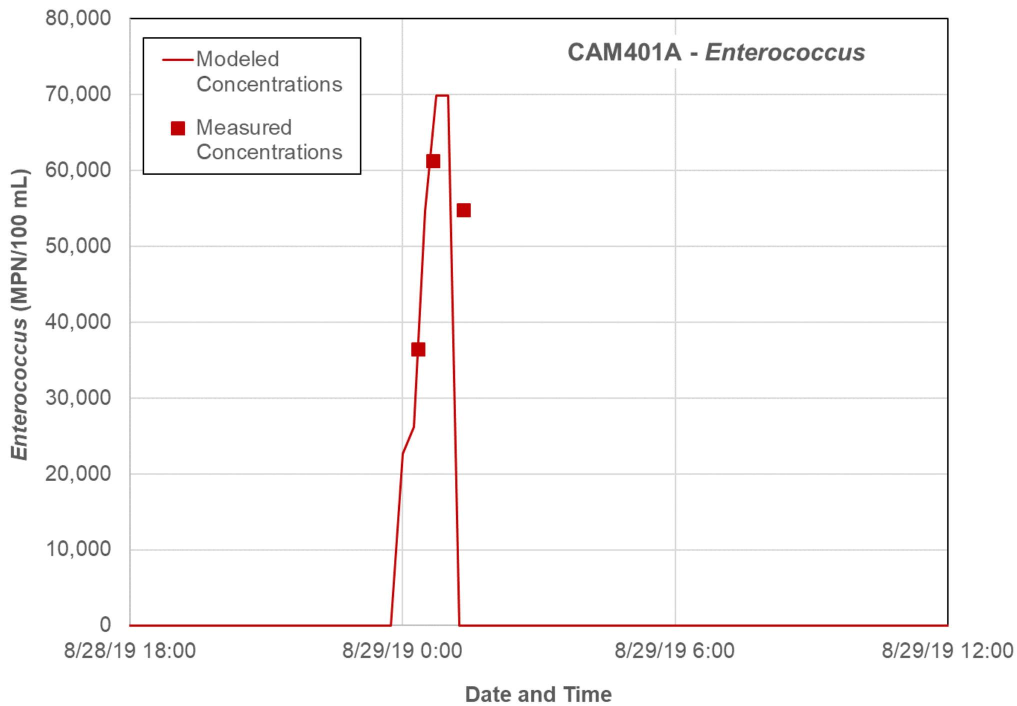


Figure 2-13. Measured and Calculated *Enterococcus* Counts at CAM401A for the 8/29/2019 Storm

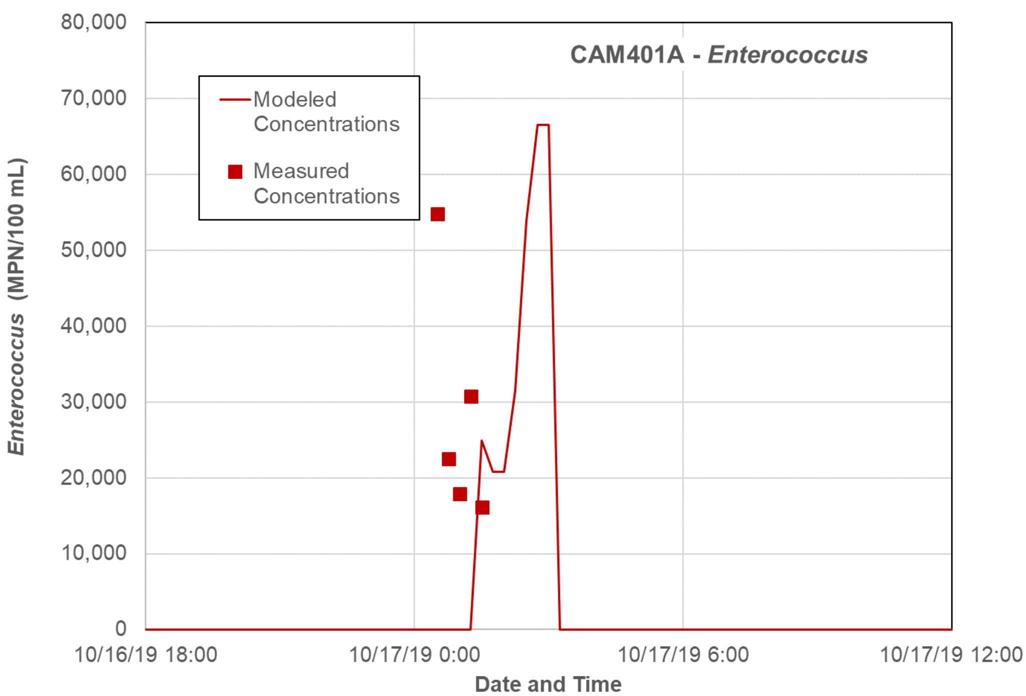


Figure 2-14. Measured and Calculated *Enterococcus* Counts for the 10/17/2019 Storm

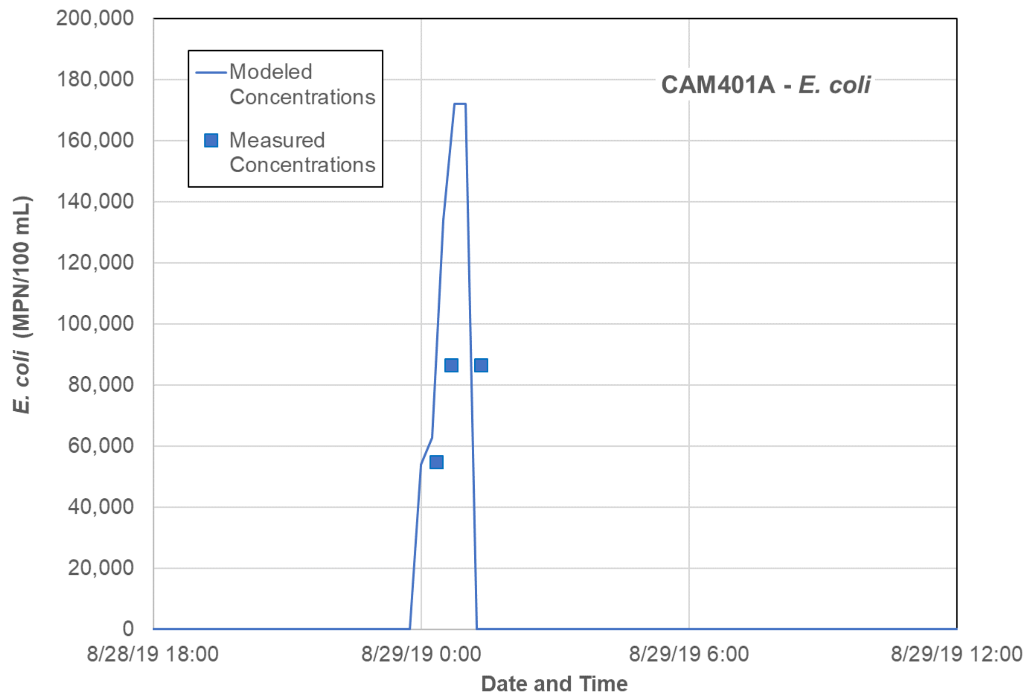


Figure 2-15. Measured and Calculated *E. coli* Counts at CAM401A for the 8/29/2019 Storm

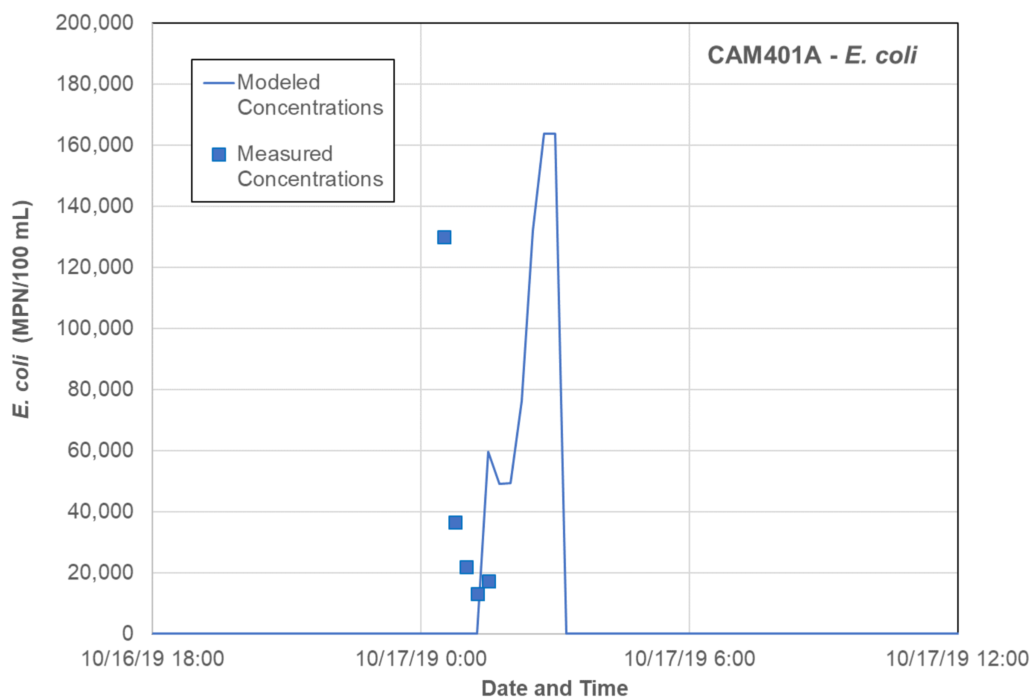


Figure 2-16. Measured and Calculated *E. coli* Counts at CAM401A for the 10/17/2019 Storm

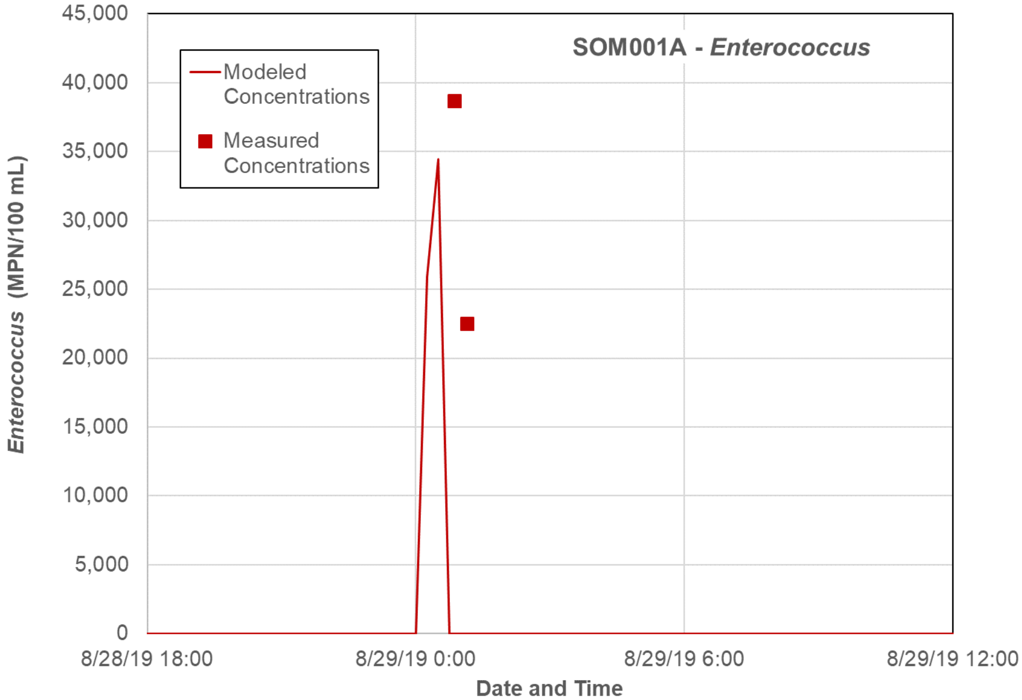


Figure 2-17. Measured and Calculated *Enterococcus* Counts at SOM001A for the 8/29/2019 Storm

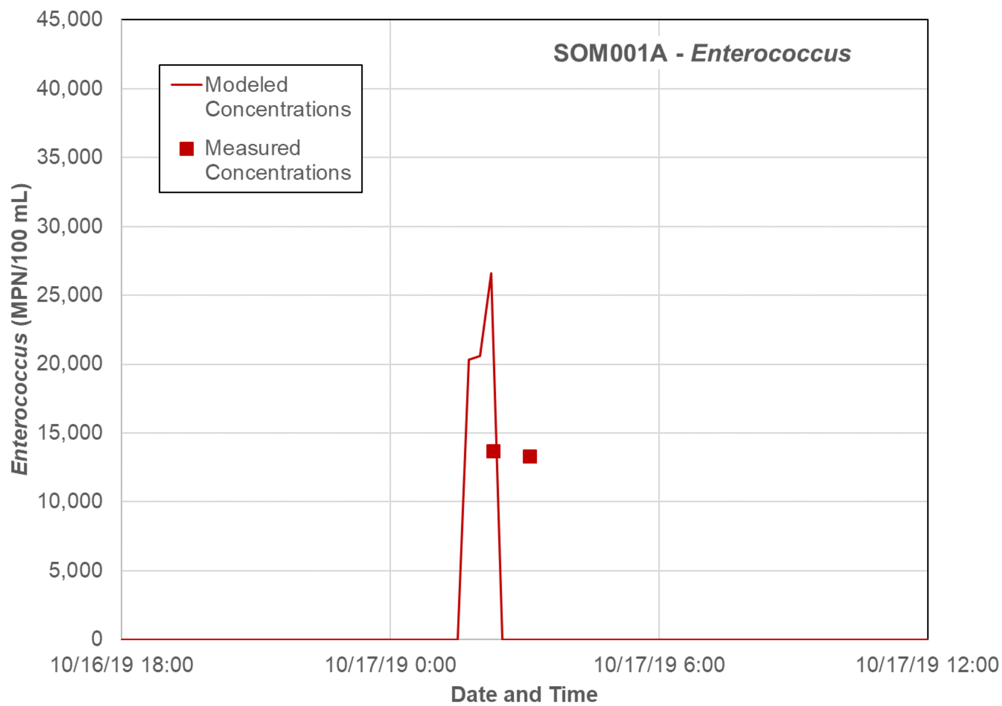


Figure 2-18. Measured and Calculated *Enterococcus* Counts at SOM001A for the 10/17/2019 Storm

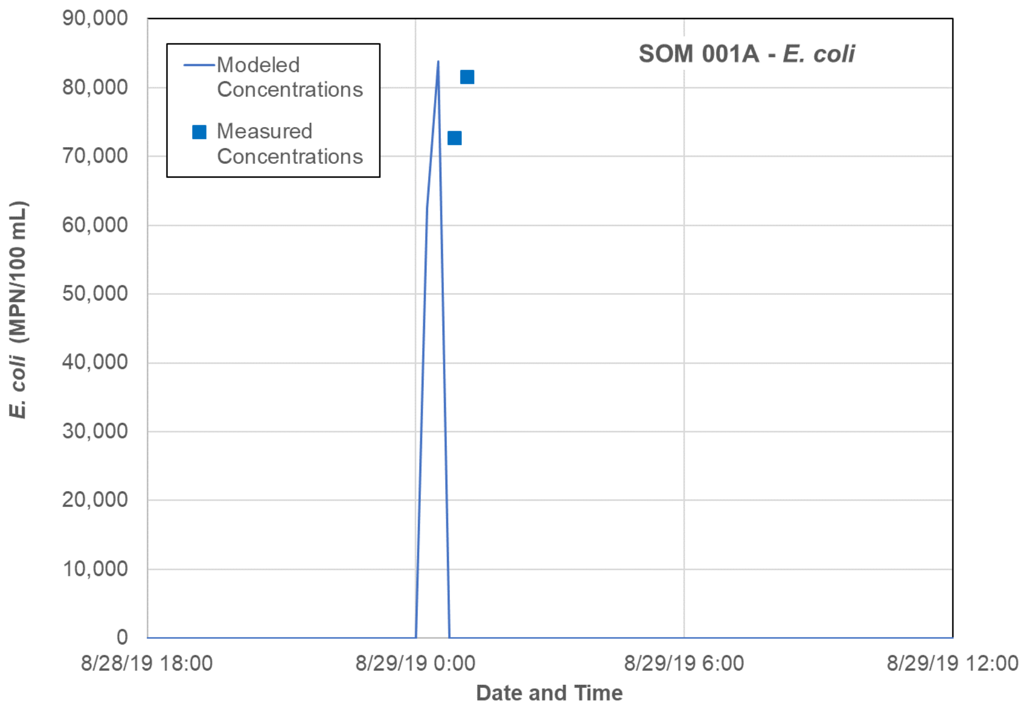


Figure 2-19. Measured and Calculated *E. coli* Counts for at SOM001A for the 8/29/2019 Storm

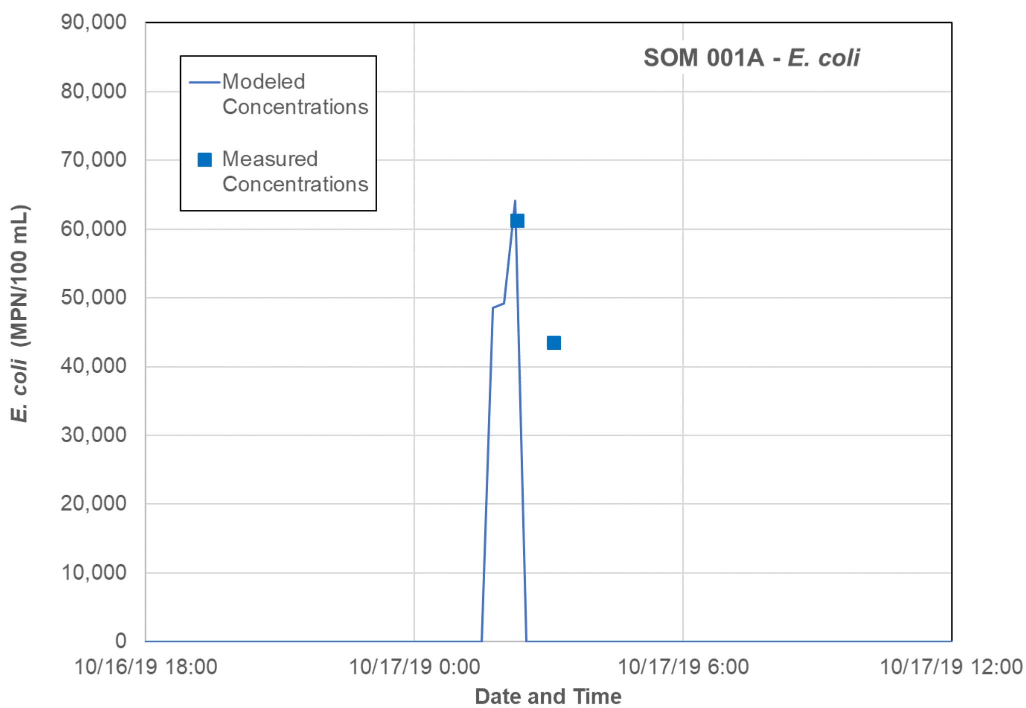


Figure 2-20. Measured and Calculated E. coli Counts for at SOM001A for the 10/17/2019 Storm

While the *Enterococcus* counts in the sanitary and non-sanitary fractions, and the *E. coli* counts in the non-sanitary fractions for the untreated CSOs in the Alewife Brook/Upper Mystic River model were the same as used for the Charles River model, the *E. coli* count in the sanitary fraction for the Alewife Brook/Upper Mystic River model was substantially lower than for the Charles River. As described above, the 7,000,000 MPN/100 mL value used for the sanitary fraction for the Charles River, when added to the infiltration flow, would bring the combined sanitary/infiltration count down into the middle of the range of the measurements at Deer Island. The value of 2,500,000 MPN/100 mL for the sanitary fraction used for the Alewife Brook/Upper Mystic River model was towards the low end of the measured values for the North System at Deer Island. However, the combined sanitary/infiltration count would still be within the range of the measurements at Deer Island.

In comparing the sampling data at Cottage Farm/Prison Point summarized in Table 2-2 above with the sampling data from outfalls CAM401A and SOM001A summarized in Table 2-3, it is clear that the measured *E. coli* counts at Cottage Farm/Prison Point are much higher relative to the *Enterococcus* counts than for the measurements at outfalls CAM401A and SOM001A. Therefore, using the same *E. coli* count in the sanitary fraction for Alewife Brook/Upper Mystic River as used for Cottage Farm would have resulted in model output much higher than the observed *E. coli* count in the CSO. The tributary area for the Alewife Brook/Upper Mystic River system is substantially different and hydraulically independent of the Charles River system, so it would not be considered unusual to specify a different count in the sanitary fraction.

The sanitary fraction approach to modeling bacteria counts in CSOs is a well-established approach that has been used in other major CSO programs such as New York City and San Francisco. In New York City, *E. coli* was not modeled, but the count of *Enterococcus* in the sanitary fraction ranged from 400,000 to 1,000,000 CFU/100 mL in hydraulically independent parts of the city (NYC DEP 2015, NYC DEP 2014). In San Francisco, the *Enterococcus* counts in the sanitary fraction ranged from 1,000,000 to 2,500,000 CFU/100 mL in hydraulically-independent parts of the city. Thus, it is not unusual to specify differing counts in the sanitary fraction for different hydraulic systems within a municipality.

In summary, the figures above show that the model was able to replicate the relative orders of magnitude of the measured counts in the CSO at outfalls CAM401A and SOM001A. Therefore, as a starting point for the water quality calibration, for all untreated CSOs discharging to the Alewife Brook/Upper Mystic River, the sanitary fraction was assigned an *Enterococcus* count of 1,000,000 MPN/100 mL and an *E. coli* count of 2,500,000 MPN/100 mL. Non-sanitary fractions were assigned an *Enterococcus* count of 5,500 MPN/100mL, and an *E. coli* count of 13,400 MPN/100mL.

2.3 Treated CSO Quality Assessment

For discharges from the MWRA's CSO treatment facilities – the Cottage Farm CSO Facility in the Charles River and outfall MWR205A/SOM007A from the Somerville Marginal CSO Facility in the Mystic River – effluent monitoring results from the facilities were used to generate the bacteria counts used for the modeling.

Cottage Farm CSO Facility. Flow into the Cottage Farm CSO Facility receives screening, sedimentation treatment, disinfection and dechlorination before discharge to the Charles River. For the treated discharges from the Cottage Farm CSO Facility, the arithmetic mean of the effluent bacterial counts measured between July 2018 and April 2019 was used to represent the effluent quality in the model. These values were 212 MPN/100 mL for *Enterococcus* and 394 MPN/100 mL for *E. coli*.

Somerville Marginal CSO Facility. Flow into the Somerville Marginal CSO Facility receives screening, disinfection, and dechlorination before discharge to the Mystic River. Discharge to the freshwater section of the river upstream of the Amelia Earhart Dam at outfall MWR205A/SOM007A occurs only during certain high tide conditions, when flow backs up in the outfall that discharges downstream of the dam (outfall MWR205). For the treated discharges from the Somerville Marginal CSO Facility, the average of effluent bacteria counts measured in 2018 (17 total samples) was assessed to represent the effluent quality. These values were 258 MPN/100 mL for *Enterococcus,* and 18 MPN/100 mL for *E. coli.* The high value for *Enterococcus* of 258 MPN/100 mL was due to one sample which registered 4,110 MPN/100 mL. Omitting this sample from the averaging yielded 17 MPN/100 mL for *Enterococcus,* the value used in the modeling. The stormwater flows discharging to the outfall downstream of the facility are accounted for in the hydrology model.

2.4 Stormwater Quality Assessment

The *Enterococcus* and *E. coli* counts in stormwater used in the model were based on an assessment of stormwater quality measurements that were available from monitoring events for the communities that discharge to the Alewife Brook/Upper Mystic River and to the Charles River. Grab samples were collected in 2019 at two stations in Cambridge discharging to the Charles River shown in Figure 2-21, and at multiple stations discharging to the Alewife Brook/Upper Mystic River in Arlington, Cambridge, and Medford shown in Figure 2-22. Grab samples were collected at the Somerville stations shown in Figure 2-22 in 2020. The tributary areas to the sampled outfalls for the Alewife Brook/Upper Mystic River are outlined in red in Figure 2-22. The stormwater monitoring stations used for the 2019 data collection are briefly described below, followed by a summary of the measurements. The Monitoring Plan for the CSO and SW outfalls was included with the DEP approved Variances and is posted on the DEP website: https://www.mass.gov/doc/mwra-receiving-water-modeling-of-upper-mystic-riveralewife-brook-and-charles-river-basin-work/download.

A key question to resolve was whether to use constant average values for *Enterococcus* and *E. coli* counts for all stormwater inputs, or if a basis could be established for varying the stormwater counts based on factors such as rainfall or tributary area parameters. Discussions of an assessment of correlations of the data with several rainfall and tributary area factors are presented, and seasonal impacts are discussed.

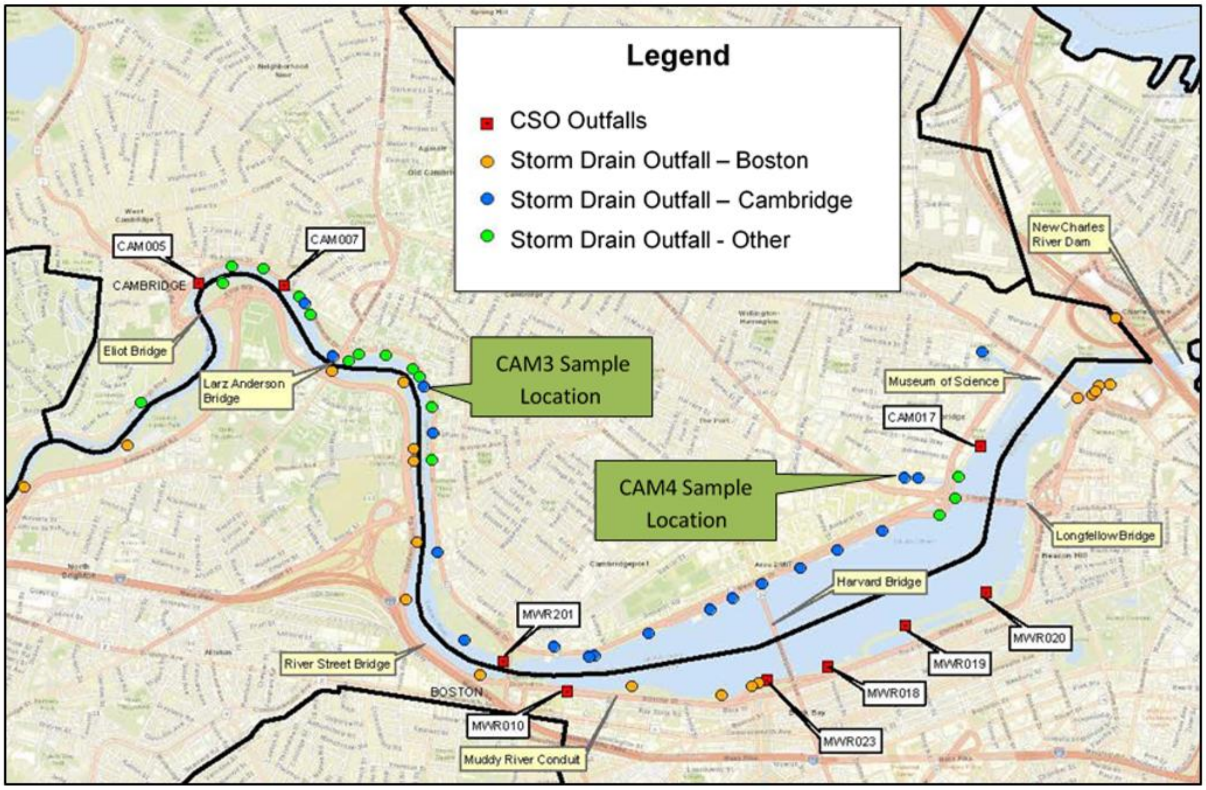


Figure 2-21. Stormwater Monitoring Stations for the Charles River

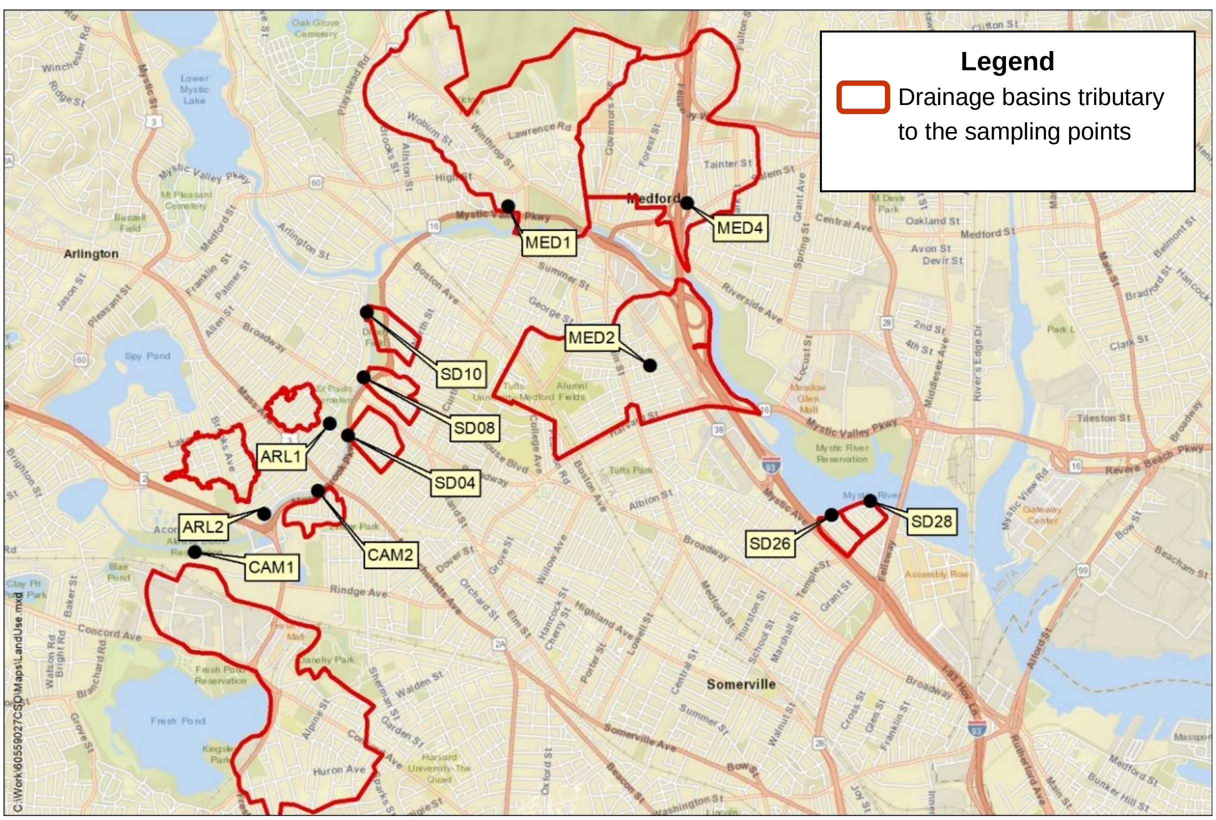


Figure 2-22. Stormwater Monitoring Stations for Alewife Brook/Upper Mystic River

Description of Stormwater Monitoring Stations

To the extent that communities had information on likelihood of illicit discharges to stormwater catchments, the stormwater sampling program was designed to include a mix of drains including those suspected to be contaminated, and those thought to be clean. However, samples collected before the start of storms do not indicate an obvious effect of illicit connections at any of the drains.

Medford

The sampling locations for the 2019 monitoring period in Medford were:

- MED1, Daly Road/Meetinghouse Brook. This site collects the majority of its drainage from the Middlesex Fells Reservation and a smaller portion from single-family residential area.
- MED2, Willis Street/Two Penny Brook. This site collects stormwater flow from a densely populated area of Medford and from an area of Somerville.
- MED4, Salem St. Circle/Gravelly Brook. This area collects the majority of its stormwater flow from residential areas of Medford characterized by single-family dwellings, and a portion of the stormwater runoff originates from the Middlesex Fells Reservation. The MED4 location is downstream of a previously sampled location, MED3, which had a number of access issues.

The drainage areas cover a large portion of Medford and represent the land-use types in Medford that discharge stormwater to the Upper Mystic River.

The sampling was conducted by MWRA staff.

Cambridge

Staff from the City of Cambridge sampled two locations on Alewife Brook and two locations discharging to the Charles River, with samples sent to a contract laboratory for analysis.

- CAM1, Cambridge Park Dr., influent into constructed wetland. As noted in Table 2-3, the contributing catchment is 75% Industrial, commercial and residential.
- CAM2, Harrison Avenue (former CAM400 CSO outfall), D40 (Alewife Brook). The upstream catchment is 73% commercial and residential.
- CAM3, DeWolfe St., Drainage area D21
- CAM4, Broad Canal, Drainage Area D07

Somerville

The City of Somerville sampled three locations that drain to the Alewife Brook, and two that drain to the Mystic River. The City utilized a contractor for sampling and sent the samples to the MWRA for analysis. The sampling locations were:

- SD04, Alewife Brook, 15-inch pipe
- SD08, Alewife Brook, 24-inch pipe. Former CSO outfall SOM002 at Powder House Boulevard. This location is thought to be affected by illicit connections.
- SD10, Alewife Brook, 36-inch pipe.
- SD26, Ten Hills drainage area, former CSO outfall SOM007. Not thought to be affected by illicit connections.
- SD28, Ten Hills drainage area, 16-in pipe.

Arlington

MWRA sampled two stormwater sites in Arlington.

- ARL1, Waldo Park upstream of Outfall OF-372. As noted in Table 2-3, the contributing catchment is 80% residential and 20% undeveloped.
- ARL2, Lafayette Street, upstream of Outfall OF-33. The contributing catchment is 35% undeveloped.

Stormwater Monitoring Results

Results from the sampling conducted in 2019 and 2020 are summarized in Table 2-4, together with the storm rainfall depth, peak intensity and number of prior dry days. For each storm sampled, three to four samples were collected at each location, with the first sample collected prior to the storm, except for ARL2, which could not be sampled before storms because it did not have any dry weather flow. The bacterial counts in the samples showed significant variability. The bacteria results for each storm summarized in Table 2-4 are the arithmetic average of the individual samples for each storm, omitting the leading dry weather sample. See discussion on page 34 regarding use of arithmetic average versus geometric mean for this evaluation. The average and standard deviation presented for each sample location represent the average and standard deviation for all the individual samples taken at each location, omitting the dry weather samples (not the average of the average values presented for each storm). Similarly, the average and standard deviation presented for each municipality were calculated from all of the samples from each municipality, omitting the dry weather samples. The average and standard deviation for “All Data” shown in Table 2-4 were calculated from all of the individual sample values, omitting the dry weather samples.

As indicated in Table 2-4, the stormwater sampling data included a range of values, but wet weather sampling data outliers were not excluded from the data presented. Since the stormwater samples were collected from the stormwater pipes, the sample data would have included the influence of illicit connections if present. Thus, use of the average stormwater concentrations as model inputs would include the influence of illicit connections, although those illicit connections could not be quantified as a whole. In general, the data are consistent with what would be expected for end-of-pipe stormwater sampling within the general project area.

Table 2-4. 2019-2020 Stormwater Sampling Bacterial Results

Storm Data												
Date	10/7/2019	10/27/2019	11/18/2019	11/24/2019	12/13/2019	5/8/2020						
Depth (in) (1)	0.16	1.43	0.24	1.51	1.41	0.41						
Duration (hr)	2.5	10.5	6	17	17.25	14.25						
Peak 15-minute Intensity (in/hr)	0.16	0.56	0.12	0.6	0.24	0.07						
Prior Dry Days	2	3	5	1	2.2	7						
***Enterococcus* (MPN/100 mL)**												
	Average by Storm(2(3))						**By Station(4)**		**By Town(5)**		**All Data(6)**	
							Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
ARL1	9,195	25,150	4,723	10,605			10,599	9,790	8,406	8,020	5,476	20,933
ARL2	3,723	4,423		8,223			5,614	3,805				
CAM1	918	960		4,678	1,130		1,922	1,817	2,832	2,887		
CAM2	1,154	306		4,412	990		1,716	2,354				
CAM3	7,116	2,938		4,772	9,180		6,002	3,259				
CAM4	1,508	1,364		1,656	2,232		1,690	1,034				
MED1	7,135	4,418	1,200	1,030			3,503	3,398	9,762	31,221		
MED2	4,125	4,375	3,556	2,080			3,454	2,415				
MED4	78,250	4,468	9,574	3,380			21,980	63,429				
SD04						1,265	1,265	239	797	704		
SD08						348	348	224				
SD10						1,768	1,768	498				
SD26						50	50	0				
SD28						660	660	383				

Table 2-4 (Cont.). 2019-2020 Stormwater Sampling Bacterial Results

Date	10/7/2019	10/27/2019	11/18/2019	11/24/2019	12/13/2019	5/8/2020						
Depth (in) (1)	0.16	1.43	0.24	1.51	1.41	0.41						
Duration (hr)	2.5	10.5	6	17	17.25	14.25						
Peak 15-minute Intensity (in/hr)	0.16	0.56	0.12	0.6	0.24	0.07						
Prior Dry Days	2	3	5	1	2.2	7						
***E. coli* (MPN/100 mL)**												
	Average by Storm(2)(3)						**By Station(4)**		**By Town(5)**		**All Data(6)**	
							Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
ARL1	14,030	28,895	8,015	2,910			11,258	14,964	19,358	32,994	13,394	29,046
ARL2	2,670	4,600		74,980			29,666	45,966				
CAM1	1,760	24,940		5,640	504		8,211	26,515	11,361	31,953		
CAM2	402	150		700	512		441	393				
CAM3	46,200	3,610		4,480	15,580		17,468	18,511				
CAM4	640	2,750		9,346	64,560		19,324	54,383				
MED1	3,800	3,148	10,578	625			4,456	7,187	14,625	23,995		
MED2	8,210	6,928	9,848	2,000			6,655	6,573				
MED4	27,518	27,915	49,454	22,114			32,198	34,230				
SD04						2,650	2,650	551	10,676	23,947		
SD08						358	358	246				
SD10						47,200	47,200	34,388				
SD26						50	50	0				
SD28						1,110	1,110	658				

Notes:
1. From Somerville Marginal rain gauge.
2. Average of individual wet weather samples taken during the storm.
3. Half the detection limit (50 MPN/100 mL) used for nondetects when calculating averages.
4. Average and standard deviation of all wet weather samples taken for each station for all storms sampled.
5. Average and standard deviation of all wet weather samples taken at all stations in the community for all storms sampled.
6. Average and standard deviation of all wet weather samples taken.

It is generally recognized that stormwater quality varies during the storms, with higher values at the beginning of the storms, commonly designated as the first flush. Bacterial counts in individual samples depend on when the samples were collected relative to the first flush and time of peak intensity.

Observations on the data in Table 2-4 are summarized below:

- In Arlington, ARL1 had lower average *E. coli* counts than ARL2, but the trend was reversed for *Enterococcus*. The two stations have comparable land use, although ARL2 has a higher fraction of undeveloped land.
- In Cambridge, CAM1 and CAM2 have comparable land use and had relatively low counts of both *E. coli* and *Enterococcus*. CAM2 had very low *E. coli* counts and relatively low *Enterococcus* counts.
- In Medford, MED4 had significantly higher counts than the other two stations for both *E. coli* and *Enterococcus*, but it has a relatively high fraction of undeveloped land and low commercial land use.
- In Somerville, the average *Enterococcus* counts at SD8, SD26 and SD28 were the lowest of all of the sampling locations assessed. The average *E. coli* counts at SD10 were the highest of all the sampling locations assessed.

These observations capture the variability that is typically encountered in stormwater quality sampling for bacteria.

Correlations of Stormwater Bacterial Counts to Storm Characteristics and Catchment Land Use

Potential correlations of the stormwater bacterial counts with storm characteristics and catchment land use were explored, to see whether it would be appropriate to apply different stormwater counts to different land use characteristics or storm characteristics. Correlations evaluated included storm depth and number of prior dry days, and catchment area, percent undeveloped land, undeveloped area, percent residential, and residential area.

Plots were developed of measured *Enterococcus* and *E. coli* counts as a function of the following parameters:

- Storm depth
- Number of prior dry days
- Total tributary area
- Percent undeveloped area
- Total undeveloped area
- Percent residential area
- Total residential area

None of the plots showed a clear relationship between the parameter assessed and measured *Enterococcus* or *E. coli* counts. The plots are included in Appendix F. Since no clear correlations could be established between bacteria counts and rainfall depth, antecedent dry days, or land use, the average of all individual wet weather sample results for *Enterococcus* and *E. coli* (shown in red in Table 2-4), were used for the purpose of computing bacteria loading inputs to the receiving water model from stormwater in Medford, Arlington, Cambridge and Somerville.

For modeling, it is not practical to specify variable bacterial counts based on measurements whose relationship with the storm start, peak and end is variable. From a conservation of mass (actually bacterial counts) point of view, flow-weighted counts would be best, but these require flow-based sampling or concomitant flow measurements, which are not available for the data currently collected. Given these realities, averaging measured bacterial counts during each storm is a reasonable approach for representing the counts in the stormwater. In the absence of flow-weighted bacterial counts, arithmetic averages were used. Geometric means are indicators of the central tendency of log-normal distributed data, and are appropriately used to compare different distributions, but are not as appropriate for estimating total load. Use of the geometric mean would generally underestimate the total loading.

Seasonal Variations

Another factor that may affect bacterial counts in stormwater is the season. It has been shown that stormwater bacterial counts tend to be lower in the winter, early spring and fall than in the summer (Selvakumar and Borst, 2006). This finding was confirmed by the measurements at Stations 001 and 012, downstream of the Watertown Dam where elevated bacterial counts cannot be attributed to CSOs. This seasonal variation in bacterial counts was accounted for in the model developed for the Charles River upstream boundary condition (Appendix A) by decreasing the bacteria buildup rates in the winter and fall. The stormwater quality measurements summarized in Table 2-4 were collected between October and December of 2019 for Arlington, Cambridge and Medford, and in May of 2020 for Somerville. Thus, the impact of seasonality could not be evaluated for the individual sample locations. This factor was further evaluated during model calibration (see Section 4.3.7).

2.5 Baseflow Quality Assessment

Baseflow is flow that enters a stream from sources not associated with stormwater runoff. Baseflow that enters a stream through a storm drain outfall can include groundwater infiltration and can also include flows from illicit sanitary connections to the storm drain. Groundwater infiltration directly to a stream, not through a storm drain, can also be a source of baseflow. Baseflow occurs during both dry and wet weather and can vary seasonally as a result of changes in groundwater levels. The limited available data on the quality of baseflow included samples collected prior to the beginning of storms as part of the stormwater sampling program described above, and dry weather sampling data collected by the BWSC from their storm drains.

The average bacterial counts for the dry weather samples (collected prior to the beginning of the storms) from the Arlington/Cambridge/Medford/Somerville sampling program described above were 890 MPN/100 mL for *Enterococcus* and 3,100 MPN/100 mL for *E. coli*. Median values from the BWSC data, collected in 2011 and 2012, were 1,300 MPN/100 mL for *Enterococcus* and 5,200 MPN/100 mL for *E. coli*. It should be noted that the BWSC data were collected prior to illicit connection removal and best management practices/green infrastructure implementation and may no longer be representative of conditions at the outfalls sampled.

The values for baseflow were used as a starting point for the dry weather calibrations of the water quality models and were adjusted as needed to match dry weather in-stream measured bacterial counts. The baseflow loadings during wet weather are usually overwhelmed by the much larger loadings from wet weather sources (CSO and stormwater), so the baseflow component typically has little impact on the calibration of wet weather conditions. In addition, different approaches were taken to establish base flows at the model upstream boundaries, as described in more detail in Sections 4 and 5, below.

3. Model Calibration Process and Data

3.1 Calibration Process

Model calibration is the process of tuning model parameters to achieve a satisfactory match between model predictions and field measurements. Not all model parameters can be tuned, however. Parameters based on physical measurements, such as the water body bathymetry, should not be changed. Similarly, the CSO flows calculated by a calibrated collection system hydraulic/hydrologic model cannot be changed in the water quality model to provide better match between model and measurements.

The Delft-3D and InfoWorks models are mechanistic models, which means that processes are described using formulations reflective of the relevant physical, chemical and biological phenomena. The reason some parameters need to be calibrated is that they represent an aggregate of complex phenomena. For example, bacterial die-off is due to senescence, grazing, light inactivation and settling, among other phenomena. In the models, die-off is simulated using a first order decay formulation in which a die-off rate represents the net effect of these phenomena and needs to be adjusted to provide the best match with measurements.

Model calibration is also needed to address the large variability of the measurements, for example stormwater bacterial counts. Measurements cannot be detailed enough to provide stormwater bacterial counts as a function of time during storms at all the stormwater discharge locations (point and non-point). They also vary by several orders of magnitude due to a range of factors. Therefore, some interpretation of the measurements is needed. Because sampling can not fully characterize such variable conditions, professional judgement is used to adjust the bacterial counts within the range observed, to better reproduce observed receiving water quality.

3.2 Calibration Data

In this report, the term “calibration data” refers to data with which model results are compared during the calibration process. For the two water quality models, the calibration data are MWRA’s extensive in-stream monitoring data (Wu and Goodwin, 2017; Wu and Goodwin, 2018; Goodwin and Wu, 2019; Goodwin et al., 2020). These data include the results of water quality sampling and analysis at 17 stations in the Charles River and 17 stations in the Alewife Brook/Upper Mystic River. The locations of these monitoring stations are shown in Figure 3-1.

Prior to 2016, Combined Sewer Overflow Receiving Water Monitoring Program samples were collected on weekdays with rotation amongst the receiving water segments. Starting in 2016 MWRA began to sample the receiving water segments in two-week rotating blocks. Weekend sampling during and after storm events was added for the Charles River and Mystic River in 2017. At each station, near-surface water samples were collected and for deeper stations near-bottom samples were also collected. The samples were tested for several water quality parameters including *Enterococcus* and *E. coli*.

For this calibration report, the calibration data were limited to year 2018 sampling, which included 14 rounds of wet weather sampling in the Charles River, and 10 rounds of sampling in the Alewife Brook/Upper Mystic River for totals of 1,082 samples in the Charles River and 1,057 samples in the Alewife Brook/Upper Mystic River. The 2018 sampling data provides a sufficient range of data to conduct the calibration. Previous water quality models of Alewife Brook/Upper Mystic River and Charles River covered a more limited number of storms. For example, the Charles River model used for the CSO

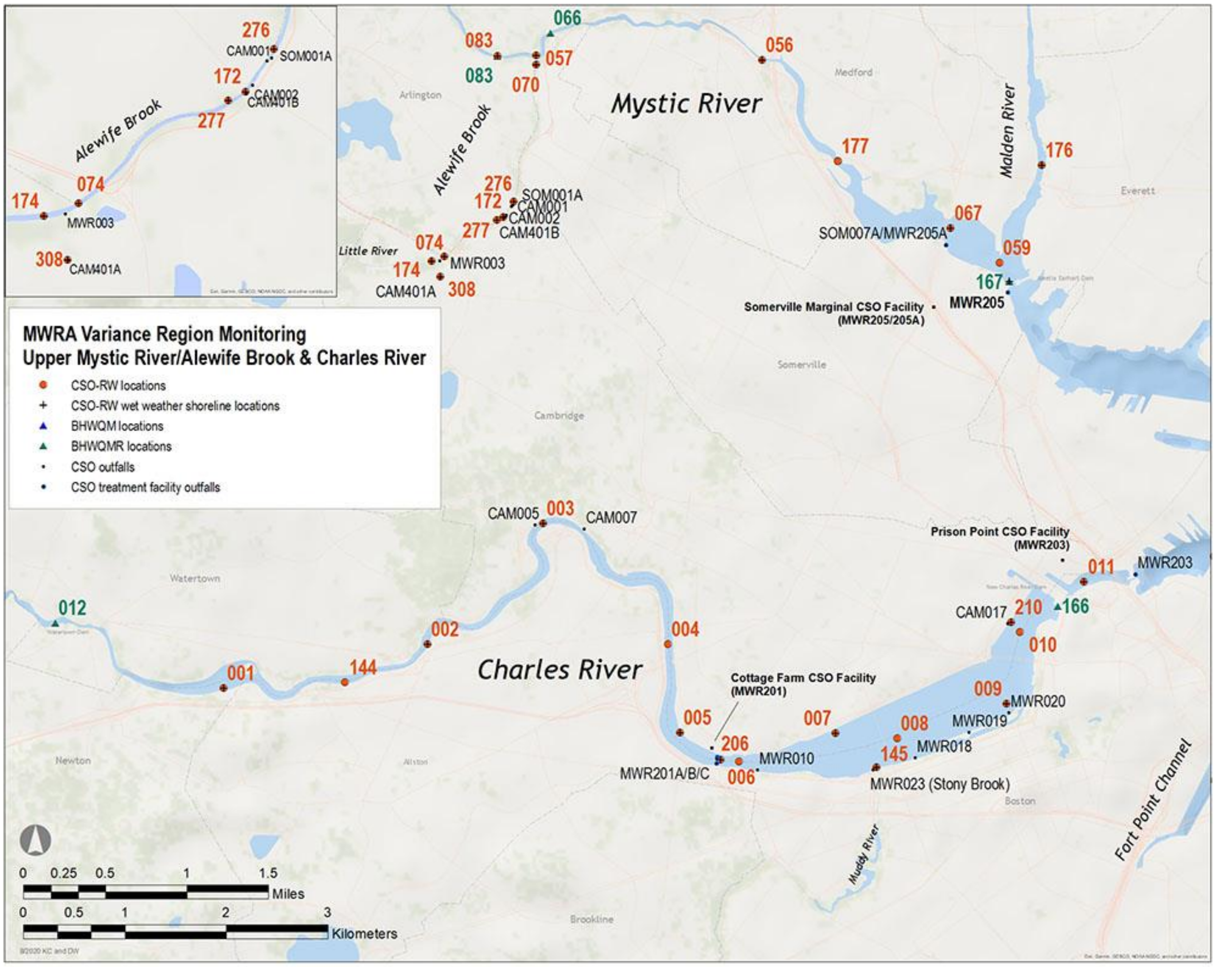


Figure 3-1. MWRA Receiving Water Monitoring Stations in Model Domains

LTCP covered two periods of 4 and 6 days, respectively (Metcalf & Eddy, 1998). In contrast, for the present exercise, the models are run in continuous mode for up to one year. Assessing the longer-duration continuous model runs is important because bacterial counts observed in dry weather were shown to be due in part to prior wet weather discharges (Metcalf & Eddy, 1998).

A separate model validation step, where performance of the model would be checked against a data set separate from that used for calibration, was not conducted with these models. However, since the model was calibrated over an entire year, covering a range of storm events, inter-event periods, groundwater conditions, etc., the variety of conditions within the calibration period were sufficient to demonstrate that the calibrated model is sound and defensible. As judged by how well model output agrees with the observations under the range of conditions assessed (as demonstrated in the sections below), the model is suitably calibrated to conduct the water quality assessments, and the lack of a validation step does not detract from the credibility of the model results.

3.3 Calibration Parameters

The main calibration parameters were:

- *E. coli* and *Enterococcus* die-off rates

- Stormwater and CSO bacterial counts

These two parameters are further discussed below. Stream bottom roughness, simulated by Manning's equation, and diffusion coefficients are also parameters that are amenable to adjustments during calibration; however, these parameters have a limited impact on the water quality and were not changed during calibration.

3.3.1 Bacterial Die-off

Bacterial die-off is the result of several different mechanisms including senescence, grazing, light inactivation and settling. In the models, die-off is simulated using a first order decay formulation in which a die-off rate represents the combined effect of these phenomena.

Previous Charles River modeling simulated fecal coliform with a die-off rate given by the following formula (DHI, 2000)

$$K = 0.6 \times 7.4^{I} \times 1.09^{(T-20)}$$

Where K = die-off rate (day^{-1}), I = light intensity averaged over the depth (kW/m^{2}), and T = temperature (^{o}C). This formulation includes some of the various parameters influencing die-off. However, light intensity and water temperature vary during the day and during the year so that application to design storms (and even to the Typical Year) would not be practical. Another formulation for fecal coliform based on about 100 in-situ and laboratory measurements for fresh water (Mancini, 1978) is:

$$K = 0.8 \times 1.07^{(T-20)}$$

These two expressions are relatively close to each other. These expressions are for fecal coliform, but similar temperature dependence likely applies for *E. coli* and *Enterococcus*, which are the focus of the present modeling. Typical river temperatures in April are on the order of 7^{o}C, for which the above formula gives K = 0.33 day^{-1}. Typical river temperatures in July are on the order of 26^{o}C, which yields K = 1.2 day^{-1}. Thus, temperature effects appear to be significant.

For fecal coliform in marine waters, based on about 100 in-situ and laboratory measurements, the expression was derived: k = (0.8 + 0.006 %seawater) x 1.07$^{(T-20 \text{ degC})}$ day^{-1} (Mancini, 1978). This expression suggests that the die-off rates are larger in saline than fresh waters. *Enterococcus* are generally considered to have a slower die-off rate than coliform. However, in two separate studies, fecal coliform and *Enterococci* were tracked in a sewage plume and the sampling data indicated comparable die-off rates (Adams and Stolzenbach, 1991; Noble et al 2003).

Studies of bacterial die-off have been recently reviewed (Korajkic et al, 2019), pointing to the complexity of the matter. Following is an excerpt from the Korajkic paper (with reference citations removed): *"In these studies, decay of E. coli and enterococci from cattle, bovine, deer, goose, and ovine feces was considerably slower than that of organisms originating from sewage or human feces. In contrast, Fecal indicator bacteria (FIB) from dog and seagull feces decayed more rapidly than those from sewage and human feces. FIB isolated from environmental water, soil, and sediments typically decayed more slowly than FIB from sewage or organisms originating from dog, bovine, deer, or goose feces. Two studies comparing the decay rates of FIB from primary (human feces) and postprimary (raw and treated wastewater and septage) sources found that organisms from septage decayed more slowly than organisms from feces and raw wastewater while there was no difference in decay for FIB derived from* *raw versus treated wastewater. The source of the inoculum also affected the bacterial response to the environmental stressors, as the decay rate of E. coli from cattle feces, but not human feces, was significantly higher under light than under dark conditions.*

To further test this assertion, we compared the reported decay rates of closely related species (e.g., E. coli to E. coli O157:H7 or Salmonella spp. and various microbial source tracking (MST) markers. The results of this analysis revealed that the decay rates of even closely related species or strains were frequently not comparable."

Based on the above it would not be beneficial or appropriate to use a sophisticated parameterization to estimate die-off rates. Therefore, constant values, developed during the calibration, were used to represent all conditions. Another reason for this decision is that unambiguous results are needed for CSO and stormwater impacts during design storms, independent of the time of their occurrence. Based on previous modeling of these water bodies, initial values of the die-off rates for *Enterococcus* and *E. coli* were set at 0.8 day^{-1} (MWRA,1996).As described below in Sections 4 and 5, as part of the calibration process, the impact of increasing the die-off rate to 1.6 day^{-1} was assessed for both the Charles River and Alewife Brook/Upper Mystic River. However, increasing the die-off rate did not improve the calibration, and a die-off rate of 0.8 day^{-1} was retained.

3.3.2 CSO and Stormwater Bacterial Counts

As described in Section 2, CSO and stormwater bacterial counts are applied to:

- the modeled sanitary and non-sanitary fractions of CSO,
- the modeled treated CSO discharges from the MWRA's CSO facilities, and
- the modeled separate stormwater discharges.

In addition, bacterial counts were applied to baseflow sources as described in Section 2.5.

The initial CSO, stormwater, and baseflow bacterial counts used in the models were developed from monitoring that was conducted on the Deer Island Treatment Plant influent, CSO facility influent and effluent, CSO outfalls and stormwater outfalls. In Section 2, it was noted that the measured stormwater counts did not correlate to any of a range of factors including storm characteristics and land use. It was further noted that the impact of seasonal variation could not be fully gauged from the monitoring data.

Previous studies (Selvakumar and Borst, 2006), as well as a detailed analysis of Charles River bacterial counts downstream of Watertown Dam described in Section 4.3.7, show that bacterial counts in stormwater are lower in the winter and late fall than in the late spring and summer. As for the die-off rates, this seasonal dependence was not included in the modeling (except for calibration of the Charles River model upstream boundary condition). Where appropriate, the initial CSO, stormwater, or baseflow bacterial counts derived from monitoring were adjusted during calibration so that model output better matched in-stream measurements. These adjustments are detailed in Sections 4 and 5.

3.4 Calibration Metrics

A first measure of calibration is generally visual, by comparison of model predictions with measurements displayed graphically. This approach is commonly called the Weight-of-Evidence approach. For the current modeling, the main element of the Weight-of-Evidence approach is the general shape of the bacterial count versus time curves, including peaks and lows and criterion exceedance time. A caveat is that the measurements are few (for example daily, at discrete monitoring stations and at different times during the day), and thus do not provide a complete depiction of the bacterial count variations with time. Because of the rapid variation of bacterial counts versus time at the beginning of an event, large differences between model and measured values can result from a slight shift of the timing of the modeled versus the measured values. For this reason it is important to calibrate over a number of storms so that the general trends of the responsiveness of the model versus measured values can be assessed.

Quantitative measures of model to measurement comparison are desirable to impartially establish that one set of calibration parameters is better than another. One such quantitative metric is the Wilmott "Index of Agreement" defined as follows (Wilmott, 1981):

$$IA = 1 - \frac{\sum_{i=1}^{n} \left| P_i - O_i \right|^2}{\sum_{i=1}^{n} \left(\left| P_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2}$$

where *P* and *O* are the predicted and observed time series respectively and $\overline{O}$ is the time-average of the observed time series, i is an index refering to individual measurements (and corresponding predictions) and n is the total number of measurements. IA varies between 0 and 1, with 1 showing perfect agreement between the model output and the observed time series. Values of IA were computed from model output at all stations, with corresponding observations, from each calibration run.

4. Charles River Receiving Water Quality Model

4.1 Previous Models

Several hydrodynamic and water quality models for the lower Charles River have been developed in the past, and are briefly reviewed below, with mention of elements relevant to the present modeling.

4.1.1 Metcalf & Eddy, 2002

This two-dimensional model was developed using the MIKE21 software for the MWRA CSO Long Term Control Plan. The model used the latest information available at the time, incorporating data from an extensive sampling plan conducted by the U.S. Geological Survey (USGS) and was calibrated to two storms from the sampling period. The parameters analyzed using the MIKE21 model were fecal coliform, dissolved oxygen (DO), and biochemical oxygen demand (BOD).

Bacterial die-off was simulated using first order decay with a decay coefficient calculated as a function of temperature, salinity, and light. Light variation during the day was calculated based on a user-specified maximum light intensity and model calculated sunrise and sunset times (based on the latitude of the study area and time of year). As the model was two-dimensional, light was averaged over depth based on a user-specified Secchi disk depth or light attenuation factor. A consequence of this approach was that actual values of the die-off coefficient were not apparent, i.e. not displayed as model output or otherwise documented.

The "salt wedge", or intrusion of saltwater into the basin at depth from the locks downstream, was simulated by setting all water depths greater than 7.0 meters to 7.0 meters, under the assumption that saltwater at greater depths would not mix with the freshwater above. The model used the buildup/washoff formulation (Huber and Dickinson, 1988). for the specification of the upstream boundary condition at the Watertown Dam. This formulation is also used in the present model (Appendix A), recalibrated with in-stream monitoring data from 2017 and 2018. The downstream boundary was specified as a constant water surface elevation equal to 108.0 feet (Metropolitan District Commission [MDC]datum), consistent with the operational procedure at the New Charles River Dam which strives to maintain an approximately constant water level upstream of the dam.

Attention was paid to dry weather conditions, where it was observed that that dry-weather counts in the basin were influenced by previous wet-weather events, even when separated by several dry-weather days. As a result, the dry-weather loadings back-calculated from river measurements were higher than the dry-weather loadings derived directly from point discharge measurements. Ultimately it was decided that initial conditions would be specified rather than performing dry-weather calibration runs.

The model was subsequently used to simulate an entire 3-month recreation season to assess the benefits of several measures including CSO LTCP implementation, as well as basic and extreme levels of stormwater Best Management Practices (BMP) application. Results were presented in terms of contours of hours of exceedance of the 200 colonies/100 mL fecal coliform swimming standard level, as well as plots of acres of violation of this standard as a function of time.

4.1.2 Tetra Tech, 2005

This model was a coupled hydrodynamic and water quality modeling system, implemented with the EFDC software, to support the implementation of a eutrophication total maximum daily load (TMDL) for the Lower Charles River Basin. The model was a three-dimensional, time variable water quality model that simulated algal dynamics and dissolved oxygen levels in the Basin to assess acceptable pollutant load allocations for nutrients and heat. This model did not assess bacteria, and was therefore not directly relevant to the current modeling.

4.1.3 Hellweger and Masopust, 2008

This model used the ECOMSED software for hydrodynamics and RCA for water quality. These two models are 3-dimensional, but the salinity intrusion was not simulated, and hence, vertical gradients were negligible so that “a two-dimensional model would probably have been adequate”. The principal water quality parameter simulated was *E. coli*. Non-CSO and CSO input counts were assigned values of 1.5 x 10^5 MPN/100 ml and 3.5 x 10^7 MPN /100 mL respectively. These values are much higher (by factors of 10 or more) than those used in the current modeling. The high *E.coli* counts assumed in the Hellweger model were not based on stormwater or CSO monitoring and it is not clear which CSOs were included in the model, since the period that was simulated was towards the end of the Stony Brook Sewer Separation project. Nevertheless, the model satisfactorily reproduced measurements.

The bacterial population was divided into labile (fast decay) and refractory (slow decay) fractions, and die-off was simulated using the first-order decay process, with rate constants of 2.5 and 0.25 day^{-1}, respectively. Simulations conducted with die-off rates varying with sunlight intensity did not improve model results.

Detailed receiving water quality monitoring was conducted as part of the study, which showed variable plume configurations, primarily driven by wind. Pronounced high-frequency variability was also observed in the bacterial counts, possibly due to tidally scheduled flow releases at the New Charles River Dam, although the frequency was not clearly stated in the paper. The paper only addressed a small number of storms so its results are relevant but should not be considered representative of the full range of conditions over the course of a year, or even an entire season, as are simulated using the model developed here. It is also not clear how the model would have performed using CSO and stormwater concentrations that were more reflective of the measured data presented above in Section 2.

4.2 Model Software

The primary software used for the current Charles River modeling is the Delft3D FM (Flexible Mesh) model suite. This is the newest software engine developed by Deltares for hydrodynamic and water quality simulations in one, two and three dimensions. The Delft3D-FM system includes the D-Flow FM model for hydrodynamics (water levels and velocities) and the Delft3D-WAQ model for water quality. These models use a flexible mesh, also referred to as an “unstructured grid,” which allows local refinement of the grid to better simulate local features of interest.

The Delft3D FM system was selected for this application because of its multidimensional capabilities. The Charles River is relatively wide, even in sections upstream of the basin. Previous water quality modeling conducted in 2002 indicated that CSO discharges, because of their low discharge velocity, had a tendency to hug the shore and slowly spread across the river. This tendency would create the potential for water quality variations across the river width, particularly in the basin. In the vertical direction, however, except for the basin the river is shallow enough that vertical mixing of CSO and stormwater discharges is rapid. Therefore, Delft3D was applied in two-dimensional mode, for which bacterial counts are assumed vertically uniform. In the basin, a salinity intrusion has been observed and the way this is treated by the current model is discussed at the end of section 4.3.2.

Among the multidimensional models available, Delft3D was selected because of its flexibility and range of capabilities.

4.3 Model Development

4.3.1 Model Extent and Grid

The model extends from the New Charles River Dam and locks to the Watertown Dam as shown in Figure 4-1. The area was divided into 4,400 grid cells as shown in Figure 4-2. In general, the river width was divided into at least 5 cells, and many more in wider sections. Stormwater and CSO flow inputs as a function of time were specified at 85 outfalls shown in Figure 4-1. CSO flow inputs were based on the MWRA's collection system hydraulic/hydrologic model, and the stormwater flow inputs were based on the Cambridge ICM model, the BWSC stormwater Model and a model developed by the USGS. The stormwater input locations on Figure 4-1 are color-coded based on the model used to generate the inputs. The input locations modeled by the USGS include outfalls not specifically covered by either the Cambridge or BWSC stormwater models, and may include outfalls under the jurisdiction of DCR, MassDOT, or other entities, as well as direct stream inflows. The bacteria counts applied to the flow inputs are described in subsections below.

4.3.2 Bathymetry

The bathymetry data for the Charles River Delft3D model were derived from a project carried out by the Charles River Alliance of Boaters (CRAB) and the MIT Sea Grant College Program. A group of researchers carried out depth measurements covering the areas between the New Charles River Dam and the Watertown Dam during 2016/2017 using a Lowrance HDS-7 chartplotter/fish finder with Point-1 GPS and HST-WSBL broadband sonar transducer. In the wide areas of the river, the survey lines were spaced between 30 and 65 feet apart, and in the narrow areas several passes were made to provide good resolution. River level fluctuations during the surveys were accounted for by incorporating several depth measurement locations into the final processing of the sonar data.

A salinity intrusion of seasonally varying size exists in the Charles River Lower Basin (Ayuso, 1995, Breault et al, 2000). Efforts have been made to reduce the salinity intrusion by improving the Charles River Dam locks as well as vertical mixing. An objective of the New Charles River Dam and Locks built in the late 1970s was to reduce the entry of harbor water into the basin. Despite the new dam, harbor water still enters the basin particularly during times of high-recreational boating use, when the gates of the locks are opened more frequently to allow boats into or out of the Charles River. Conversely, during periods of high river flow, water is pumped out of the basin at depth and can result in complete removal of the salinity intrusion (Breault et al, 2000).

The salinity intrusion has an effect on the water quality in the Charles River basin and should be accounted for. In previous modeling, it was simulated by raising the river bottom to the elevation of the interface, since the flow is mainly confined to the upper freshwater layer. However, bacteria are present in the intrusion and are thought to result from the settling of bacteria attached to solid particles from the upper freshwater layer (Ayuso, 1995). The flow velocities in the basin are low, thereby promoting settling, but the flow velocities upstream are also low and settling occurs throughout. Therefore, bacteria settling

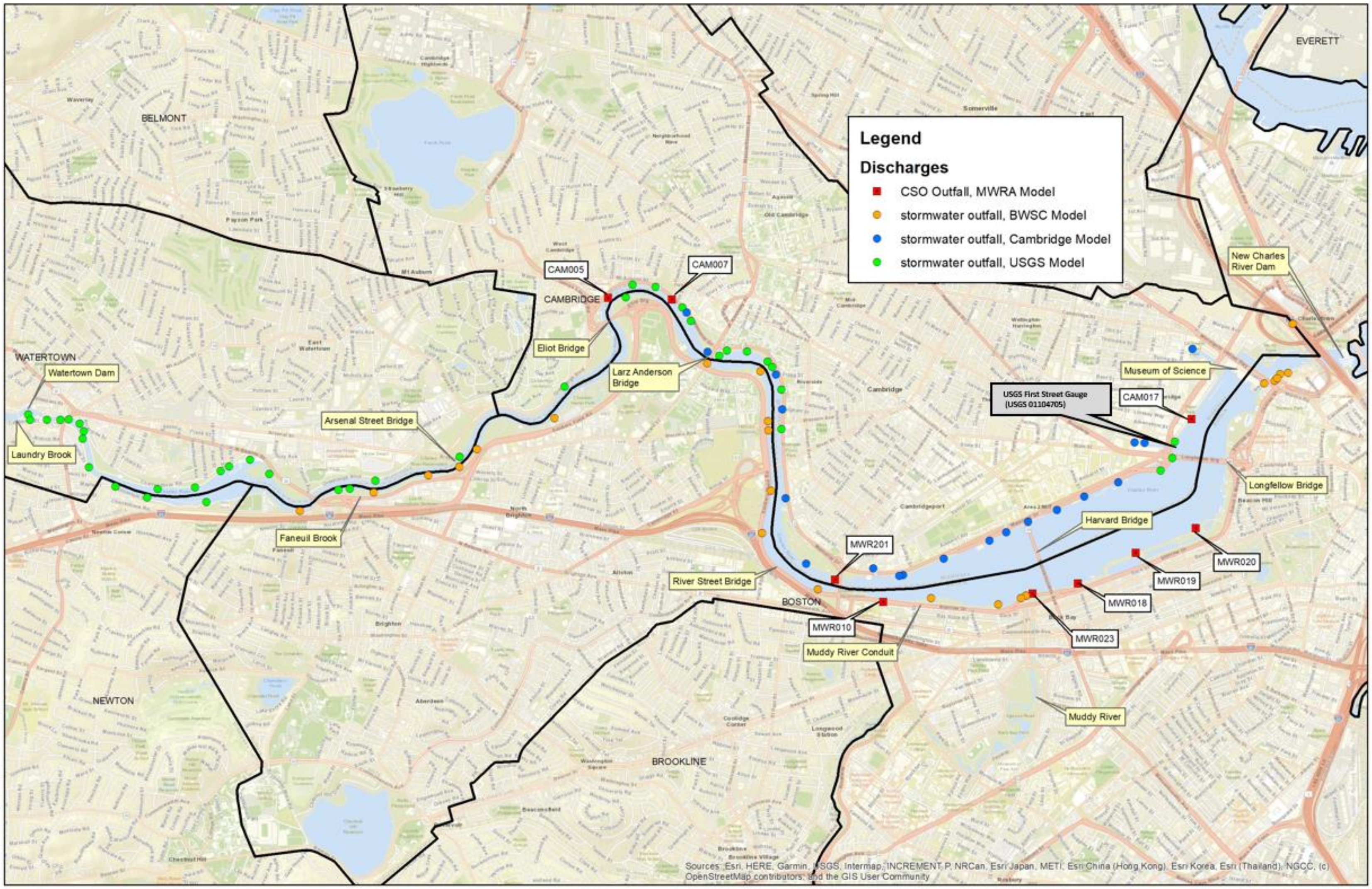


Figure 4-1. Stormwater and CSO Discharges to the Charles River

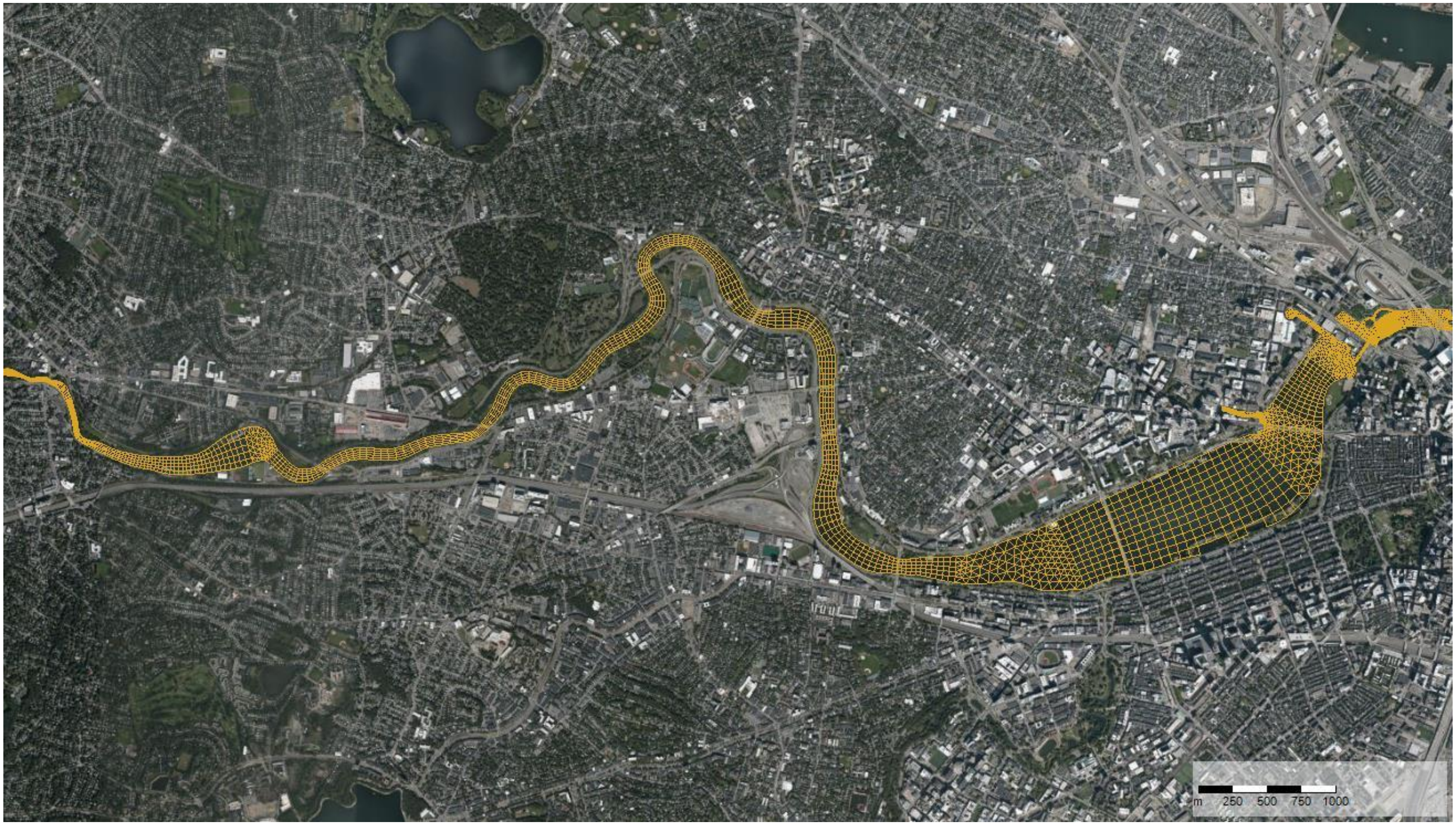


Figure 4-2. Charles River Model Grid

in the intrusion is not much different than bacteria settling to the river bottom upstream, and the intrusion can legitimately be simulated as a boundary, with settling incorporated in the bacterial die-off.

Although the intrusion grows and shrinks due to lock openings and high flow events, simulating these variations in the model is not practical and it is not believed to have a significant effect on bacterial counts in the upper part of the water column. In addition, most recreational activities take place in the upper few feet of the river so the salinity intrusion would not impact the suitability of the water for recreational uses. Therefore, as for previous modeling, the intrusion was simulated by limiting the water depth in the model to 7 m (23 ft) wherever the bathymetric measurements indicated it was deeper.

4.3.3 CSO Flows

The flowrates of the CSOs discharging to the Charles River were specified based on results from the calibrated MWRA collection system hydraulic/hydrologic model, driven by rainfall hyetographs. The collection system hydraulic/hydrologic model also provided an estimate of the fraction of sanitary flow (hereinafter called the “sanitary fraction”) in each CSO discharge as a function of time during the storm, as explained in Section 2.

4.3.4 CSO Quality

For untreated CSO discharges, *Enterococcus* and *E. coli* counts were specified based on time-varying sanitary fractions calculated by the MWRA collection system hydraulic/hydrologic model as described above in Section 2.2. The bacterial counts of the sanitary and stormwater fractions were calibrated to data measured at Cottage Farm and Prison Point influents. The initial concentrations for the sanitary and non-sanitary fractions of the flow were set at 1,000,000 MPN/100 mL and 5,500 MPN/100 mL, respectively for *Enterococcus*, and 7,000,000 MPN/100 mL and 13,400 MPN/100 mL, respectively, for *E. coli*. The predicted flow-weighted average sanitary fractions and the predicted flow-weighted counts for *Enterococcus* and *E. coli* at the CSO outfalls to the Charles River and the influents to the Cottage Farm and Prison Point CSO Facilities for 2018 are presented in Table 4-1. The sanitary fraction was computed for wet weather flows at each outfall over the course of the year (2018 rainfall). For each outfall, the sanitary fraction shown in Table 4-1 is the flow weighted average in the discharge pipe over the periods when the outfalls were discharging flow. For example, at outfall CAM005, 0.02% of the total predicted volume discharged at that outfall for 2018 was sanitary flow based on the modeled tracer analysis. Figure 4-3 shows the plot of the modeled flow and sanitary fraction versus time at outfall CAM005 for the August 11, 2018 storm. Figure 2-1 above presents an example of how the sanitary fractions varied over time for the influent flow at Cottage Farm and Prison Point during the November 10, 2018 storm.

As indicated in Table 4-1, the CSO outfalls all have relatively low sanitary fractions. For the Cambridge outfalls, the low sanitary fractions reflect sewer separation work that has been conducted in the upstream tributary areas. For the MWRA outfalls, the local tributary area to outfall MWR010 has been separated. Outfall MWR023 is the discharge from the Stony Brook Conduit, which is mostly stormwater and stream flow. The CSO regulators remaining tributary to the Stony Brook Conduit are all relatively inactive. Outfalls MWR018 to MWR020 discharge off of the Boston Marginal Conduit, which receives most of its flow from the Old Stony Brook Conduit, which is again mostly stormwater. The low sanitary fraction in the Prison Point influent is consistent with the low sanitary fractions in the upstream systems. At Cottage Farm, the relatively higher sanitary fraction is driven by the flow from the upstream separately sewered communities along the Charles River Valley Sewer and South Charles Relief Sewer. The flow-weighted counts for Cottage Farm and Prison Point are generally consistent with the sampling data presented in Section 2, while the flow-weighted counts for the CSOs are consistent with the relatively low sanitary fractions in the flow tributary to the outfalls. The impact on the predicted flow-weighted concentrations at the outfalls of tuning adjustments to the counts in the non-sanitary fractions is presented in Section 4.4 below.

Table 4-1. Predicted Sanitary Fractions and Flow-weighted Counts for 2018

Location	Flow-weighted Sanitary Fraction (%)(1)	Flow-weighted Counts (MPN/100 mL)	
		Enterococcus	*E. coli*
CAM005	0.02%	5,691	14,841
CAM007	1.76%	23,008	136,494
MWR010	0.00%	5,500	13,500
MWR023	0.03%	4,316	12,212
MWR018	0.63%	11,787	57,666
MWR019	0.51%	10,595	49,292
MWR020	0.47%	10,127	46,002
CAM017	0.07%	6,169	18,200
Cottage Farm Influent	16.62%	170,765	1,174,424
Prison Point Influent	0.3%	33,192	207,940

Note:

(1) For each untreated CSO outfall, the sanitary fraction shown is the flow weighted average in the discharge pipe over the periods when the outfalls were discharging flow. For Cottage Farm and Prison Point, the sanitary fraction shown is the flow weighted average in the facility **influent** while the facility was active,

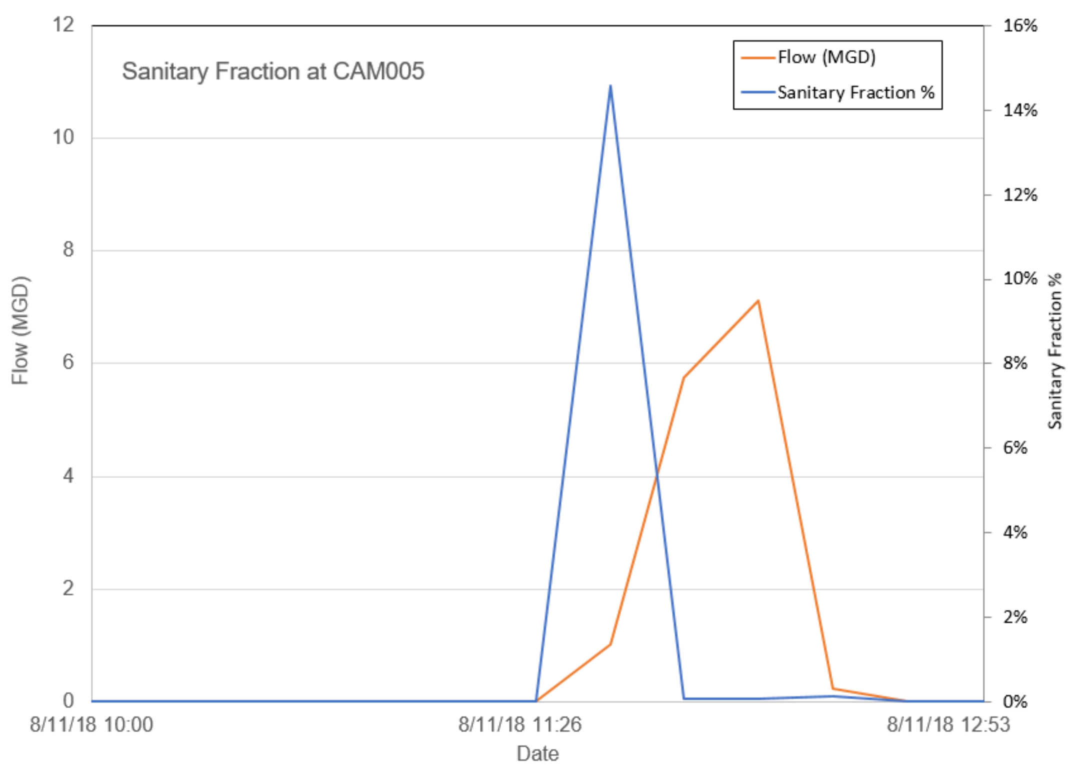


Figure 4-3. CAM005 Sanitary Fraction vs Time for the August 11, 2018 Storm Event

As described above in Section 2.3, for the treated discharges from the Cottage Farm CSO Facility, the average of the effluent bacterial counts measured between July 2018 and April 2019 were used to represent the effluent quality. These values were 212/100 mL for *Enterococcus* and 394/100 mL for *E. coli*.

4.3.5 Stormwater Flows

Stormwater (and CSO) discharge locations to the Charles River are shown above in Figure 4-1. Stormwater flows discharging to the Charles River were specified based on three stormwater collection systems models, which include:

i) The *Boston Water and Sewer Commission* (*BWSC) Stormwater Model (2012-17)*
ii) The *United States Geological Survey (USGS) Charles River Stormwater Model (2002)*
iii) The *Cambridge ICM Model (2015-18).*

Figure 4-1 shows which model was used for the different stormwater inputs.

In all cases, the most recent model version was used to calculate the stormwater flows. In particular, for areas that have been recently separated, for example in Cambridge, the stormwater flows were simulated with models that reflected the separation completed at the time of the calibration data (2018). Each of these models is summarized below.

BWSC Stormwater Model

The *BWSC Stormwater Model* simulates stormwater flows in the City of Boston. BWSC's stormwater model is currently using the software package PCSWMM, a graphical user interface to USEPA Stormwater Management Model (SWMM) developed by Computational Hydraulics International (CHI). The model covers inputs to 208 permitted stormwater outfalls within Boston, draining approximately 36 square miles. The model was designed to simulate hydrology using the EPA SWMM RUNOFF methodology (USEPA, 2015), but also adds groundwater infiltration and inflow (I/I) routines to simulate the impact of antecedent moisture conditions during large storm events. This model was used to specify the discharges from the City of Boston stormwater outfalls to the Charles River.

USGS Charles River Stormwater Model

As part of an extensive evaluation of the Charles River water quality, the USGS developed and calibrated four separate stormwater models for:

i) Laundry Brook
ii) Faneuil Brook
iii) Muddy River/Stony Brook
iv) Ungauged stormwater areas (areas for which flow meter data were not available) (USGS, 2002-b)

Extensive efforts were made to develop runoff parameters depending on land use and other factors. Twenty storms were used for model calibration ranging in depth from 0.31 to 1.8 inches, which resulted in observed discharges of 1.6 to 59 ft^3/s. These models were used for the previous Charles River water quality modeling but is only used here in areas where other models are not available, specifically for areas of Newton and Watertown that drain below the Watertown Dam.

Cambridge ICM Model

This model which includes the stormwater areas in the City of Cambridge, was provided by the City for use in this project. The storm drain pipes included in the Cambridge ICM model are shown in the blue lines in Figure 4-4. The pink area generally outlines the runoff areas tributary to the storm drains. This model was implemented with the InfoWorks ICM software using the SWMM Runoff methodology without using the groundwater routines.

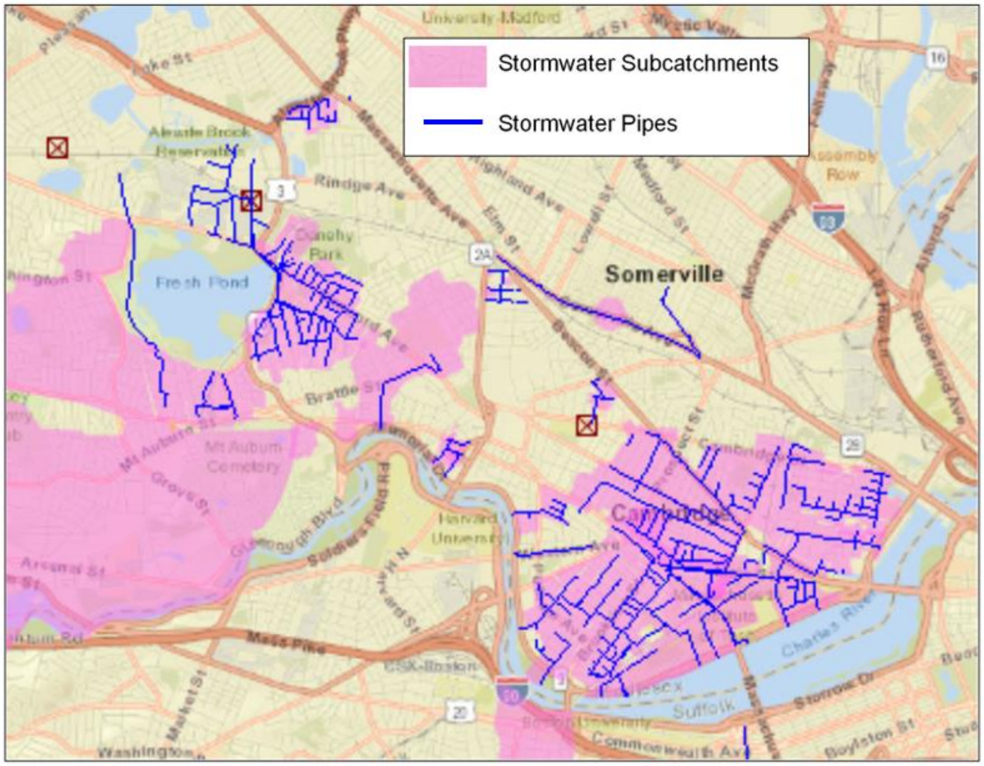


Figure 4-4. Stormwater Areas covered by the Cambridge ICM Model

4.3.6 Stormwater Quality

Enterococcus and *E. coli* counts in stormwater discharging to the Charles River were assigned the average values described in Section 2.4, subject to adjustment during the calibration process as described further in Section 4.4. Those values were 5,500 MPN/100 mL for *Enterococcus*, and 13,400 MPN/100 mL for *E. coli*.

BWSC conducted stormwater quality monitoring for three dry days and three wet days in the fall of 2011 and again in the spring of 2012 at 20 monitoring sites (CDM Smith, 2015). These data are summarized in Table 4-2. Because of the illicit connection removal and BMP/GI implementation, the 2011-12 data are no longer applicable. Nevertheless, these data are interesting. The BWSC wet weather *Enterococcus* counts are slightly higher than the 5,500 MPN/100 mL average listed in Table 2-4. The BWSC wet weather *E. coli* counts, however, are much less than the 13,400 MPN/100 mL value listed in Table 2-4. BWSC is in the process of conducting a two- year stormwater monitoring program to confirm the effectiveness of the illicit connection removal and BMP/GI implementation.

Table 4-2. Median Stormwater Bacterial Counts from Boston 2011-2012 Monitoring

	Enterococcus **(MPN/100 mL)**	***E. coli*** **(MPN/ 100 mL)**
Dry Weather	1,300	5,200
Wet Weather	7,200	8,200

The BWSC Stormwater Model simulates water quality loading to the drain system as a function of land use type. The model also includes estimates of dry weather illicit connection loads, which were used to simulate dry weather sources. This model, however, generated results that varied considerably from one outfall to the other and with time, and could not readily be adjusted to improve the match to measured counts in the Charles River. Therefore, fixed bacterial counts were used for the dry weather flow and wet weather flows based on monitoring conducted in stormwater drains described in Section 2.4 and Section 2.5, and adjusted based on model calibration with in-stream water quality measurements.

4.3.7 Upstream Boundary Conditions

Flow and water quality need to be specified at the upstream end of the model (at the Watertown Dam) as a function of time. During wet weather events, flows and pollutant concentrations at the Watertown Dam increase due to upstream runoff and non-point sources. As documented in previous studies and in the MWRA stream monitoring, the increases in flow and pollutant concentration are substantial, and have considerable impact on water quality downstream of the dam. Therefore, the accuracy of the upstream boundary condition is important.

For the Lower Charles River model, both upstream flows and bacterial counts must be specified. Flows can be estimated from measurements at the USGS gauge at Waltham (No. 01104500) using the following relationship (USGS, 2002b).

$$Q_{WD} = 6.8097\, Q_{WG}^{0.7334} \quad \text{for} \quad Q_{WG} < 450 \text{ cfs}$$
$$Q_{WD} = 3.6605\, Q_{WG}^{0.8341} \quad \text{for} \quad Q_{WG} > 450 \text{ cfs}$$

Where Q_{WD} = Flowrate at Watertown Dam (cfs) and Q_{WG} = flow at Waltham gauge (cfs)

Enterococcus and *E. coli* measurements were available in the Watertown Dam area for the calibration periods (when MWRA in-stream water quality monitoring data were available), but were not collected frequently enough to be used for the model boundary condition; furthermore, such measurements are not available for the design storms or the Typical Year. Therefore, a means of estimating upstream bacterial counts was needed.

To that effect, a model based on the buildup-washoff formulation was used to estimate the bacterial counts at the Watertown Dam based on measured flows in the river at the USGS Waltham gauge. Dry weather counts were established by applying constant *Enterococcus* and *E. coli* counts to the river baseflow (non-storm flow), while wet weather loadings were generated from the buildup-washoff formulation. This model and its calibration to measured bacterial counts are described briefly below and in more detail in Appendix A.

The measurements used for the calibration were conducted by MWRA at Stations 012 and 001 (see Figure 3-1 for locations). Station 012 is located at the Watertown Dam. Historically, data at this station were collected at 2-week intervals and were not coordinated with storms. However, starting in the spring of 2019, Station 012 was added to the MWRA's storm sampling program. Station 001 is located approximately 1 mile downstream of the Watertown Dam, and storm data were collected at this monitoring station starting in 2017. Samples were collected at daily intervals for several days following selected storms. Laundry Brook is located between the Watertown Dam and Station 001. While the bacteria counts previously observed in this brook were high, its impact on the total bacteria load to the Charles River is minor compared to the loads coming over the Watertown Dam, because the Laundry Brook flow is much less than that of the Charles.

Enterococcus and *E. coli* data collected in 2017 and 2018 at MWRA Stations 001 and 012 are plotted in Figures 4-5 to 4-8 together with rainfall (at the MWRA Ward Street gauge) and the Charles River flows at the Watertown Dam. The rainfall and flow data are at 15-minute intervals. These plots are presented for general observations; higher resolution plots including comparison with the buildup-washoff model are presented in Appendix A. The stream flow peaks indicate times of wet weather influence and the bacteria levels frequently exceed the standards. Review of the bacterial data for Stations 012 and 001 was presented in the *Review of Monitoring Data* report (AECOM, 2019). Conclusions of this review are summarized below.

- Data collected at Station 012, which are not coordinated with storms, are more representative of dry weather conditions than those collected at Station 001, and *Enterococcus* and *E. coli* counts at Station 012 are generally less than those measured at Station 001.

- The storm-based sampling conducted at Station 001 shows a fairly consistent decrease of *Enterococcus* and *E. coli* counts with time following the storms (with some exceptions).

- *The E. coli* counts are consistently higher than the *Enterococcus* counts, but mainly for the lower values where the *E. coli* counts are on the order of 6 times the *Enterococcus* counts. The higher *E. coli* counts are only about 1.5 to 2.0 times the *Enterococcus* counts. This difference was taken into account in the buildup-washoff model by adjusting the buildup rates and base flow counts.

- About 40% of the *Enterococcus* and 20% of the *E. coli* counts exceed the statistical threshold values (STV) of 130 MPN/100 mL for *Enterococcus* and 410 MPN/100 mL for *E. coli* specified in the 2019 proposed revision to the Massachusetts Bacterial Standards for Class B Waters.

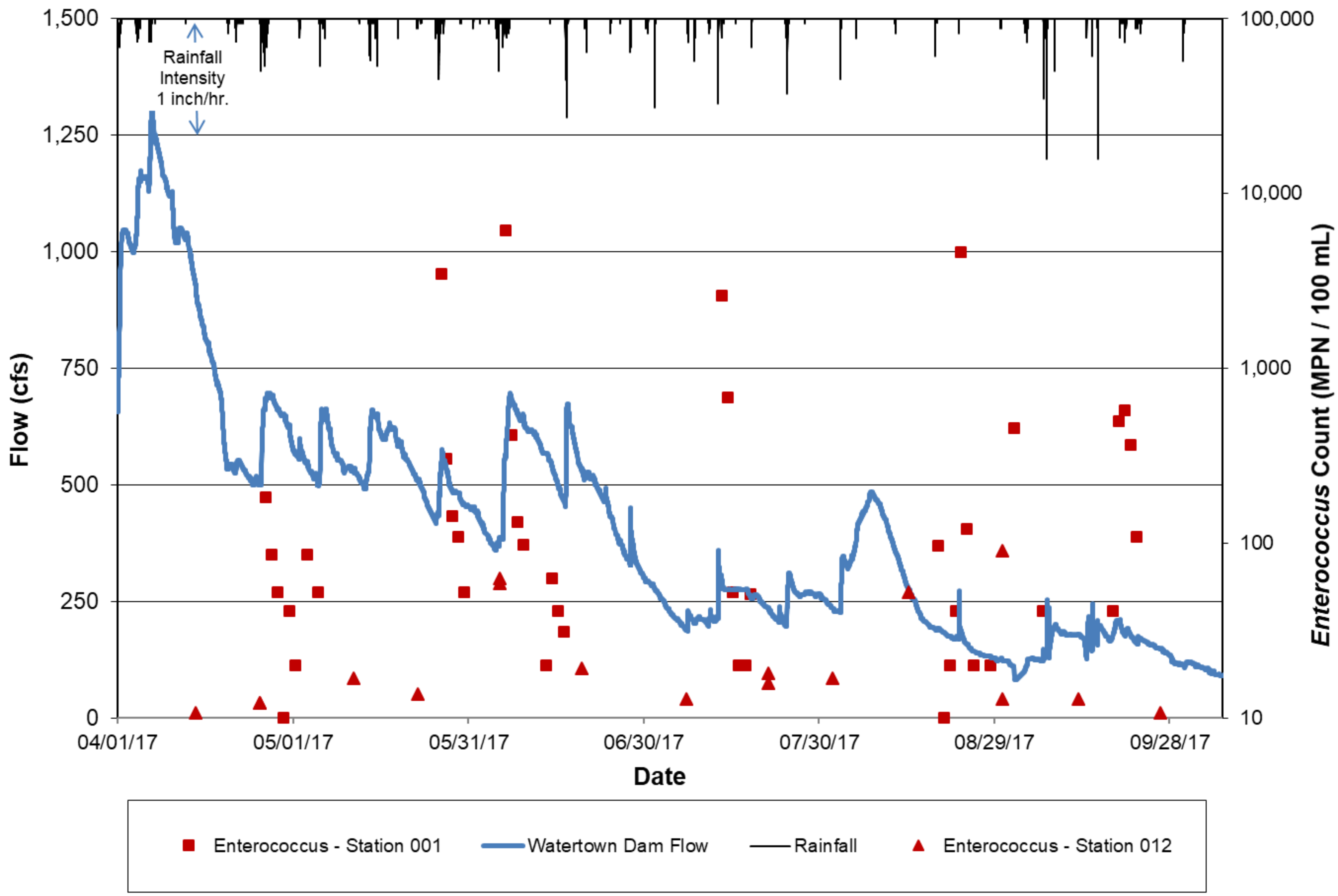


Figure 4-5. *Enterococcus* Measurements at Stations 001 and 012 for 2017

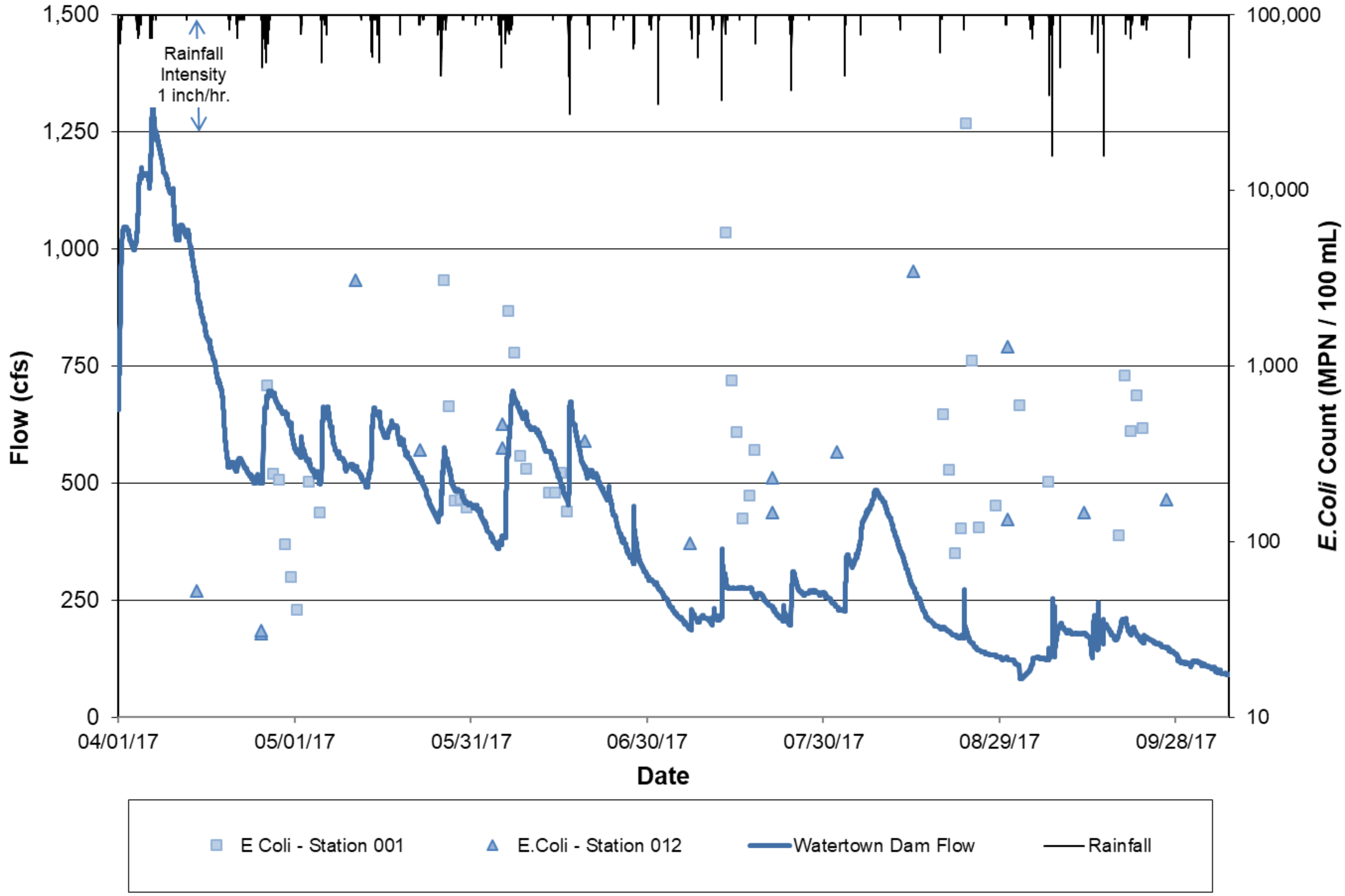


Figure 4-6. *E. coli* Measurements at Stations 001 and 012 for 2017

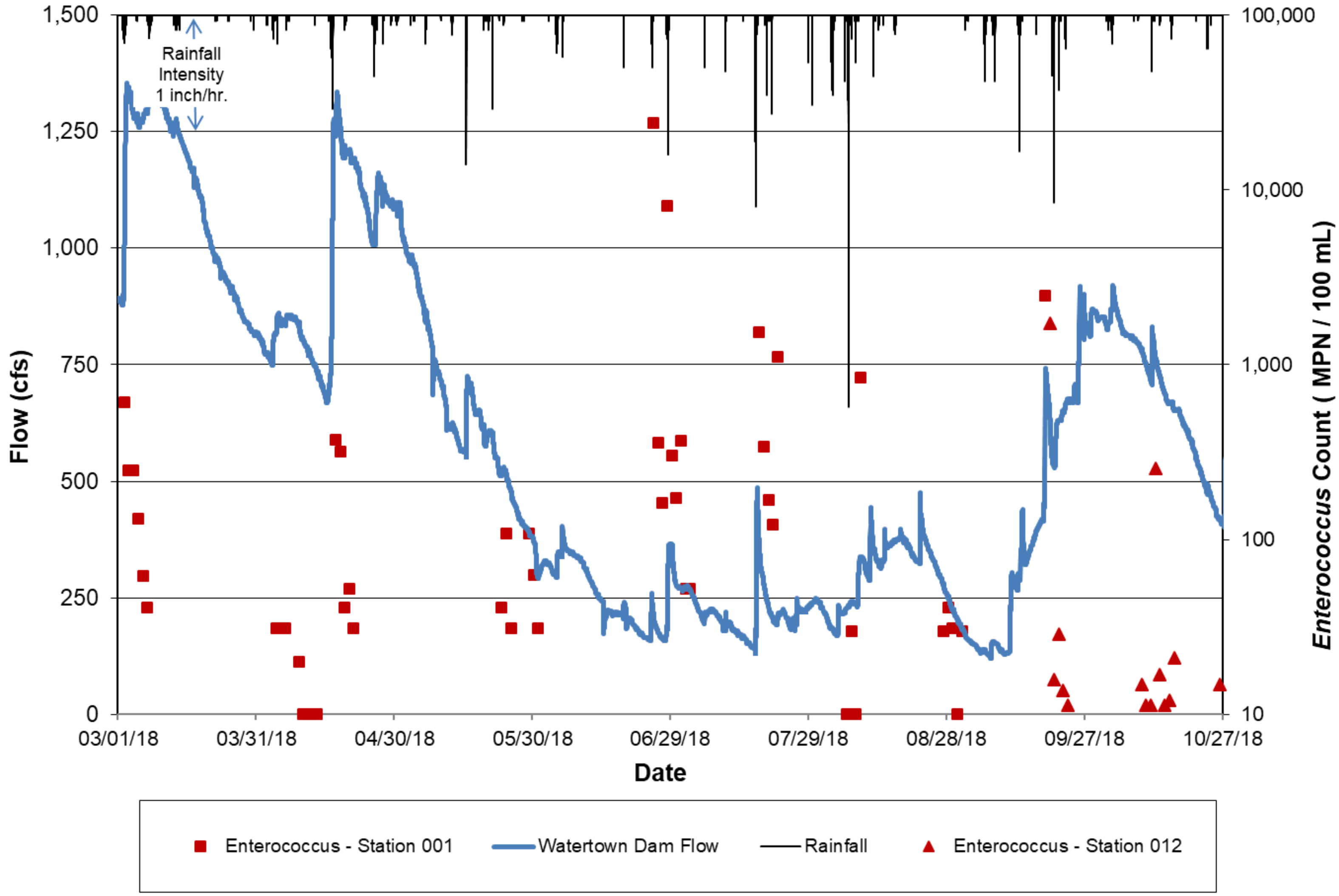


Figure 4-7. *Enterococcus* Measurements at Stations 001 and 012 for 2018

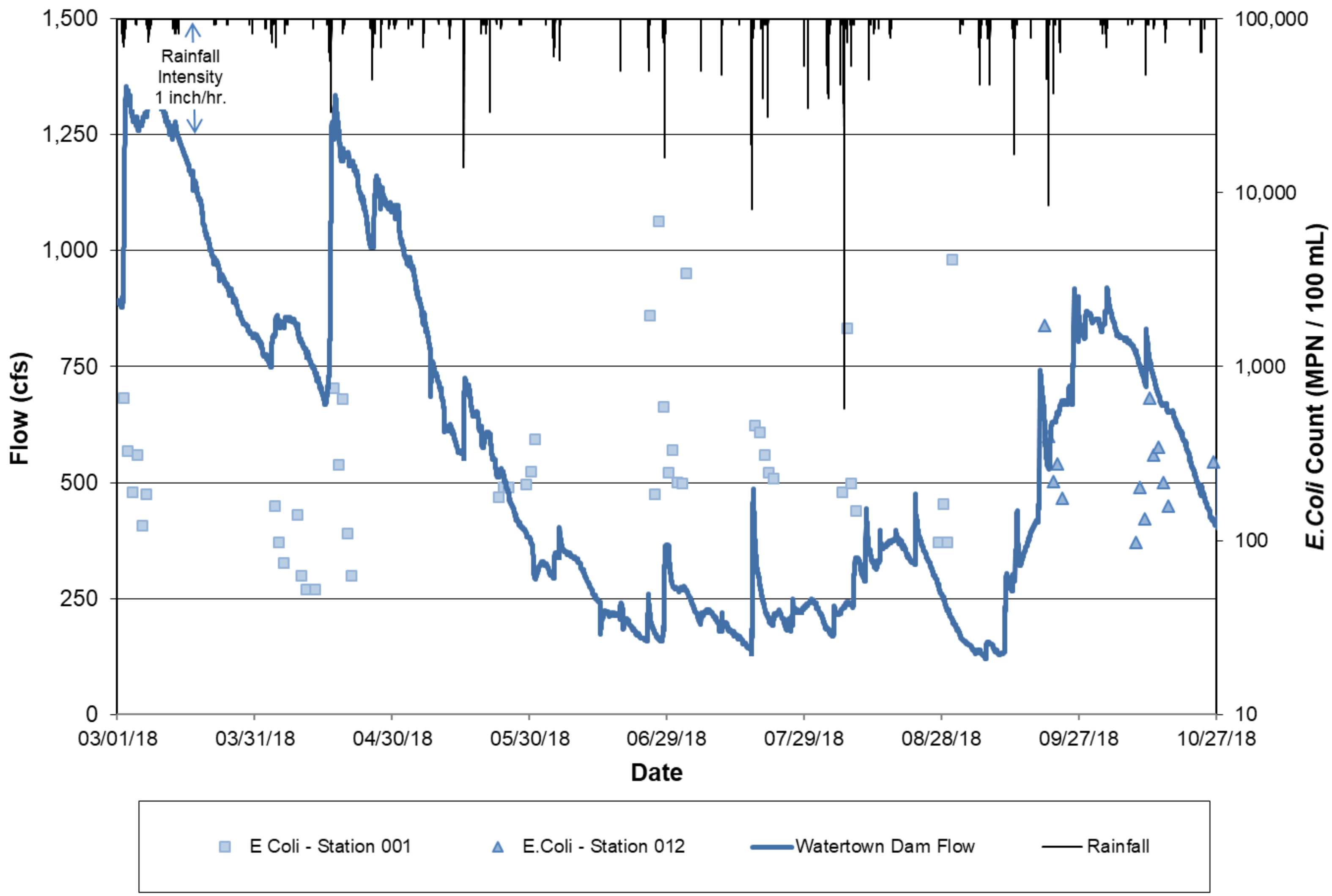


Figure 4-8. E. coli Measurements at Stations 001 and 012 for 2018

- In dry weather, the *E. coli* counts are higher than the *Enterococcus* counts, but the difference diminishes for wet weather.

- Peak *Enterococcus* and *E. coli* counts at Stations 001 and 012 measured in the spring and fall are significantly less than those measured in the summer (Selvakumar and Borst, 2006). This observation is in contrast to the expectation that faster bacterial die-off during warmer temperatures (Mancini et al, 1978; DHI, 2000) would lead to lower summer counts. Bacteria in stormwater are due mainly to dogs, birds and other wildlife. Reduced dog walking, bird migration and wild animal hibernation may be causes for the reduced bacteria counts in the winter and fall. This seasonality was taken into account in the buildup- washoff model by reducing the deposition rate in the winter, early spring and fall.

Buildup-Washoff Model

Estimation of bacteria counts at Watertown dam for the purpose of transient water quality modeling in the Lower Charles was previously accomplished using a buildup-washoff approach (Metcalf & Eddy, 1994 and 2004). This is the approach used for pollutant generation modeling in SWMM (Huber and Dickinson, 1988). In this approach, pollutants are assumed to buildup in the catchment during dry weather and get washed off by runoff at a rate dependant on the runoff intensity. This is an approximation for the 265 mi^2 Charles drainage area upstream of Watertown Dam. Among other simplifications, it does not account for bacterial die-off that occurs during the travel time from upper reaches of the river to the dam site. Nevertheless, the approach simulates some of the mechanisms that lead to increased counts in the river, and it produces simulated bacterial counts at Watertown Dam that resemble those observed. Therefore, with judicious calibration, it can be used to provide estimates of upstream water quality boundary conditions.

The equations used in the buildup-washoff model are listed in Appendix A, which also shows plots of model-calculated bacterial counts compared to measurements at Stations 012 and 001. The parameters that were found to provide the best match, with the average measured and modeled results and the Index of Agreement, are listed in Table 4-3.

Table 4-3. Watertown Dam Build-up/Washoff Coefficients

	Build-up Rate		Washoff Coeffi-cient	Washoff Exponent	Die-off Rate	Base Flow Count			
	A (count/mi^2/day)	Winter/ Fall Ratio	α ($day^{\beta-1}$ $ft^{-3\beta}$)	β (unitless)	K (day^{-1})	C_B count/100ml	Average Measured MPN/100ml	Average Model MPN/100ml	IA
Entero 2017	1.7×10^{11}	0.2 / 0.5	8×10^{-4}	1.4	0.5	45	405	408	0.92
Entero 2018							331	358	0.89
E. coli 2017	3.5×10^{11}	0.2 / 0.5	8×10^{-4}	1.4	0.5	134	997	1,094	0.87
E. coli 2018							623	601	0.92

4.3.8 Downstream Boundary Conditions

At the New Charles River Locks and Dam water is discharged at low tide and pumped out of the basin in anticipation of wet weather events, with the goal of maintaining a stable water level. Water surface elevation measurements are conducted at a USGS gauge just upstream of the dam. Typical measurements are presented in Figure 4-9, showing water level fluctuations synchronized with the tide (with a magnitude on the order of 1 ft) and occasional lows associated with storms.

For the model, the water levels measured at the New Charles River Dam USGS gauge were specified as the downstream boundary condition.

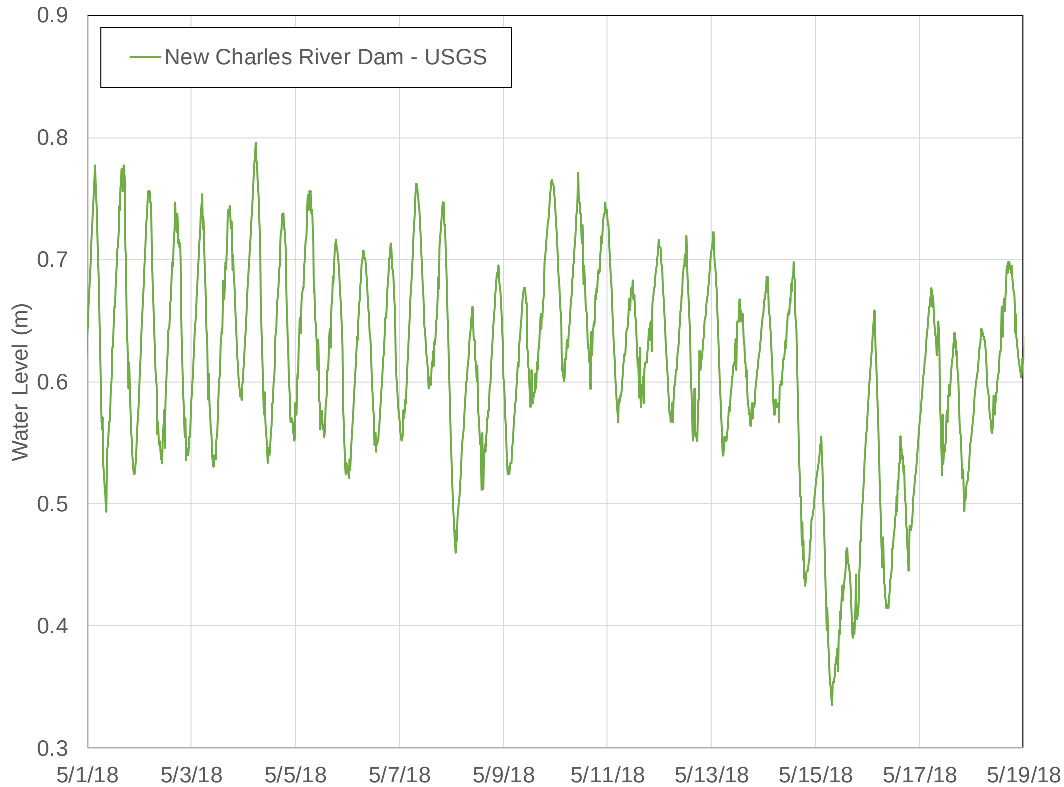


Figure 4-9. Water Levels Measured at the USGS Gauge at the New Charles River Dam (NGVD29)

4.3.9 Initial Model Parameters

Bacterial counts

For treated CSOs, initial *Enterococcus* and *E. coli* counts of 1,000,000 MPN/100 mL and 7,000,000 MPN/100 mL, respectively, were used for the sanitary fraction and 5,500 MPN/100 mL and 13,400 MPN/100 mL for the non-sanitary fraction, as discussed in Section 2.2.1.

For treated discharges from the Cottage Farm Facility, initial *Enterococcus* and *E. coli* counts of 212 MPN/100 mL and 394 MPN/100 mL, respectively, were used, as discussed in Section 2.3. These values were not changed in the calibration.

For stormwater discharges, initial *Enterococcus* and *E. coli* counts of 5,500 MPN/100 mL and 13,400 MPN/100 mL, respectively, were used.

Riverbed Roughness Coefficient (Manning's n)

A value of n = 0.023 was initially specified, representative of natural river conditions (Chow, 1959). This coefficient remained unchanged.

Dispersion coefficient

The Delft3D model uses a dispersion coefficient formula to simulate the diffusion processes associated with turbulence, vertical shear (which is not accurately represented in two-dimensional models) and subgrid scale processes (flow features such as eddies of a size smaller than the model grid). Based on previous modeling of the Charles River a value of 0.2 m^2/s was used (MWRA, 1996).

Bacterial Die-Off

A die-off rate of 0.8 day^{-1} was used, consistent with the discussion in Section 3.3.1.

4.4 Model Calibration

4.4.1 Hydrodynamic Calibration

The water level boundary condition specified at the New Charles River Dam resulted in minor backflow into the basin from downstream. This backflow, however, did not affect the hydrodynamic calculations, as shown in Figure 4-10, where measured and calculated water levels at the USGS First Street gauge (shown on Figure 4-2) are compared.

Calculated water levels at the Watertown Dam are plotted in Figure 4-11 together with the USGS water levels at the New Charles River Dam. This plot shows that the water level fluctuations at the New Charles River Dam propagate upstream with minimal attenuation. The average water level at the Watertown Dam is higher than at the New Charles River dam, reflecting the expected net downstream flow.

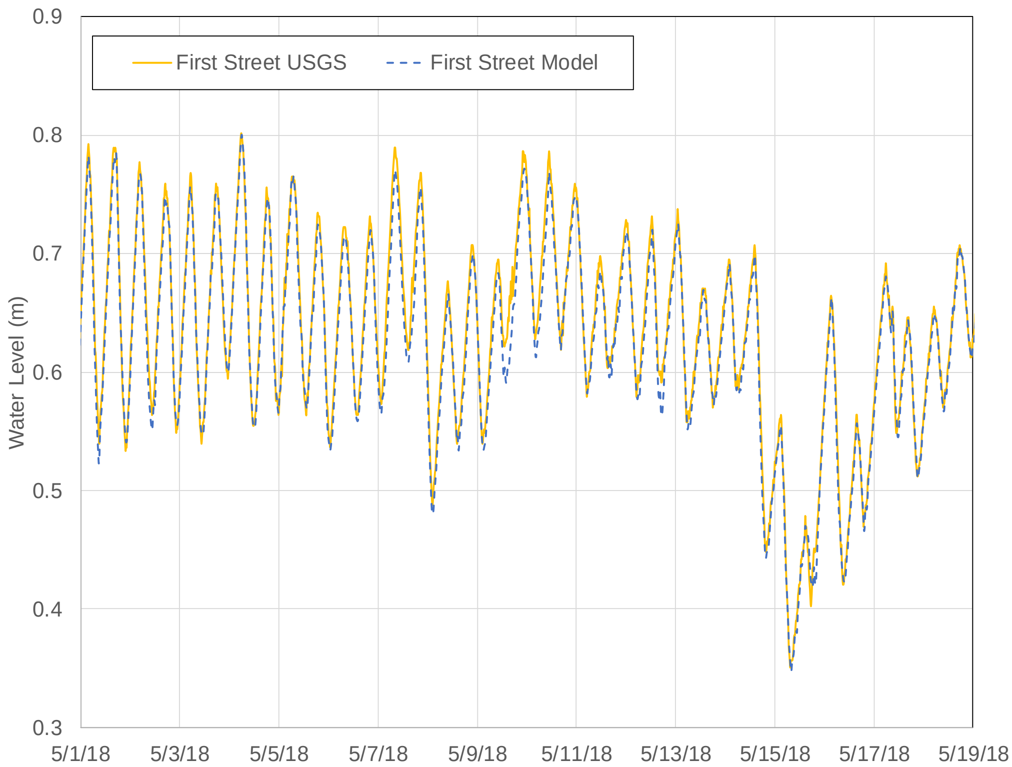


Figure 4-10. Measured and Calculated Water levels at the USGS First Street Gauge (USGS 01104705)

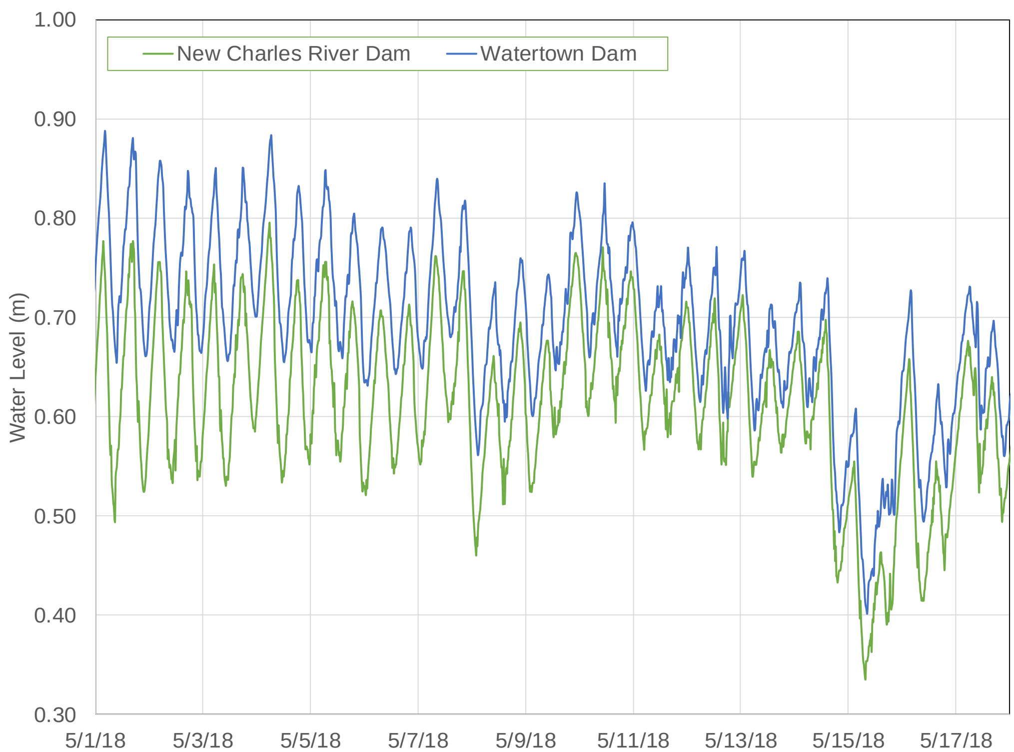


Figure 4-11. Model Water Levels at the New Charles River Dam and Watertown Dam

4.4.2 Water Quality Calibration

Water Quality calibration was conducted for the period of April to October 2018 for which MWRA in-stream monitoring data were available. The larger storms (with depths greater than 0.3 inches or with CSO activation) are summarized in Table 4-4. This table is provided to allow correlations to be made between predicted water quality variations and wet weather events with and without CSO activations. Of particular interest are the storms of July 17, August 11 and September 18, which had discharges at several CSO outfalls. Most of the untreated CSO volumes were less than 1 MG, although larger discharge volumes occurred on July 17 at MWR018 (2.65 MG) and MWR019 (1.12 MG) and on August 11 at MWR018 (1.38 MG). The Charles River flows at the Watertown Dam were on the order or 400 cfs on both of these days.

4.4.2.1 Dry Weather Calibration

The in-stream monitoring shows elevated bacterial counts in the Charles River during dry weather. Previous modeling indicated that some of the dry weather bacterial counts were due to previous discharges, whose effect can last for several days. Dry weather sources, for example illicit sanitary connections to storm drains, can also contribute to dry weather bacterial counts in the river. In contrast with previous modeling that covered individual storms, the current modeling is continuous and, therefore, accounts for residual loads from previous discharges. However, the residual loads from wet weather events alone were not sufficient to match measured dry weather counts in the river, so additional dry weather loading sources needed to be added.

The USGS and BWSC stormwater models include the simulation of dry weather flows, and bacterial counts were assigned to those dry weather flows to simulate dry weather bacterial loading sources. Establishing the counts in the dry weather flows was an iterative process. Initial runs using the dry weather counts measured in storm drains prior to wet weather (890 MPN/100 mL for *Enterococcus* and 3,100 MPN/100 mL for *E. coli*, as described in Section 2) were found to result in over-prediction of the in-river counts during dry weather. Through a process of trial-and-error, the dry weather counts measured at Stations 012 at the Watertown Dam and Station 001 about one mile downstream of the dam (45 MPN/100 mL for *Enterococcus* and 134 MPN/100 mL for *E. coli,* see Table 4-3 and Appendix A*)* were found to result in a better match of the predicted in-river counts to the measured counts in dry weather.

While the selected values for the dry weather counts were lower than the average of the dry weather flow measurements from storm drains described in Section 2, it is noted that only two of the storm drains in that assessment discharged to the Charles River (CAM3 and CAM4), so the calculated averages of 890 MPN/100 mL for *Enterococcus* and 3,100 MPN/100 mL for *E. coli* would not be considered a definitive assessment of the dry weather loading from storm drains into the Charles River. Rather, they were used as a starting point for an iterative calibration process that ultimately led to the selection of concentrations that resulted in predicted dry-weather in-river counts that matched the in-river measurements. The values of 45 MPN/100 mL for *Enterococcus* and 134 MPN/100 mL for *E. coli* were applied to the modeled baseflows discharging to the Charles River during dry weather. These values were adjusted during wet weather as described below.

Table 4-4. Storm Characteristics and CSO Activations in the Charles for 2018

Date	Rainfall(1)		Predicted CSO Volume from MWRA Collection System Hydraulic/Hydrologic Model (MG)							
	Depth (in)	Peak 15-min Intensity (in/hr)	CAM005	CAM007	CAM017	MWR018	MWR019	MWR020	Cottage Farm	MWR023
4/3/2018	0.75	0.24								
4/15/2018	2.43	0.8							5.32	
4/25/2018	1.07	0.52								
4/27/2018	0.42	0.24	0.041							
5/15/2018	0.98	1.28	0.035							0.016
6/4/2018	0.76	0.32								
6/24/2018	0.48	0.44	0.055							
6/27/2018	1.21	1.2	0.076							
7/6/2018	0.37	0.44	0.035							
7/17/2018	2.39	1.64	0.21	0.20	0.093	2.65	1.12	0.84	14.9	0.221
7/22/2018	0.38	0.48								
7/25/2018	0.68	0.84	0.031							
8/4/2018	0.66	0.76								
8/8/2018	0.73	0.68								
8/11/2018	2.36	3.36	0.14	0.091		1.38	0.31	0.044		0.130
8/14/2018	0.01	0.04	0.032							
9/10/2018	1.31	0.56								
9/12/2018	0.9	0.56								
9/18/2018	1.18	1.16	0.34	0.70		0.26	0.25	0.25	3.06	
9/25/2018	1.82	1.6	0.018							0.026
9/26/2018	0.36	0.64								
9/28/2018	0.44	0.28								
10/1/2018	0.67	0.24								
10/11/2018	0.71	0.48								
10/27/2018	1.65	0.36								
10/29/2018	0.77	0.52	0.048							
11/2/2018	1.91	0.64								
11/5/2018	1.2	0.4								
11/9/2018	1.6	0.52							4.42	
11/13/2018	1.23	0.24								
11/16/2018	1.43	0.4								
11/19/2018	0.63	0.16								
11/25/2018	0.84	0.44								
11/26/2018	1.58	0.28								
12/2/2018	0.8	0.24								
12/16/2018	0.65	0.24								
12/21/2018	0.77	0.2								
12/28/2018	0.33	0.12								
12/31/2018	0.4	0.24								

Notes: (1) Rainfall data from Ward Street Headworks gauge; storms of less than 0.3 inches omitted unless a CSO activation occurred.

4.4.2.2 Wet Weather Calibration

The wet weather calibration was primarily conducted for *Enterococcus*, with corresponding parameter values applied to *E. coli*. Many different model simulations were conducted with different combinations of parameters including primarily the bacterial counts in stormwater and die-off rates. A summary of parameters for some of the later model runs for *Enterococcus* and *E. coli* are provided in Tables 4-5 and 4-6, respectively, including values of the Index of Agreement calculated over the entire data set for the run. The set of conditions that was found to match measurements for *Enterococcus* best corresponded to run 46. The set of conditions that was found to match measurements for *E. coli* best corresponded to run 47. The set of parameters identified as best, and used in the final calibrated model, in some cases does not result in the simulation with the highest IA value. This is because, in addition to the goal of maximizing IA, the "weight of the evidence" method has been prioritized; in cases where the final calibrated model runs do not have the highest IA, they are among the highest. The parameters corresponding to these runs are summarized in Table 4-7. These runs used a die-off of 0.8 day^{-1} for *Enterococcus,* and the same die-off rate was found suitable for *E. coli*.

The impact on the calibration of increasing the die-off rate was also evaluated. As described in Section 3.3.1, a die-off rate of 0.8 day^{-1} was used for the calibration. For this analysis, the effect of increasing the die-off rate to 1.6 day^{-1} was assessed. In reviewing the results of this analysis, some locations clearly showed that the 0.8 day^{-1} resulted in a much better match of measured values than the 1.6 day^{-1} value. Figure 4-12 and 4-13 show a comparison of the 0.8 day^{-1} and 1.6 day^{-1} die-off rates at stations 009 and 010 for the September through November 2018 period. Figure 4-14 and 4-15 show a similar comparison for stations 166 and 011 for the March through April 2018 period. These plots show a good match with the in-stream measurements with the 0.8 day^{-1} die-off rate, but show the model significantly under-predicting the measurements with the 1.6 day^{-1} die-off rate. However, for most stations during most of the year, very little difference was seen in the model versus measurements comparisons using the different die-off rates. For six of the 14 stations assessed, the model versus measurements match was slightly improved for the July 21, 2018 storm with the 1.6 day^{-1} die-off rate. However, the model versus measurements match for other storms occurring during the summer months at those stations was not affected by the change in die-off rate.

While a higher die-off rate might be expected during the summer months (since die-off generally increases with temperature), the model versus measurements comparisons did not support using a higher summertime die-off rate at most stations for most summer rain events. As a result, this analysis supported the use of a constant 0.8 day^{-1} die-off rate. The use of a constant die-off rate also avoids ambiguities as to the season assigned to the design storms.

Table 4-5. Partial Charles River *Enterococcus* Model Runs Log

Run No.	Run Interval	Corresponding Hydrology Run	Dry Weather Baseflow *Enterococcus* (MPN/100mL)	Stormwater *Enterococcus* (MPN/100mL)	CSO *Enterococcus* (MPN/100mL)	Die-off Coeff (1/day)	Dispersion coeff (m^2/s)	IA	Comments
8	May-17	Run 2	5,600	5,600	Using Sanitary Fraction 1,000,000 MPN/100 mL	0.80	1.00	0.265	BWSC pollution loads added and concentration boundary condition (BC) at Watertown dam added
9	As above	Run 6	As above	As above	As above	As above	As above	0.29	downstream level BC was changed to be level in hydrodynamics run
10	As above	Run 2	As above	As above	As above	As above	As above	0.26	same as run 8
11	As above	Run 6	As above	As above	As above	As above	As above	0.201	updated upstream concentration BC and initial condition set at 45 MPN/100mL
12	As above	Run 16	As above	As above	As above	As above	As above	0.31	includes USGS flows, and cottage farm flow is broken up to threes pots
13	April 15 - May 31,2018	Run 32	6,700	6,700	As above	As above	As above	0.30	switched to the 2018 run
14	April - May, 2018	Run 32	As above	As above	As above	As above	0.20	0.23	lowered the dispersion coefficient
15	As above	Run 32	As above	As above	As above	As above	As above	0.23	run with 20% increase in Watertown BC
18	As above	Run 58	880	As above	As above	As above	As above	0.33	changed the concentration at USGS2, USGS5, and USGS11, so the dry weather periods have a concentration of 880 MPN/100mL and for the storms its 6,700 MPN/100mL
19	As above	Run 60	880	As above	As above	As above	As above	0.30	for all stormwater areas it uses 880 MPN/100mL during dry periods and 6,700 MPN/100mL for storm events, this is also in Delft3d 2020, and doesn't average flow or tracer values when preparing WAQ .csv files
20	March-June, 2018	Run 60	880	As above	As above	As above	As above	0.18	same as run 19, but for a longer period
21	As above	Run 60	400	As above	As above	As above	As above	0.18	changed the concentration for the baseflow to 400 MPN/100mL

Table 4-5. Partial Charles River *Enterococcus* Model Runs Log

Run No.	Run Interval	Corresponding Hydrology Run	Dry Weather Baseflow *Enterococcus* (MPN/100mL)	Stormwater *Enterococcus* (MPN/100mL)	CSO *Enterococcus* (MPN/100mL)	Die-off Coeff (1/day)	Dispersion coeff (m^2/s)	IA	Comments
22	As above	Run 60	45	10,000/6,700	As above	As above	As above	0.16	changed concentration of baseflow to 45 MPN/100mL, and stormwater concentration for upstream USGS and BWSC inputs to 10,000
23	As above	Run 60	As above	As above	As above	1.6	As above	0.20	changed the die-off rate
24	March-April, 2018	Run 60	As above	As above	As above	0.8	As above	0.18	increased the baseflow cut-off for USGS and BWSC sources
26	March-June, 2018	Run 60	As above	As above	As above	As above	As above	0.18	increased the baseflow cut-off for two MWRA CSO sources
27	As above	Run 60	As above	As above	As above	As above	As above	0.18	increased the baseflow cut-off for some BWSC sources
31	As above	Run 64	As above	10,000	As above	As above	As above	0.36	increased the baseflow cut-off for some BWSC and USGS sources, and increased storm concentration to 10,000 MPN/100mL for all locations
34	March-November, 2018	Run 69	As above	As above	As above	As above	As above	0.43	run for the full year
37	As above	As above	As above	As above	As above	As above	As above	0.43	increased baseflow threshold for November
42	As above	As above	As above	As above	As above	As above	As above	0.43	same as run 37 but saving .map and this file
43	As above	As above	As above	As above	As above	As above	As above	0.43	same as 42 but with mass loading corrected at sanitary 5 for east and west pipes
46	As above	Run 71	As above	As above	As above	As above	As above	0.44	Run with hydro run 71 to included updated discharge areas and updated concentrations at several stormwater inflows
53	As above	Run 71	As above	As above	As above	1.6	As above	0.35	Assess 1.6 die of rate

Table 4-6. Partial Charles River *E.coli* Model Runs Log

Run No.	Run Interval	Corresponding Hydrology Run	Dry Weather Baseflow *E.coli* (MPN/100mL)	Stormwater *E.coli* (MPN/100mL)	CSO *E.coli* (MPN/100mL)	Die-off Coeff (1/day)	Dispersion coeff (m^2/s)	IA	Comments
36	March-November, 2018	run 69	134	14,000	Using Sanitary Fraction 6,000,000 MPN/100 mL	0.80	0.20	0.36	initial E.coli run
38	As above	As above	As above	As above	As above	As above	As above	0.36	increased baseflow threshold for November
40	As above	As above	As above	As above	Sanitary Fraction 7,000,000 MPN/100 mL	As above	As above	0.27	increased CSO *E.coli* concentration
41	As above	As above	As above	20,000	Sanitary Fraction 6,000,000 MPN/100 mL	As above	As above	0.38	increased stormwater *E.coli* concentration
44	As above	As above	As above	14,000	As above	As above	As above	0.36	same as run 38 but with mass loading corrected at sanitary 5 for east and west pipes
47	As above	run 71	As above	As above	Sanitary Fraction 7,000,000 MPN/100 mL	As above	As above	0.36	Run with hydro run 71 to included updated discharge areas and updated concentrations at several stormwater inflows

Table 4-7. Selected Model Parameters

	Stormwater Count (MPN/100 mL)	Dry Weather Base Flow Count(1) (MPN/100 mL)	CSO Sanitary Fraction Count (MPN/100 mL)	CSO non-Sanitary Fraction Count (MPN/100 mL)	Die-off Rate (Day-1)
Enterococcus	10,000	45	1,000,000	10,000	0.8
E. coli	14,000	134	7,000,000	14,000	0.8

Note:

(1) These counts were applied to modeled baseflow during dry weather. In wet weather, the baseflow was assigned the same counts as the stormwater.

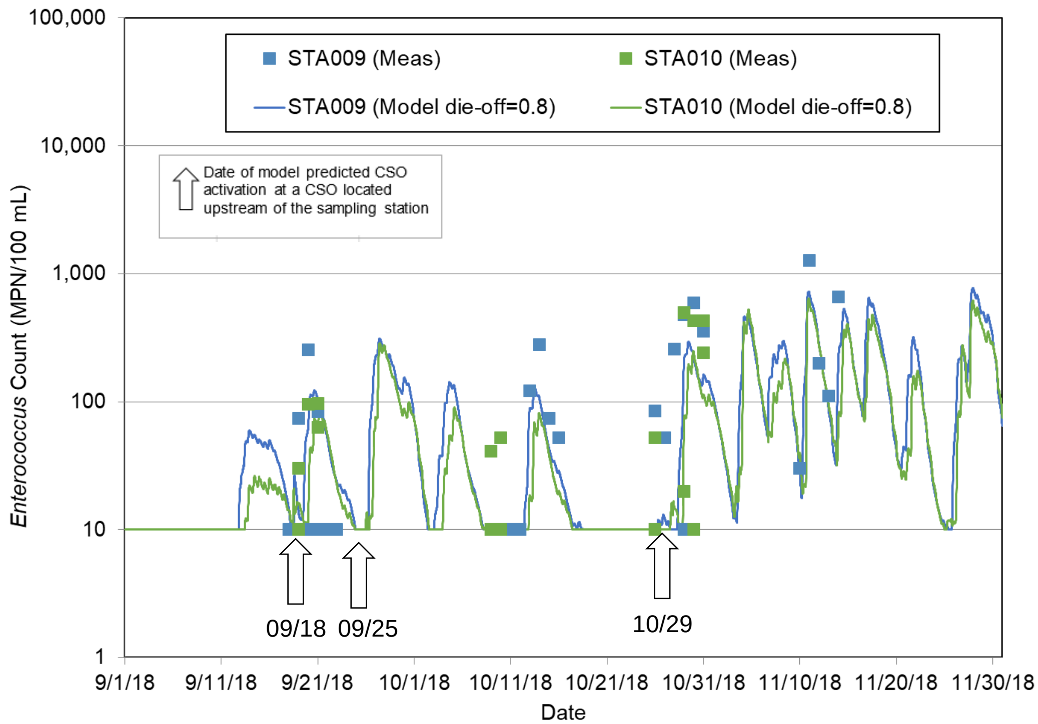


Figure 4-12. Measured and Calculated *Enterococcus* at Stations 009 and 010 for September and November 2018 with die off rate of 0.8 day^{-1}

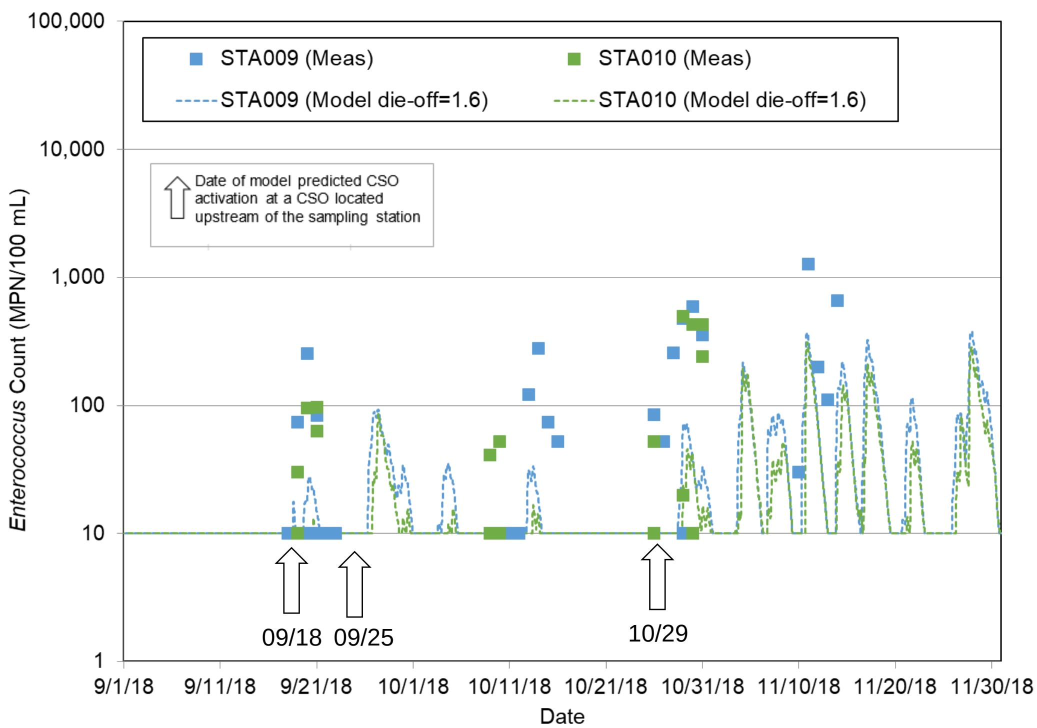


Figure 4-13. Measured and Calculated *Enterococcus* at Stations 009 and 010 for September and November 2018 with die off rate of 1.6 day^{-1}

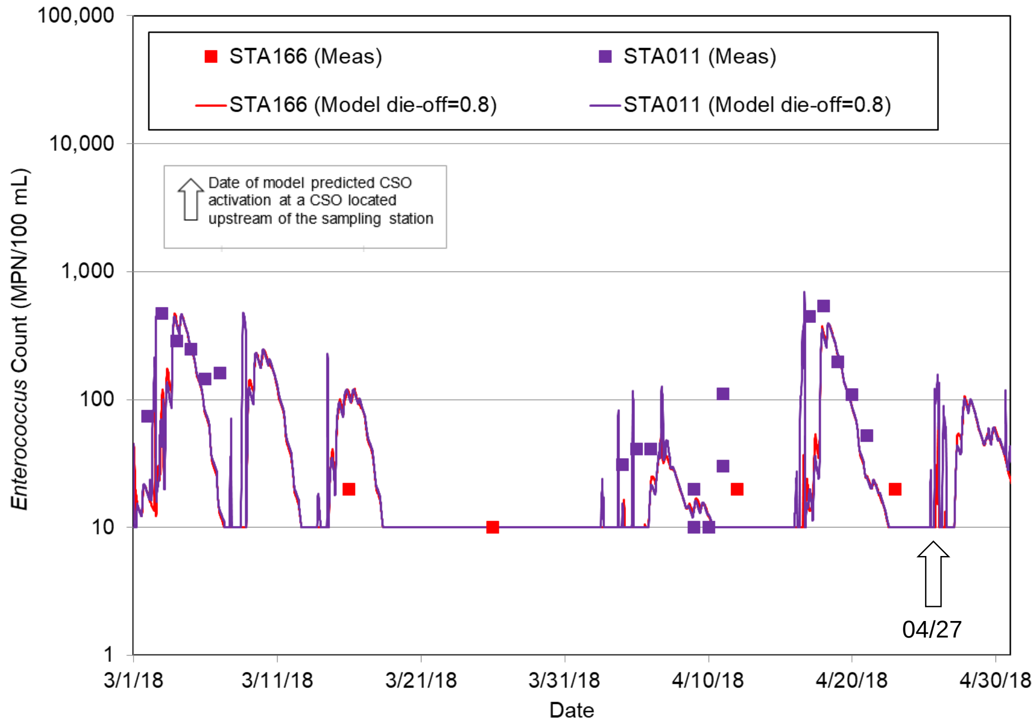


Figure 4-14. Measured and Calculated *Enterococcus* at Stations 166 and 011 for March and April 2018 with die off rate of 0.8 day^{-1}

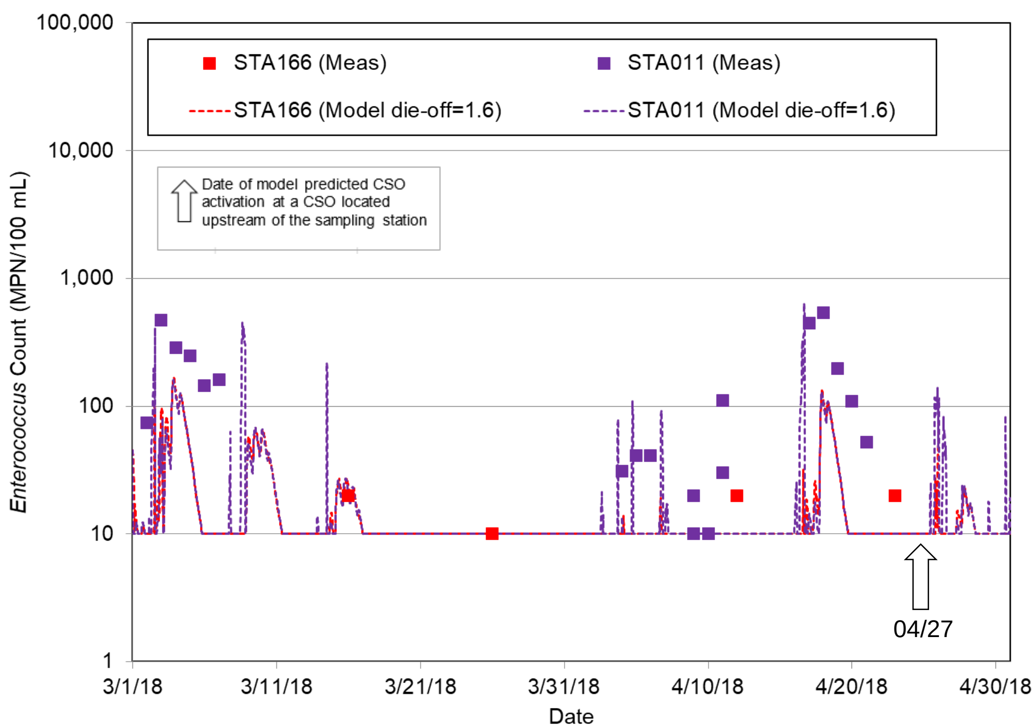


Figure 4-15. Measured and Calculated *Enterococcus* at Stations 166 and 011 for March and April 2018 with die off rate of 1.6 day^{-1}

The *Enterococcus* and *E. coli* counts applied to the sanitary fraction of the modeled CSO flows were based on the values documented in Section 2, and those values were not changed. The starting point for the *Enterococcus* and *E. coli* counts applied to stormwater, and to the non-sanitary fraction of the CSO flows was the average values derived from the stormwater monitoring described in Section 2.2. These values were tuned during calibration to better match the measured counts in the receiving water. As indicated in Table 4-7, the final values for the stormwater and non-sanitary fraction of the CSO were 10,000 MPN/100 mL for *Enterococcus*, and 14,000 MPN/100 mL for *E. coli*. These values were also applied to the modeled baseflows (Section 2.5) discharging to the Charles River during wet weather.

As described in Section 2, the initial counts for *Enterococcus* and *E. coli* used for the non-sanitary fraction of the CSO flow were calibrated to measured values at Cottage Farm and Prison Point. The tuning of these values as part of the wet weather calibration did not significantly affect the comparison to the measured values at Cottage Farm and Prison Point. Figure 4-16 presents a plot of measured versus predicted *Enterococcus* counts at Cottage Farm and Prison Point for the 11/10/18 storm, with the revised non-sanitary fraction count of 10,000 MPN/100 mL for *Enterococcus.* Figure 4-17 presents a similar plot with the revised non-sanitary fraction count of 14,000 MPN/100 mL for *E. coli*. These plots are not noticeably different from the plots presented in Figures 2-3 and 2-4 in Section 2, indicating that the tuning of the non-sanitary fraction counts did not significantly affect the predicted influent concentrations at Cottage Farm and Prison Point.

The model-computed CSO concentrations were much more sensitive to changes in the sanitary fraction counts than changes to the non-sanitary fraction counts. Therefore, increasing the sanitary fraction counts would result in model CSO counts no longer matching measured CSO counts, while changes to the non-sanitary fraction counts within the ranges used did not significantly change the model/measurement comparisons for the CSOs. Therefore, to increase in-stream counts to match the in-stream measurements without adversely affecting the model/measurement comparison for CSO concentrations, increasing the non-sanitary fraction counts was needed.

Table 4-1 above presented the predicted sanitary fractions and flow-weighted counts for the CSOs to the Charles River and the Cottage Farm and Prison Point Facility influent flow, based on the original non-sanitary fraction counts of 5,500 MPN/100 mL for *Enterococcus* and 13,400 MPN/100 ml for *E. coli*. Table 4-8 presents the flow-weighted counts for the CSOs to the Charles River and the Cottage Farm and Prison Point Facility influent flow, based on the non-sanitary fraction counts of 10,000 MPN/100 mL for *Enterococcus* and 14,000 MPN/100 ml for *E. coli* that were the result of tuning adjustments to better match the measured counts in the receiving water. The revised counts applied to the non-sanitary fraction resulted in increases in the flow-weighted counts at the CSO outfalls, with the increase in *Enterococcus* counts at the CSO outfalls being greater than the increase in the *E. coli* counts at the outfalls. This difference makes sense, since the tuning for the wet weather calibration increased the *Enterococcus* counts in the non-sanitary fraction by a larger margin than the increase in the *E. coli* counts.

Figures 4-18 and 4-19 present additional examples of the measured and calculated *Enterococcus* levels at Stations 001 and 144 for July and August 2018, and September through November 2018, respectively. These stations are located upstream of the active CSOs in the Charles River. Figures 4-20 and 4-21 present examples of the measured and calculated *Enterococcus* levels at Stations 011 and 166 for July and August 2018, and September through November 2018, respectively. These stations are located at the downstream end of the Charles River. These plots show a close correlation between calculated and measured *Enterococcus* values for these periods. The measured and modeled peak counts at the stations upstream of the CSOs are generally higher than the measured and modeled peak counts at the downstream end, downstream of the active CSOs. Additional plots of calculated *Enterococcus* counts compared to measured values for several sets of monitoring stations spanning the length of the modeled portion of the river are provided in Appendix B. Similar plots for *E. coli* are provided in Appendix C.

At monitoring Stations 009, 010 and 011 bottom samples collected at depths varying from 4 to 9 meters had salinity levels indicating that these samples were in the salt intrusion. These samples exhibited bacterial counts that were generally slightly lower but not markedly different than the surface samples. The model assumed that the top of the salt intrusion was at a depth of 7 meters and placed an artificial river bottom at this depth. Although some of the bottom samples would therefore not fall within the part of the water column included in the model, both surface and bottom sample results were included.

The plots presented in Appendix B and C demonstrate that the model reasonably matches the measured values and should be suitable for the intended uses on this project as described in Section 6.2.

Table 4-8. Predicted Sanitary Fractions and Flow-weighted Counts for 2018 with Adjusted Non-Sanitary Fraction

Location	Sanitary Fraction (%)(1)	Flow-weighted Counts (MPN/100 mL)	
		Enterococcus	***E. coli***
CAM005	0.02%	10,190	15,341
CAM007	1.76%	27,428	136,985
MWR010	0.00%	10,000	14,000
MWR023	0.03%	7,547	12,571
MWR018	0.63%	16,258	58,163
MWR019	0.51%	15,072	49,789
MWR020	0.47%	14,606	46,500
CAM017	0.07%	10,666	18,700
Cottage Farm Influent	16.62%	174,517	1,174,924
Prison Point Influent	0.3%	37,566	208,524

Note:

(1) For each untreated CSO outfall, the sanitary fraction shown is the flow weighted average in the discharge pipe over the periods when the outfalls were discharging flow. For Cottage Farm and Prison Point, the sanitary fraction shown is the flow weighted average in the facility **influent** while the facility was active.

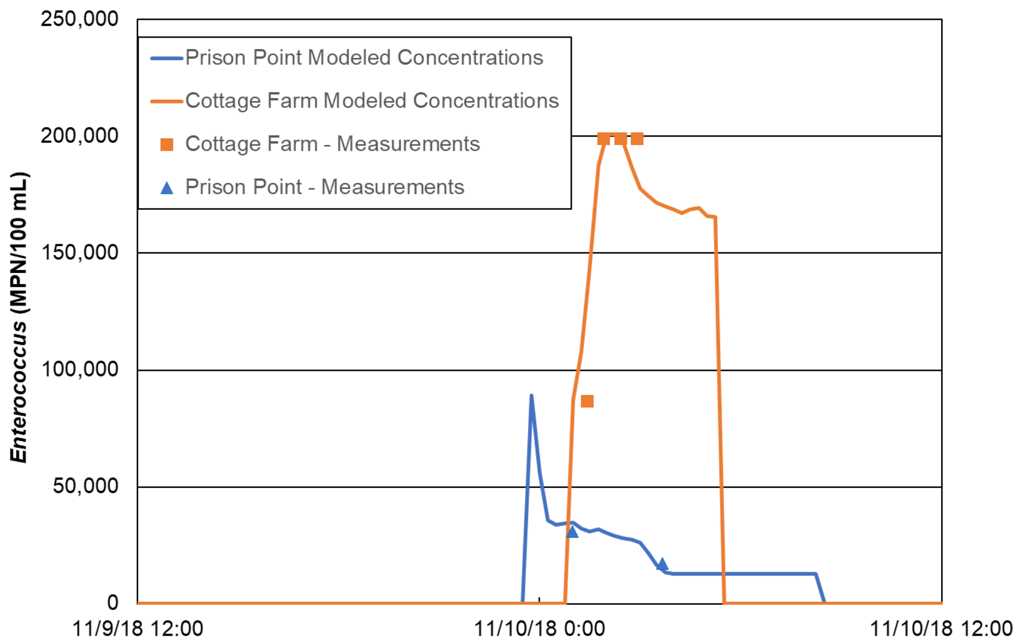


Figure 4-16. Model versus Measured *Enterococcus* Counts at Cottage Farm and Prison Point, with Adjusted Non-Sanitary Fraction

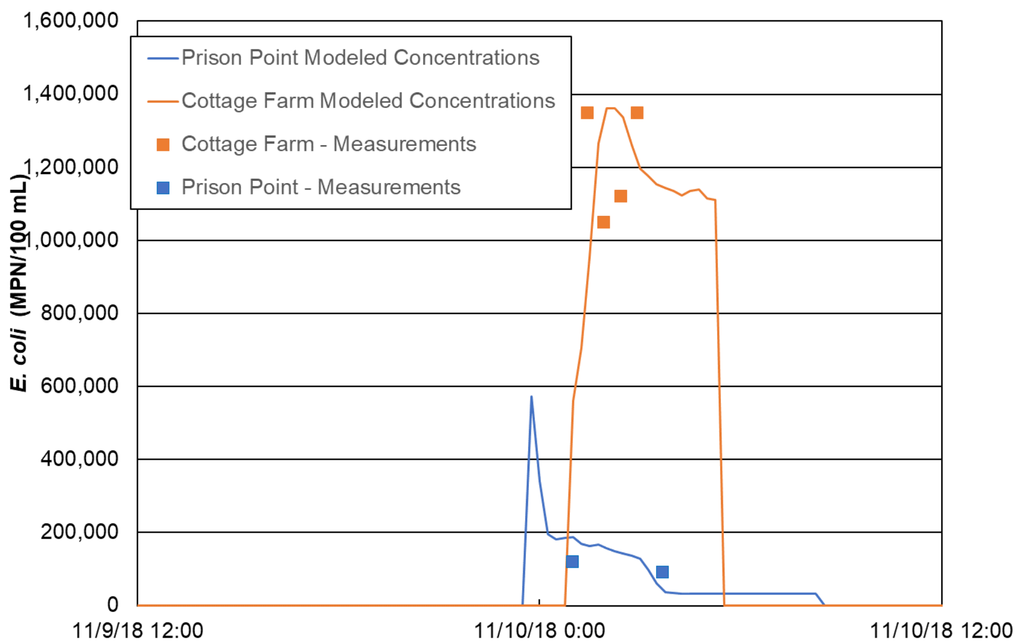


Figure 4-17. Model versus Measured *E. coli* Counts at Cottage Farm and Prison Point, with Adjusted Non-Sanitary Fraction

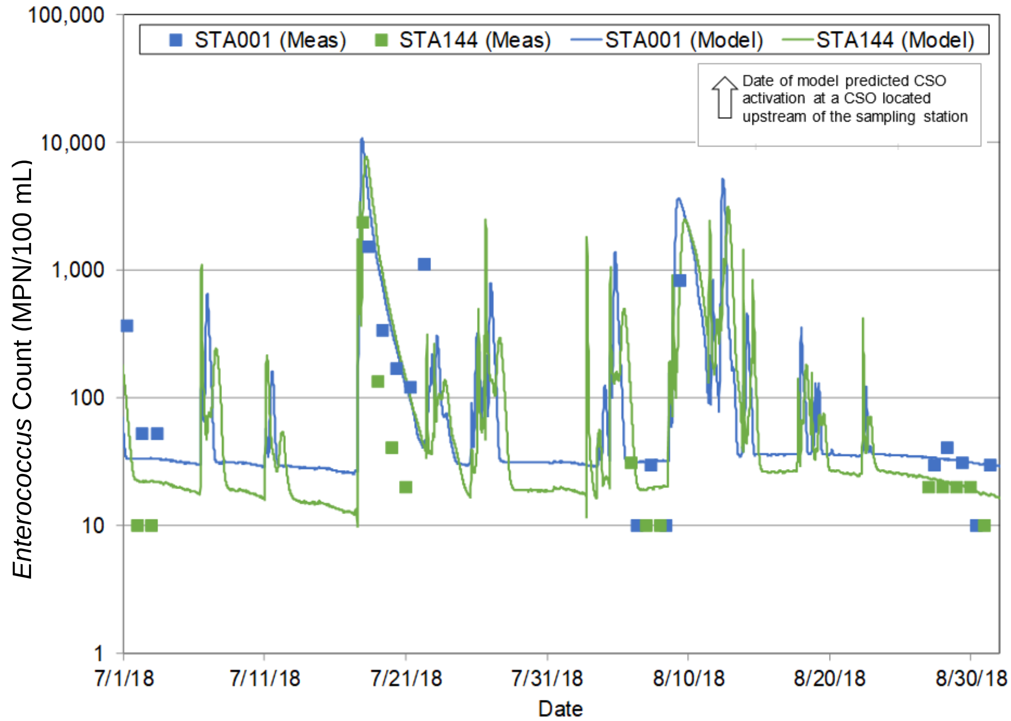


Figure 4-18. Measured and Calculated *Enterococcus* at Stations 001 and 144 for July and August 2018 with die off rate of 0.8 day^{-1}

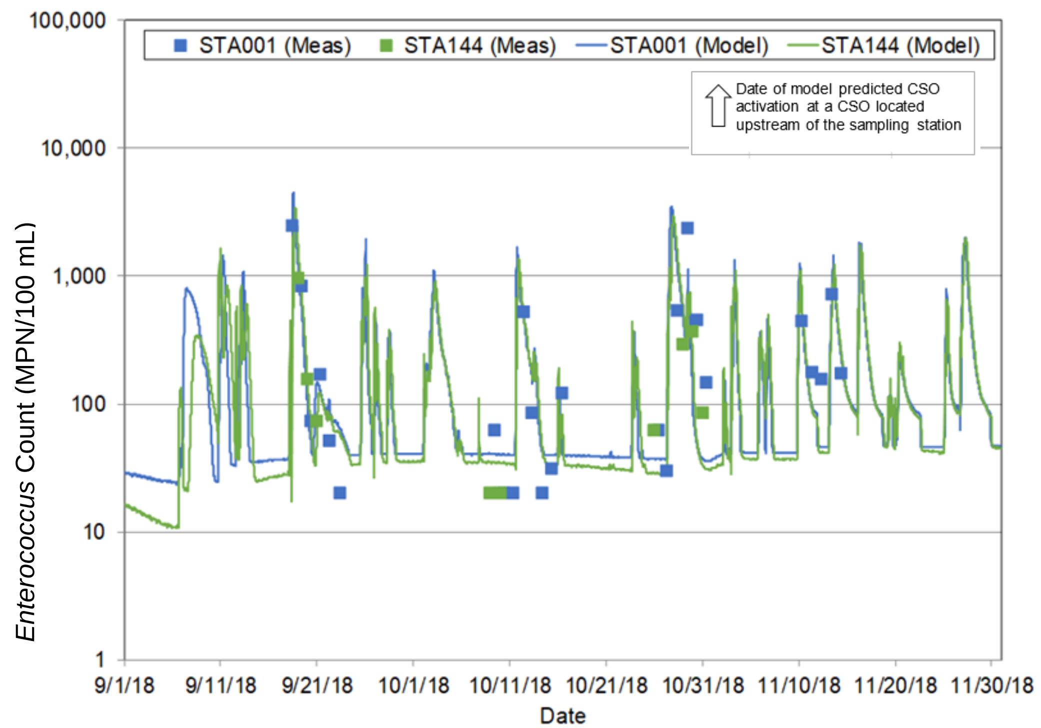


Figure 4-19. Measured and Calculated *Enterococcus* at Stations 001 and 144 for September through November 2018 with die off rate of 0.8 day^{-1}

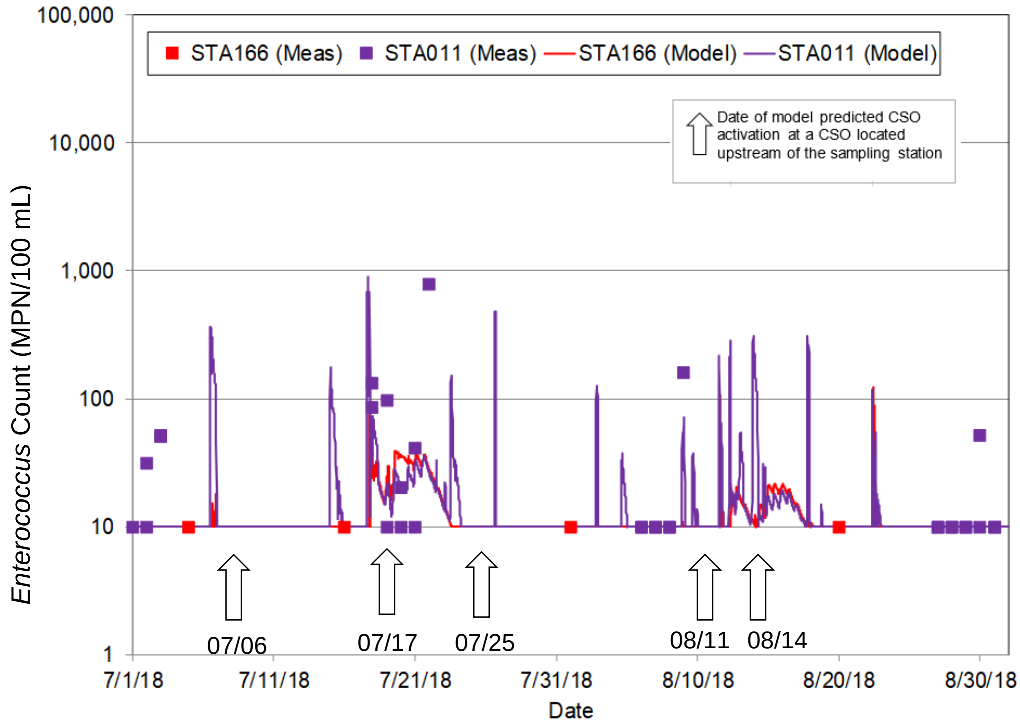


Figure 4-20. Measured and Calculated *Enterococcus* at Stations 011 and 166 for July and August 2018 with die off rate of 0.8 day^{-1}

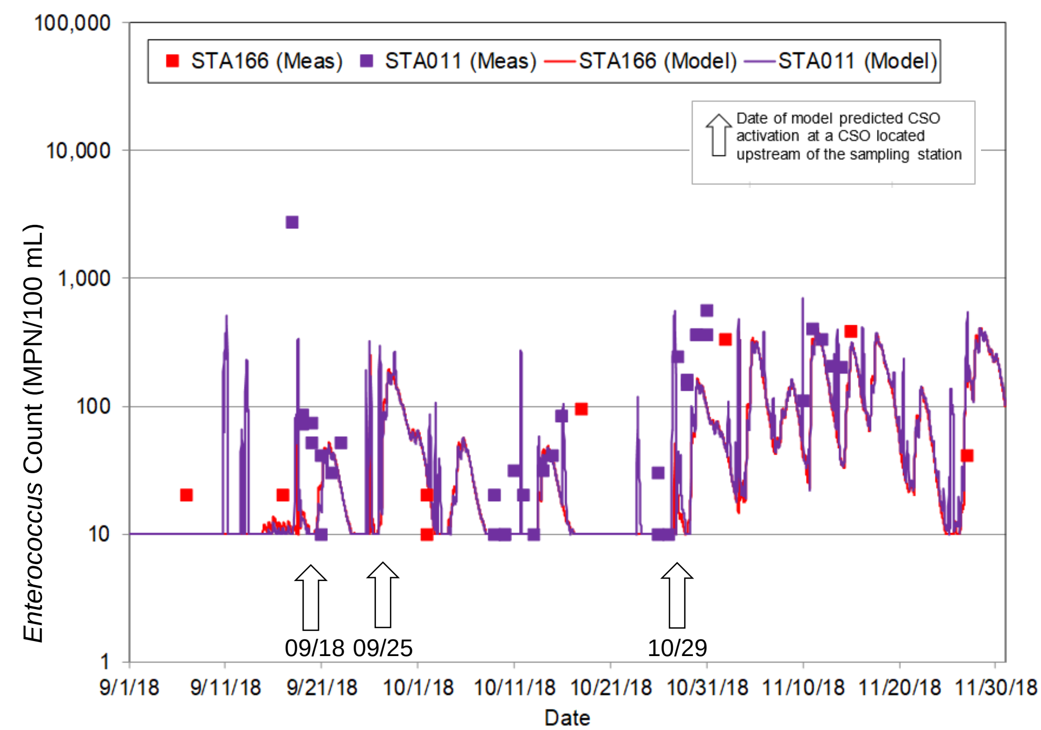


Figure 4-21. Measured and Calculated *Enterococcus* at Stations 011 and 166 for September through November 2018 with die off rate of 0.8 day^{-1}

5. Alewife Brook and Upper Mystic River Model

5.1 Previous Models

A hydrodynamic and water quality model of Alewife Brook/Upper Mystic River was developed for the CSO LTCP using the CE-QUAL-RIV1 software (MWRA 1996). That model simulated fecal coliform (with a die-off rate of 0.8 day^{-1}), BOD, DO and suspended solids. The model used fecal coliform counts of 538,000 colonies/100 mL for untreated CSO, 200 colonies/100 mL for treated CSO and 30,250 colonies/100 mL for stormwater. The current models use *Enterococcus* and *E. coli* counts, shown in Table 5-1, and these are based on the proportion of sanitary flow, and sampling data collected during 2019. Simulations were conducted for the 3-month and 1-year design storm, each with a duration of 8 days.

5.2 Model Software

The software used for the current Alewife Brook/Upper Mystic River model is InfoWorks ICM, a comprehensive one-dimensional hydraulic and water quality model in common use worldwide. This software is currently used for the MWRA collection system hydraulic/hydrologic modeling. Reasons for selecting InfoWorks ICM for the Alewife Brook/Upper Mystic River water quality modeling included: i) an ICM model of the Mystic River basin had previously been developed for FEMA, ii) the software can simulate bacteria, iii) Alewife Brook and the Upper Mystic River are narrow enough that there is no need to resolve across-river structure, so a two-dimensional model was not required, and iv) MWRA owns licenses of the software, which will be beneficial for future uses.

This model originally consisted of FEMA Flood Insurance Study (FIS) models developed in HEC RAS (Hydrologic Engineering Center River Analysis System) and HEC HMS (Hydrologic Modeling System), which were converted to InfoWorks ICM by the City of Cambridge. The original FIS model was calibrated to a range of storms, with an emphasis on larger storms (ENSR Corporation, 2007).

5.3 Model Development

5.3.1 Model Extent and Grid

The FEMA model covers the entire Mystic River watershed. Since the scope of this project focused on water quality in Alewife Brook and the Upper Mystic River, there was no need to assess water quality in the Mystic Lakes or the further upstream tributaries. The transition from the Lower Mystic Lake to the Mystic River would have been an ideal location to establish a boundary condition for the rest of the downstream model. A USGS flow gauge is located downstream of the Lower Mystic Lake (No. 01103010 – Mystic River at Arlington, MA – see Figure 5-1), but this gauge could not be used as a boundary condition for a truncated model due to concerns about the reliability of the data. The gauge measures velocity and water level. However, flow measurements at this station have been reported to be difficult (Verdi, 2019). For example, the gauge has reported periods of up to a month with consistent negative flow, i.e. flow towards the lakes. Because the Upper Mystic River between the Amelia Earhart Dam and the Lower Mystic Lakes is very flat, cessation of release at the dam at high tide creates a positive wave that propagates up to the Lower Mystic Lake and can cause negative flows. However, sustained periods of negative flows, for up to one month, are not realistic.

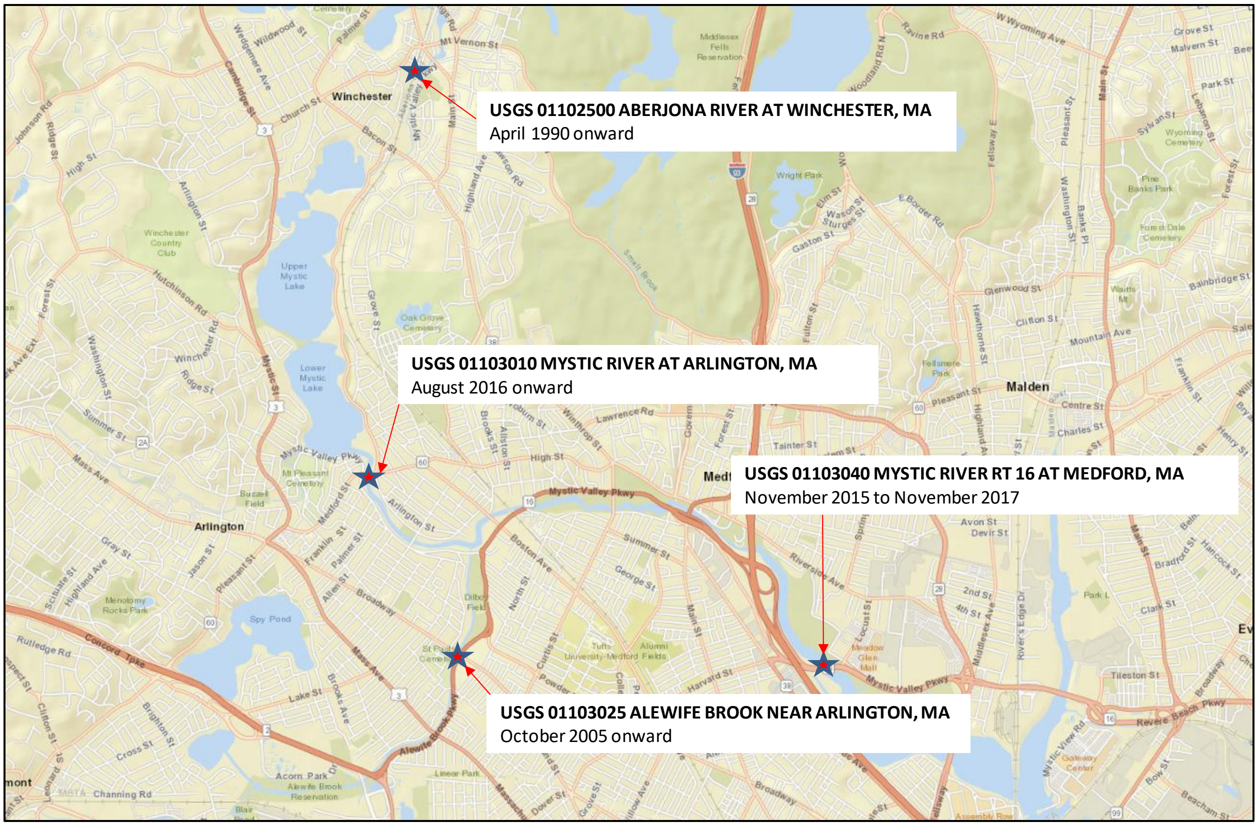


Figure 5-1. USGS Flow Gauges in the Mystic River Basin

Because the Mystic River at Arlington MA gauge was unreliable, a different approach had to be taken to establish a boundary condition at the upstream end of the Mystic River. Simply using the next upstream gauge, located on the Aberjona River upstream of the Upper Mystic Lake (USGS gauge 01102500 Aberjona River at Winchester, MA - see Figure 5-1) would not be appropriate because it would not take into account the flow regime and dynamics of the Upper and Lower Mystic Lakes, and the dam between the two lakes. Therefore, the selected approach was to truncate the FEMA model in two steps. First, the portion of the model upstream of the Aberjona River at Winchester, MA gauge was removed and the flows measured at that gauge were input as a boundary condition to the downstream portion of the remaining model. In a second step, that remaining model was further truncated at a point just downstream of the Lower Mystic Lake, and flows calculated by the first model at that location were imposed as a boundary condition to the further truncated model. That second model, truncated just downstream of the Lower Mystic Lake, was then used to assess water quality in the Alewife Brook/Upper Mystic River. That model extends from the boundary downstream of the Lower Mystic Lake to the Amelia Earhart Dam, and extends up Alewife Brook from the confluence with the Mystic River to Little Pond.

5.3.2 Bathymetry

Bathymetry was developed from a boat-based survey conducted on July 30-31, 2003 using a vessel equipped with a precision echo sounder and GPS transponder integrated with a laptop computer running the Hydrographic Survey Package (HYPACK) software (ENSR Corporation, 2007). Cross-section profiles were specified along 278 transects, shown in Figure 5-2.

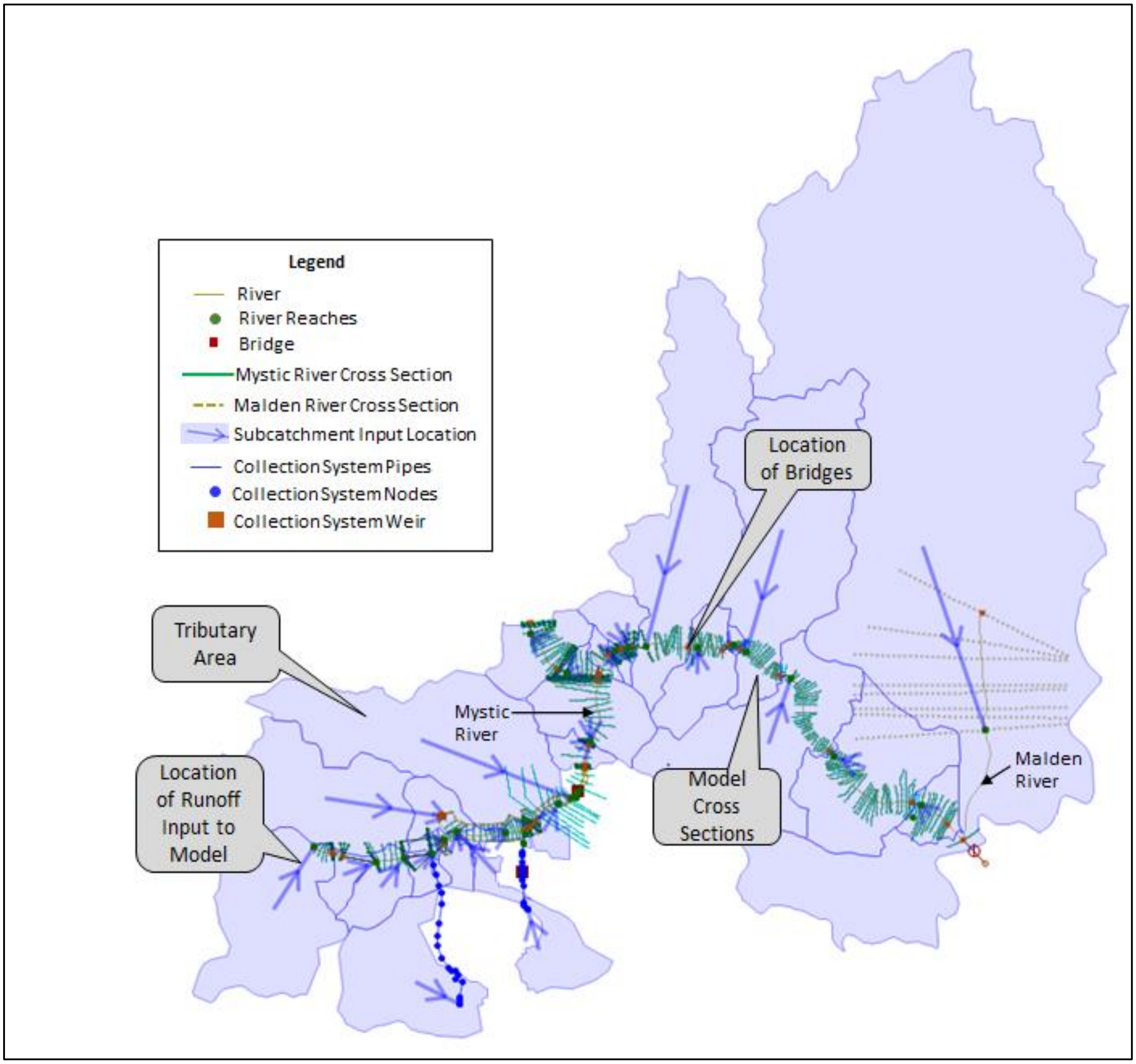


Figure 5-2. Mystic River Basin Model Coverage and Transects

5.3.3 CSO Flows

The flowrates of the CSO discharging to the Alewife Brook and Upper Mystic River were specified based on results from the calibrated MWRA collection system hydraulic/hydrologic model based on rainfall hyetographs. The collection system hydraulic/hydrologic model also provided an estimate of the sanitary fraction in each CSO discharge as a function of time during the storm.

5.3.4 CSO Quality

For untreated CSO discharges, *Enterococcus* and *E. coli* counts were specified based on time-varying sanitary fractions calculated by the MWRA collection system hydraulic/hydrologic model as described above in Section 2.2. The bacterial counts of the sanitary and stormwater fractions were calibrated to data measured at outfalls CAM401A and SOM001A. The initial concentrations for the sanitary and non-sanitary fractions of the flow were set at 1,000,000 MPN/100 mL and 5,500 MPN/100 mL, respectively for

Enterococcus, and 2,500,000 MPN/100 mL and 13,400 MPN/100 mL, respectively, for *E. coli*. Based on those counts, the predicted flow-weighted sanitary fractions and predicted flow-weighted counts for *Enterococcus* and *E. coli* at the CSO outfalls to Alewife Brook/Upper Mystic River for 2018 are presented in Table 5-1. For each outfall, the sanitary fraction shown in Table 5-1 is the flow weighted average in the discharge pipe over the periods when the outfalls were discharging flow. Figure 2-1 above presents an example of how the sanitary fractions varied over time for the influent flow at Cottage Farm and Prison Point during the November 10, 2018 storm.

Table 5-1. Predicted Sanitary Fractions and Flow-weighted Counts for 2018

Location	Flow-weighted Sanitary Fraction (%)(1)	Flow-weighted Counts (MPN/100 mL)	
		Enterococcus	*E. coli*
MWR003	1.23%	17,768	44,074
CAM401B	2.95%	34,868	86,831
CAM401A	2.01%	25,517	63,450
CAM002	0.39%	9,364	23,063
CAM001	7.60%	81,117	202,470
SOM001A	3.34%	38,710	96,436
SOM007A(2)	N/A	17	18

Notes:

(1) For each outfall, the sanitary fraction shown is the flow weighted average in the discharge pipe over the periods when the outfalls were discharging flow.

(2) For outfall SOM007A, the flow-weighted counts reflect the treated discharge concentrations from the Somerville Marginal CSO Facility. The sanitary fraction method was not applied to the treated discharge. Counts applied to the treated discharge were based on the average values of measured counts sampled from facility effluent in 2018.

As indicated in Table 5-1, most of the CSO outfalls have relatively low sanitary fractions, with outfall CAM001 having the highest, at 7.6%. The low sanitary fractions generally reflect sewer separation work that has been conducted in the upstream tributary areas. The flow-weighted counts for outfalls CAM401A and SOM001A are generally consistent with the sampling data presented in Section 2. The impact on the predicted flow-weighted concentrations at the outfalls of tuning adjustments to the counts in the non-sanitary fractions is presented in Section 5.4 below.

As described above in Section 2.3, for the treated discharges from the Somerville Marginal CSO Facility, the average of the effluent bacterial counts measured in 2018 was used in the modeling to represent the effluent quality. These values were 17 MPN/100 mL for *Enterococcus* (omitting an outlier of 4,110/100 mL), and 18 MPN/100 mL for *E. coli.* The flow-weighted counts for outfall SOM007A shown in Table 5-1 reflect the Somerville Marginal Facility treated discharge. The sanitary fraction method was not applied to the treated discharge.

5.3.5 Stormwater Flows

Stormwater discharges to the Alewife Brook and Upper Mystic River were calculated using a reformulation of the Mystic River Basin model hydrology. The FEMA model, as well as its version converted to InfoWorks, were calibrated to a range of storms. The calibration focused on larger storms, with up to a 100-year return period (ENSR Corporation, 2007). The model used the Clark Hydrograph with the addition of the RTK method (which uses unit hydrographs defined by the fraction of rainfall volume entering the sewer system as rainfall-derived infiltration/inflow ["R"], the time to peak ["T"], and the ratio of time of recession to T [“K”]) to reproduce the larger flows, and the model specified fixed base flow inputs at several locations (ENSR Corporation 2007; Che et al, 2016; USEPA, 2016).

For the purpose of this study, variable base flows were needed to properly simulate the calibration periods and the Typical Year. Therefore, the model hydrology was replaced by the SWMM RUNOFF hydrology with the groundwater routines. The latter simulates the infiltration of stormwater into the ground and the groundwater discharge to the stream, as shown in Figure 5-3. Only the surface runoff and soil store elements of the model were used, as those elements were found to be sufficient to match measured flows. An important aspect of this hydrologic model is that it simulates both the rapid and the slow responses to wet weather events. These two responses have different water quality characteristics.

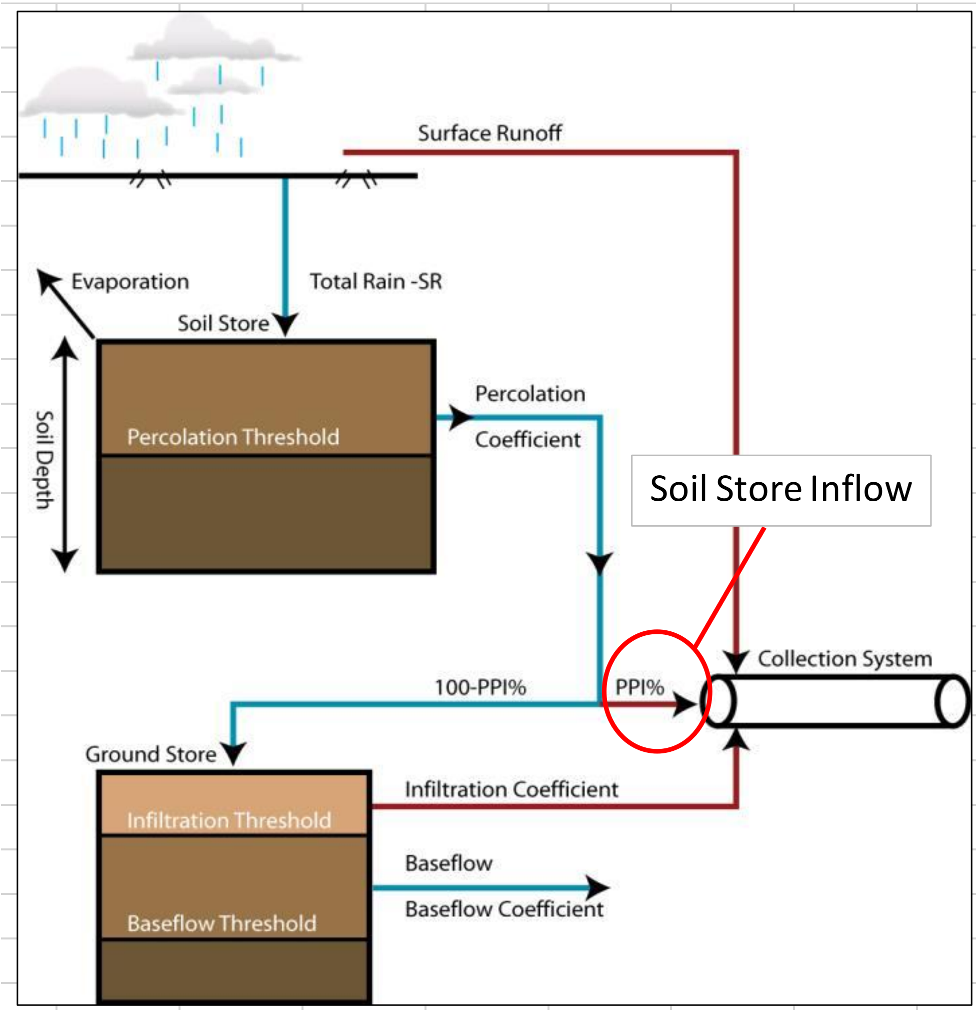


Figure 5-3. SWMM Runoff Hydrology Schematic

The fast response has surface runoff characteristics, with relatively high bacterial counts, while the slow response has much lower bacterial counts, representative of dry weather conditions.

The hydrology parameters required for the SWMM RUNOFF model were derived from the original model and the calibration described in Section 5.4.1. The model parameters were:

- Percent impervious - developed from the Mass GIS mapping

- Sub-catchment slopes - developed from the Mass GIS mapping
- Basin widths - first set equal to the radius of the circle with the same area as the sub-catchment and adjusted during calibration
- Percent routed from impervious to pervious areas – adjusted during model calibration
- Evaporation rate –specified at monthly intervals based on air temperature
- Evaporation depth (the water depth in the soil store below which evaporation is no longer active) –assessed during model calibration, typically between 6 and 10 ft.
- Percolation threshold (the depth of water in the soil store above which discharge from the soil store to the river starts to occur) –assessed during calibration
- Percolation coefficient (the proportionality constant between the percolation flow and the soil store water depth above the percolation threshold) –assessed during calibration.
- Percolation Percentage infiltrating (PPI%): The percent of water in the soil above the percolation threshold that can enter the sewer. The remainder enters the ground store. A larger percentage increases the volume of the soil response. The initial value for this project will be determined using meter analysis. This is also referred to above as the Soil Store Inflow.

5.3.6 Stormwater Quality

Based on the analysis presented in Section 2.2, average counts of 5,500 MPN/100 mL and 13,400 MPN/100 mL for *Enterococcus* and *E. coli*, respectively, were used initially subject to tuning during the calibration process.

5.3.7 Upstream Boundary Conditions

Flow and bacterial counts needed to be specified at the following upstream boundaries of the model:

i) Mystic River downstream of the Lower Mystic Lake
ii) Alewife Brook, upstream end
iii) Malden River, upstream end

For the Mystic River downstream of the Mystic Lakes, flows were specified based on the results of the model extending to the upstream USGS gauge in the Aberjona River, and bacterial counts were adjusted during calibration. This approach was not sufficient to reproduce the bacterial counts measured at MWRA Station 083, approximately 0.8 mile downstream of the Lower Mystic Lake. Therefore, relatively high bacterial counts were specified in the stormwater and soil store inflow from the catchments discharging upstream of Station 083, as follows.

The boundaries at the upstream ends of Alewife Brook and the Malden River represent the upstream starting points of these two streams, with flows supplied by the upstream catchments. Based on calibration, these sources were assigned baseflow (dry weather) counts of 45 MPN/100 mL and 134 MPN/100 mL for *Enterococcus* and *E. coli*, respectively. Runoff flows during wet weather were assigned counts of 6,700 MPN/100 mL and 25,000 MPN/100 mL for *Enterococcus* and *E. coli*, respectively.

5.3.8 Downstream Boundary Condition

The downstream end of the model is at the Amelia Earhart Dam. The Dam is operated by the Massachusetts Department of Conservation and Recreation (DCR) with the aim of maintaining the Mystic River Basin water level within a specific range (104.5 to 106.5 MDC Datum).

DCR does not have a set, written policy of how to operate the dam; actual operation is dependent on several variables including the tide, predicted rainfall, antecedent conditions, and upstream flows.

However, on average, Lock 3 is opened once per day for drainage of the Mystic River Basin by gravity. The lock is opened at even water (i.e. when water elevation for the basin and harbor is same) during a falling tide to drain and then closed at or before even water during a rising tide to avoid saltwater flowing upstream, resulting in up to an approximate 12 hour potential draining period each day.

The USGS has a water level gauge just upstream of the Amelia Earhart Dam that has been operating since December 2007. Although the operation of the dam follows general protocols (as described above) variations occur. Therefore, to provide a more accurate specification, measured water levels at the dam were established as a downstream boundary condition for the Mystic River Basin model hydrodynamics. Tide gates were added to the model to represent operation of the locks. In the model, the tide gates allow flow out of the system at the downstream boundary, but prevent backflow into the river.

5.3.9 Initial Model Parameters

Bacterial Counts

For treated CSOs, initial *Enterococcus* and *E. coli* counts of 1,000,000 MPN/100 mL and 2,500,000 MPN/100 mL, respectively, were used for the sanitary fraction and 5,500 MPN/100 mL and 13,400 MPN/100 mL for the non-sanitary fraction, as discussed in Section 2.2.1.

For treated discharges from the Somerville Marginal Facility, initial *Enterococcus* and *E. coli* counts of 17 MPN/100 mL and 18 MPN/100 mL, respectively, were used, as discussed in Section 2.3. These values were not changed in the calibration.

For stormwater discharges, initial *Enterococcus* and *E. coli* counts of 5,500 MPN/100 mL and 13,400 MPN/100 mL, respectively, were used.

Riverbed Roughness Coefficient (Manning's n)

Different values for Manning's n were specified in the original model along different parts of the cross sections, varying between 0.015 to 0.035 based on the stream and floodway conditions. These values were vetted during the FEMA model calibration and were retained here.

Dispersion coefficient

InfoWorks ICM has the ability to include a dispersion coefficient in the water quality calculations. A test run was conducted with the dispersion coefficient incorporated, and the results were not found to be significantly different from the results of a similar run without dispersion. Therefore, dispersion was omitted for all further simulations.

Bacterial Die-Off

This parameter was discussed in Section 4.3.9 and, as concluded in this section an initial value of 0.8 day^{-1} was used for both *Enterococcus* and *E. coli*.

5.4 Model Calibration

5.4.1 Hydrologic Calibration

Hydrologic calibration was conducted with a model that extended to the Aberjona River at Winchester Gauge (USGS gauge 01102500), upstream of the Mystic Lakes, where measured flows were specified as a boundary condition. Model results were then compared to the flows measured at the Alewife Book near Arlington Gauge (USGS Gauge 01103025) as shown in Figure 5-1 above. Two other factors were considered during calibration. The first of these was the balance between rainfall, streamflow and evaporation. This analysis was conducted at monthly intervals. During each interval the volume of rainfall over the sub-catchment upstream of the Alewife Brook gauge was assessed and compared to the measured and model flow volumes at the Alewife Brook gauge. The difference between the rainfall volume and the flow volume is the evaporation and it was checked that evaporation estimated from the measured and calculated flows closely compared. Figure 5-4 presents the measured versus modeled monthly flow volume in Alewife Brook at the Alewife Brook gauge for the period of January to December, 2018. Also plotted in Figure 5-4 is the monthly rainfall volume (i.e. rainfall depth x tributary area) falling on the tributary area based on the Fresh Pond rain gauge. As indicated in Figure 5-4, the modeled stream flow generally matches the metered

Figure 5-4. Monthly Rainfall Upstream of Alewife Brook Gauge and Measured and Calculated Flow Volumes at that Gauge for 2018.

stream flow, and the largest gaps between the rainfall volume and the river flow volume generally occur in the June to September timeframe, when evaporation would be expected to have the greatest influence. The second factor derives from the water quality calibration in which bacterial counts in stormwater were initially set equal to the averages displayed in Table 2-4 (5,500 MPN/100 mL for *Enterococcus* and 13,400 MPN/100 mL for *E. coli*) and to dry weather values in the river (45 MPN/100 mL for *Enterococcus* and 134 MPN/100 mL for *E. coli*) in the soil store inflow component. These values were subject to adjustment during the water quality calibration. The catchment widths determine the duration of the stormwater flow, with large widths resulting in short duration, peaky runoff. The catchment width was adjusted to yield shapes of bacterial counts curves matching the in-stream monitoring data.

Other than the upstream boundary flows and downstream water levels, the only other model input was rainfall. Many different combinations of hydrology parameters were evaluated to achieve the best match of the metered versus modeled flows. Table 5-2 presents examples of some of the variations in parameters that were assessed, with the last row representing the final configuration used for the calibration. Calibration accuracy was gauged by visual examination of the flow versus time plots at the Alewife Brook gauge. Items of particular interest were peak flows and recession limb duration (i.e. duration to return to dry weather flow levels). Plots comparing measured and calculated stream flow at the location of the Alewife Brook USGS gauge are presented in Figures 5-5 to 5-10.

Table 5-2. Partial Log of Hydrology Model Calibration Runs

Run No.	Area analyzed	Percolation Threshold	PPI	Soil Porosity	Evapotran. Depth (ft)	Width / $\sqrt{A}$	Percent Routed to Pervious	Comments
210	Alewife	70%	99%	20	10	1	50%	Decrease "width" and "Percent routed to Pervious" to increase runoff duration but maintain the peak runoff
211	Alewife	70%	99%	20	10	0.50	50%	Decreased Width
212	Alewife	70%	99%	20	10	5.6	50%	Incorrect Width Used
213	Alewife	70%	99%	20	10	0.18	50%	Further decreased Width
214	Alewife	70%	99%	20	10	0.018	50%	Decreased Width by additional factor of 10 to increase peak flows
216	Alewife	70%	99%	20	5.0	0.018	50%	Decreased Evaporation Depth to 5 ft
217	Alewife	70%	99%	20	6.0	0.018	50%	Increased Evaporation Depth to 6 ft to assess sensitivity
218	Alewife	70%	99%	20	7.0	0.018	50%	Increased Evaporation Depth to 7 ft
220	Alewife/ Mystic	70%	99%	20	7.0	0.0018	50%	Decreased Width by an additional factor of 10
222	Alewife/ Mystic	70%	99%	20	7.0	0.0018	50%	Decreased Width by Run 213 dimensions ” by another factor of 100, changed percent routed, Increased Evaporation Depth to 7 ft (changed all factors to GRND 2)
223	Alewife/ truncated Mystic	70%	99%	20	7.0	0.0018	50%	Model was cut at the lower lakes for water quality calibration.
224	Alewife/ truncated Mystic	70%	99%	20	7.0	0.018	60%	Increased Width to increase peakiness and increase percent routed to Pervious to maintain peak flows
225	Alewife/ truncated Mystic	70%	99%	20	7	0.0178	60%	Ran Run224 for the whole year
226	Alewife/ Mystic	70%	99%	20	7	0.0089	50%	Decreased Width by factor of 2 to lengthen the runoff, reduced percent to Pervious to 50% to maintain peak flows
227	Alewife/ truncated Mystic	70%	99%	20	7	0.0089	50%	Model was cut at the lower lakes for water quality calibration.

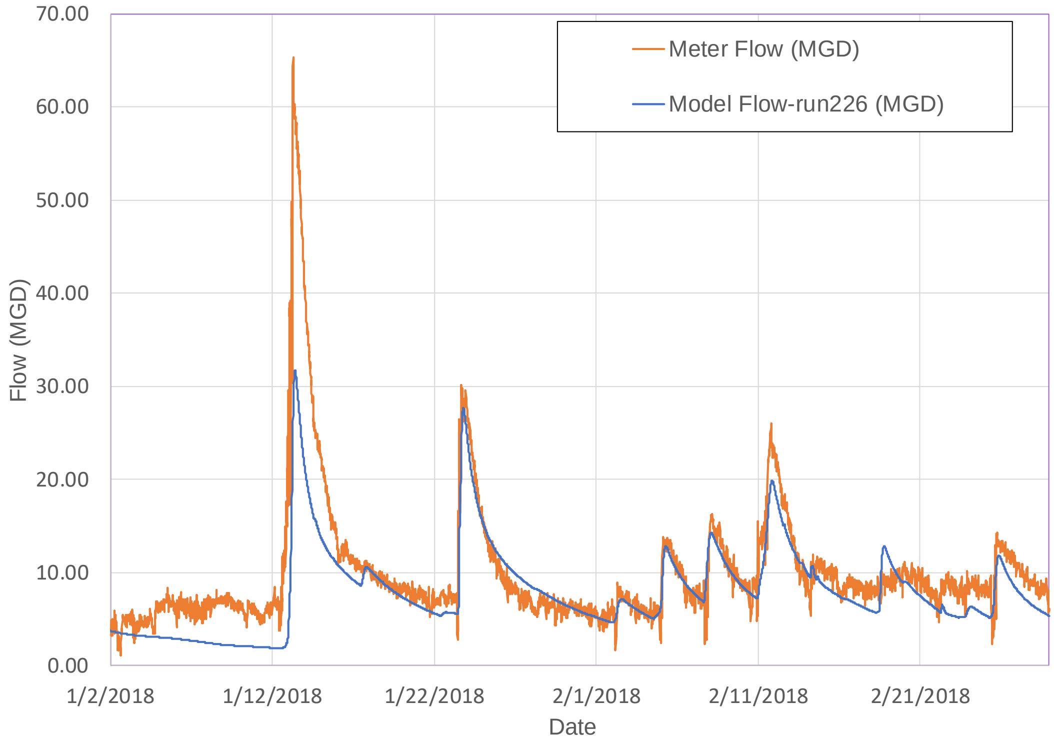


Figure 5-5. Measured and Calculated Flows at the Alewife Brook River Gauge for Jan-Feb, 2018

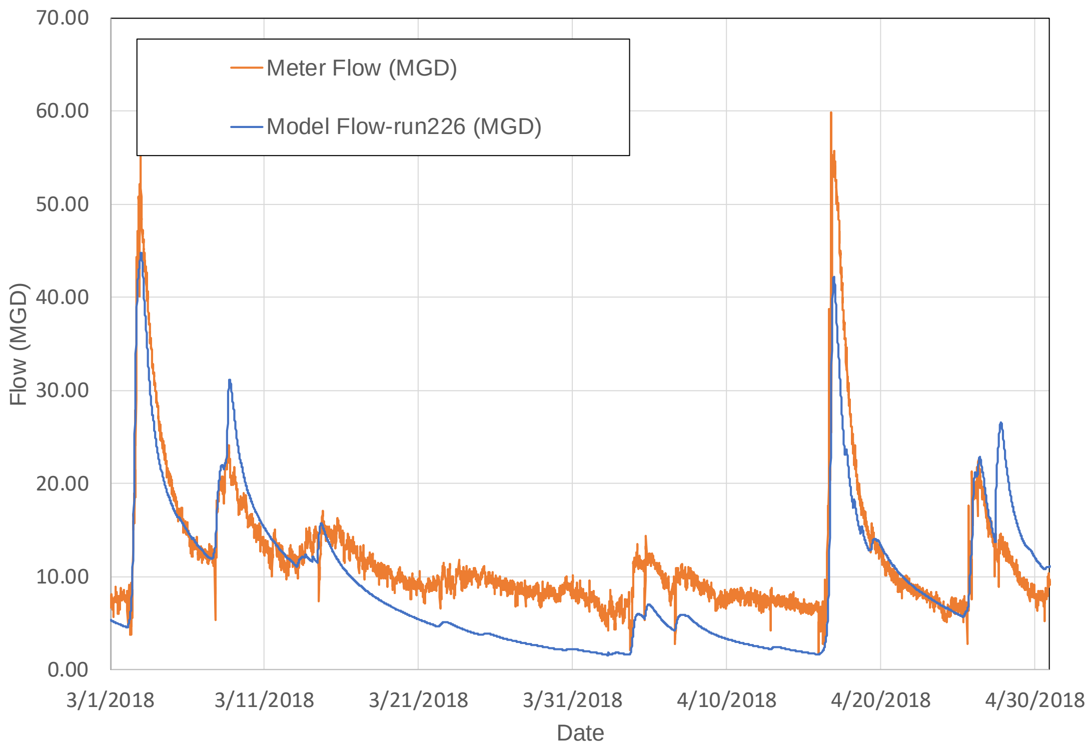


Figure 5-6. Measured and Calculated Flows at the Alewife Brook River Gauge for Mar-Apr, 2018

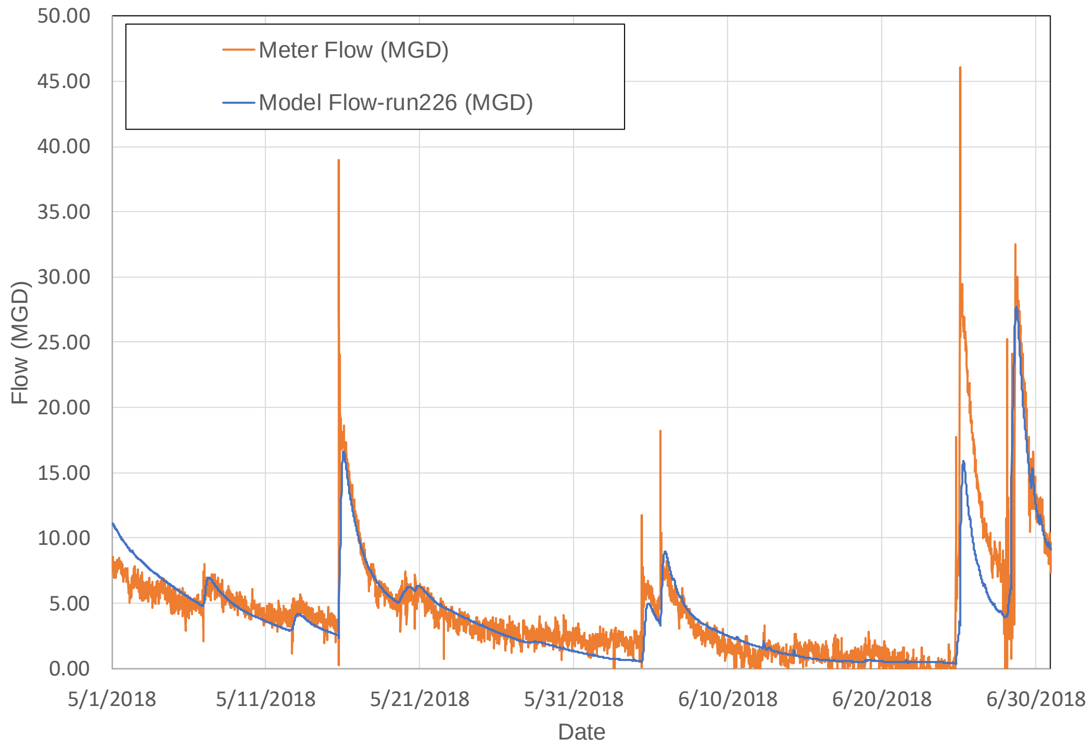


Figure 5-7. Measured and Calculated Flows at the Alewife Brook River Gauge for May-June, 2018

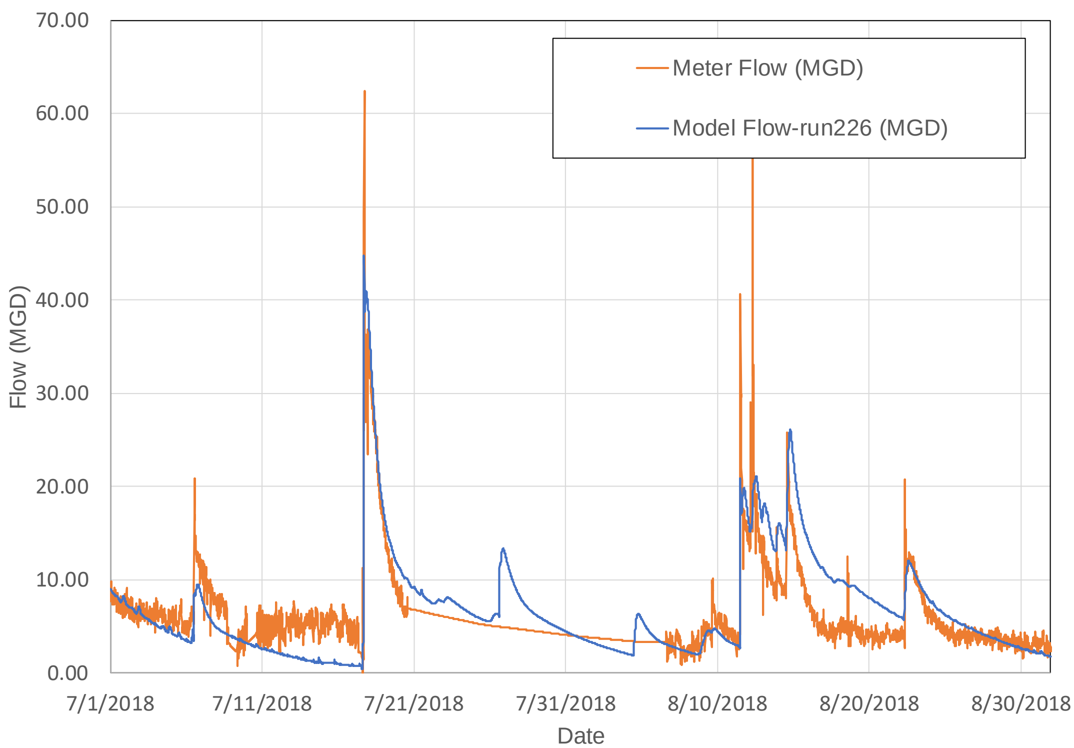


Figure 5-8. Measured and Calculated Flows at the Alewife Brook River Gauge for July-Aug, 2018

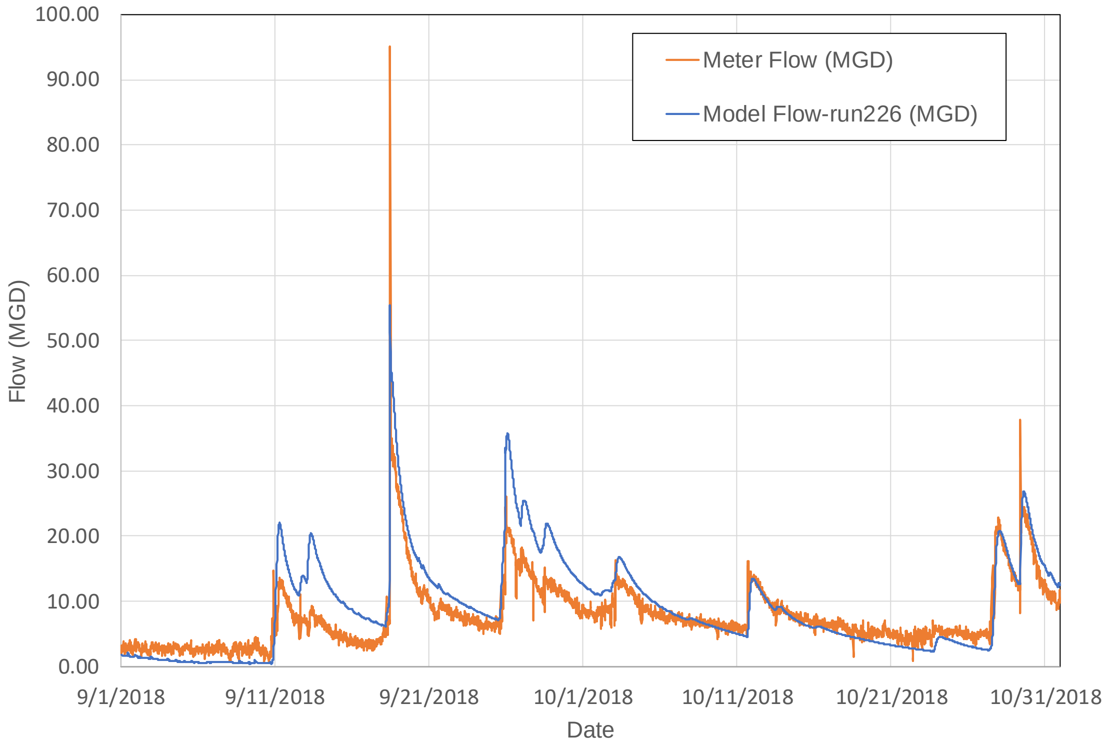


Figure 5-9. Measured and Calculated Flows at the Alewife Brook River Gauge for Sep-Oct, 2018

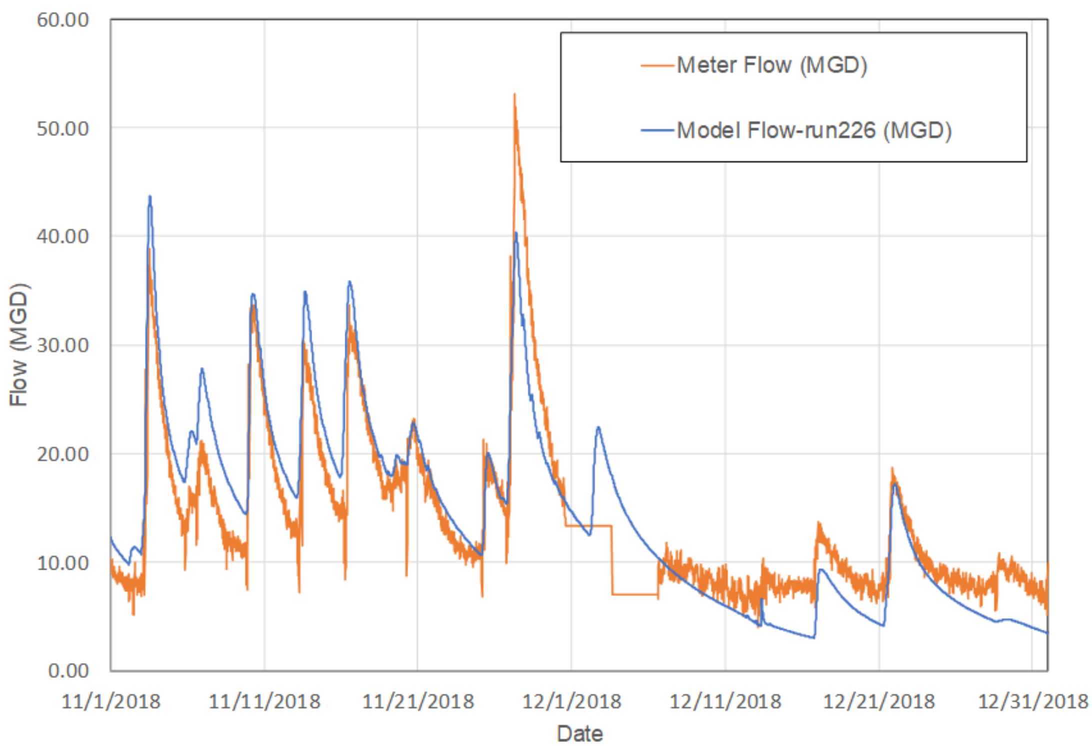


Figure 5-10. Measured and Calculated Flows at the Alewife Brook River Gauge for Nov-Dec, 2018

5.4.2 Water Quality Calibration

Model calibration was conducted for the period of April to October 2018, when MWRA in-stream monitoring measurements were available. The larger storms during this period (with depths greater than 0.3 inches or with CSO activation) are summarized in Table 5-3. The last column, labelled SOM007A, is the discharge for the Somerville Marginal CSO Facility. This outfall is located upstream of Amelia Earhart Dam and only discharges during storms that occur at high tide. This discharge is chlorinated and dechlorinated and, as stated in Section 5.3.4, the bacteria counts assigned to the facility discharge in the model were based on the average *Enterococcus* count of 17 MPN/100 mL and the average *E. coli* count of 18 MPN/100 mL from 2018 sampling measurements.

Of particular interest are the storms that generated CSOs. In general, the CSO volumes were relatively small, mostly less than 1 MG, except for three discharges of 1.41 MG (at CAM401A) and 2.65 MG (at SOM001A) on July 17 and 2.82 MG (at SOM001A) on September 18. To put these numbers in perspective, it can be noted that the average flow in the Alewife Brook at the USGS gauge during both of these storms was on the order of 20 MGD (see Figures 5-8 and 5-9). Therefore, the brook flow would provide a dilution on the order of 10:1 for these larger CSOs.

To help identify the impact of CSOs on receiving water quality, model results were plotted at in-stream monitoring station locations upstream and downstream of CSO groups. These were as follows:

- Stations 174 and 074, respectively upstream and downstream of CSOs CAM 401A, CAM004 and MWR023 – see Figures 5-11 and 5-12

- Stations 277 and 276, respectively upstream and downstream of CSOs CAM401B, CAM002, CAM001 and SOM001A – See Figures 5-11 and 5-13.

- Stations 083 and 066, on the Upper Mystic River respectively upstream and downstream of the Alewife Brook confluence – See Figure 5-11.

Plots were also produced for Stations 056 and 059, located further downstream along the Mystic River (see figure 5-11), and Station 308, located near the discharge from outfall CAM401A (see Figures 5-11 and 5-12). For Station 308, the only the model-predicted counts for 2018 are shown on the plots, as data were not available at this location for 2018.

Table 5-3. Rainfall and CSO Discharge Volumes to Alewife Brook / Upper Mystic River for 2018

Date	Rainfall[(1)]		Predicted CSO Volume from MWRA Collection System Hydraulic/Hydrologic Model (MG)						
	Depth (in)	Peak 15-Min Intensity (in/hr)	CAM001	CAM002	MWR003	CAM401A	CAM401B	SOM001A	SOM007A
4/3/2018	0.75	0.24							
4/15/2018	2.43	0.80				0.28			1.41
4/25/2018	1.07	0.52				0			
4/27/2018	0.42	0.24				0.29		0.15	
5/15/2018	0.98	1.28						0.21	
6/4/2018	0.76	0.32							
6/24/2018	0.48	0.44				0.06		0.16	
6/27/2018	1.21	1.20		<0.005		0.44		0.60	0.35
7/6/2018	0.37	0.44						0.26	
7/17/2018	2.39	1.64	<0.005	0.14	0.17	0.86	0.0976	2.65	10.65
7/22/2018	0.38	0.48							
7/25/2018	0.68	0.84						0.14	
8/4/2018	0.66	0.76							
8/8/2018	0.73	0.68							
8/11/2018	2.36	3.36		0.05		0.21	<0.005	1.21	
8/14/2018	0.01	0.04				0.19			
9/10/2018	1.31	0.56							1.98
9/12/2018	0.9	0.56				0.01			
9/18/2018	1.18	1.16	0.0073	0.44	0.29	1.41	0.12	2.82	0.18
9/25/2018	1.82	1.60				0.26		0.47	2.70
9/26/2018	0.36	0.64							
9/28/2018	0.44	0.28							
10/1/2018	0.67	0.24							
10/11/2018	0.71	0.48							
10/27/2018	1.65	0.36							2.78
10/29/2018	0.77	0.52				0.44		0.30	
11/2/2018	1.91	0.64				0.28		<0.005	5.08
11/5/2018	1.2	0.4							
11/9/2018	1.6	0.52				0.17			5.38
11/13/2018	1.23	0.24							0.08
11/16/2018	1.43	0.40							3.01
11/19/2018	0.63	0.16							
11/25/2018	0.84	0.44							
11/26/2018	1.58	0.28							2.24
12/2/2018	0.8	0.24							
12/16/2018	0.65	0.24							
12/21/2018	0.77	0.20							
12/28/2018	0.33	0.12							
12/31/2018	0.4	0.24							

Notes: (1) Rainfall data from Ward Street Headworks gauge; storms of less than 0.3 inches omitted unless a CSO activation occurred.

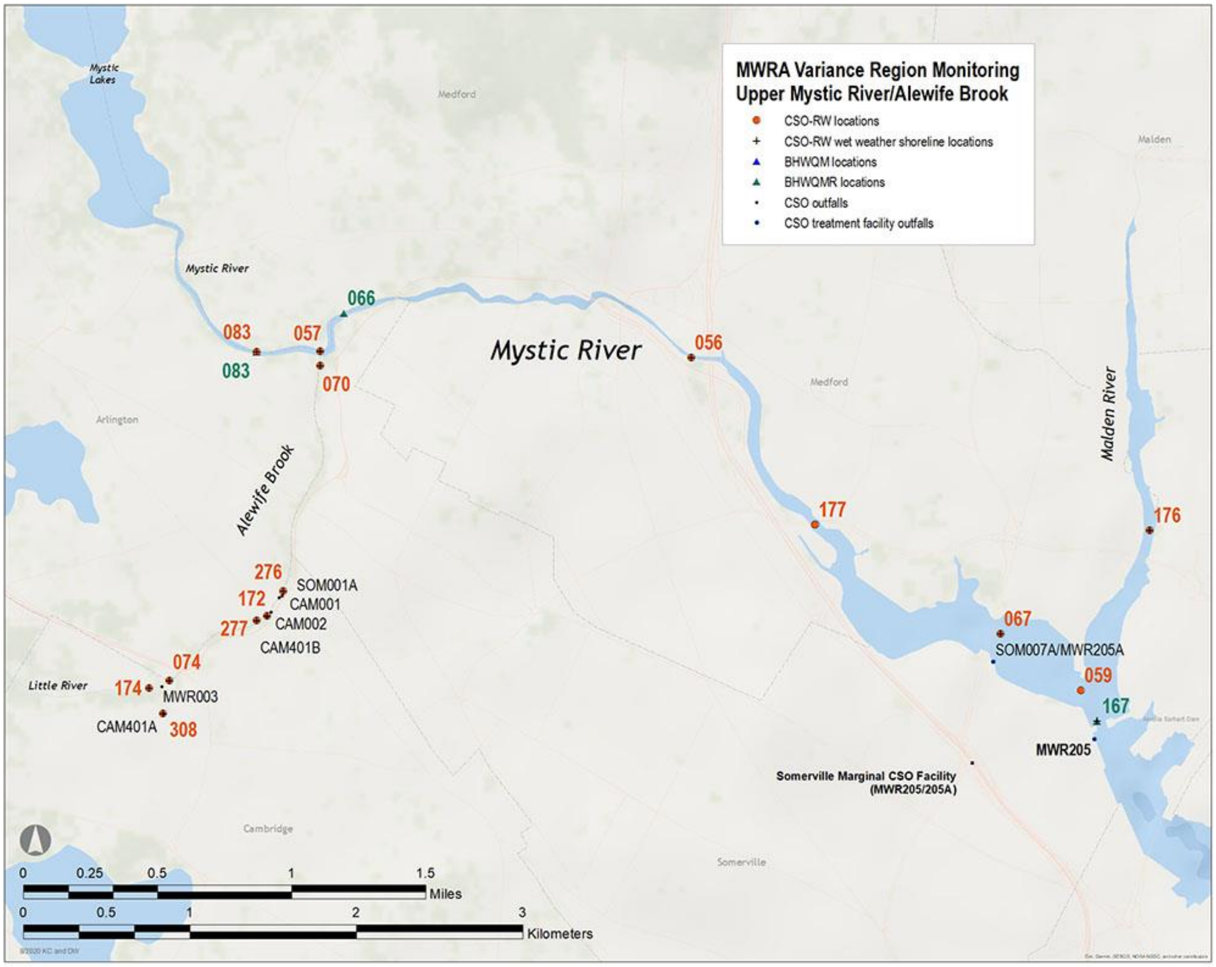


Figure 5-11. In-Stream Monitoring Stations Along Alewife Brook and Upper Mystic River

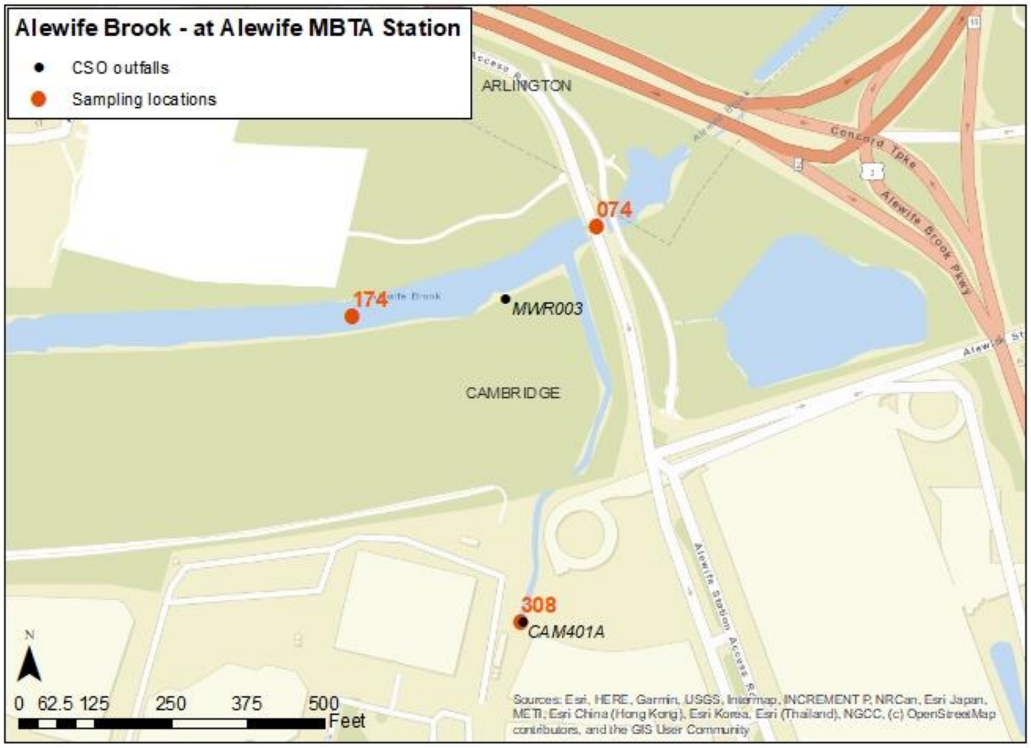


Figure 5-12. In-Stream Monitoring Stations 174 and 074

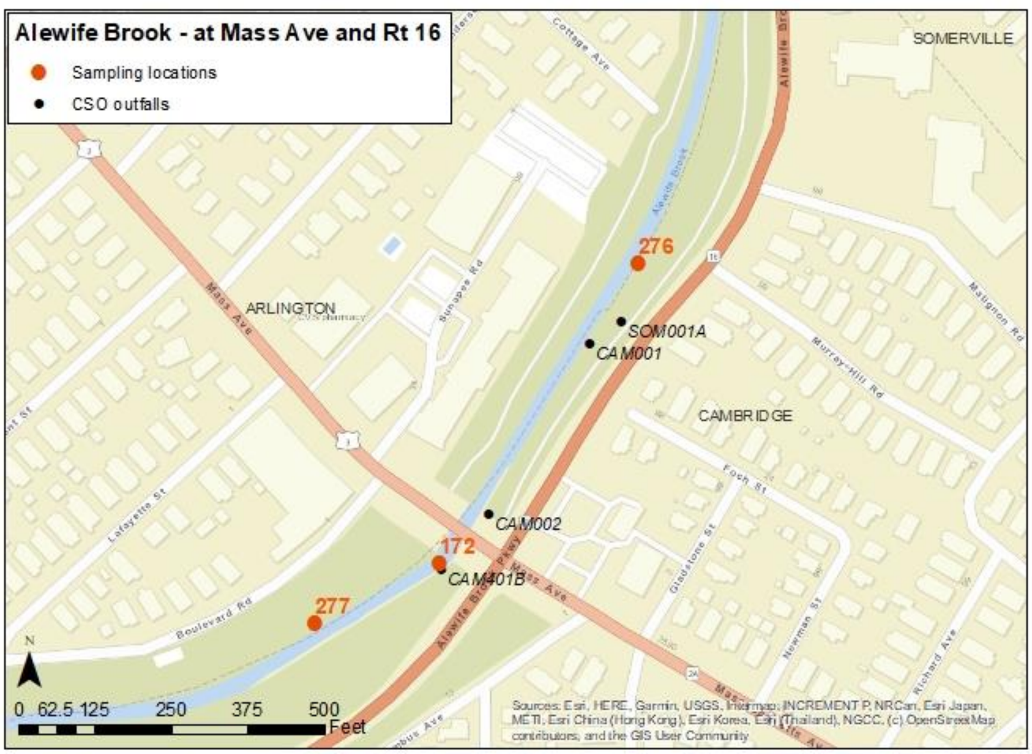


Figure 5-13. In-Stream Monitoring Stations 277 and 276

5.4.2.1 Dry Weather Calibration

Elevated bacterial counts during dry weather can be caused by previous wet weather discharges as well as “dry weather” (baseflow) sources. The latter were simulated by assigning bacterial counts to the soil store inflow. Several values were evaluated, including values representative of the dry weather discharge counts measured at several of the stormwater outfalls prior to wet weather events. These were mentioned in Section 2.2: 890 MPN/100 mL for *Enterococcus* and 3,100 for *E. coli*. These values were found to yield dry weather counts in the receiving waters that far exceeded the measurements. Following an iterative trial-and-error process, assigning counts of 45 MPN/100 mL for *Enterococcus* and 134 MPN/100 mL for *E. coli* to the baseflow were found to best replicate measured dry weather counts in the receiving waters, except for areas tributary to the Mystic River between monitoring station 083 and the outlet of the Lower Mystic Lake. For these areas, values of 10,000 MPN/100 mL for *Enterococcus* and 2,000 MPN/100 mL for *E. coli* were assigned to the baseflow. These higher values were intended to account for loads coming into the Mystic River from the Lower Mystic Lake, as the model could not reliably replicate the actual loadings coming from the Lower Mystic Lake. These values were arrived at through an iterative process to allow the model to match the measured in-stream values at station 083 and should not be interpreted as indicating a specific dry weather source such as illicit discharges between station 083 and the Lower Mystic Lake. For the Alewife Brook/Upper Mystic River model, the *Enterococcus* and *E. coli* values for the baseflow described above were applied to the modeled baseflow in both dry and wet weather.

5.4.2.2 Wet Weather Calibration

The calibration was primarily conducted for *Enterococcus*, with corresponding parameter values applied to *E. coli*. Many different model simulations were conducted with different combinations of some parameters including bacterial counts in stormwater and in soil store inflows and die-off rates. A summary of parameters for some of the later model runs for the *Enterococcus* calibration is provided in Table 5-4, including values of the Index of Agreement. The set of parameters identified as best, and used in the final calibrated model, in some cases does not result in the simulation with the highest IA value. This is because, in addition to the goal of maximizing IA, the “weight of the evidence” method has been prioritized; in cases where the final calibrated model runs do not have the highest IA, they are among the highest. Table 5-5 provides similar information for the *E. coli* calibration runs. Model runs were conducted over two-month periods (with results from one two-month period used as initial conditions for the following period), due to long model run times for the entire 1-year continuous period. Plots of model versus measurements for the different periods at the different in-stream monitoring stations are provided for the *Enterococcus* calibration in Appendix D, and for *E. coli* in Appendix E.

Similar to the Charles River evaluation presented above, the impact on the calibration of increasing the die-off rate was also evaluated for the Alewife Brook/Upper Mystic River model. As described in Section 3.3.1, a die-off rate of 0.8 day^{-1} was used for the calibration. For this analysis, the effect of increasing the die-off rate to 1.6 day^{-1} was assessed. The 1.6 day^{-1} value yielded a good match with the in-stream measurements for April and May (see Figure 5-16 and 5-18) compared to the model results using 0.8 day^{-1} (see Figures 5-17 and 5-19). But for June and July, the trend was reversed (see Figures 5-20 to 5-23). For all cases, the peak *Enterococcus* counts were well matched. The die-off rates control the rate of bacterial count decrease after storm events, and hence the length of time during which criteria exceedances occur.

Table 5-4. Partial Alewife Brook/Upper Mystic River *Enterococcus* Model Runs Log

Run No.	Run Interval	Runoff *Enterococcus* (MPN/100mL)	Soil *Enterococcus* (MPN/100mL)	CSO *Enterococcus* (MPN/100mL)	Die-off Coefficient (1/day)	Dispersion Coefficient (m^2/s)	IA	Comment
10	April-May, 2018	5,000	30	300,000	0.8	0.3	NA	Model run terminated
11	April-May, 2018	5,000	30	300,000	0.8	30	NA	Model run crashes
15	April-May, 2018	5,000	30	300,000	0.8	3	0.56	Dispersion coefficient used
13	April-May, 2018	5,000	30	300,000	0.8	0	0.47	Breaking up the inflow into each node upstream STA174 to go in more gradually
17	April-May, 2018	5,000	30	300,000	1.6	0	0.38	Die-off doubled to better match April/May measurements
19	April-May, 2018	5,000	30	300,000	1.6	0	0.82	Using Hydrology Run 224
21	June-July 2018	5,000	30	300,000	1.6	0	0.69	Using Hydrology Run 225 (Same as 224)
22	June-July 2018	5,600	45	300,000	1.6	0	0.72	Changed runoff and soil counts to 5,600 and 45 respectively
23	April-May, 2018	5,600	45	300,000	1.6	0	0.72	Using Hydrology Run 227
24	June-July 2018	5,600	45	300,000	1.6	0	0.70	Using Hydrology Run 227
25	April-May, 2018	6,700	45 (1,000 upstream of station 083)	300,000	1.6	0	0.76	Changed runoff count to 6,700 to match in-stream monitoring data. Increased soil store count upstream of 083 to improve match there.
26	April-May, 2018	As previous	45 (10,000 upstream of station 083)	300,000	1.6	0	0.76	Increased soil store count upstream of station 083 to 10,000 to better match in-stream monitoring data
27	June-July 2018	As previous	As previous	300,000	1.6	0	0.78	As previous run
28	April-May, 2018	As previous	45 (10,000 upstream of station 083)	300,000	0.8	0	0.74	Die-off changed to 0.8 and Enterococcus count for Somerville Marginal changed to 17 / 100 mL.
30	April-May, 2018	6,700 (20,000 upstream of station 083)	45 (10,000 upstream of station 083)	300,000	0.8	0	0.75	Same as previous with runoff count upstream of 083 increased to 20,000
31	April-May, 2018	As previous	As previous	Based on Sanitary Fractions, 1,000,000	0.8	0	0.76	Changed CSO Enterococcus to sanitary fraction formulation

Table 5-4. Partial Alewife Brook/Upper Mystic River *Enterococcus* Model Runs Log

Run No.	Run Interval	Runoff *Enterococcus* (MPN/100mL)	Soil *Enterococcus* (MPN/100mL)	CSO *Enterococcus* (MPN/100mL)	Die-off Coefficient (1/day)	Dispersion Coefficient (m^2/s)	IA	Comment
				MPN/100 mL for sanitary fraction				
32	June-July 2018	As previous	As previous	As Run 31	0.8	0	0.83	As previous
33	June-July 2018	6,700 (40,000 upstream of station 083)	200 (20,000 upstream of station 083)	As Run 31	0.8	0	0.83	Increased stormwater and soil store inflow counts upstream of Station 083
34	April-May, 2018	As previous	800 (20,000 upstream of station 083)	As Run 31	0.8	0	0.64	Increased soil store inflow counts to 800 based on storm drain dry weather data
35	April-May, 2018	As previous	Same as Run 33	As Run 31	0.8	0	0.74	Decreased soil store inflow count back to 200
36	August-Sept 2018	As Run 31	As Run 31	As Run 31	0.8	0	0.82	Same as Run 31
37	April-May, 2018	As Run 31	As Run 31	As Run 31	1.6	0	0.76	Same as Run 31 with die-off doubled
38	June-July 2018	As Run 31	As Run 31	As Run 31	1.6	0	0.78	Changed Die-off coefficient to 1.6
40	Oct-Nov 2018	As Run 31	As Run 31	As Run 31	0.8	0	0.57	Die-off back to 0.8 for last two months

Rows shaded green are for the final set of parameters

Table 5-5. Partial Alewife Brook/Upper Mystic River *E. coli* Model Runs Log

Run No.	Run Interval	Runoff *E. coli* (MPN/100mL)	Soil *E. coli* (MPN/100mL)	CSO *E. coli* (MPN/100mL)	Die-off Coefficient (1/day)	Dispersion Coefficient (m^2/s)	IA	Comment
39	April-May, 2018	14,000 (50,000 upstream of station 083)	134 (25,000 upstream of station 083)	Based on Sanitary Fractions, 2,500,000 MPN/100 mL for sanitary fraction	0.8	0	0.58	
41	April-May, 2018	14,000 (50,000 upstream of station 083)	134(25,000 upstream of station 083)	As Run 39	1.6	0	0.63	Changed Die-off coefficient to 1.6
42	April-May, 2018	20,000 (50,000 upstream of station 083)	134(25,000 upstream of station 083)	As Run 39	0.8	0		Changed Die-off coefficient to 0.8 and runoff to 20,000
43	April-May, 2018	25,000 (50,000 upstream of station 083)	134 (5,000 upstream of station 083)	As Run 39	0.8	0	0.63	Changed to 5,000 upstream of station 83 and runoff to 25,000
46	April-May, 2018	25,000 (50,000 upstream of station 083)	134 (5,000 upstream of station 083), changed Boundary condition concentration to 13	As Run 39	0.8	0	0.63	Changed Boundary condition concentration to 13
48	August-Sept, 2018	25,000 (50,000 upstream of station 083)	134 (5,000 upstream of station 083) changed Boundary condition concentration to 13	As Run 39	0.8	0	0.74	Changed Boundary condition concentration to 13
49	April-May, 2018	25,000 (50,000 upstream of station 083)	134 (2,000 upstream of station 083), changed Boundary condition concentration to 13	As Run 39	0.8	0	0.63	Changed to 2000 upstream of station 83
50	April-May, 2018	25,000 (50,000 upstream of station 083)	134 (2,000 upstream of station 083), changed Boundary condition concentration to 10	As Run 39	0.8	0	0.63	Changed Boundary condition concentration to 10
51	June-July 2018	25,000 (50,000 upstream of station 083)	134 (2,000 upstream of station 083), changed Boundary condition concentration to 10	As Run 39	0.8	0	0.26	As previous
52	August-Sept, 2018	25,000 (50,000 upstream of station 083)	134 (2,000 upstream of station 083), changed Boundary condition concentration to 10	As Run 39	0.8	0	0.74	As previous
53	Oct-Nov, 2018	25,000 (50,000 upstream of station 083)	134 (2,000 upstream of station 083), changed Boundary condition concentration to 10	As Run 39	0.8	0	0.31	As previous

Rows shaded green are for the final set of parameters

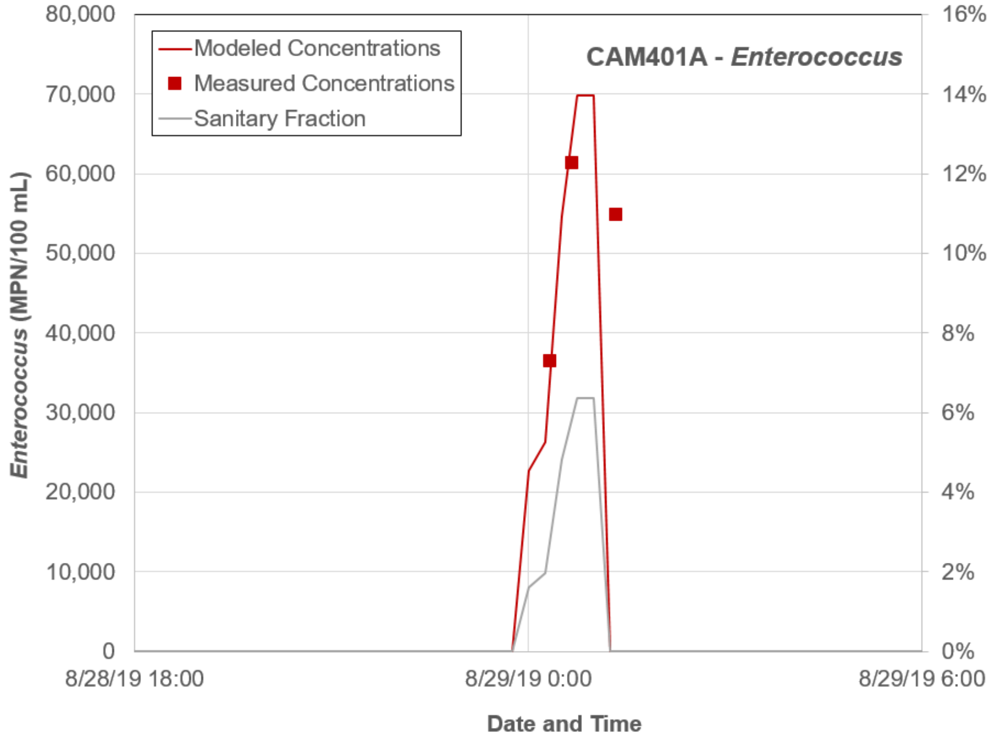


Figure 5-14. Measured versus Modeled *Enterococcus* Counts at Outfall 401A with Revised non-Sanitary Fraction Counts

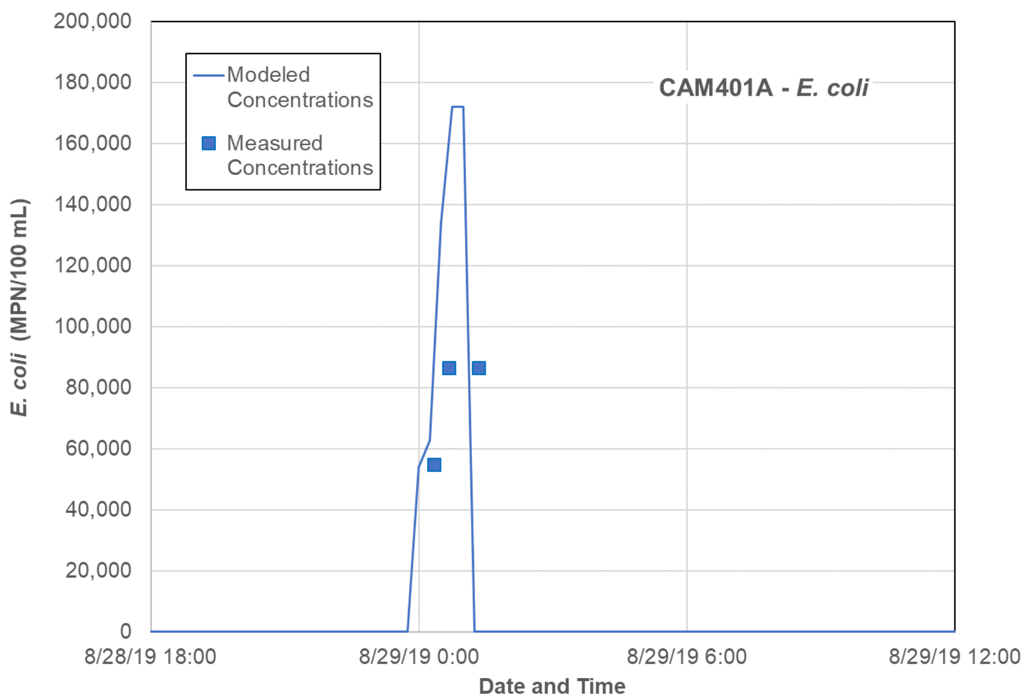


Figure 5-15. Measured versus Modeled *E. coli* Counts at Outfall 401A with Revised non-Sanitary Fraction Counts

The observation that the larger die-off rate provides a better match to the April-May measurements and the smaller die-off provided a better match for the June-July measurements is counter to the fact that die-off generally increases with temperature. Because of this, and to avoid ambiguities as to the season to assign to design storms, a fixed die-off rate was used, and 0.8 day^{-1} was selected, as it is more conservative than the higher rate.

It should be noted that some of the low values (e.g. <10 MPN/100mL) predicted by the model during certain dry weather periods may not reflect actual conditions in Alewife Brook for those periods. The modeled bacterial counts in Alewife Brook drop to very low values in the summer because the dry weather loadings are delivered by the soil store (groundwater) discharges, which are very low in the summer. The dry weather bacterial levels in the summer can be influenced by other sources such as wildlife loading, which are not included in the model. However, the model's wet weather results are not very sensitive to (the much smaller) assumed dry weather inputs.

Two additional parameters that were tuned for calibration included the *Enterococcus* and *E. coli* counts in the non-sanitary fraction of the CSOs, and the *E. coli* counts in the separate stormwater. As described above, the *Enterococcus* and *E. coli* counts in the non-sanitary fraction of the CSOs were initially defined from the overall average values of the stormwater sampling conducted in 2019 and 2020 (5,500 MPN/100 mL for *Enterococcus*, and 13,400 MPN/100 mL for *E. coli*. With these values, the predicted bacteria counts in the CSO at outfalls CAM401A and SOM001A were shown to match the measured values. The predicted flow-weighted bacterial counts at the outfalls for 2018 are presented above in Table 5-1.

As part of the calibration to measured values in the receiving waters, the counts in the non-sanitary fraction of the CSOs were modified to 6,700 MPN/100 mL for *Enterococcus*, and 14,000 MPN/100 mL for *E. coli*. Figures 5-14 and 5-15 show the plots of modeled versus measured *Enterococcus* and *E. coli* counts at outfall CAM401A for the August 29, 2019 storm. As indicated in these figures, with the revision to the counts in the non-sanitary fraction, the modeled values still reasonably match the measured values. A similar finding was noted for the modeled versus measured counts at outfall SOM001A. Figure 5-14 also shows the plot of the modeled sanitary fraction versus time at outfall CAM401A for the August 29, 2019 storm.

Table 5-6 presents the flow-weighted counts at the outfalls to Alewife Brook/Upper Mystic River with the revised counts in the non-sanitary fraction. This change resulted in slight increases in the flow-weighted counts at the CSOs except for outfall SOM007A, which is a treated discharge.

For the separate stormwater, the *Enterococcus* counts at all locations except the runoff areas tributary to the Mystic River between station 083 and the Lower Mystic Lake were tuned to 6,700 MPN/100 mL, while the *E. coli* counts needed to be increased to 25,000 MPN/100 mL in order to match wet weather counts in the receiving waters. While this value was higher than the overall average of all the measurements presented in Table 2-4, it was less than the averages found for individual storms at stormwater sampling locations ARL1 and 2, CAM1, 3 and 4, MED4 and SD10, as shown in Table 2-4. For the runoff areas tributary to the Mystic River between station 083 and the Lower Mystic Lake, the *Enterococcus* counts were increased to 20,000 MPN/100 mL, while the *E. coli* counts were increased to 50,000 MPN/100 mL. Similar to the case for the dry weather calibration described above, the actual wet weather loadings directly from the lake could not be reliably replicated by the model. As a result, the wet weather loadings into the Mystic River upstream of station 083 had to be increased to account for the wet weather loads from the Lower Mystic Lake.

Table 5-6. Predicted Sanitary Fractions and Flow-weighted Counts for 2018 with Revised non-Sanitary Fraction Counts

Location	Sanitary Fraction (%)(1)	Flow-weighted Counts (MPN/100 mL)	
		Enterococcus	*E. coli*
MWR003	1.23%	18,953	44,666
CAM401B	2.95%	36,033	87,413
CAM401A	2.01%	26,693	64,038
CAM002	0.39%	10,560	23,660
CAM001	7.60%	82,226	203,024
SOM001A	3.34%	39,870	97,016
SOM007A(2)	N/A	17	18

Notes:

(1) For each outfall, the sanitary fraction shown is the flow weighted average in the discharge pipe over the periods when the outfalls were discharging flow.

(2) For outfall SOM007A, the flow-weighted counts reflect the treated discharge concentrations from the Somerville Marginal CSO Facility. The sanitary fraction method was not applied to the treated discharge. Counts applied to the treated discharge were based on the average values of measured counts sampled from facility effluent in 2018.

The set of conditions that was found to match measurements for *Enterococcus* best corresponded to runs 31, 32, 36 and 40 highlighted in green in Table 5-4 above. The set of conditions that was found to match measurements for *E-coli* best corresponded to runs 50, 51, 52 and 53 highlighted in green in Table 5-5 above. The parameters corresponding to these runs are summarized in Table 5-7. As noted above, plots of calculated *Enterococcus* counts compared to measured values for several sets of monitoring stations spanning Alewife Brook and the Upper Mystic River are provided in Appendix D. Similar plots for *E. coli* are provided in Appendix E.

The plots presented in Appendix D and E demonstrate that the model reasonably matches the measured values, and should be suitable for the intended uses on this project as described in Section 6.2.

Table 5-7. Selected Model Parameters

	Stormwater Count(1) (MPN/100 mL)	Baseflow Inflow Count(2) (MPN/100 mL)	CSO Sanitary Fraction Count (MPN/100 mL)	CSO non-Sanitary Fraction Count (MPN/100 mL)	Die-off Rate (Day-1)
Enterococcus	6,700	45	1,000,000	6,700	0.8
E. coli	25,000	134	2,500,000	14,000	0.8

Notes:

(1) For runoff areas tributary to the Mystic River between station 083 and the Lower Mystic Lake, stormwater counts of 20,000 MPN/100mL for *Enterococcus* and 50,000 MPN/100mL for *E. coli* were applied, to account for loadings from the Lower Mystic Lake.

(2) For baseflow inputs to the Mystic River between station 083 and the Lower Mystic Lake, counts of 10,000 MPN/100mL for *Enterococcus* and 2,000 MPN/100mL for *E. coli* were applied, to account for loadings from the Lower Mystic Lake.

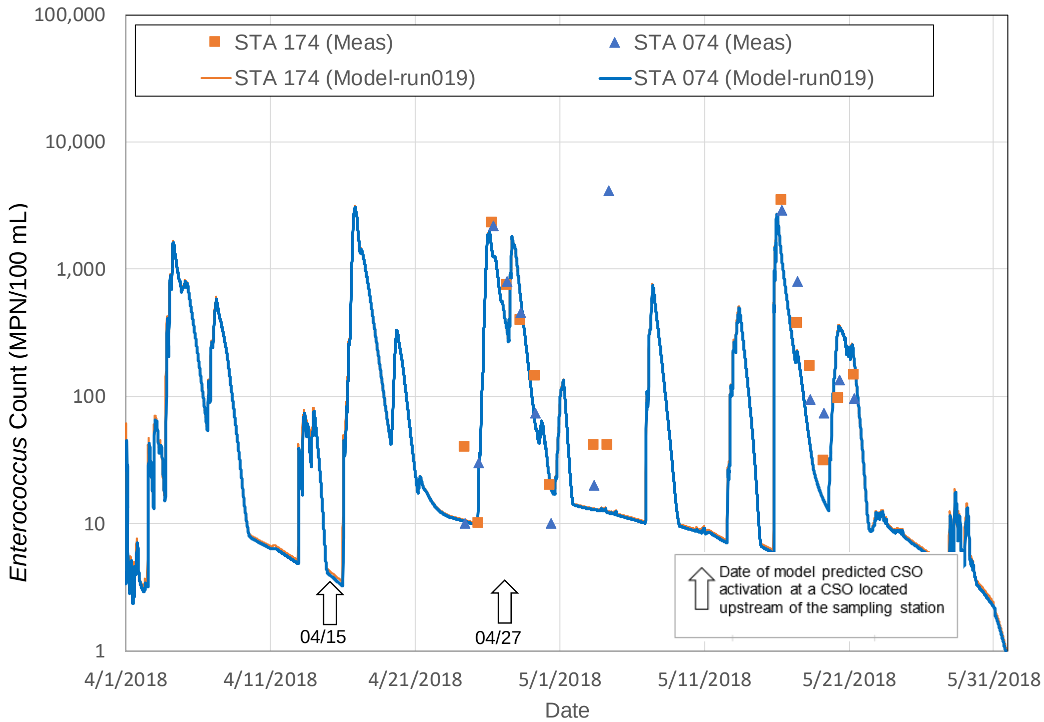


Figure 5-16. Measured and calculated *Enterococcus* at Stations 074 and 174 for April and May 2018 with die off rate of 1.6 day^{-1}

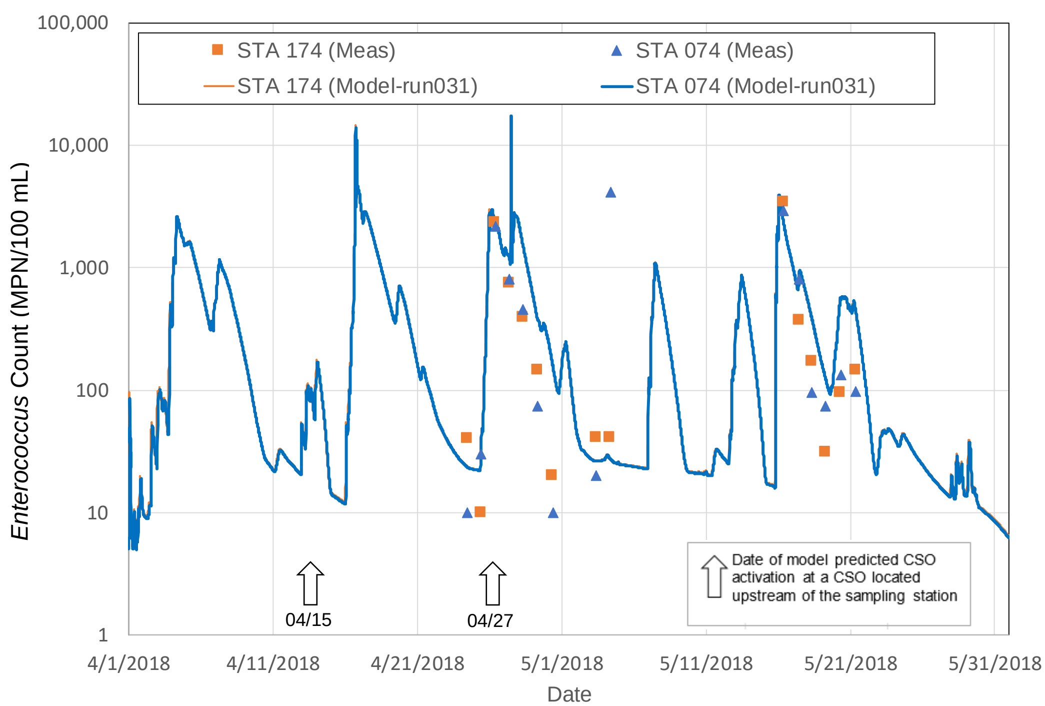


Figure 5-17. Measured and calculated *Enterococcus* at Stations 074 and 174 for April and May 2018 with die off rate of 0.8 day^{-1}

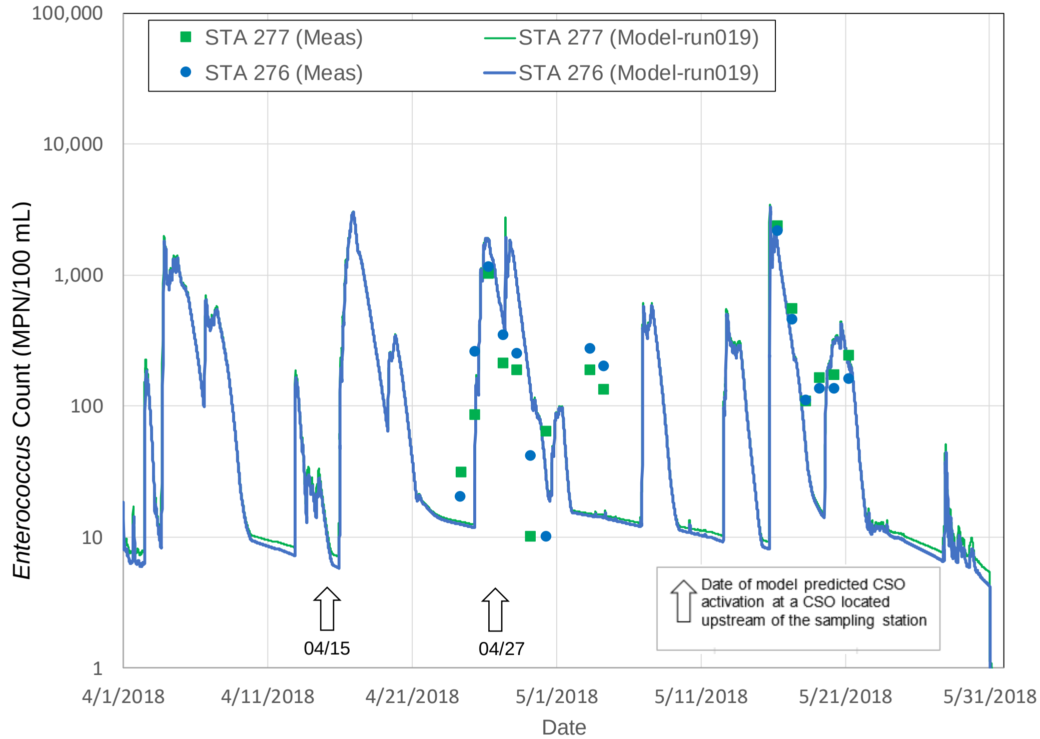


Figure 5-18. Measured and Calculated *Enterococcus* at Stations 276 and 277 for April and May 2018 with die off rate of 1.6 day^{-1}

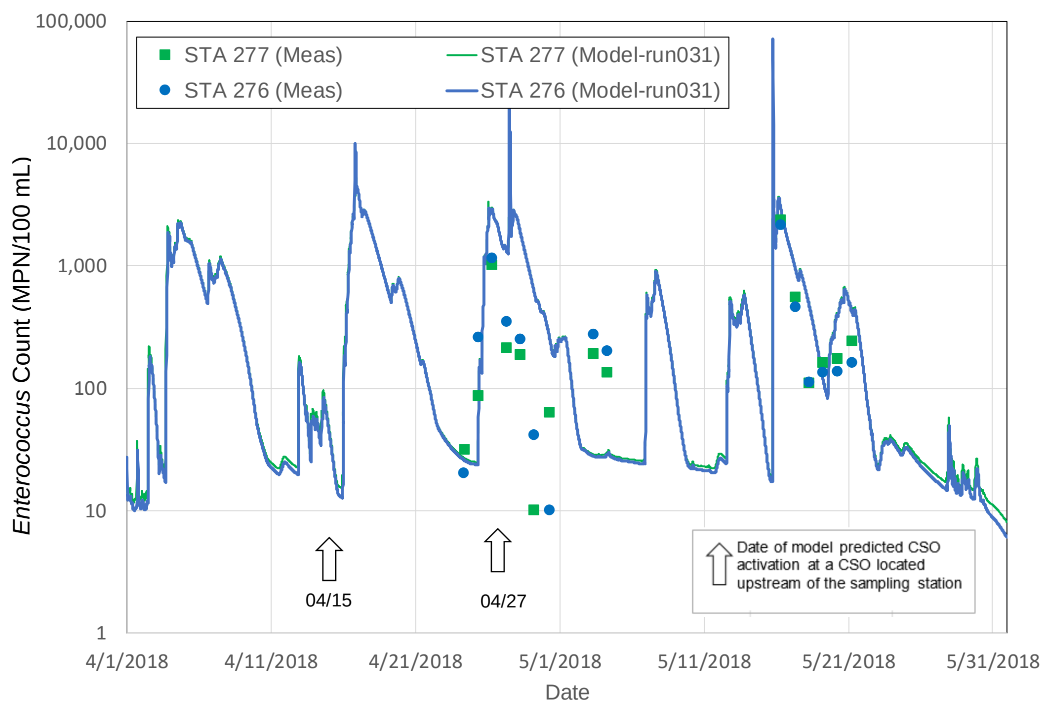


Figure 5-19. Measured and Calculated *Enterococcus* at Stations 276 and 277 for April and May 2018 with die off rate of 0.8 day^{-1}

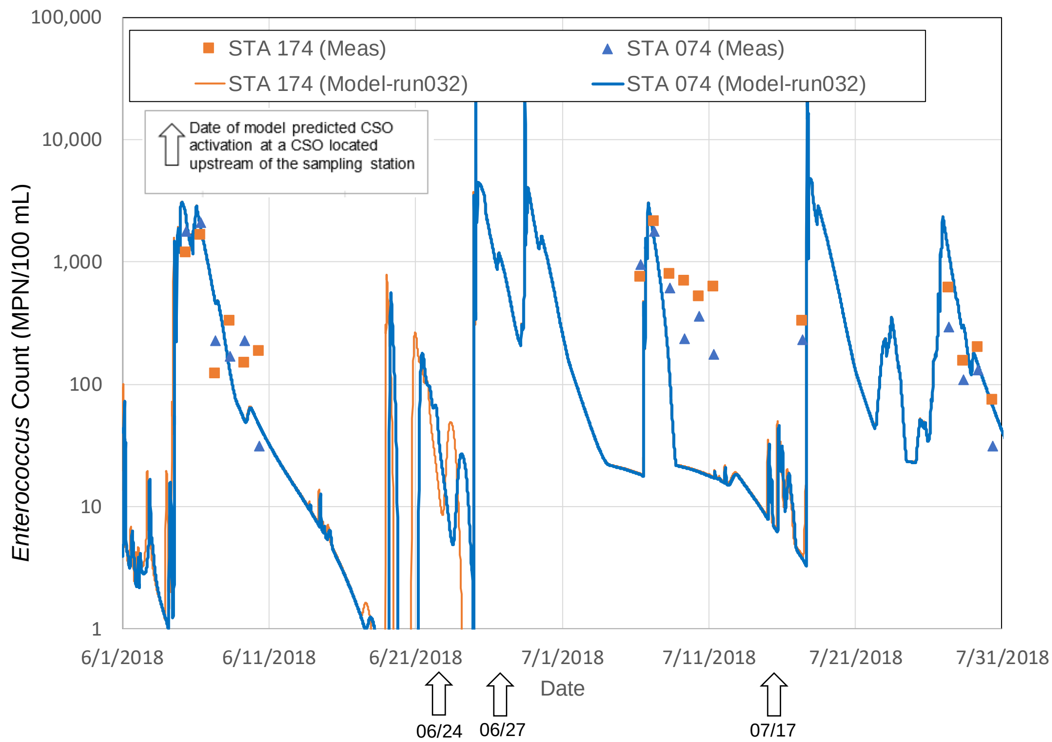


Figure 5-20. Measured and calculated *Enterococcus* at Stations 074 and 174 for June and July 2018 with die off rate of 1.6 day^{-1}

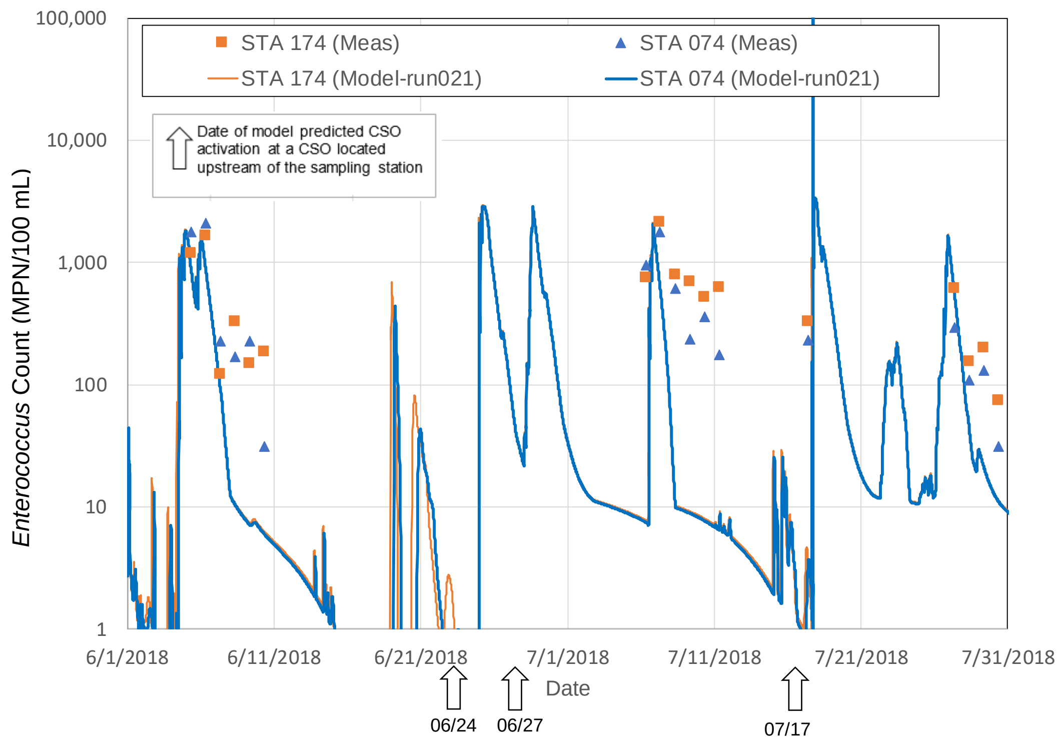


Figure 5-21. Measured and Calculated *Enterococcus* at Stations 074 and 174 for June and July 2018 with die off rate of 0.8 day^{-1}

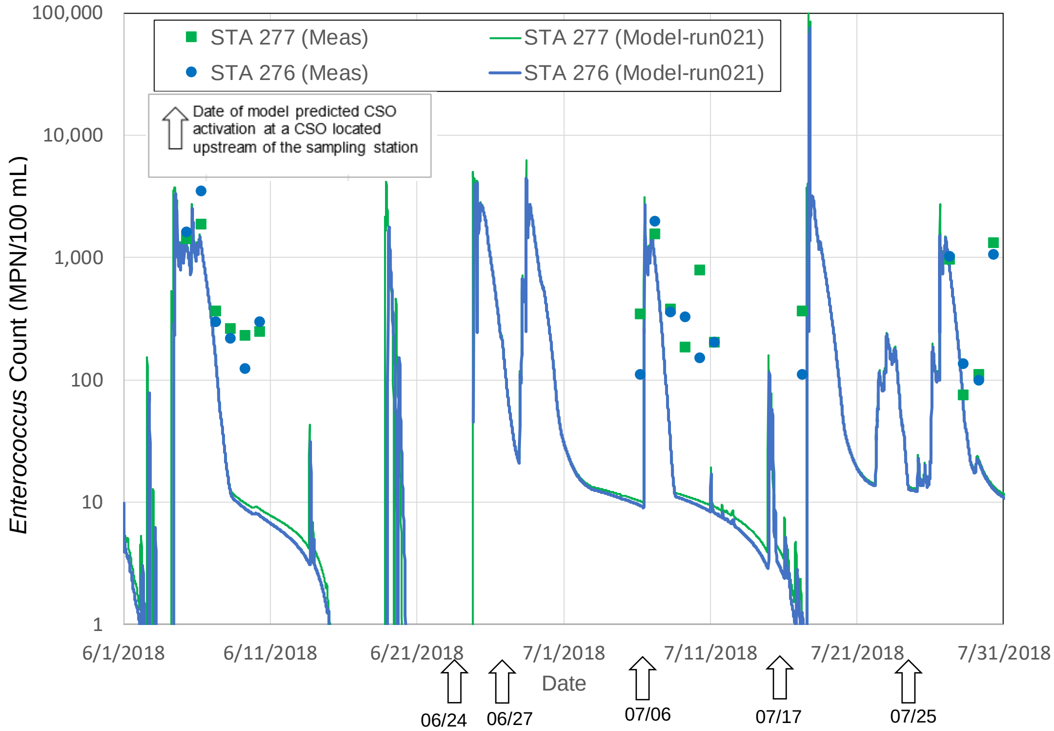


Figure 5-22. Measured and Calculated *Enterococcus* Counts at Stations 276 and 277 for June and July with a die-off rate of 1.6 day-1

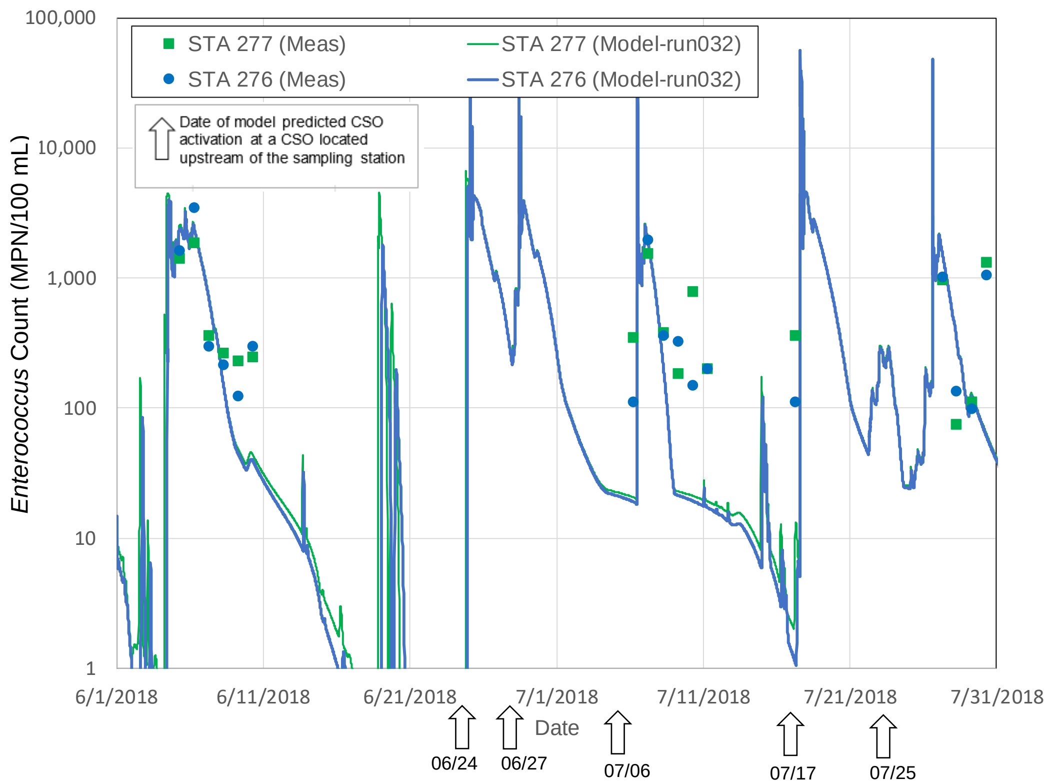


Figure 5-23. Measured and Calculated *Enterococcus* Counts at Stations 276 and 277 for June and July with a die-off rate of 0.8 day-1

6.0 Summary and Conclusions

This report describes the development and calibration of hydrodynamic and water quality models of the Charles River and Alewife Brook/Upper Mystic River. These models will be used to assess the remaining impact of CSOs and other pollutant sources on water quality in these receiving waters after improvements made by implementing the MWRA CSO Long Term Control Plan over the last 30 years. Further model predictions will influence consideration given to whether further investments in CSO mitigation will result in meaningful water quality improvements and whether emphasis on non-CSO contributions of pollution would be more cost-effective. As shown in Table 4-2 of the April 2020 Semiannual CSO Discharge Report No. 4, under 2019 conditions, the total remaining CSO volume for the Typical Year is predicted to be 430 MG, of which 40 MG (9%) is untreated. This represents significant progress since 1992 conditions, where 1,457 MG of CSO discharged in the Typical Year, with 759 MG (52%) untreated. As described below, the water quality model will be a critical tool in understanding the relative impacts of the remaining CSO discharges on attainment of water quality standards, as well as the impacts of other non-CSO sources. This understanding is needed so that further mitigation efforts, if required, can be cost-effectively targeted at the appropriate sources.

6.1 Model Development and Calibration

Charles River Model

The Charles River model was calibrated for the period of April to October 2018 using MWRA in-stream water quality measurements for comparison to model-predicted levels of *Enterococcus* and *E. coli*. The two-dimensional model was developed in Delft3D with inputs including upstream boundary conditions to establish flow and water quality at the upstream end of the model and stormwater and CSO discharge volumes. Fixed bacterial counts were used for the base flow and stormwater flow components based on the overall average values of *Enterococcus* and *E. coli* counts measured in storm drains tributary to the Charles River and Alewife Brook/Upper Mystic River from the communities of Arlington, Cambridge, Medford and Somerville. For the treated discharges from the Cottage Farm CSO Facility, the average of the effluent bacterial counts measured between July 2018 and April 2019 were used to represent the effluent quality. For untreated CSO discharges, *Enterococcus* and *E. coli* counts were specified based on time-varying sanitary fractions calculated by the collection system model. The bacterial counts of the sanitary and stormwater fractions were calibrated to bacteria concentrations measured at Cottage Farm and Prison Point influents.

The Charles River water quality measurements were compared to model predictions for dry weather periods as well as for storm events with and without CSO activations. The calibration was primarily conducted for *Enterococcus* with corresponding parameter values applied to *E. coli.* The calibration plots prepared demonstrate that the model reasonably matches the measured values and should be suitable for the intended uses on this project as described in Section 6.2.

Alewife Brook/Upper Mystic River Model

The Alewife Brook/Upper Mystic River model was also calibrated for the period of April to October 2018 using MWRA instream water quality measurements for comparison. The model software used for this model is Infoworks ICM. The one-dimensional river model was updated with inputs including upstream boundary conditions to establish flow and water quality at the upstream end of the model, and stormwater and CSO discharge volumes. Fixed bacterial counts were used for the base flow and stormwater flow components based on the overall average values of *Enterococcus* and *E. coli* counts measured in storm drains tributary to the Charles River and Alewife Brook/Upper Mystic River from the communities of

Arlington, Cambridge, Medford and Somerville. For the treated discharges from the Somerville Marginal CSO Facility, the average of the effluent bacterial counts measured between June and November of 2018 were used to represent the effluent quality. For untreated CSO discharges, *Enterococcus* and *E. coli* counts were specified based on time-varying sanitary fractions calculated by the collection system model. The bacterial counts of the sanitary and stormwater fractions were calibrated to bacteria concentrations measured at outfalls CAM401A and SOM01A, which discharge to Alewife Brook.

The Alewife Brook and Upper Mystic water quality data was compared to model predictions for dry weather periods as well as for storm events with and without CSO activations. The calibration was primarily conducted for *Enterococcus* with corresponding parameter values applied to *E. coli.* The calibration plots prepared demonstrate that the model reasonably matches the measured values and should be suitable for the intended uses on this project as described in Section 6.2.

6.2 Water Quality Model Application

This report documents the model calibration process and concluded that the receiving water models are reasonably calibrated and are suitable to be applied for further evaluations. The purpose of these receiving water models is to quantify the water quality improvements and to specifically identify the CSO versus non CSO contributions including:

- Whether remaining CSO impacts preclude attainment of bacterial Water Quality Standards and water quality-based requirements of the Clean Water Act
- Whether the implemented CSO controls are performing as expected in terms of water quality improvements relative to the Long Term Control Plan (LTCP) and Variance Reports

After the water quality assessment is complete an alternatives analysis will be conducted. Both the water quality assessment and alternatives simulations are described in more detail below.

The model calibration efforts described in the sections above were focused on providing a model that could be used specifically to assess the relative impacts of the remaining CSO on water quality. Sufficient field data were collected in order for the model to be appropriately used to conduct the evaluations to assess the performance of the MWRA's implemented LTCP as described below. In order for the model to distinguish or quantify time- or spatially-varying stormwater concentrations, loadings specifically from illicit connections, or impacts of temperature or sunlight on bacterial die-off rates, additional field measurements and analysis would be necessary and are not planned at this time, and are not necessary for the models' intended purpose.

Water Quality Assessment

The water quality assessment will estimate the effects of wet weather sources on present-day water quality and compare them to the water quality impacts expected after completion of the LTCP. The assessment will include running the models for the 3-month and 1-year design storms as well as the Typical Year for current conditions. Simulations will be conducted with loadings from CSOs, stormwater and upstream boundaries for *Enterococcus* and *E. coli*. Tracers for each individual source and constituents will be used in the simulations so that the relative contributions of the various sources to the total predicted concentrations of *Enterococcus* and *E. coli* in the receiving waters can be assessed. Because the transport equation is linear, results with loadings from different sources are additive. Thus, the water quality effects of CSOs, stormwater, and boundary conditions will be able to be separated using this approach. In addition, model runs will be conducted with varied bacterial loadings to assess the sensitivity of findings to variations in loading concentrations.

Results will be presented in contour plots of bacterial counts (for the Charles River) and plots of bacterial counts as a function of distance (for Upper Mystic River/Alewife Brook) for various times as well as tables of bacterial water quality standards exceedance durations for the different sources and conditions.

The results of the evaluations comparing current conditions to the LTCP goals will be presented in the Water Quality Assessment report.

Alternatives Simulations

After the water quality assessment is complete, the models will be used to evaluate a range of bacterial loading reduction scenarios. Alternatives will be evaluated including the following:

- Scenarios with bacterial concentrations from non-CSO sources set to: i) zero, ii) 50% of the water quality standard and iii) 100% of the water quality standard.
- Scenarios applying a range of statistically-derived CSO bacteria concentrations based on sampling data (e.g., median, 25th percentile, 75th percentile).
- Additional scenarios that may assess the impact of additional CSO reduction opportunities.

Each of the simulations will be conducted for the 3-month and 1-year storms and the Typical Year. The results and analysis of the alternatives will be presented in the Alternatives Simulation Report.

The results of the MWRA's CSO Post Construction Monitoring and Performance Assessment program will be presented in the Post Construction Compliance Monitoring Report.

7.0 References

AECOM. 2020. Review of Monitoring Data. CSO Post Construction Monitoring Performance Assessment. March 2020.

Ayuso, A. 1995. Analysis of Bacterial Contamination in the Charles River. MS Thesis, Department of Civil and Environmental Engineering, MIT.

Ahmad, A., Dada, A. and Usup, G. 2014. *Survival of Epidemic, Clinical, Faecal and Recreational Beach Enterococci Strains with Putative Virulence Genes and Marine and Fresh Waters.* Scientific Research Publishing.

Bras, R. 1989. Hydrology. An Introduction to Hydrologic Science. Addison Wesley.

Breault, R.F., Barlow L.K., Reisig, K.D. and Parker, G.W. 2000. Spatial Distribution, Temporal Variability and Chemistry of the Salt Wedge in the Lower Charles River, Massachusetts, June 1998 to July 1999. Water Resources Investigation Report 00-4124

CDM-Smith. 2015. *Stormwater Model Report*. Report prepared for the Boston Water and Sewer Commission.

Che, D., Nangare, M. and Mayes, L.W. 2014. Determination of Clark's Unit Hydrograph Parameters for Watersheds. ASCE, Journal of Hydraulic Engineering 19(2): 384-387

Chow, V.1959. *Open Channel Hydraulics*. McGraw-Hill.

DHI. 2000. *MIKE 21/3 Water Quality Module Reference Manual*

ENSR Corporation. 2007. *Mystic River Basin FIS Hydrologic and Hydraulic Modeling Report*. Report prepared for the Federal Emergency Management Agency, Region 1.

Goodwin C., Ellis-Hibbett D., Wu D. 2020. Summary of CSO receiving water quality monitoring in Upper Mystic River/Alewife Brook and Charles River, 2019. Boston: Massachusetts Water Resources Authority. Report 2020-05. 83 p. plus appendices.

Goodwin C, Wu D. 2019. Summary of CSO Receiving Water Quality Monitoring in Upper Mystic River/Alewife Brook and Charles River, 2018. Boston: Massachusetts Water Resources Authority. Report 2019-05. 79 p. plus appendices

Hellweger, F. L and Masopust, P. 2008. Investigating the Fate and Transport of *Escherichia Coli* in the Charles River, Boston, Using High-Resolution Observation and Modeling. Journal of the American Water Resources Association. Vol. 44, No. 2

Huber, W.C. and Dickinson, R.E. 1988. *Stormwater Management Model, Version 4. User's Manual.* US EPA Environmental Research Laboratory Report.

Korajkic, A., Wanjugi,P., Brooks, L., Cao, Y., and Harwoode, V.J.. 2019 Persistence and Decay of Fecal Microbiota in Aquatic Habitats. Microbiology and Molecular Biology Reviews, Volume 83 Issue 4

Kubaska, B. and Brocard, D. 1993. *Typicalization of1992 Rainfall*. Technical Memorandum prepared for the MWRA.

Mancini, J.L. 1978. *Numerical Estimate of Coliform Mortality Rates under Various Conditions*. Journal WPCF, Vol 50, No.11.

Metcalf & Eddy. 2004. *Evaluation of Stormwater Management Benefits to the Lower Charles River.* Report prepared for New England Interstate Water Pollution Control Commission and U.S. Environmental Protection Agency.

Metcalf & Eddy. 2003. *Results of Stormwater Monitoring for the Mystic River, Fall 2002.* Technical Memorandum prepared for the MWRA.

Metcalf & Eddy, 1994. *Receiving Water Boundary Conditions. Technical Report for Sub-Task 2.5.2 of Master Planning and CSO Facilities Planning*, prepared for the Massachusetts Water Resources Authority.

MWRA, 1996. *Development and Calibration of Water Quality Models for Boston Harbor, Charles River Basin and Mystic River/Alewife Brook.* Draft Technical Memorandum prepared by Metcalf & Eddy for the Massachusetts Water Resources Authority.

New York City Department of Environmental Protection (NYC DEP) 2014. Combined Sewer Overflow Long Term Control Plan for Westchester Creek. June 2014.

NYC DEP 2015. Combined Sewer Overflow Long Term Control Plan for Bronx River. June 2015.

Tetra Tech. 2005. *A Hydrodynamic and Water Quality Model for the Lower Charles River Basin, Massachusetts*. Report prepared for USEPA Region 1.

Selvakumar, A. and Borst, M. 2006. *Variation of Microorganism Concentrations in Urban Stormwater Runoff with Land Use and Season.* Journal of Water and Health, Vol 4, No 1.

USEPA. 2016. Storm Water Management Model Reference Manual Volume 1 – Hydrology (Revised). EPA/600/R-15/162A.

USEPA. 2015. Storm Water Management Model User's Manual Version 5.1. EPA/600/R-14/413b. Revised September 2015.

USGS. 2000. *Spatial Distribution, Temporal Variability, and Chemistry of the Salt Wedge in the Lower Charles River*, Massachusetts - June 1998 to July 1999.

USGS. 2002a. Breault, R.F., Sorensen, J. R. and Weiskel, P. K. 2002. *Streamflow, Water Quality and Contaminant Loads in the Lower Charles River Watershed, Massachusetts, 1999-2000.* Water-Resources Investigations Report 02-4137.

USGS. 2002b. Zariello, P.J. and Barlow, L.K. *Measured and Simulated Runoff to the Lower Charles River, Massachusetts, October 1999 – September 2000.* Water Resources Investigations Report 02-4129.

Verdi, R. (USGS). 2019. Personal Communication

Willmott, C.J. 1981. *On the Validation of Models*. Physical Geography.

Wu, D. and Goodwin, C. 2017. *Summary of CSO Receiving Water Quality in Upper Mystic River/Alewife Brook and Charles River, 2016.* Massachusetts Water Resources Authority, Report ENQUAD 2017-04

Wu D, Goodwin C. 2018. Summary of CSO Receiving Water Quality Monitoring in Upper Mystic River/Alewife Brook and Charles River, 2017. Boston: Massachusetts Water Resources Authority. Report 2018-03. 94 pp, plus appendices.

Appendix A – Charles River Upstream Boundary Condition

Charles River Upstream Boundary Condition Buildup-Washoff Method

Estimation of bacteria counts at Watertown dam for the purpose of transient water quality modeling in the Lower Charles was previously accomplished using a buildup-washoff approach (Metcalf & Eddy, 1994; Metcalf & Eddy, 2004). This is the approach used for pollutant generation modeling in the USEPA Stormwater Management Model (SWMM) (Huber and Dickinson, 1988). In this approach, pollutants are assumed to build up in the catchment during dry weather and get washed off by runoff during storms at a rate dependant on the runoff intensity. This is an approximation for the 265 mi^2 Charles drainage area upstream of Watertown Dam. Among other simplifications, it does not account for bacterial die-off that occurs during the travel time from upper reaches of the river to the dam site. Nevertheless, the approach simulates some of the mechanisms that lead to increased counts in the river, and it produces simulated bacterial counts at Watertown Dam that resemble those observed. Therefore, with judicious calibration, it may be used to provide estimates of upstream water quality boundary conditions.

A key aspect of the buildup-washoff formulation is handling of river flows by partitioning the total flow in to a base component $Q_b(t)$ and a component due to storms $Q_s(t)$, each in cfs, as follows. From the USGS flow records at the Waltham gauge, the total flow at the Watertown Dam is obtained as described in section 4.3.7 of this report. Before storms the total flow and base flow (non-storm flow) are the same. The storm flow is nonzero only during storms and for a 3-day period after the peak river flow associated with the storms. After that period, the total flow returns to equalling the base flow. The start of each storm is identified based on the start of rainfall at the MWRA Ward Street rain gauge (BO-DI-1), selected because it is near the Charles River. Rainfall is not used other than to identify the start times of storms, and results are not particularly sensitive to the storm start times. Storm flows are taken to last for 3 days after the river flow peaks. The 3-day duration after peak flow is based on the formula, from Bras (1990),

$$N = A^{0.2}$$

where N = time from the peak flow to the return to base flow (days) and A = basin area (mi^2) of 265 mi^2 for the Charles River upstream of the Watertown Dam.

During each storm, base flow $Q_b(t)$ is defined by a linear decrease from the start of the storm until the time of peak total flow, followed by a 3-day linear increase after the peak river flow. The decreasing period is a prolongation of the river flow before the storm, with slope assessed visually from the hydrograph prior to the start of the storm. The second leg of the base flow hydrograph goes from the end of the first leg (at the time of peak flow) to the point on the measured hydrograph 3 days after the peak. Then storm flow $Q_s(t)$ is calculated as the total flow less $Q_b(t)$.

The buildup-washoff approach yields bacterial counts in the river at the dam as a function of time, computed as the total load (sum of the base load and storm load) divided by the total flow (sum of base flow and storm flow):

$$C(t) = \frac{Q_b(t)C_b + L(t)}{Q_b(t) + Q_s(t)}$$

where base flow counts are constant at C_b, the load from the base flow is $Q_b(t)C_b$ (counts/day), and $L(t)$ (counts/day) is the load due to washoff by storm flow explained below. The base flow counts were computed as the arithmetic mean of all 2017 and 2018 dry weather samples, those preceded by at least three days without precipitation, at Station 012 nearest the dam: 45 / 100 mL for *Enterococcus* and 134 / 100 mL for *E. coli*. In the absence of flow-weighted bacterial counts, arithmetic averages were used. Geometric means are indicators of the central tendency of log-normal distributed data, and are appropriately used to compare different distributions, but are not as appropriate for estimating total load. Use of the geometric mean would generally underestimate the total loading.

The load due to washoff is calculated as follows. A linear build-up of concentration with time between storms across the watershed (Huber and Dikinson,1988) and first-order die-off of the build-up (Selvakumar et al 2006) are assumed. The equation for build-up thus has a constant term for linear growth and a decay term proportional to the build-up:

$$\frac{dP(t)}{dt} = aA - kP(t)$$

where: $P(t)$ = bacterial buildup at time t (counts), a = constant buildup rate (count day^{-1} mi^{-2}), A = drainage area (mi^2) and k = decay constant for die-off (day^{-1}). The solution to this equation, for zero initial buildup at time t=0 (which corresponds to the end of the prior storm), is:

$$P(t) = \frac{aA}{k}\left(1 - e^{-kt}\right)$$

Thus, for increasing dry weather time, the buildup tends towards a maximum value of aA/k. The time needed to reach 95% of this ultimate value is: t_{95} = 3.00 / k. Bacterial die-off rates on land during dry weather are not well documented. The value of k = 0.5 day^{-1}, somewhat smaller than die off rate in water, gives t_{95} = 6.0 days and is representative.

The load due to washoff during a storm is taken to be the product of the buildup $P(t)$, as shown in the above equation, and an empirical power-law function $\alpha Q_s(t)^\beta$ of the storm flow,

$$L(t) = P(t)\alpha Q_s(t)^\beta$$

where: L(t) = storm load, bacterial loading to stream through washoff (counts/day), and α, β = coefficients identified by calibration. The β coefficient is dimensionless, while α has units of $day^{\beta-1}$ $ft^{-3\beta}$.

This approach enables the counts in the river at the dam to be estimated from only the total streamflow measurements, the storm start times based on rainfall, and values of $C_b, a, A, k, \alpha,$ and β. Reasonable values of $C_b, A,$ and k are as noted above. Values of $a, \alpha,$ and β are calculated by an iterative optimization process to obtain the best agreement with measured river counts at Station 012 near the dam and Station 001 about 1 mile downstream from the dam.

Peak *Enterococcus* and *E. coli* counts at Stations 012 and 001 measured in the spring are significantly less than those measured in the summer. Peak counts measured in the fall are also lower than those measured in the summer, but to a lesser extent. This has been noted by others (Selvakumar and Borst, 2006). This observation is in contrast to the fact that bacterial die-off increases with temperature (Mancini et al, 1978; DHI, 2000). Bacteria in stormwater are due mainly to dogs, birds and other wildlife. Reduced dog walking, bird migration and wild animal hibernation may be causes for the reduced bacteria counts in the winter and fall. This seasonality was taken into account in the buildup-washoff calculation by using buildup rates in the winter and fall that are less than the summer buildup rate a. The winter and fall rates are the product of a and a winter ratio and fall ratio, respectively. The winter period is from January to April and the fall period is from September to December.

Table A-1 summarizes results of the optimization process, the corresponding averages of buildup-washoff values and measurements, and Index of Agreement (IA) defined in Section 3.3. Many more combinations of parameters were evaluated than listed in Table A-1, which is aimed at showing the sensitivity of the results to the parameters. The selected set of parameters is shaded in green based on the best match of average values and the highest Index of Agreement, but also based on comparisons of the calculated bacterial counts with measurements with emphasis on best agreement with maximum values during wet weather events and recovery length.

Calibration plots for *Enterococcus* and *E. coli* counts for 2017 and 2018 presented in Figures A-1 to A-4 and plots focused on one-month subsets each are presented in Figures A-5 to A-11 for *Enterococcus* in 2018. These plots show river counts values from the buildup-washoff formulation, calculated at a time step of 15 minutes, compared to measurements at Stations 012 and 001. The rainfall intensity, in units of inches/hour, at 15-minute intervals is also shown, for information only; as explained above it is not used in the calculations, except to define the start time of storms.

Near Station 001, which is about 1 mile downstream of the dam, the average river velocity based on the Delft3D model is on the order of 0.7 ft/s. At this speed the time for water to travel 1 mile is about 2.1 hours, which yields a bacteria count decay due to die-off of approximately 7% for the die-off rate of 0.8 day^{-1}. Therefore, comparing model predictions to measurements at Station 001 is appropriate, within the level of accuracy expected for this approach..

Table A-1. Watertown Dam Build-up/Washoff Coefficients

	Build-up Rate		Washoff Coefficient	Washoff Exponent	Die-off Rate	Base Flow Count	Ave Meas.	Ave Model	IA
	a (#/mi^2/day)	Winter/ Fall Ratio	α	β	K (day^{-1})	C_B #/100ml			
Entero-coccus 2017	2.0 x 10^{11}	1.0 / 1.0	8 x 10^{-4}	1.4	0.5	45	405	567	0.88
	2.0 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	45		473	0.92
	2.0 x 10^{11}	0.2 / 0.5	6 x 10^{-4}	1.4	0.5	45		417	0.91
	2.0 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.3	0.5	45		397	0.89
	1.7 x 10^{11}	0.2 / 0.5	9 x 10^{-4}	1.4	0.5	45		428	0.92
	1.7 x 10^{11}	0.2/0.5	8 x 10^{-4}	1.5	0.5	45		476	0.92
	1.7 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	45		408	0.92
Entero-coccus 2018	1.5 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.5	0.5	45	331	383	0.83
	2.0 x 10^{11}	0.2 / 0.5	6 x 10^{-4}	1.4	0.5	45		378	0.88
	2.0 x 10^{11}	0.2 / 0.5	6 x 10^{-4}	1.3	0.5	45		356	0.91
	1.7 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	45		358	0.89
E. coli *2017*	5.0 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	134	997	1,436	0.82
	4.0 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	134		1,196	0.84
	3.5 x 10^{11}	0.2 / 0.5	9 x 10^{-4}	1.4	0.5	134		1240	0.83
	3.5 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	134		1094	0.87
	3.5 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.7	134		1012	0.88
E. coli 2018	3.5 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.7	134	623	505	0.94
	3.5 x 10^{11}	0.2 / 0.5	8 x 10^{-4}	1.4	0.5	134		601	0.92

Note: Orange-shaded lines denote selected parameters

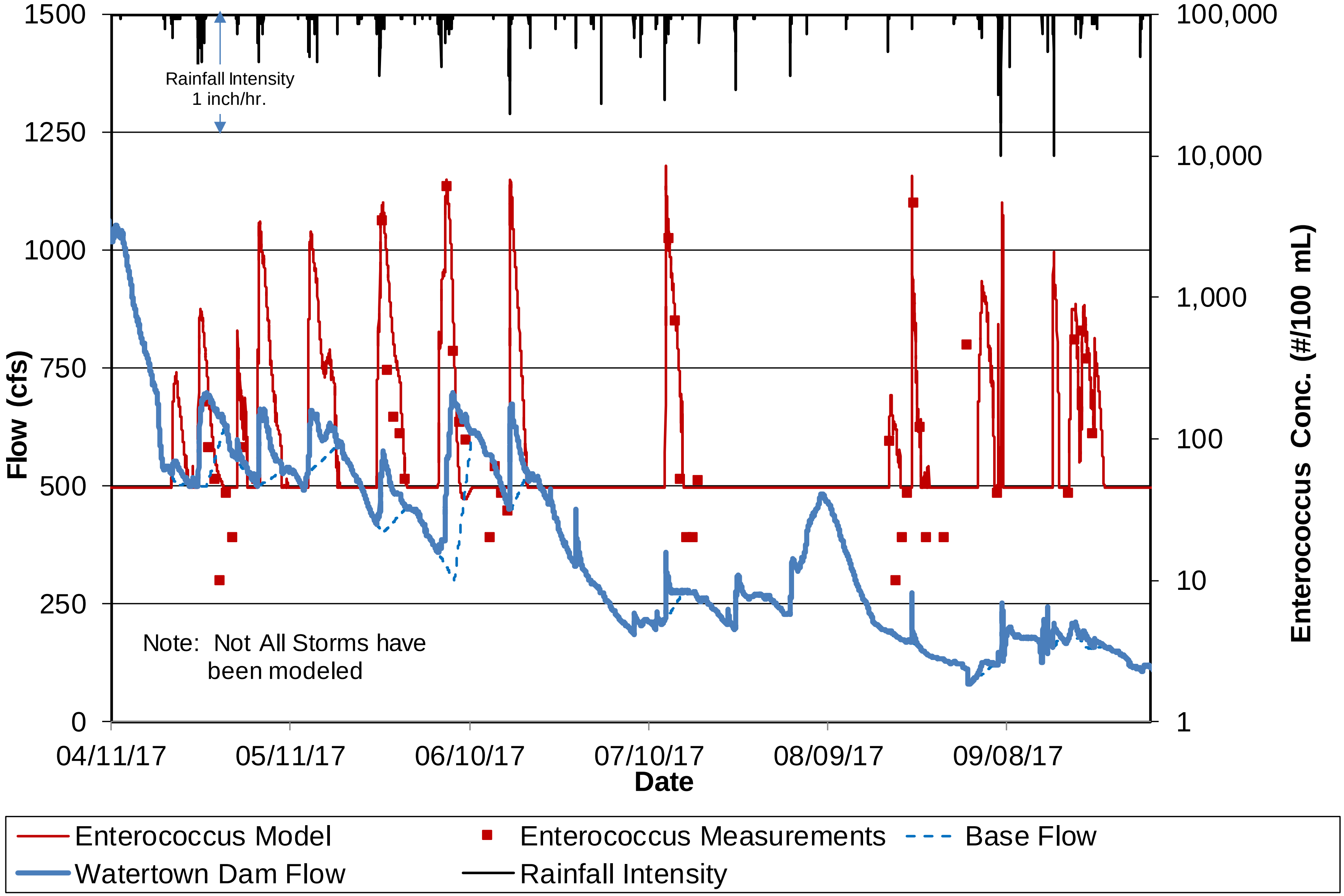


Figure A-1. Measured and Modeled *Enterococcus* Counts at Charles River Model Upstream Boundary for 2017

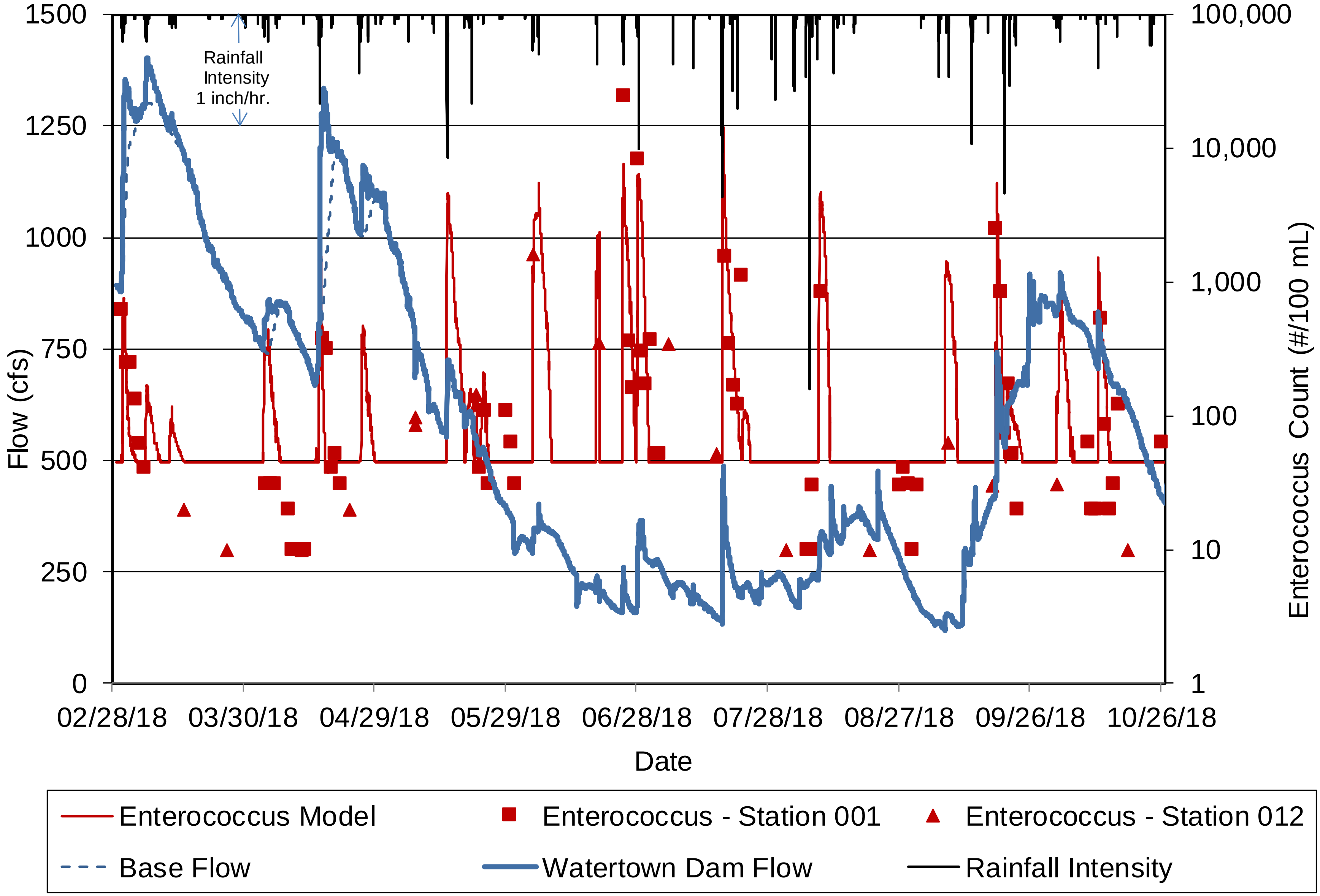


Figure A-2. Measured and Modeled *Enterococcus* at the Charles River Model Boundary for 2018

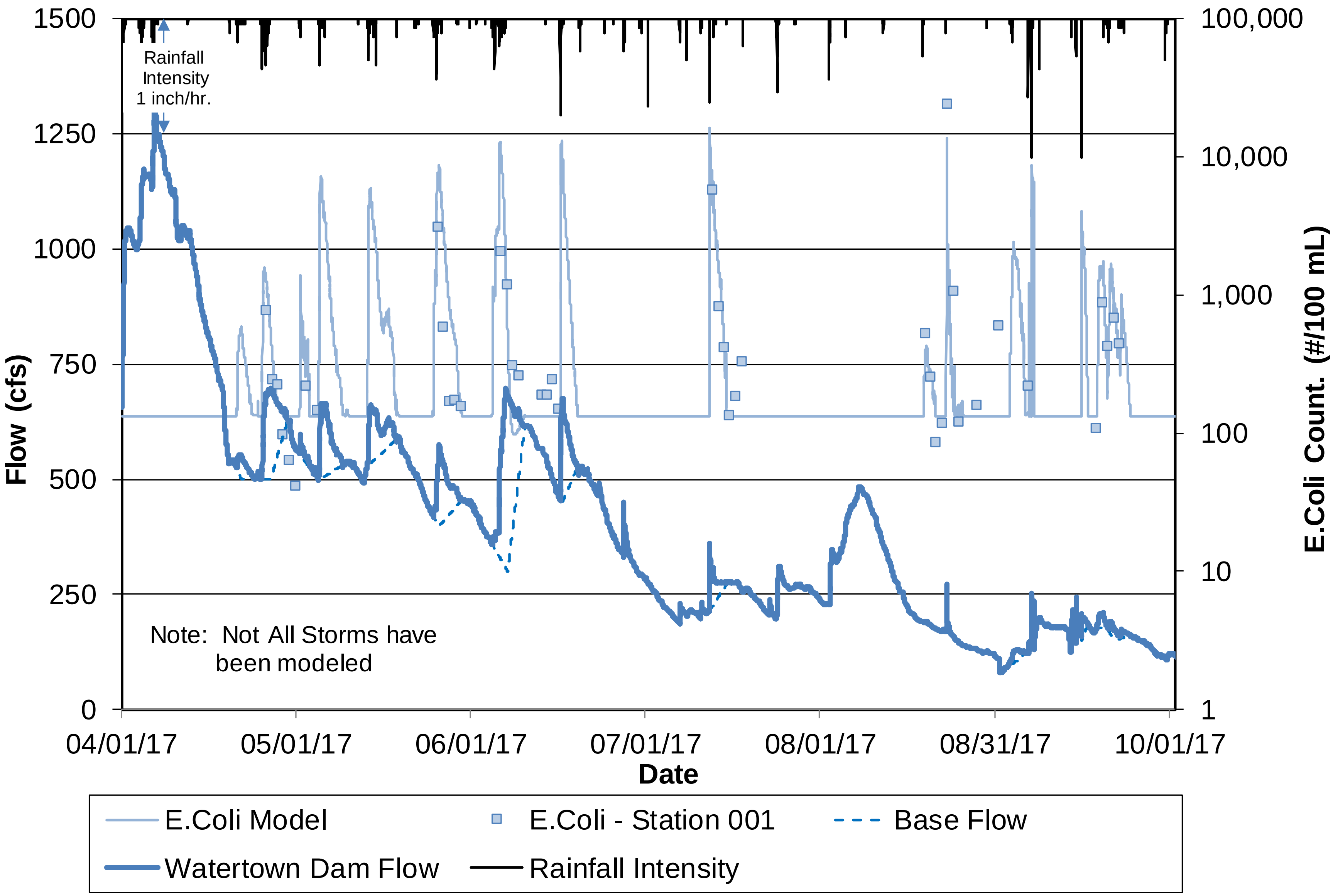


Figure A-3. Measured and Modeled *E. coli* at Charles River Model Upstream Boundary for 2017

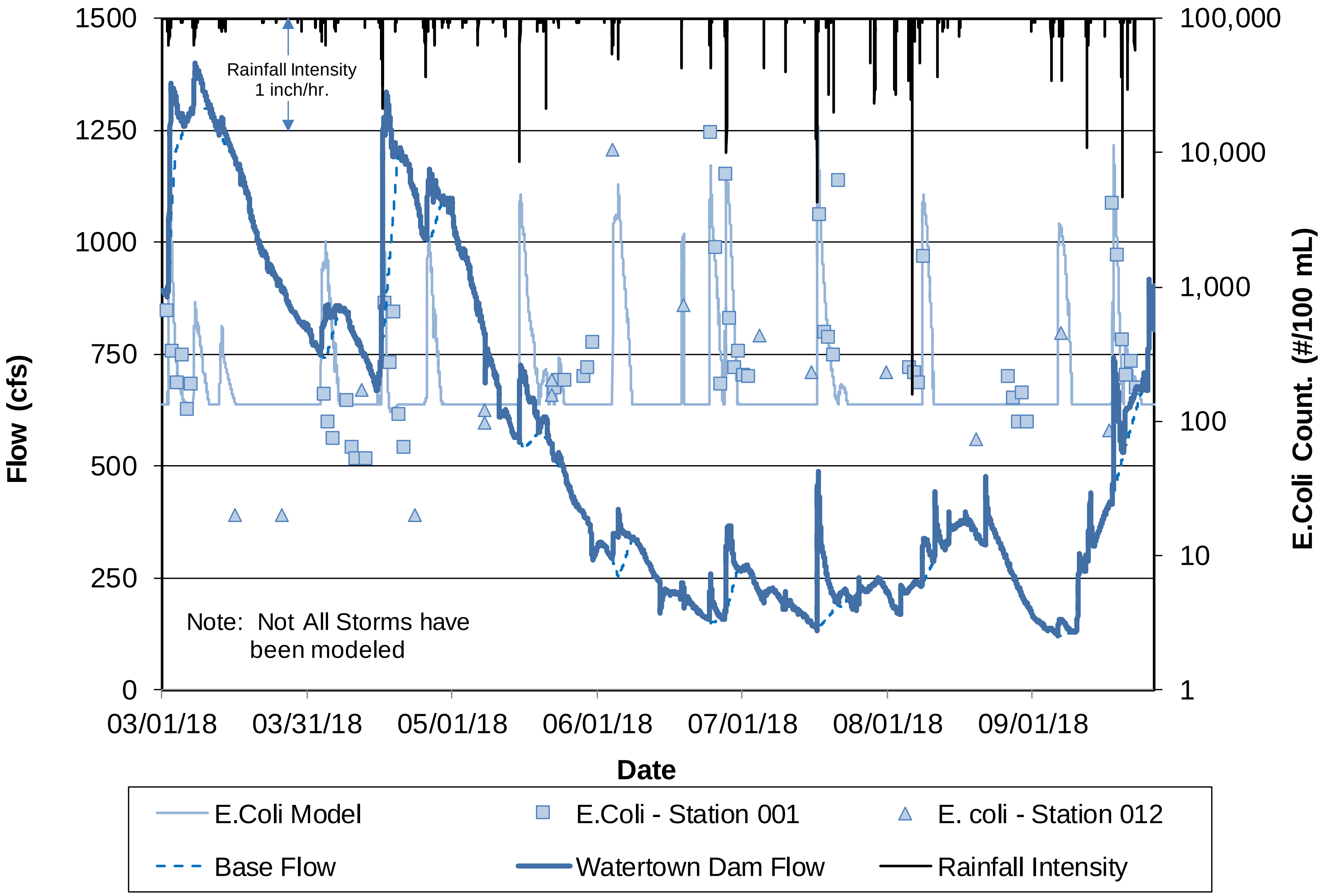


Figure A-4. Measured and Modeled *E. coli* at Charles River Model Boundary for 2018

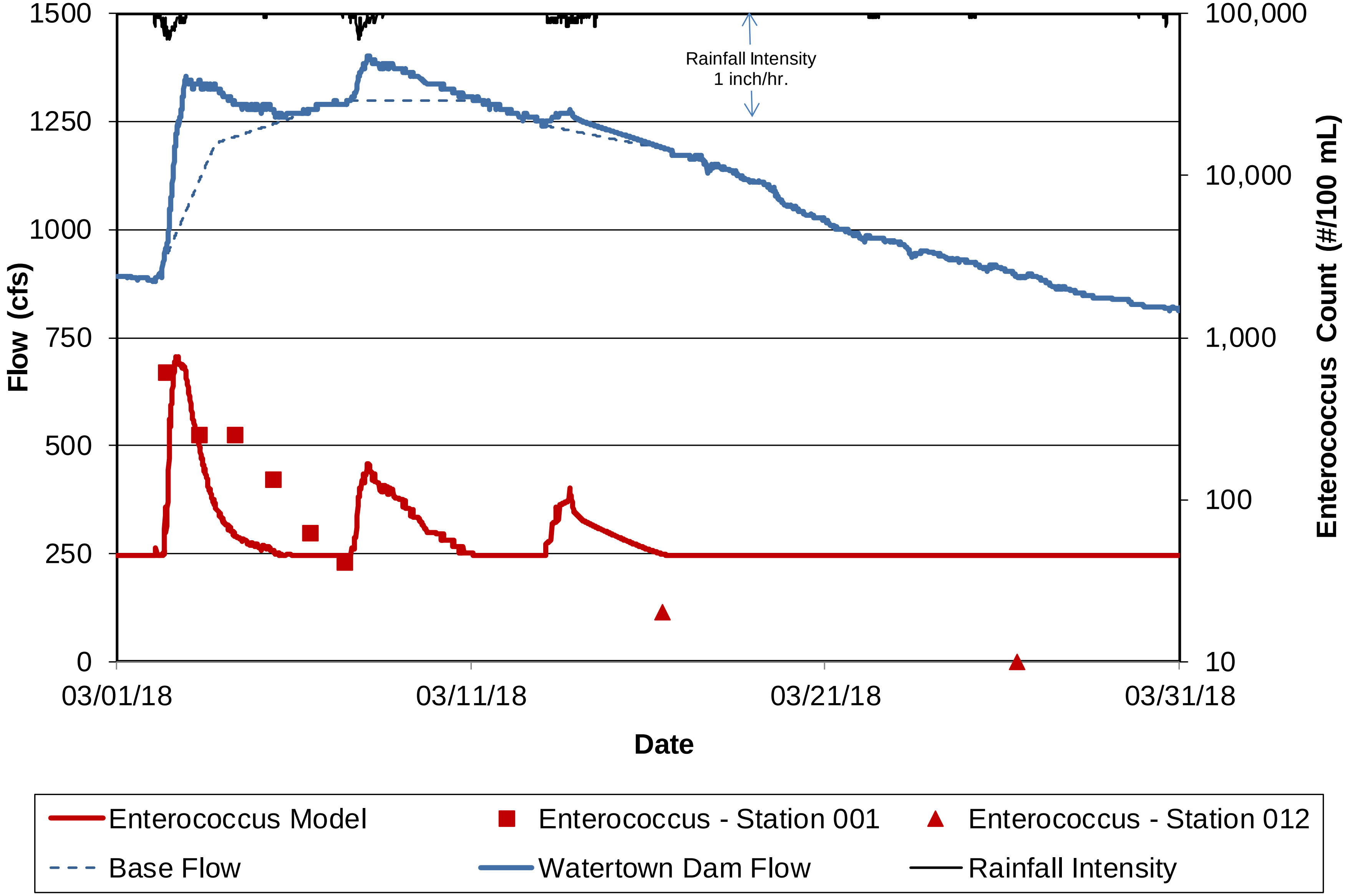


Figure A-5. Measured and Model *Enterococcus* at Charles River Model Boundary for March 2018

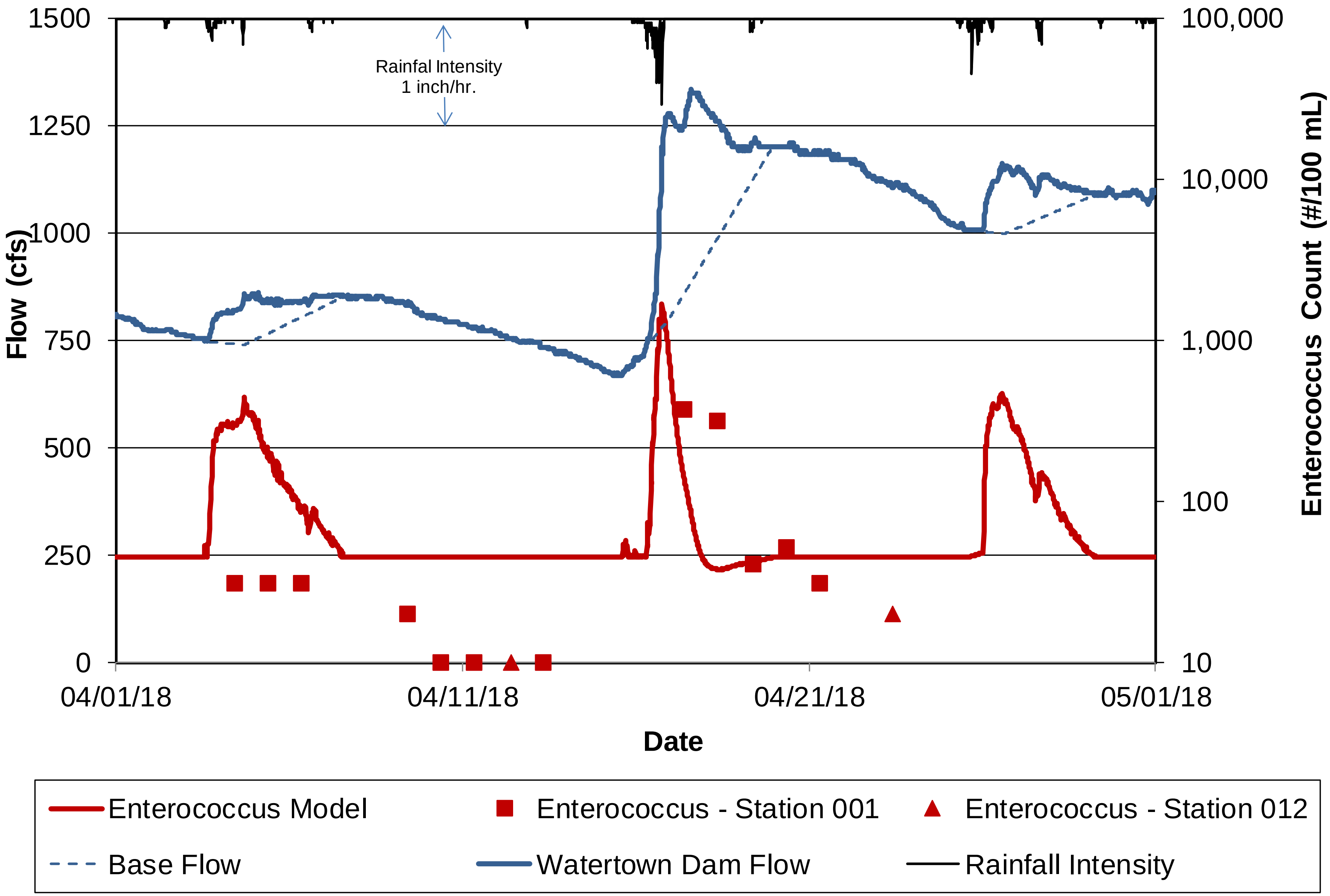


Figure A-6. Measured and Model *Enterococcus* at Charles River Model Boundary for April 2018

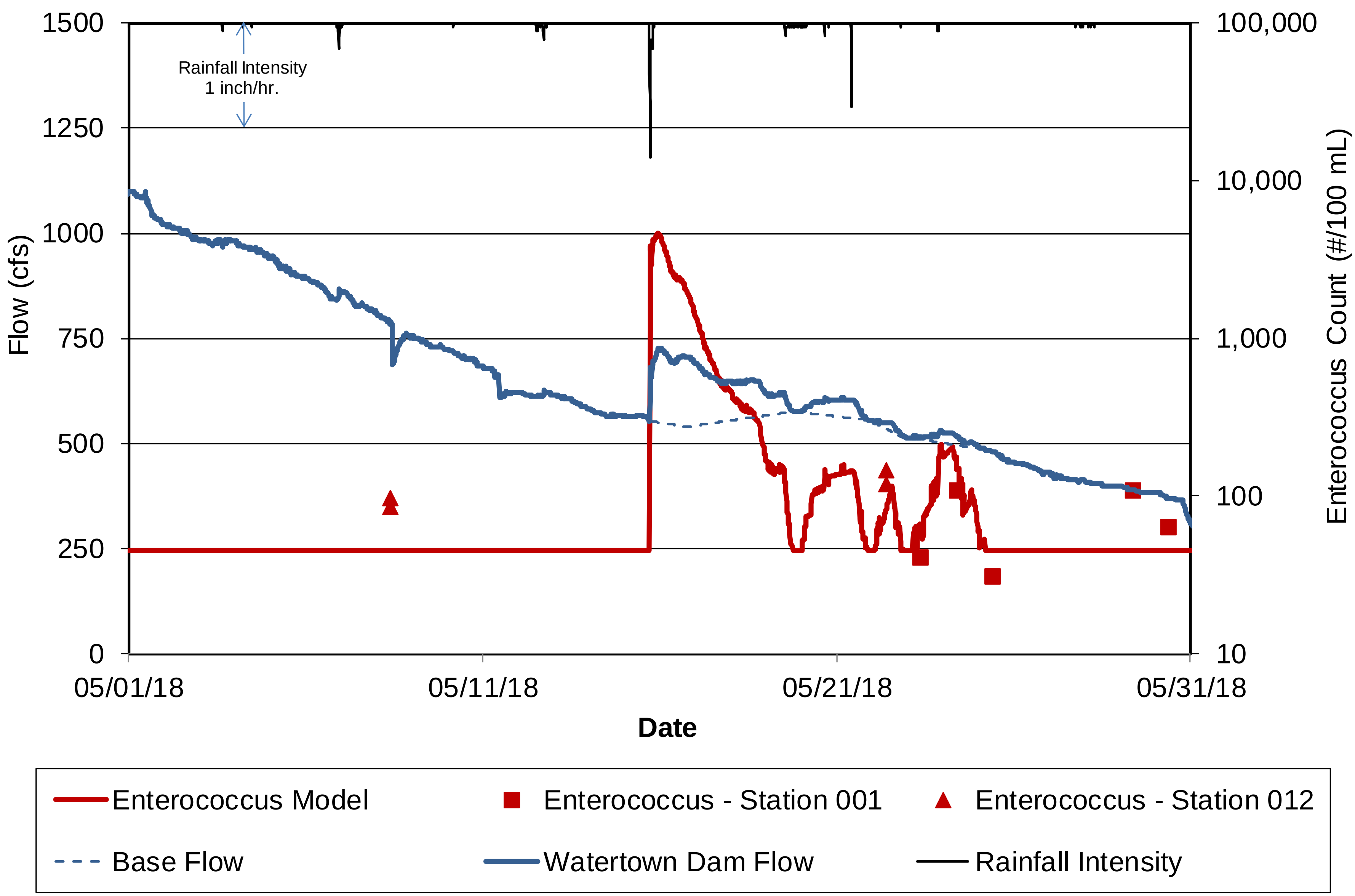


Figure A-7. Measured and Model *Enterococcus* at Charles River Model Boundary for May 2018

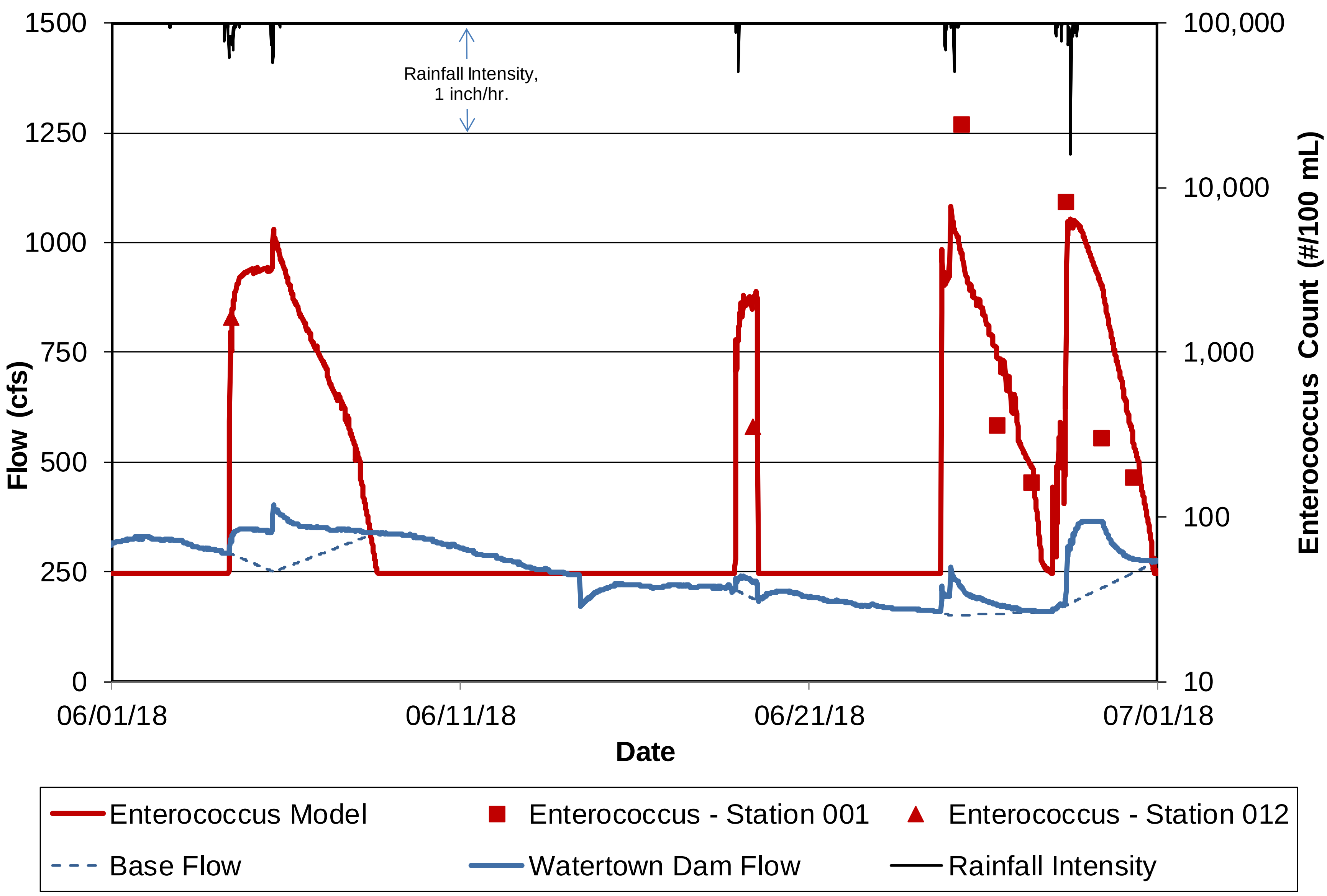


Figure A-8. Measured and Model *Enterococcus* at Charles River Model Boundary for June 2018

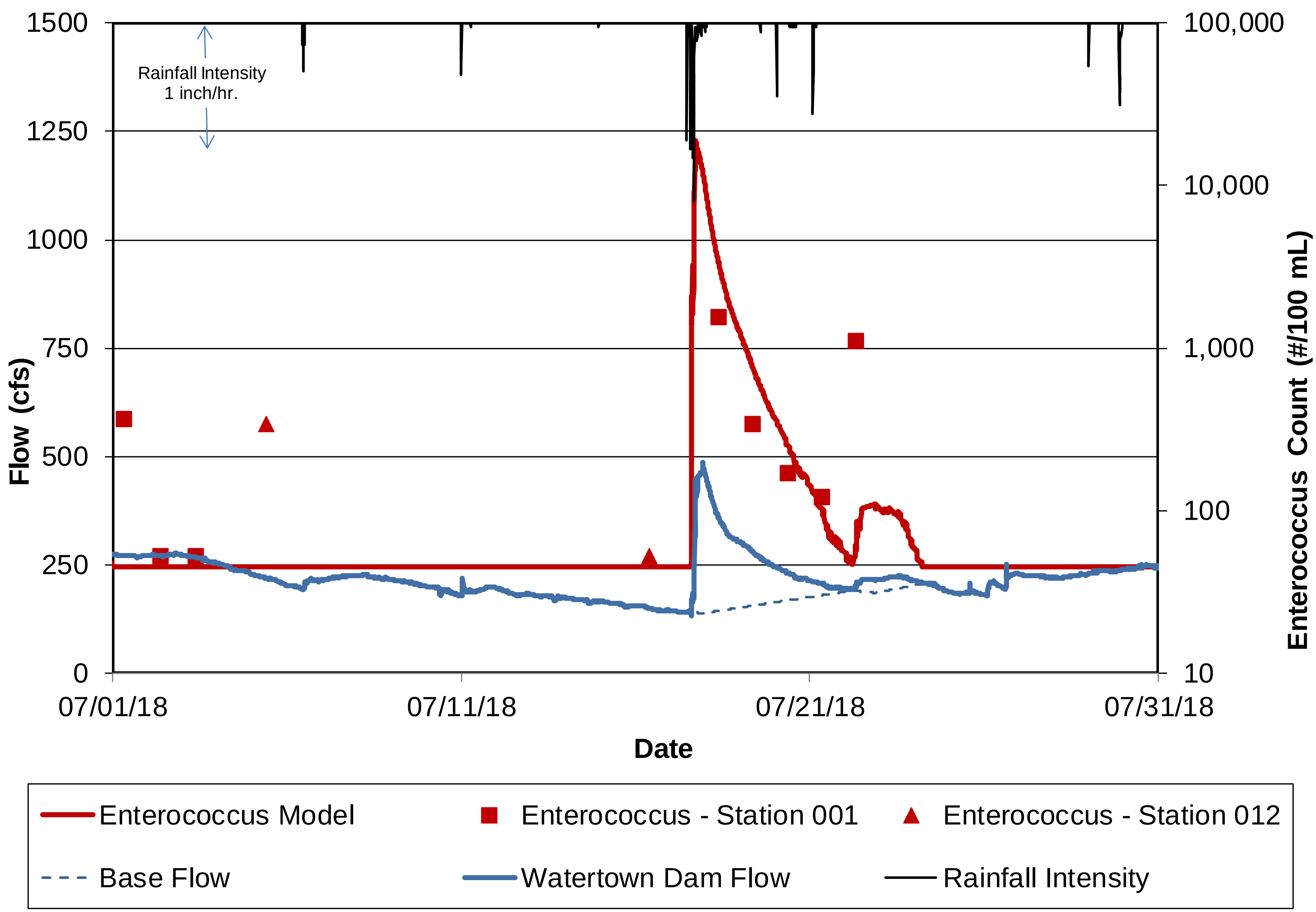


Figure A-9. Measured and Model *Enterococcus* at Charles River Model Boundary for July 2018

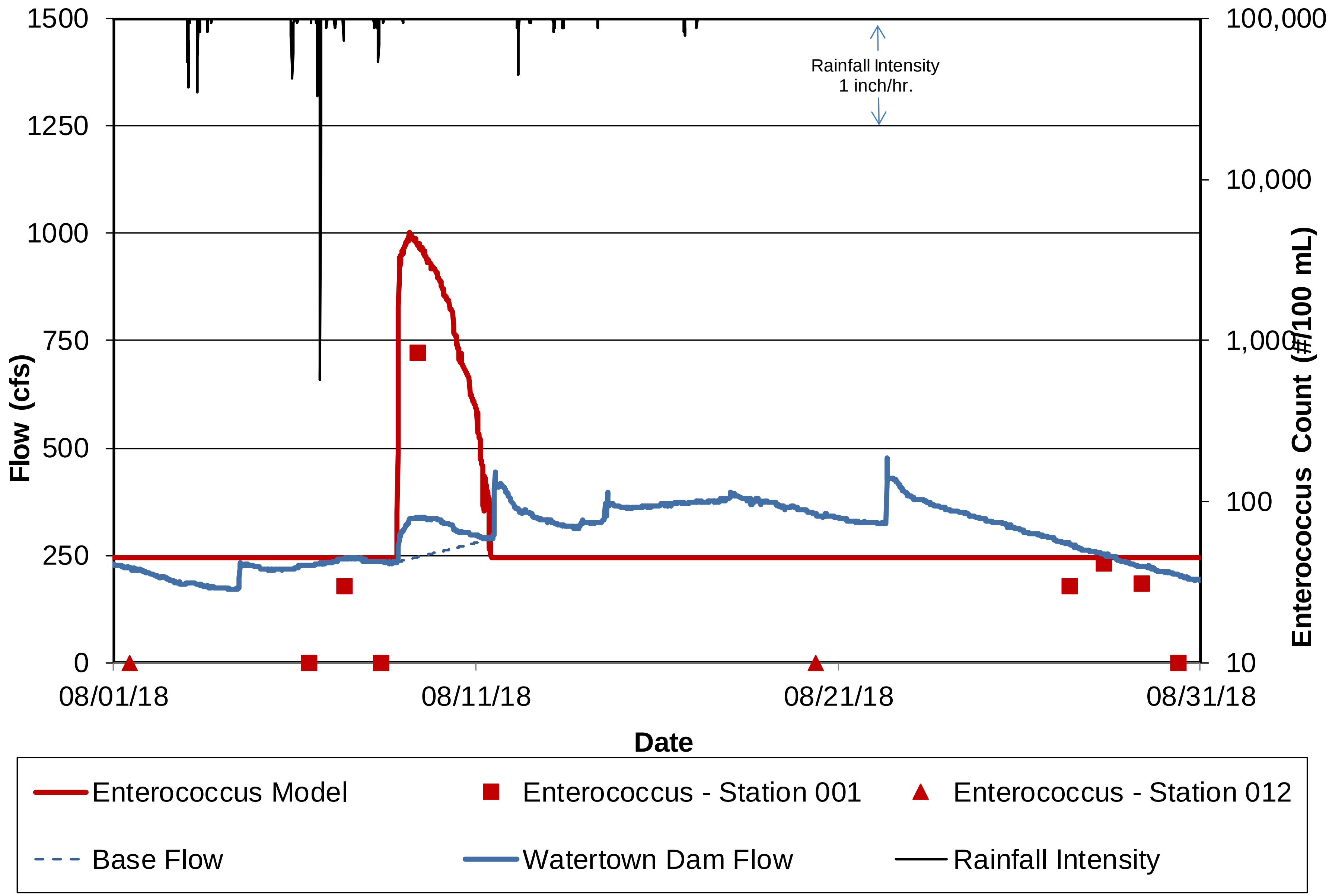


Figure A-10. Measured and Model *Enterococcus* at Charles River Model Boundary for August 2018

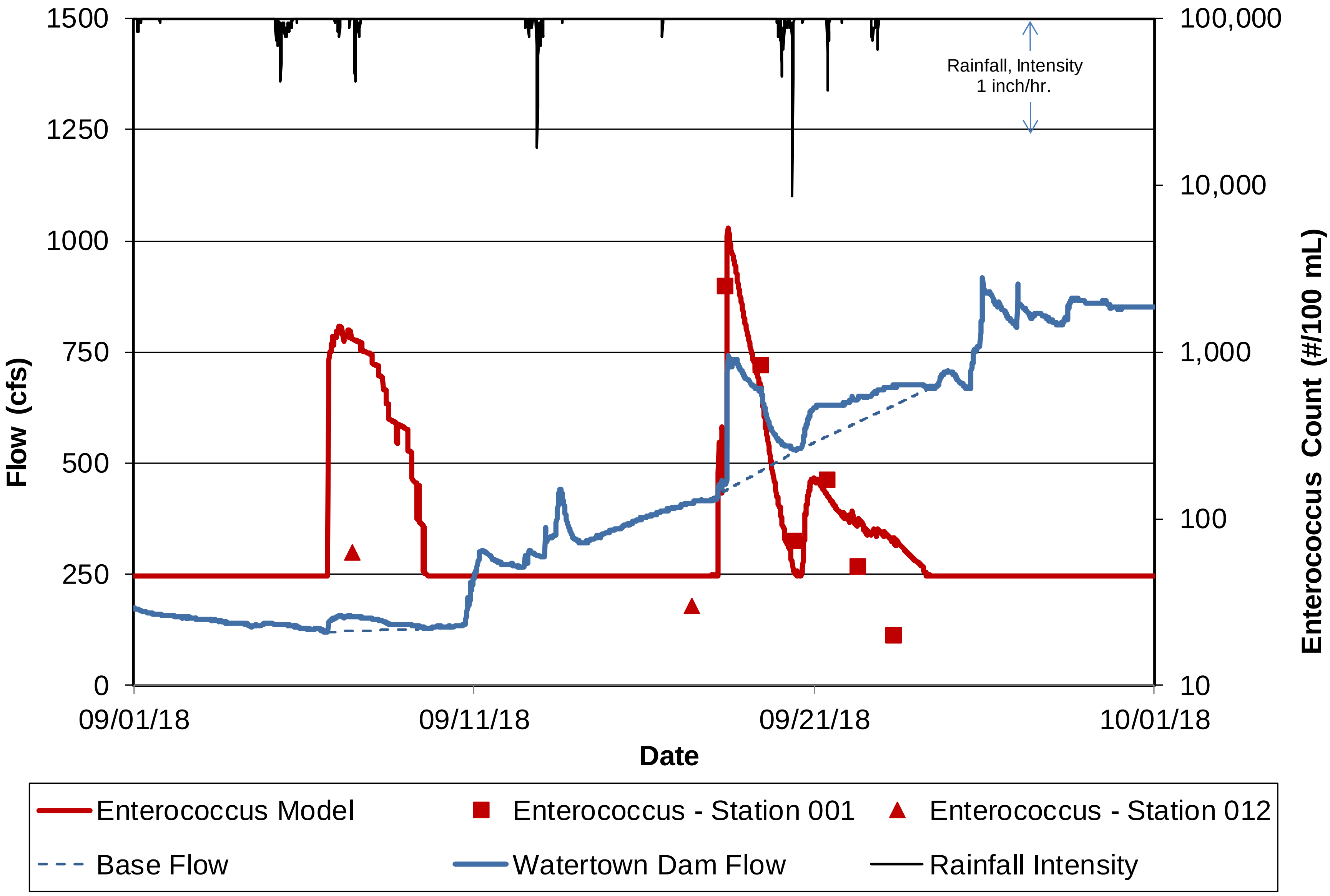


Figure A-11. Measured and Model *Enterococcus* at Charles River Model Boundary for September 2018

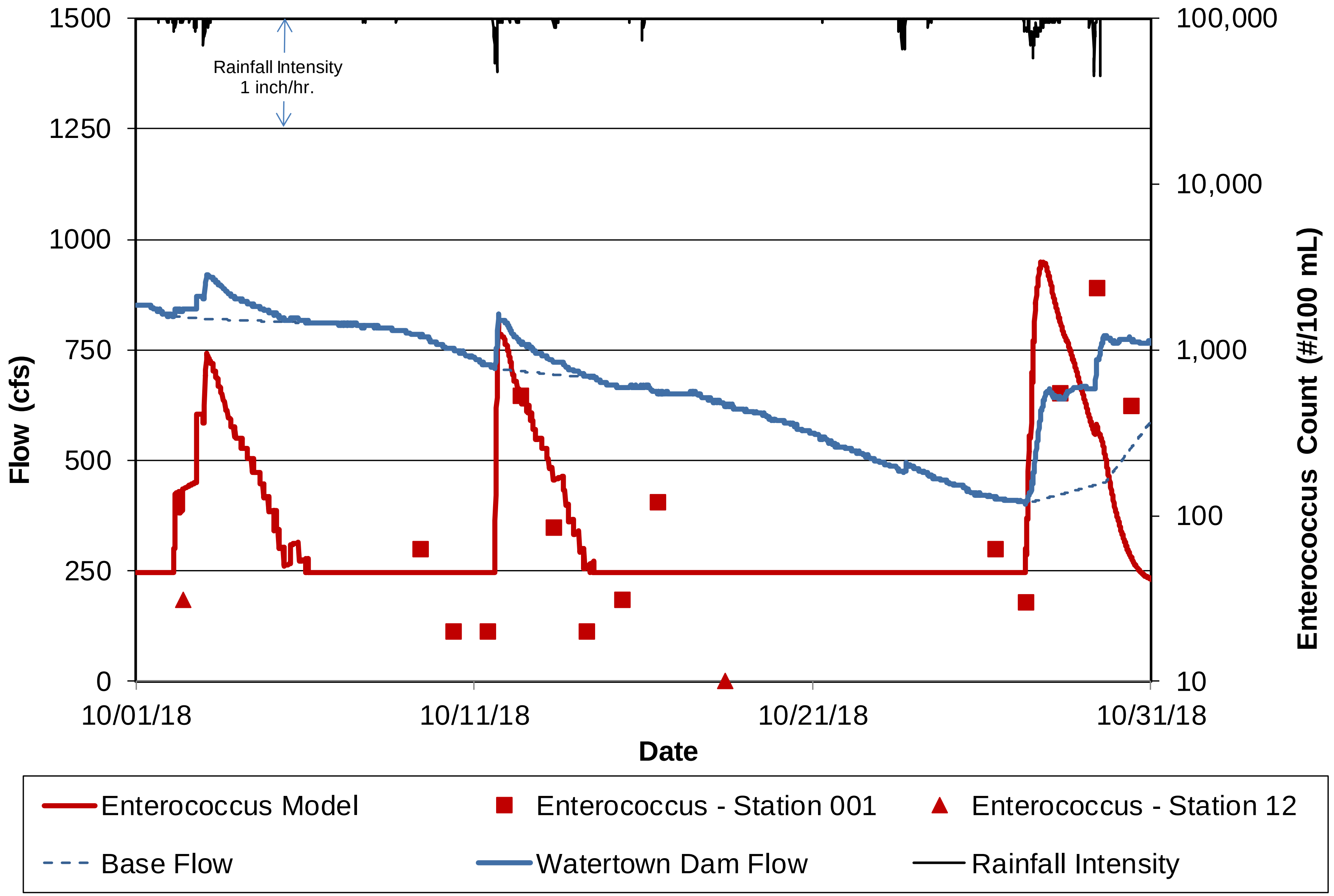
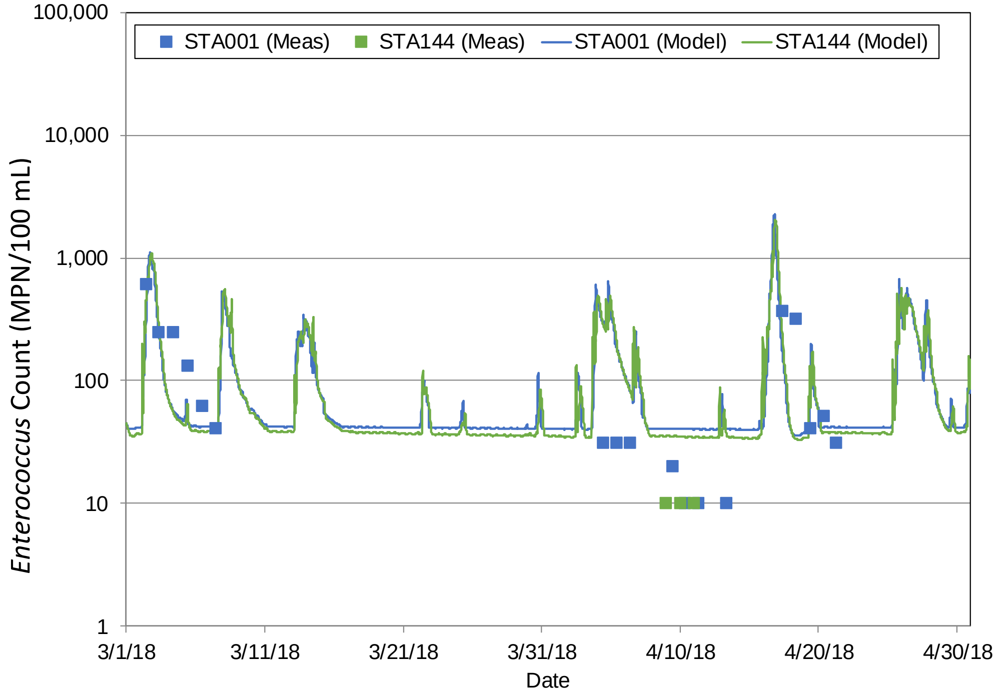
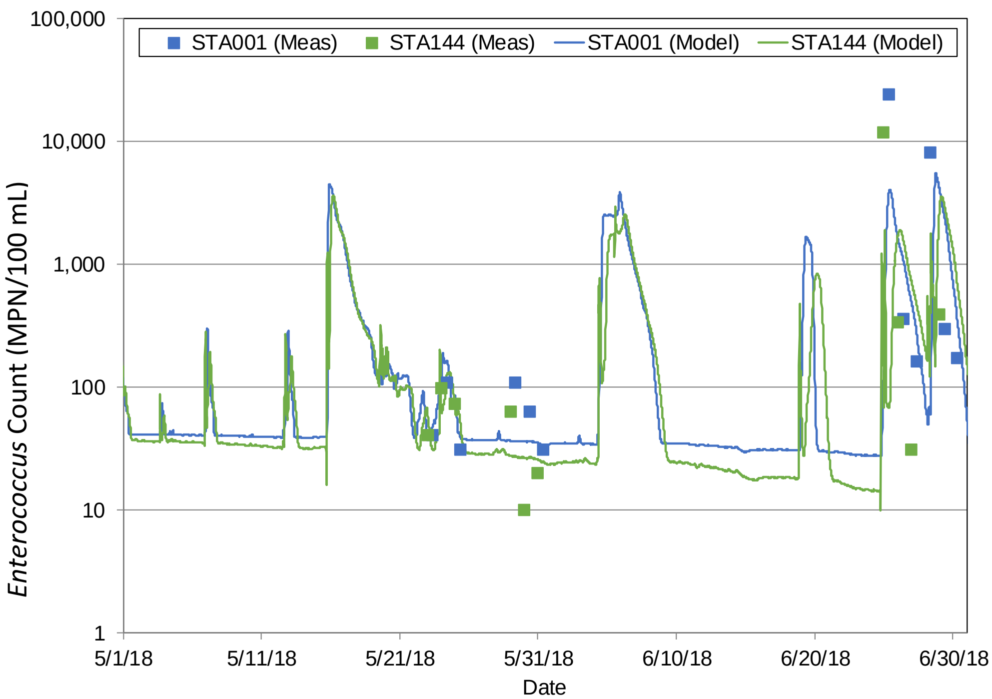


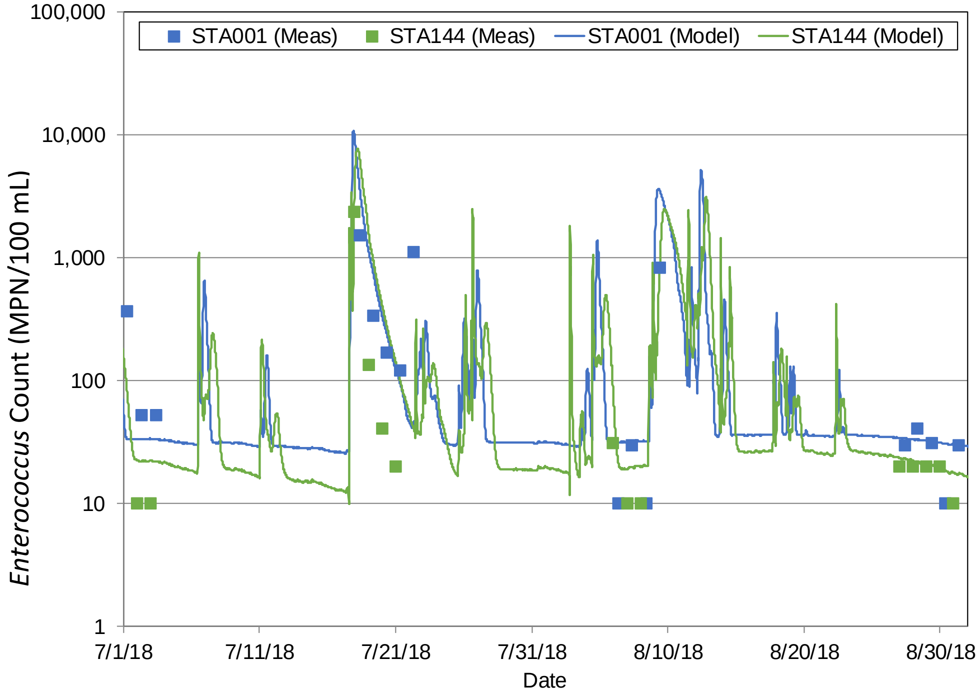
Figure A-12. Measured and Model *Enterococcus* at Charles River Model Boundary for October 2018

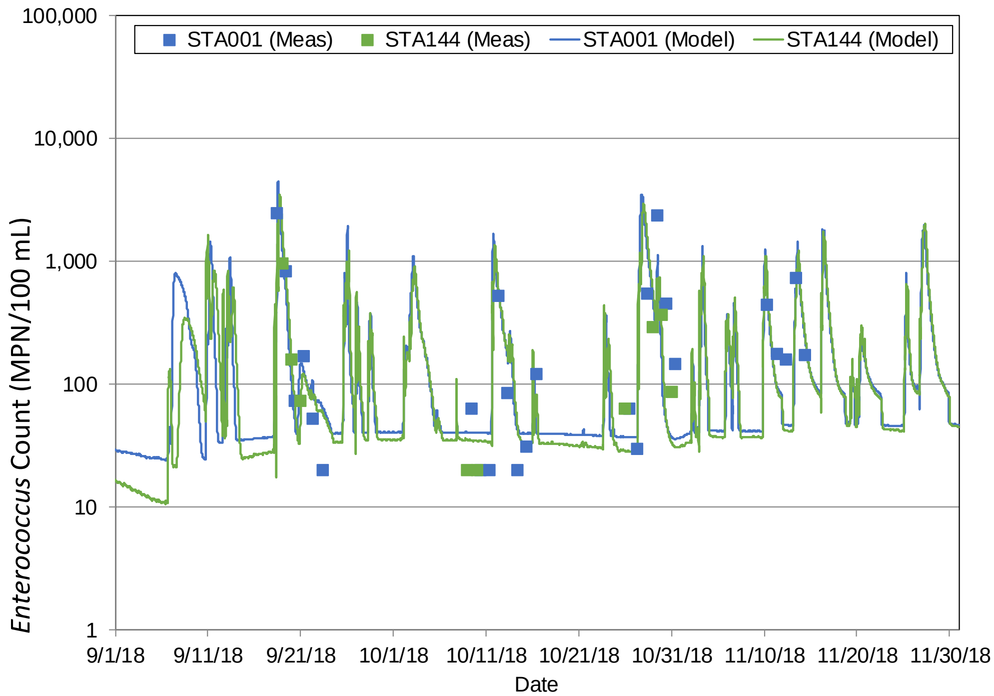
Appendix B – Charles River Model Calibration Plots – *Enterococcus*



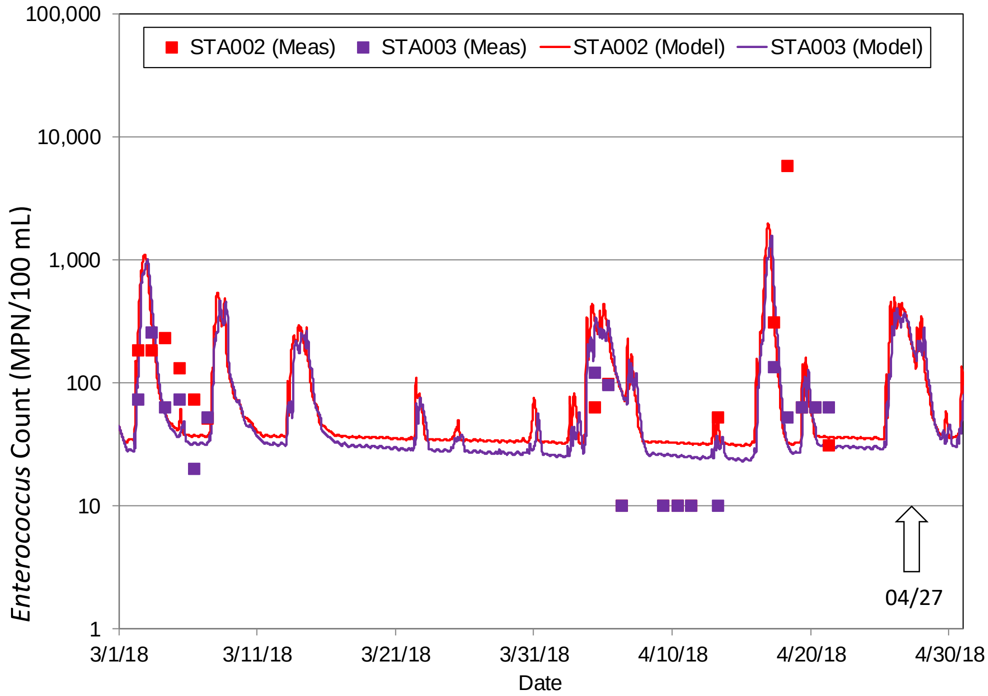


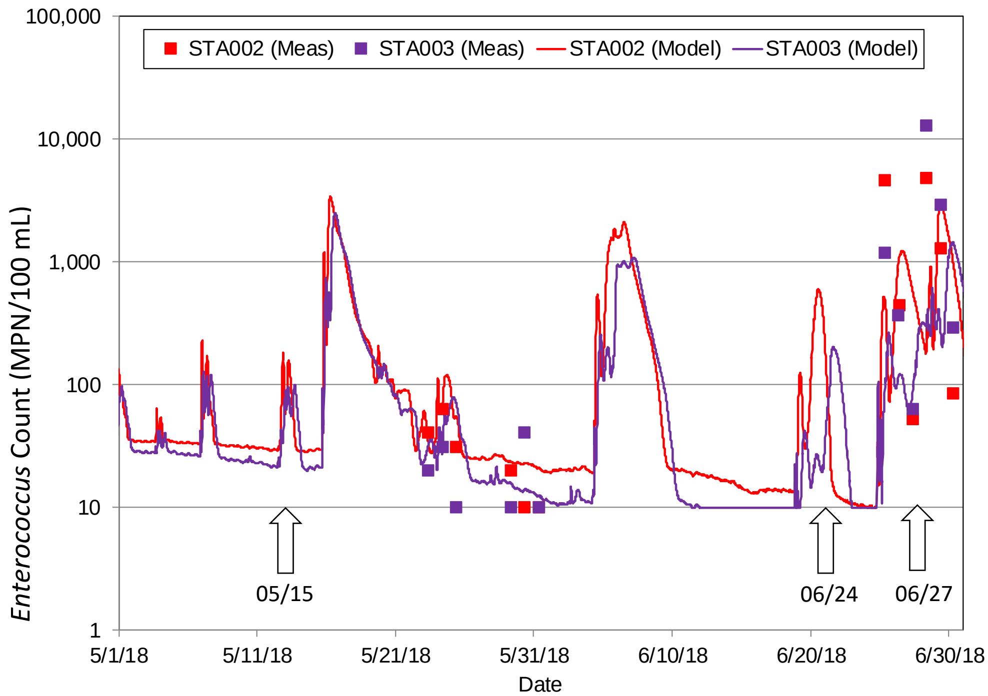
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



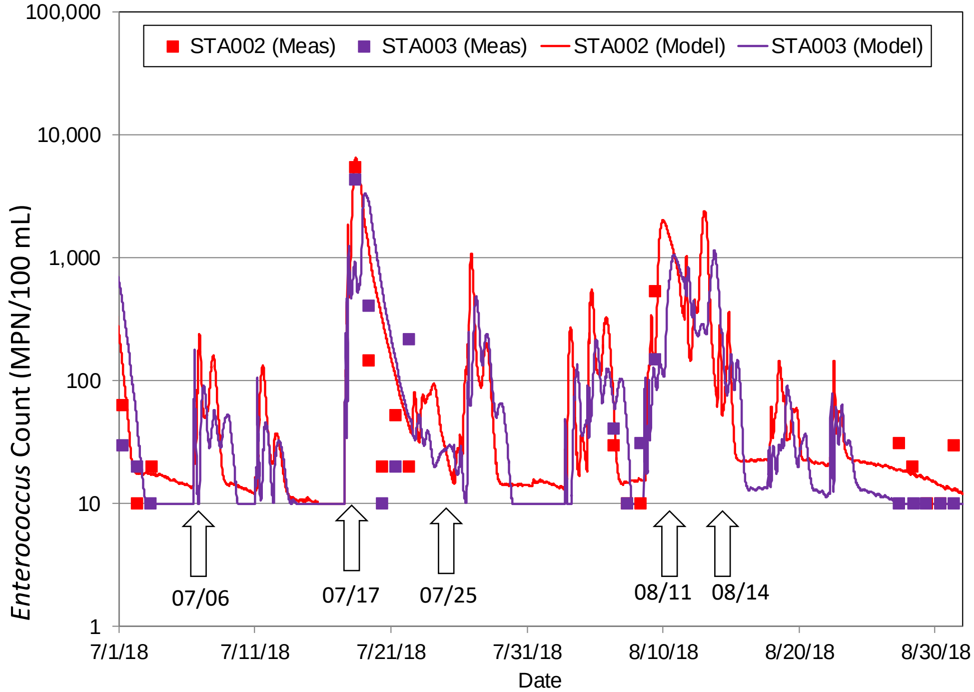


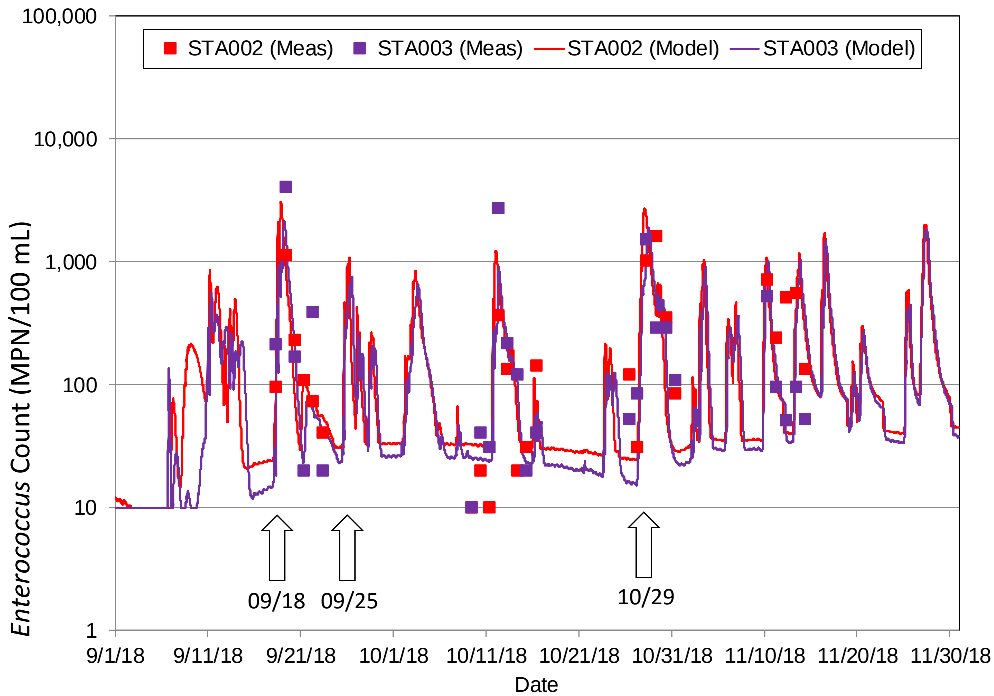
Date of model predicted CSO activation at a CSO located upstream of the sampling station



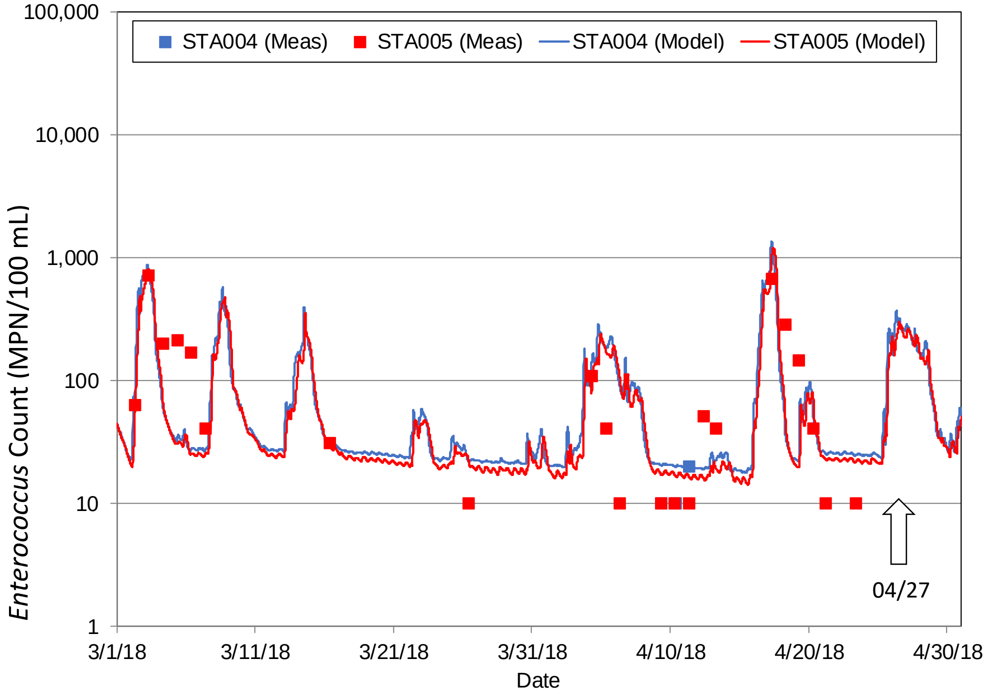


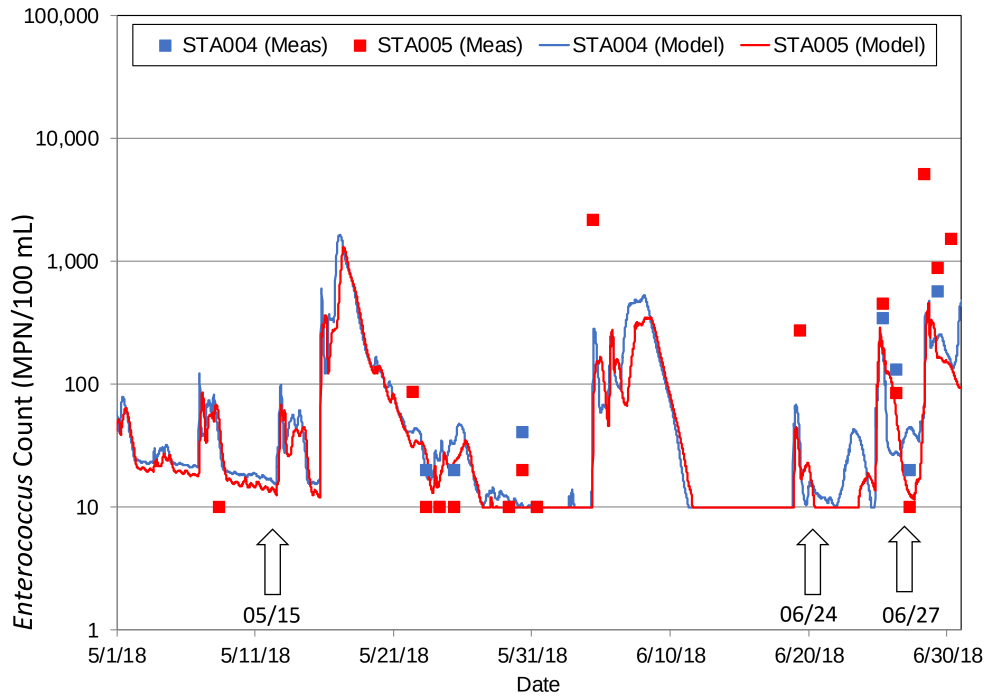
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



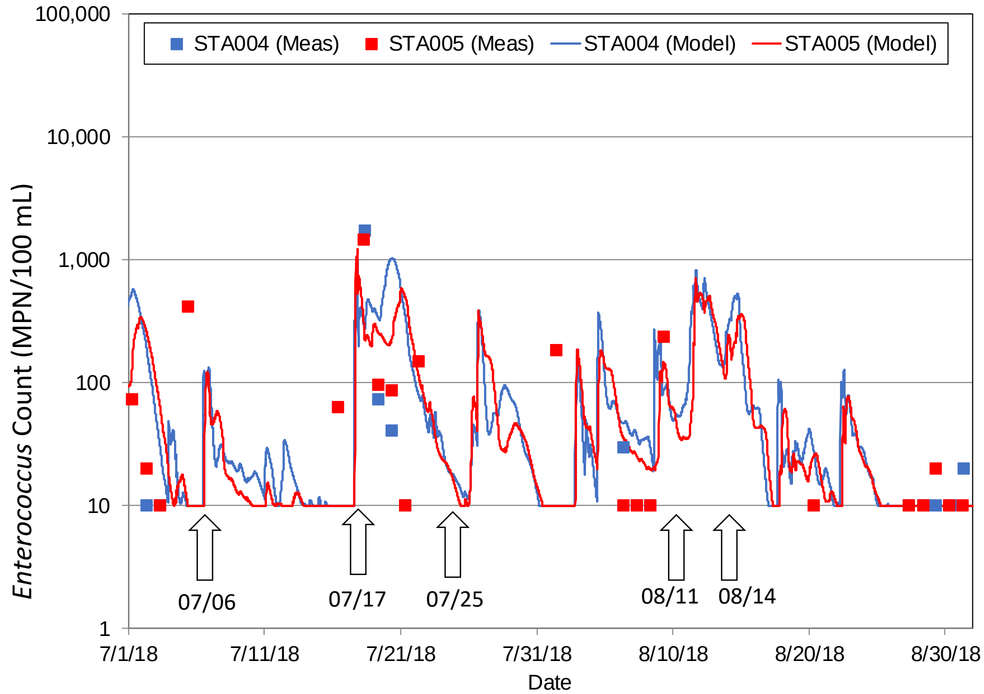


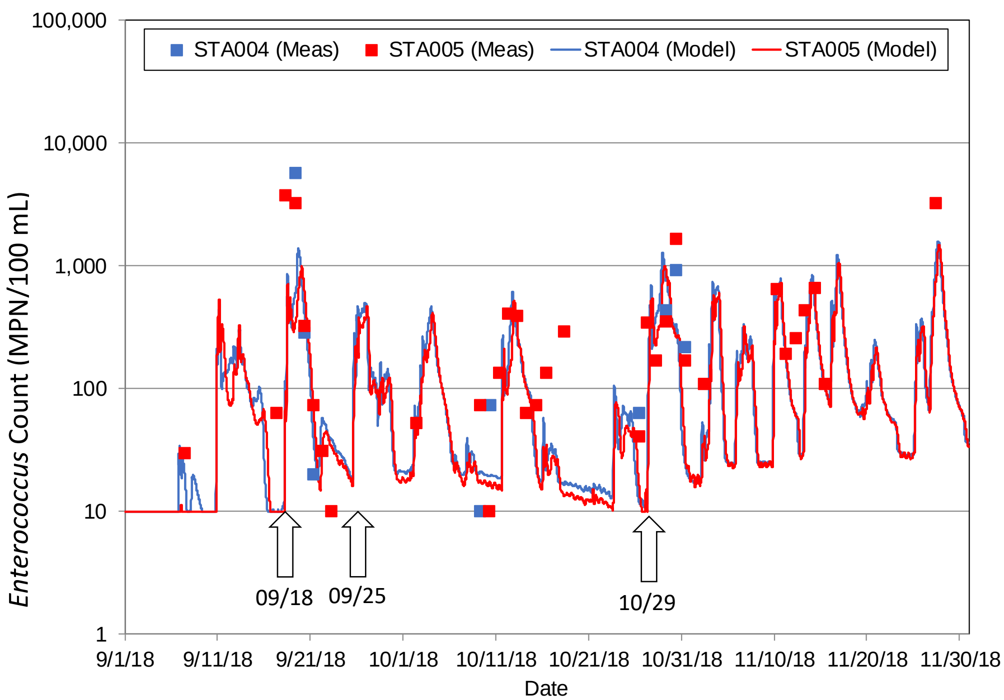
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



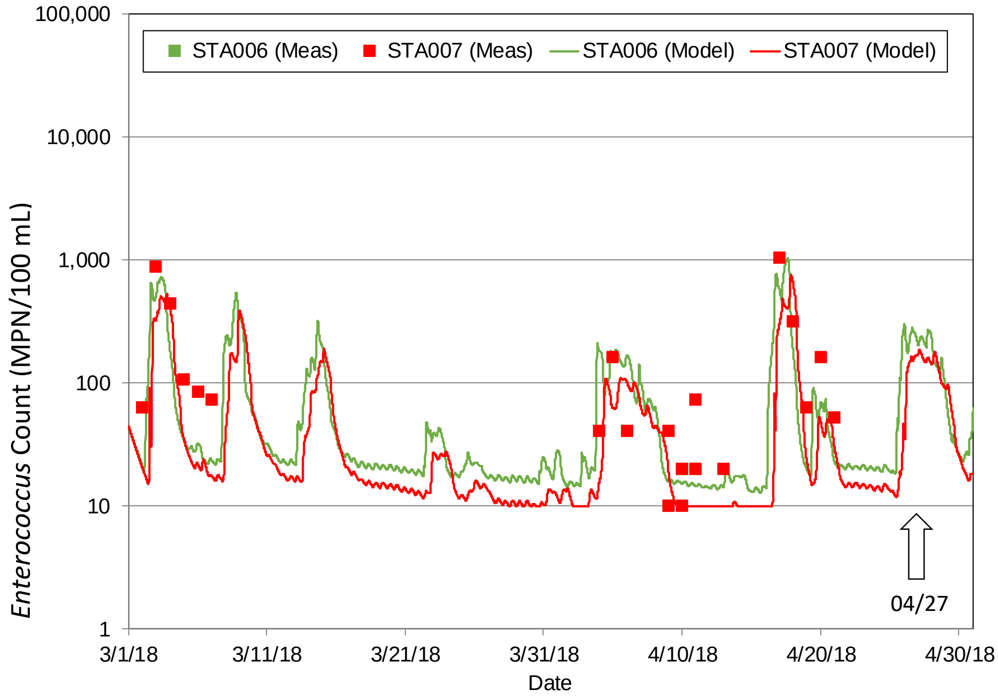


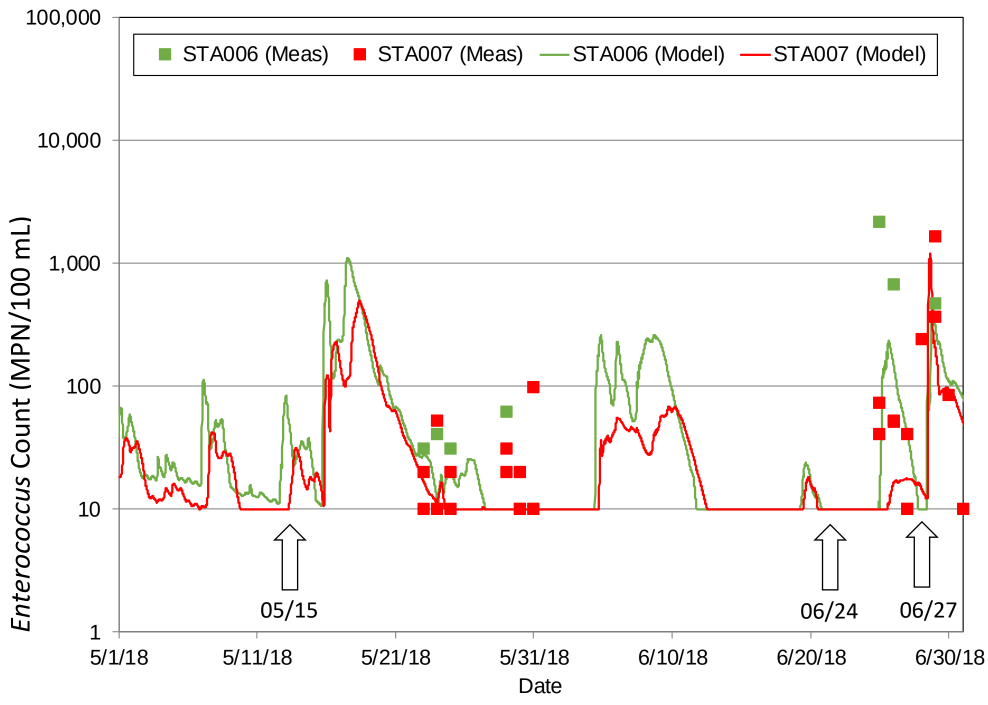
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



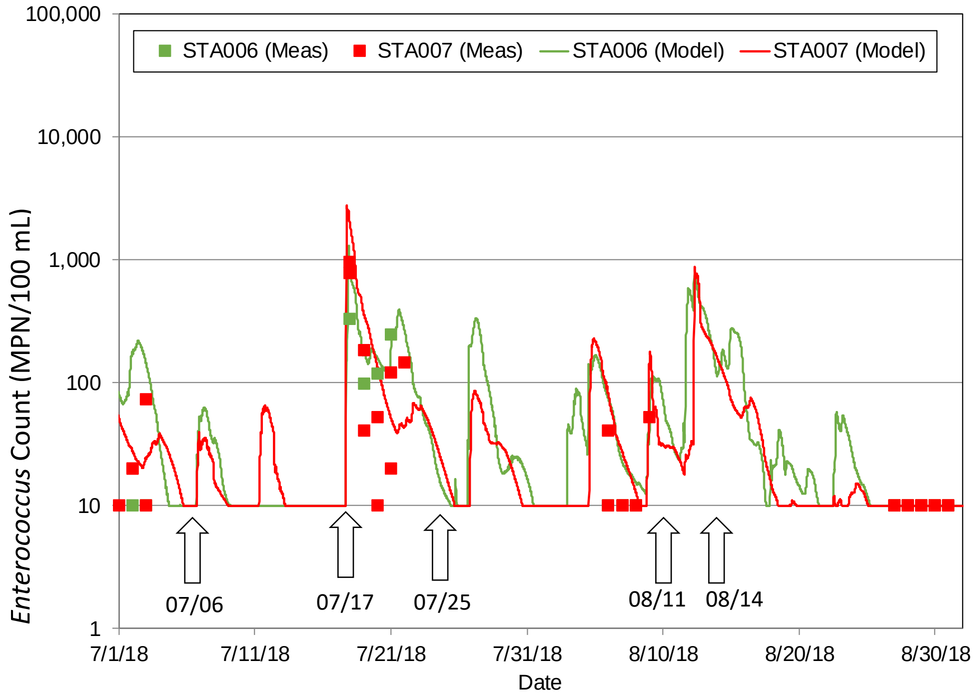


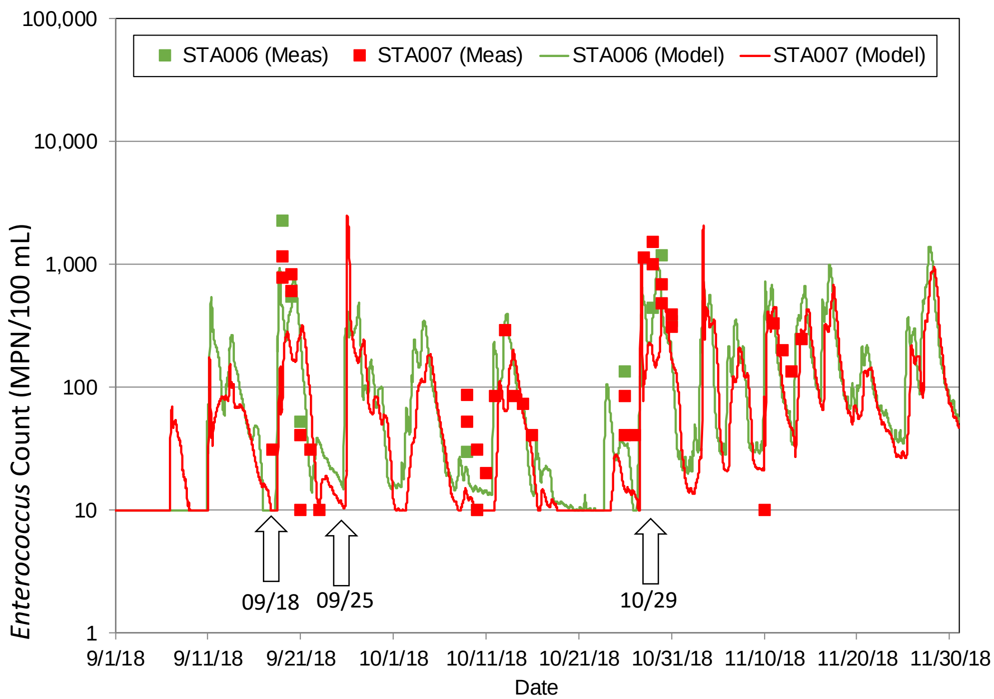
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station

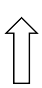


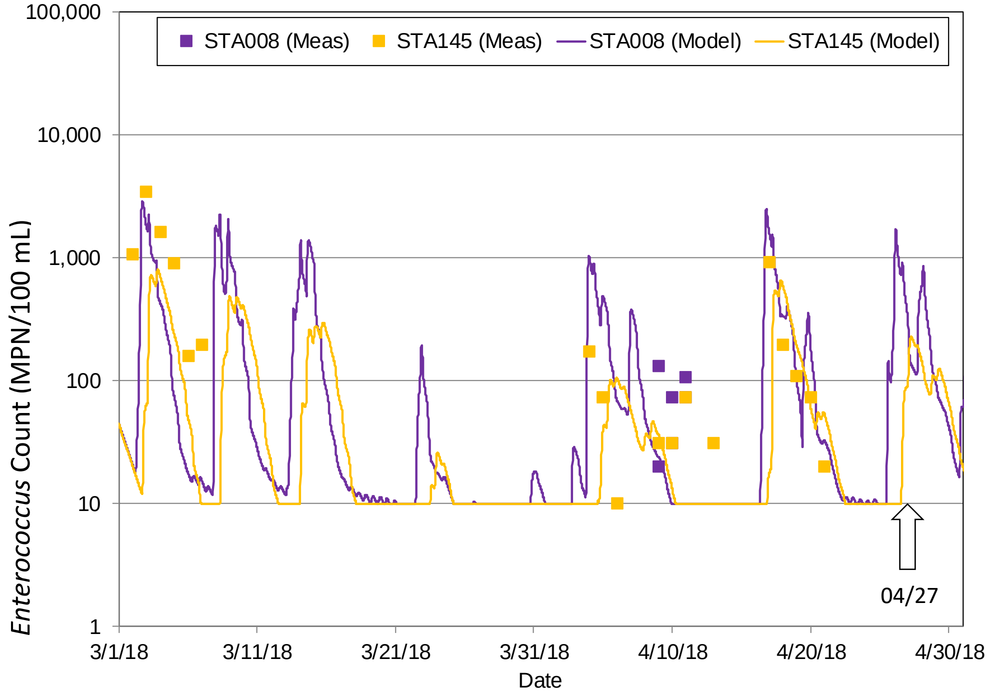


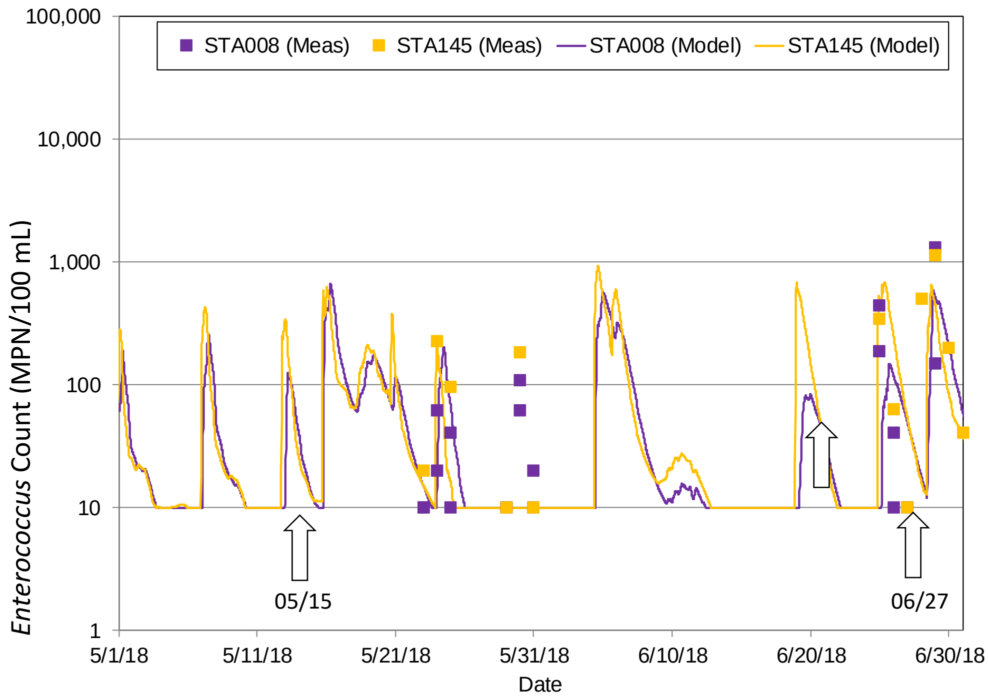
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



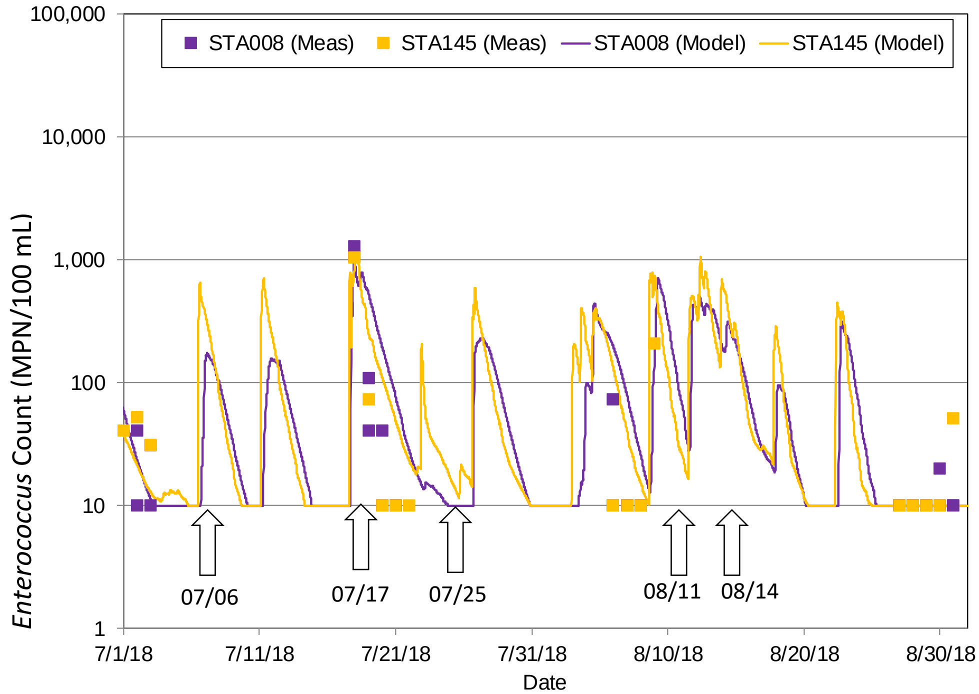


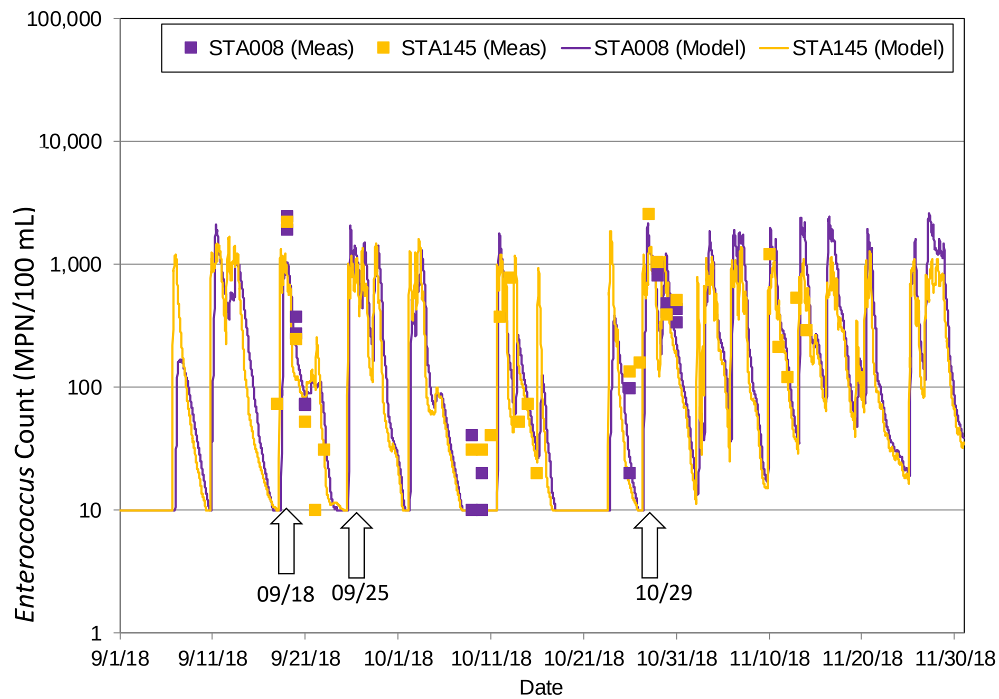

Date of model predicted CSO activation at a CSO located upstream of the sampling station



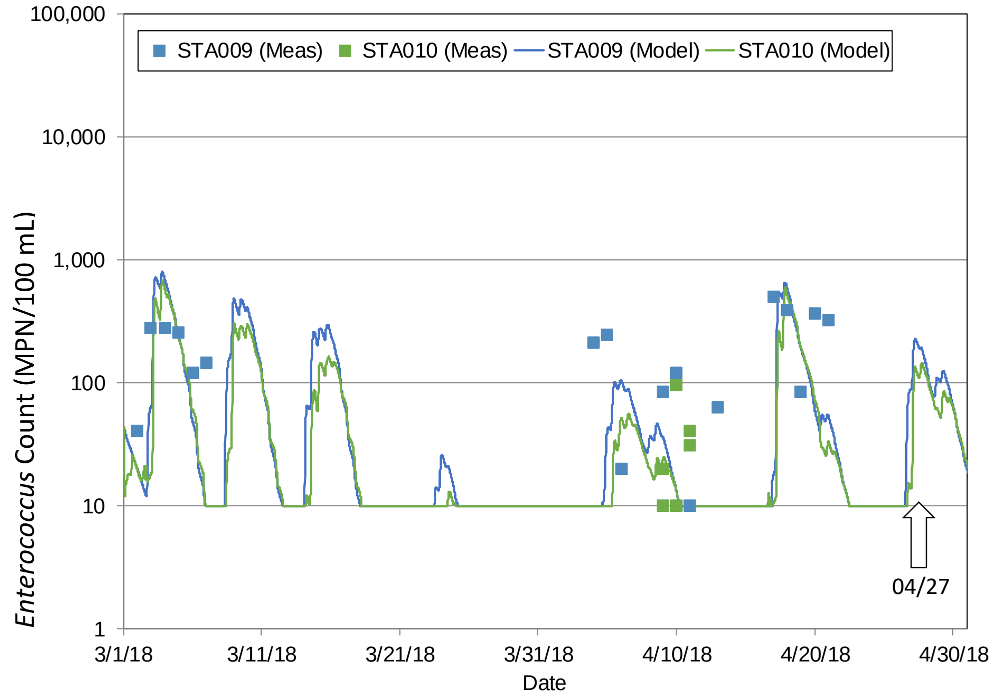


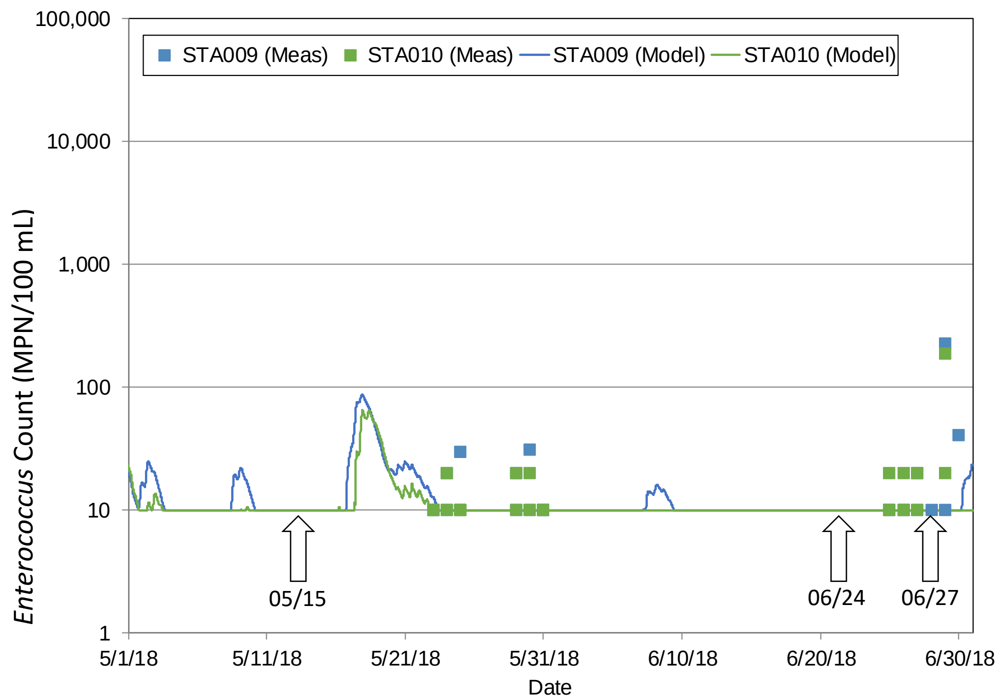
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



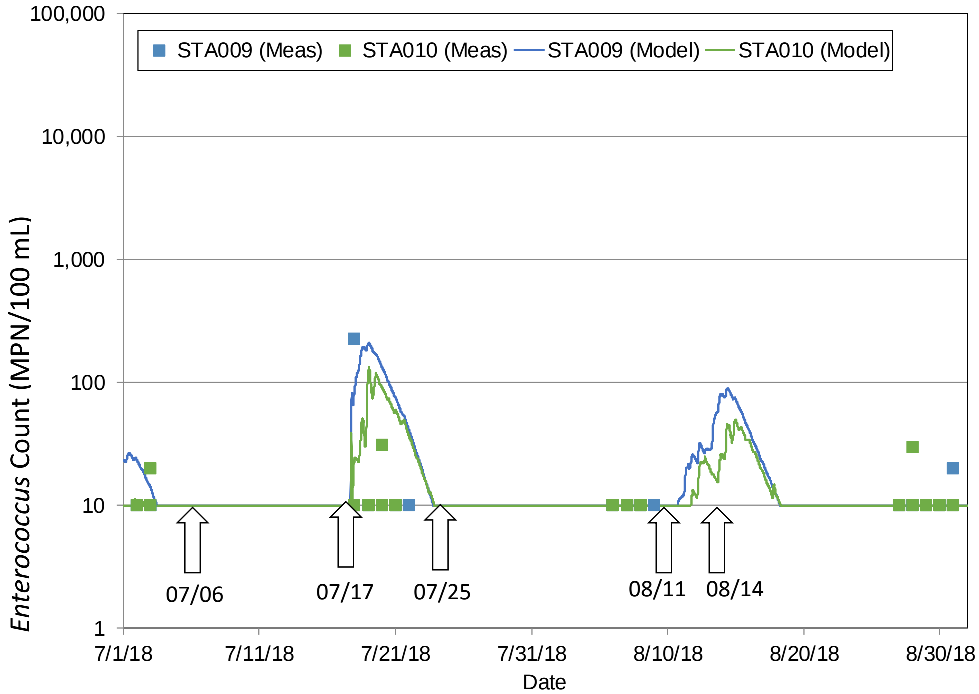


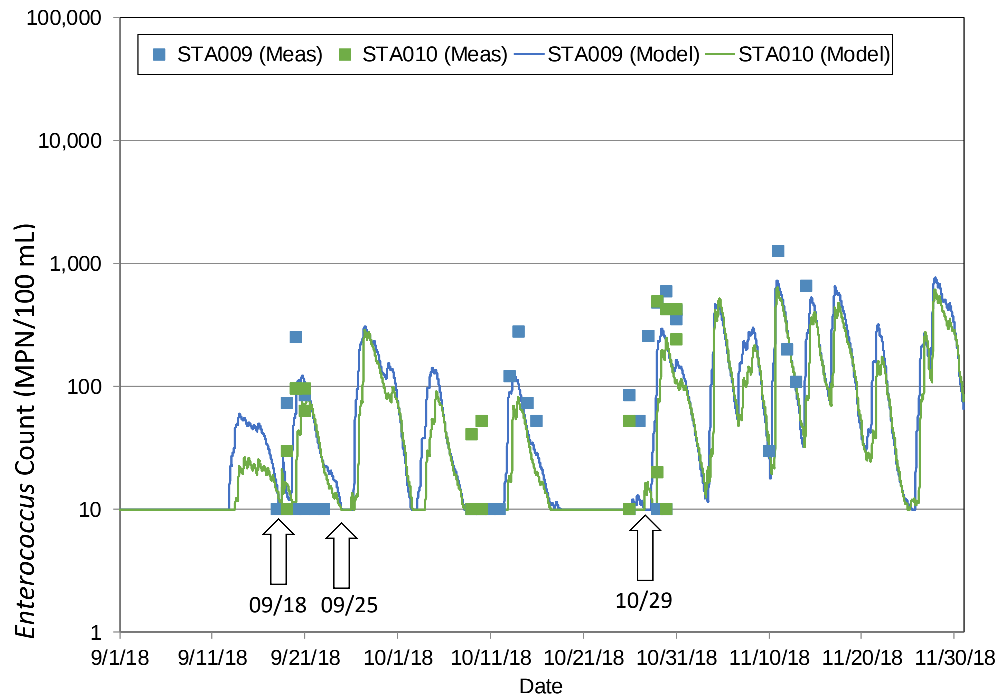
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



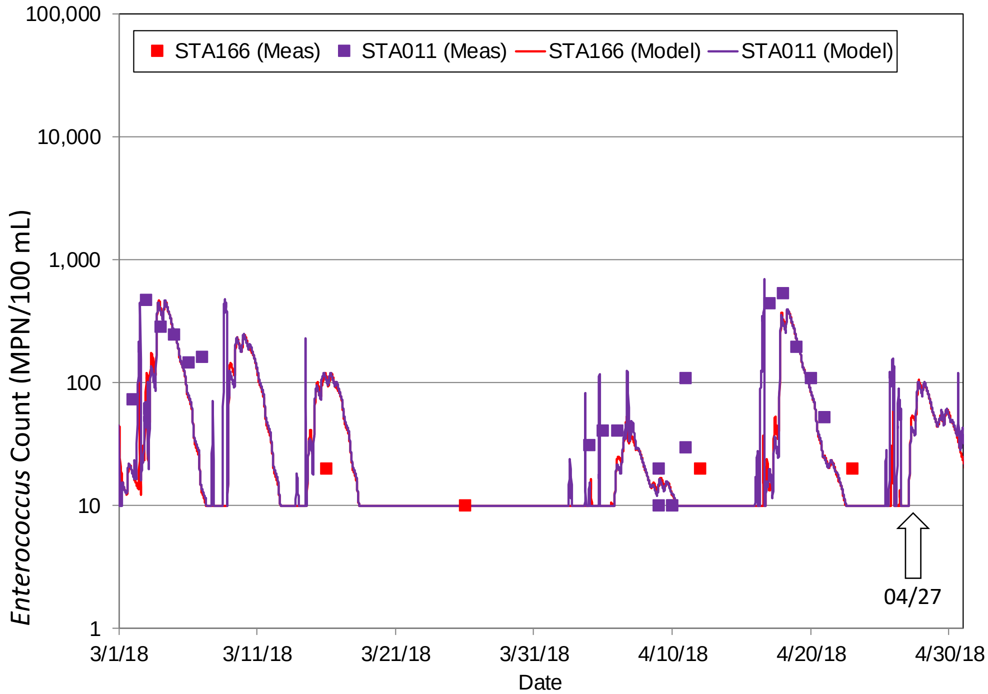


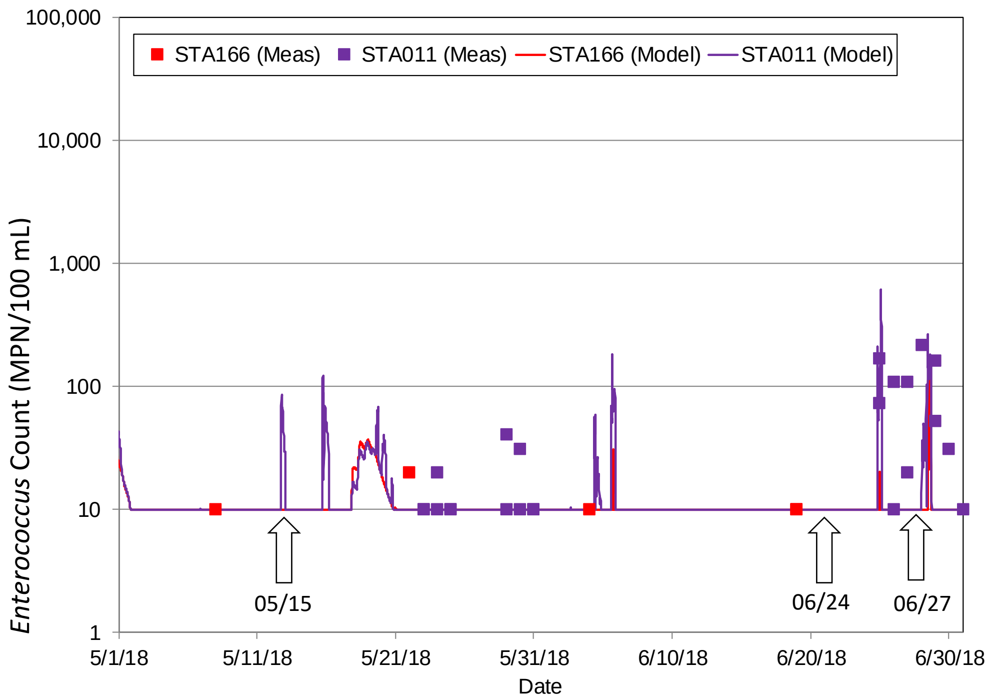
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



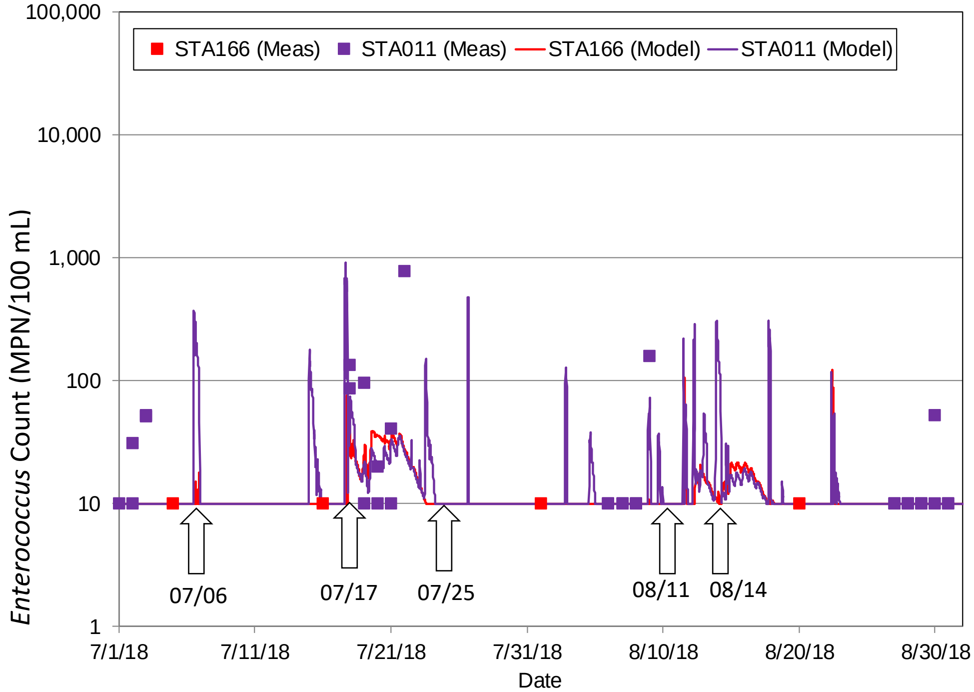


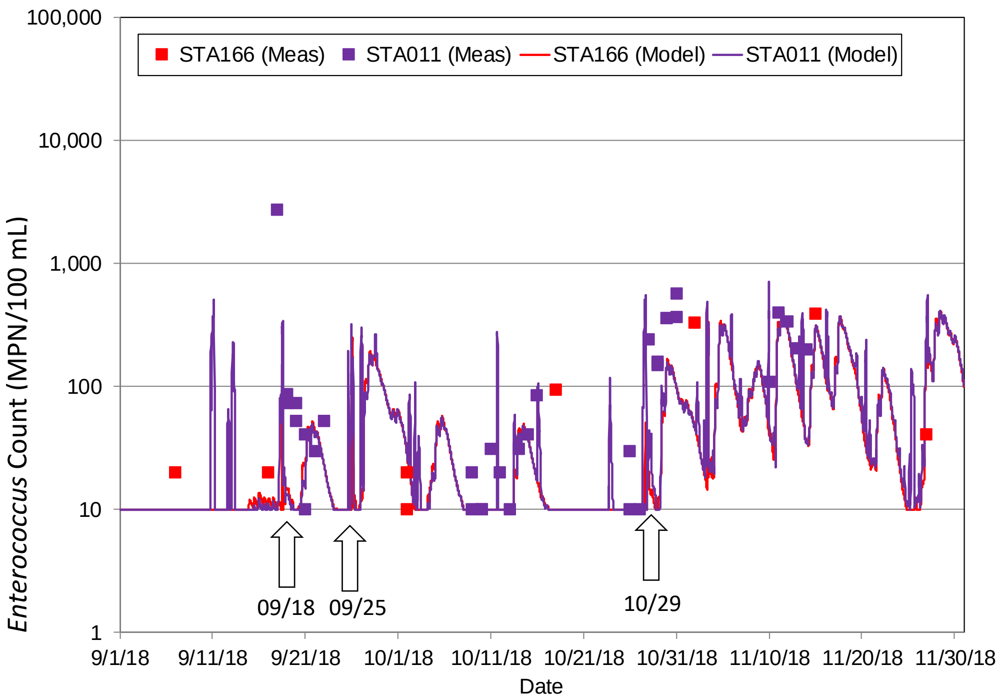
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station





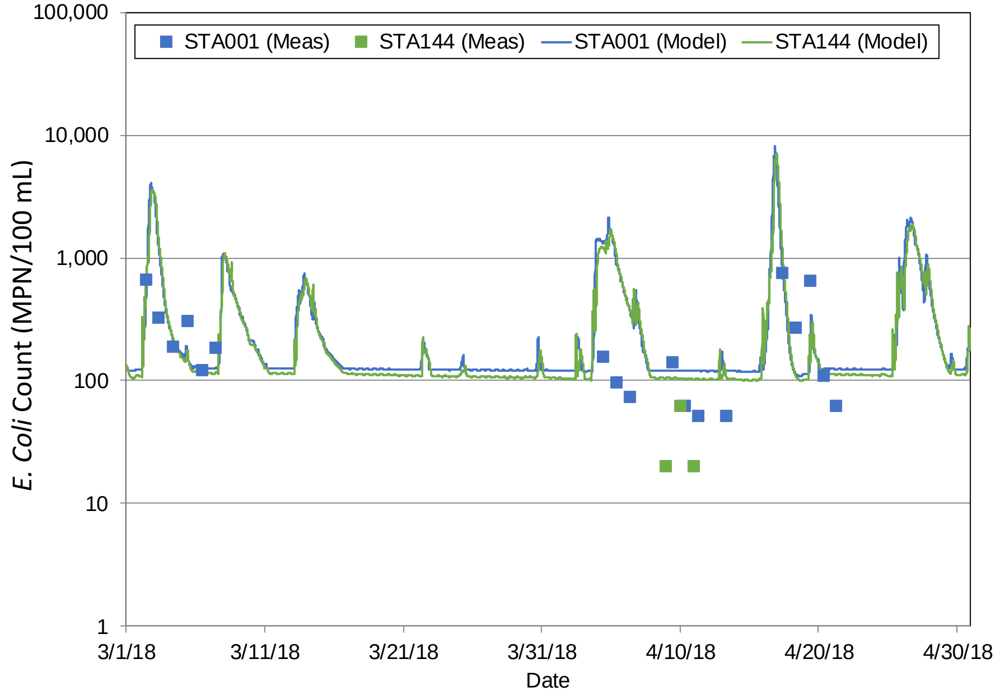
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



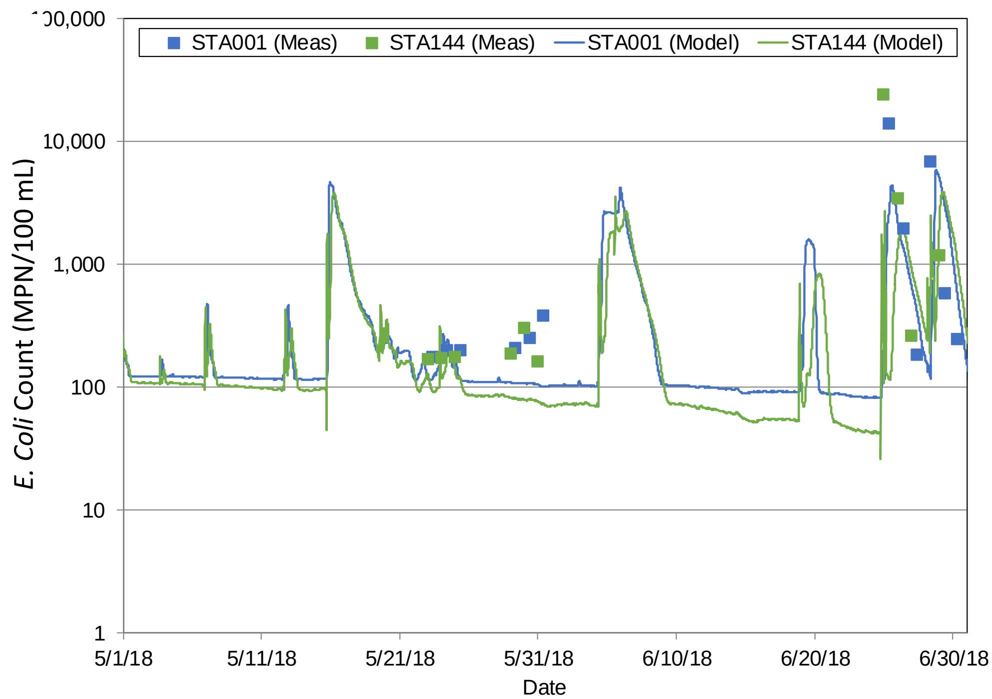


Date of model predicted CSO activation at a CSO located upstream of the sampling station

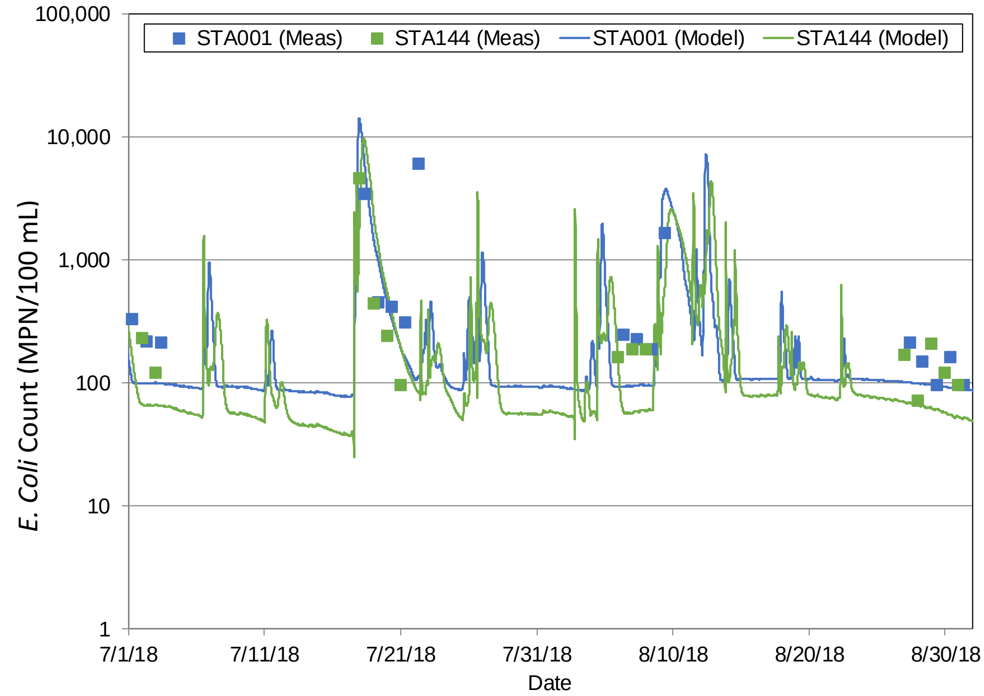
Appendix C – Charles River Model Calibration Plots – *E. coli*



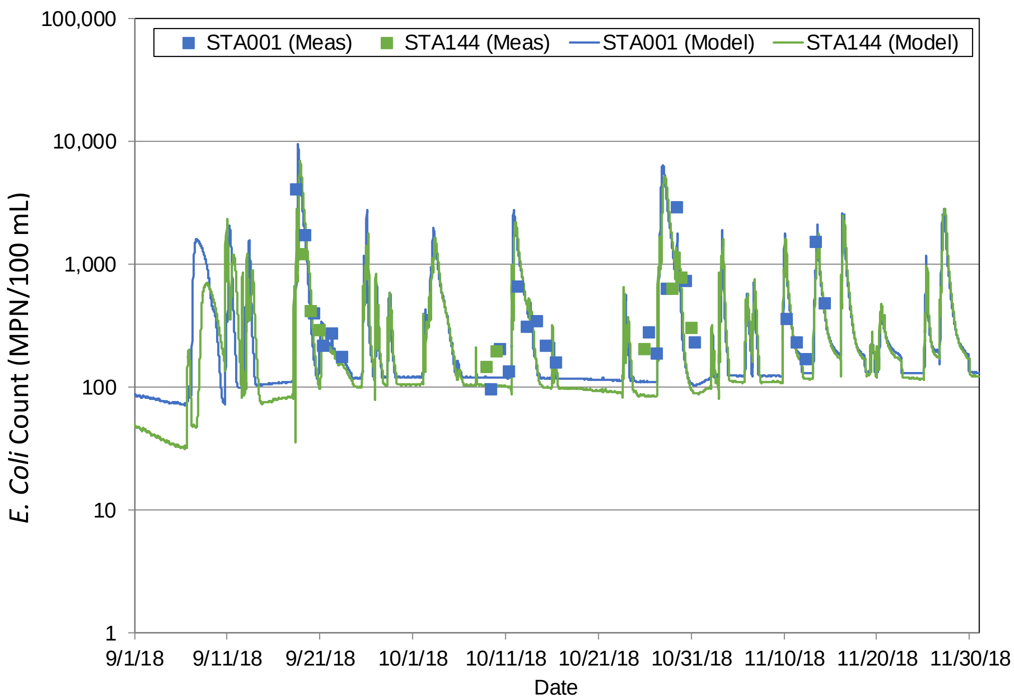
100,000
10,000
1,000
100
10
1
STA001 (Meas)
STA144 (Meas)
STA001 (Model)
STA144 (Model)
E. Coli Count (MPN/100 mL)
3/1/18
3/11/18
3/21/18
3/31/18
4/10/18
4/20/18
4/30/18
Date



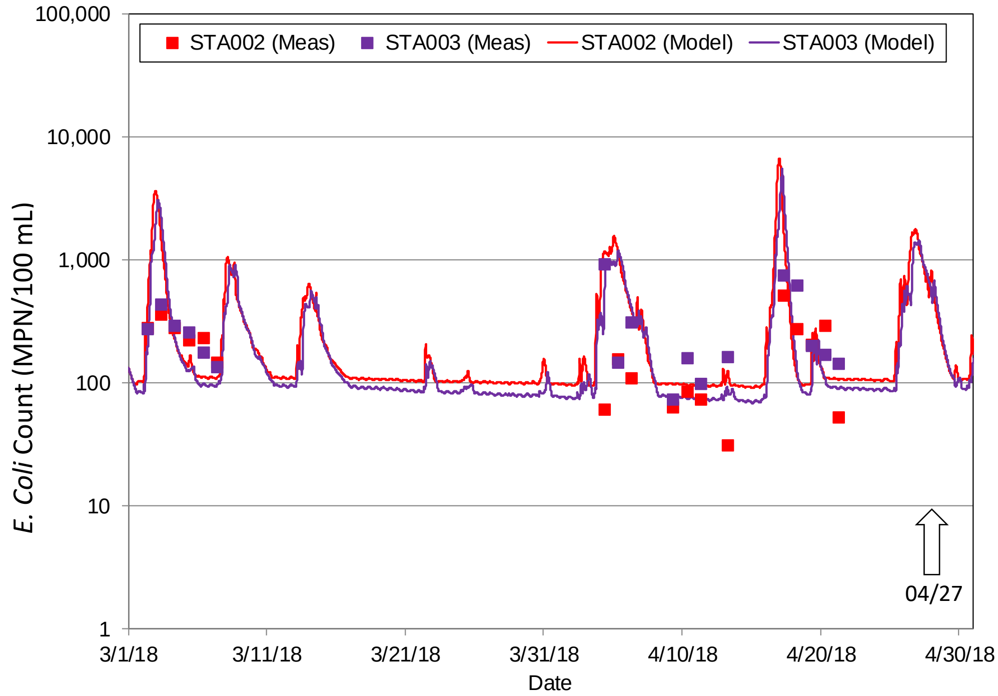
100,000
10,000
1,000
100
10
1
STA001 (Meas)
STA144 (Meas)
STA001 (Model)
STA144 (Model)
E. Coli Count (MPN/100 mL)
5/1/18
5/11/18
5/21/18
5/31/18
6/10/18
6/20/18
6/30/18
Date

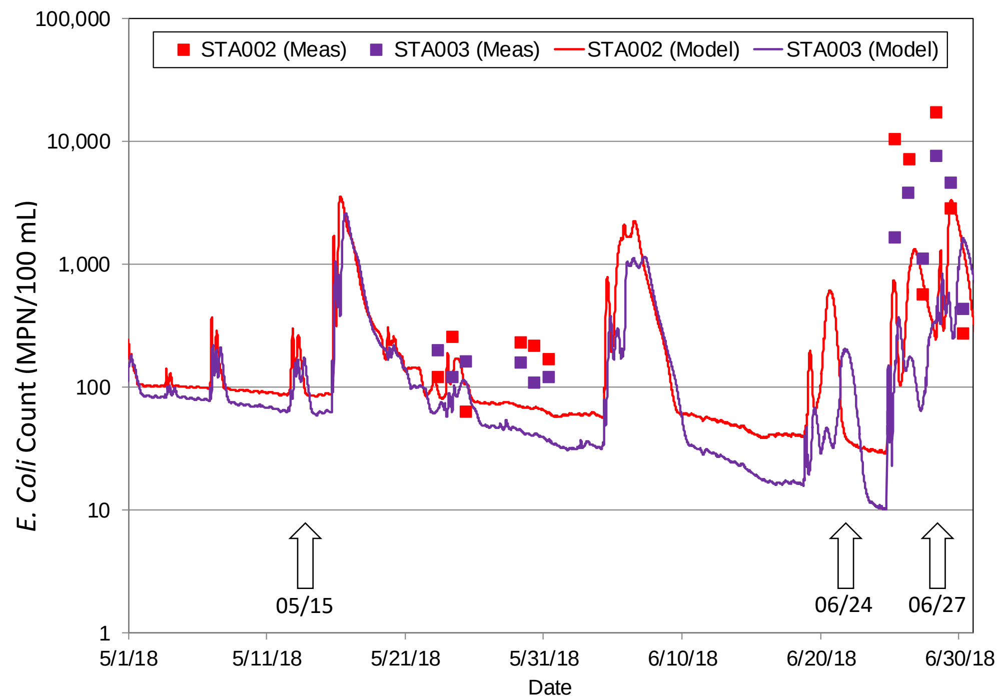


100,000
10,000
1,000
100
10
1
STA001 (Meas)
STA144 (Meas)
STA001 (Model)
STA144 (Model)
E. Coli Count (MPN/100 mL)
7/1/18
7/11/18
7/21/18
7/31/18
8/10/18
8/20/18
8/30/18
Date

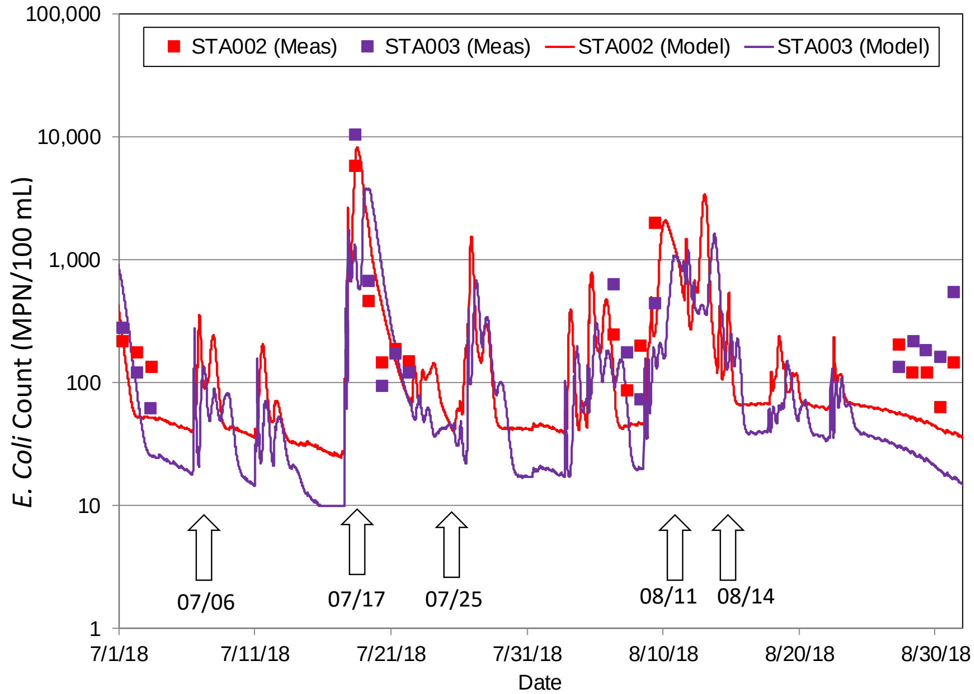


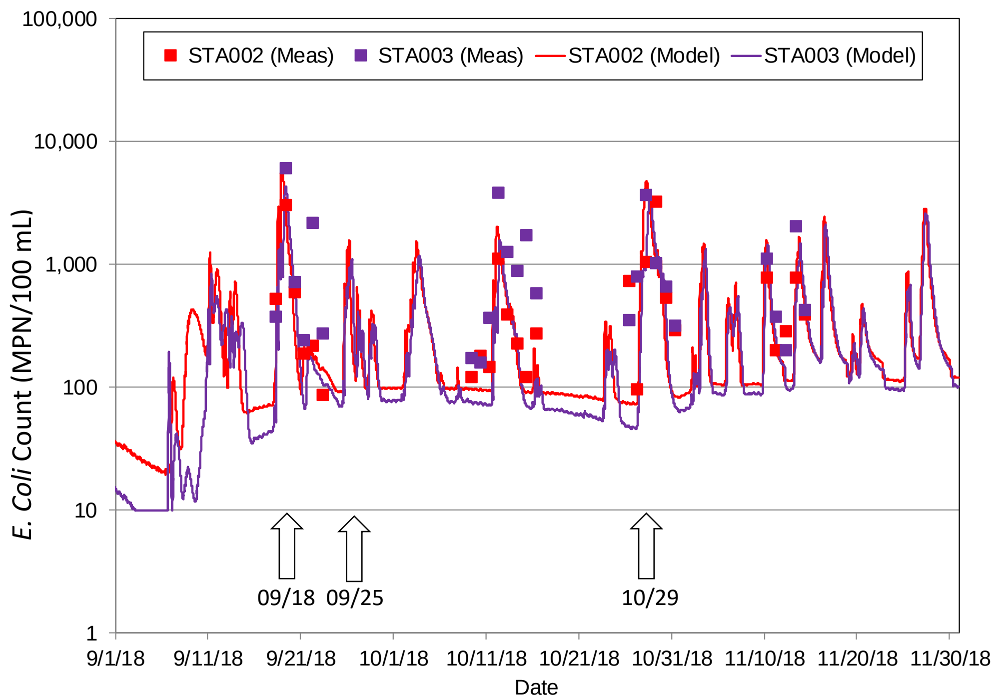
100,000
10,000
1,000
100
10
1
STA001 (Meas)
STA144 (Meas)
STA001 (Model)
STA144 (Model)
E. Coli Count (MPN/100 mL)
9/1/18
9/11/18
9/21/18
10/1/18
10/11/18
10/21/18
10/31/18
11/10/18
11/20/18
11/30/18
Date



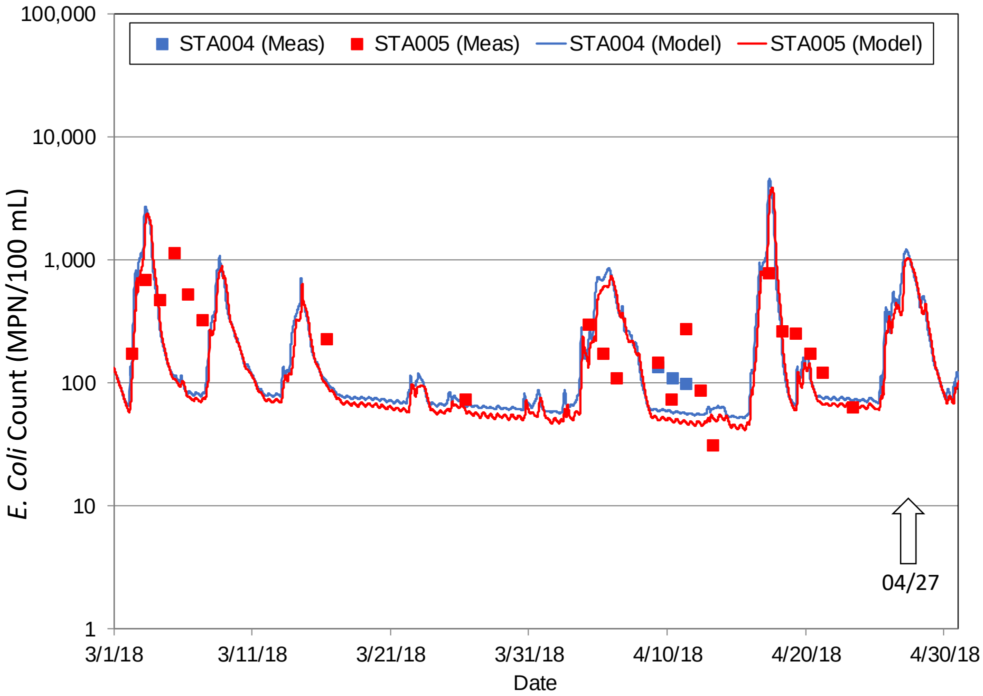


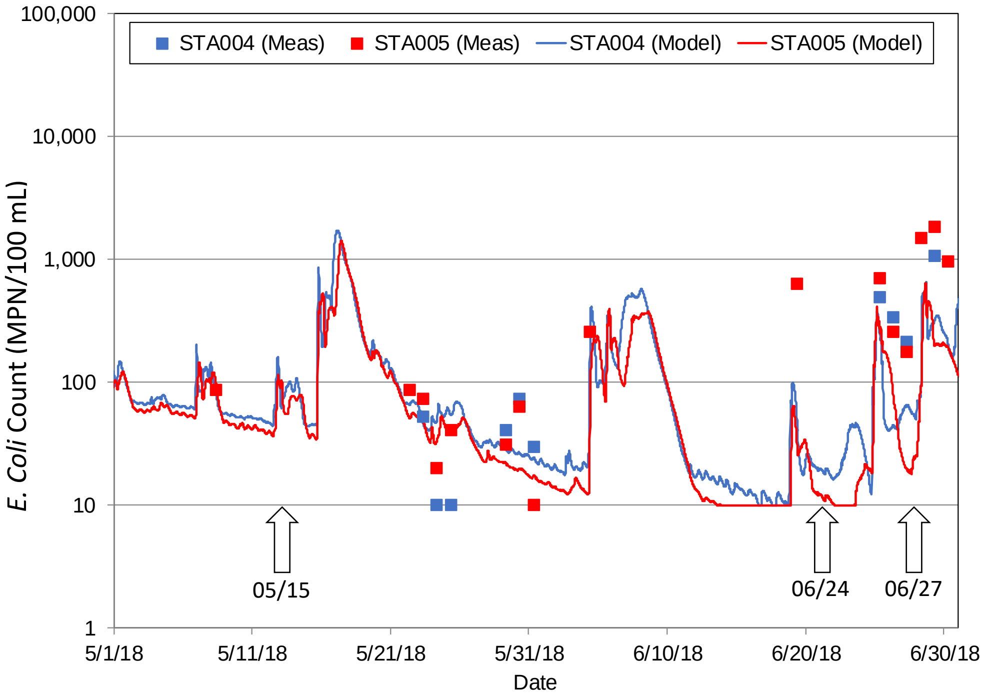
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



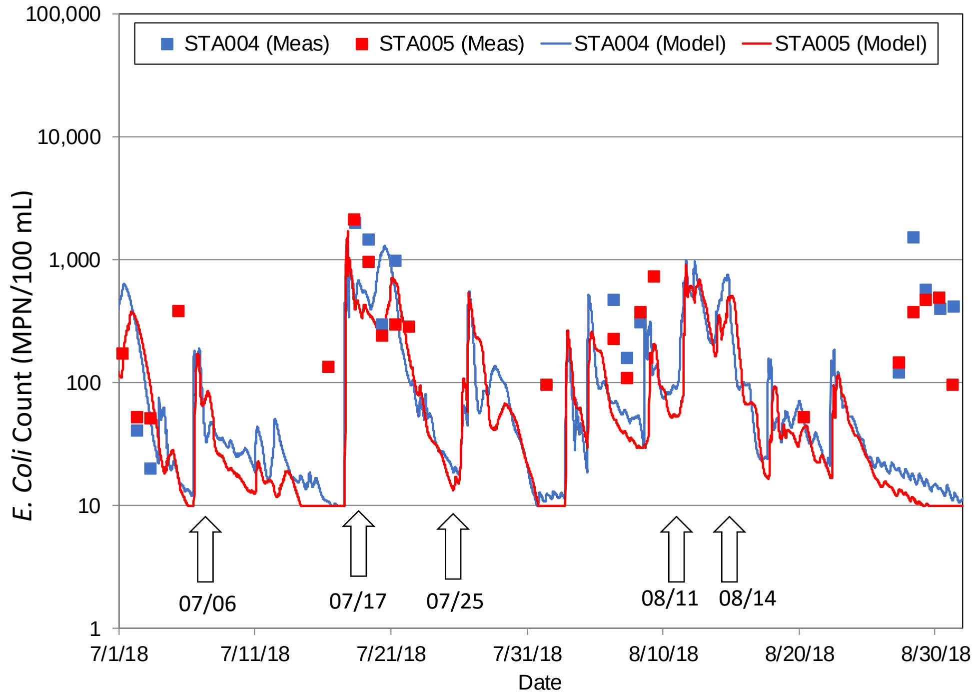


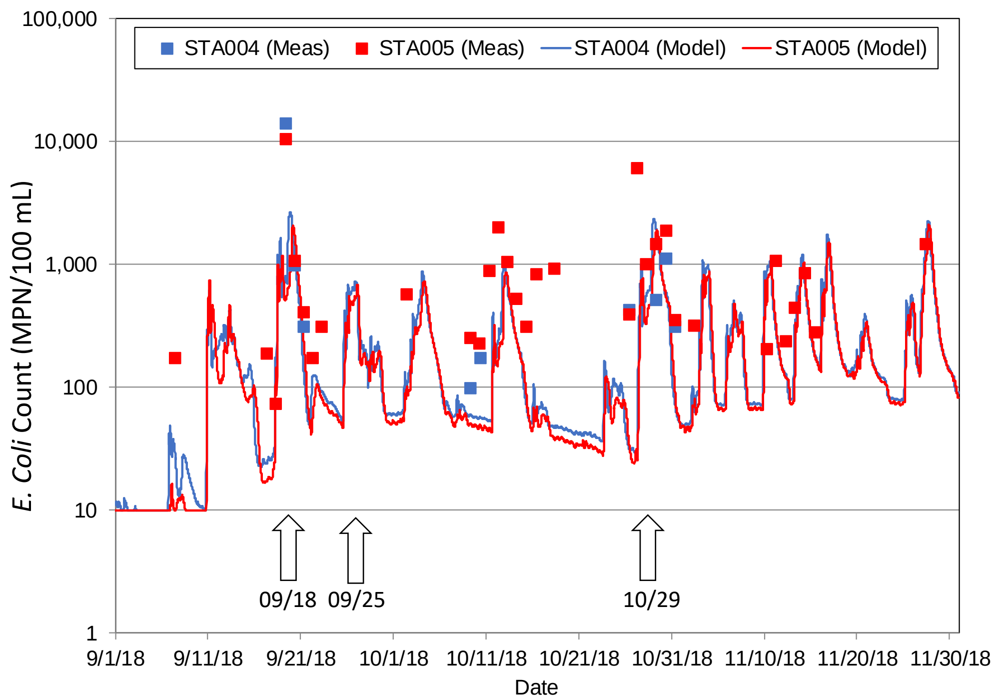
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



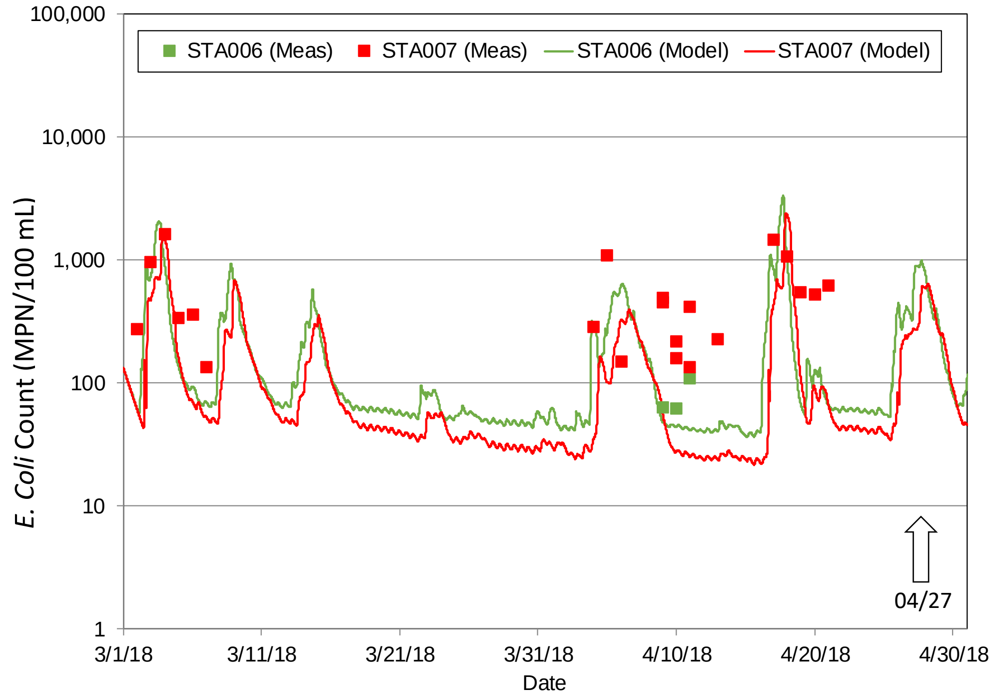


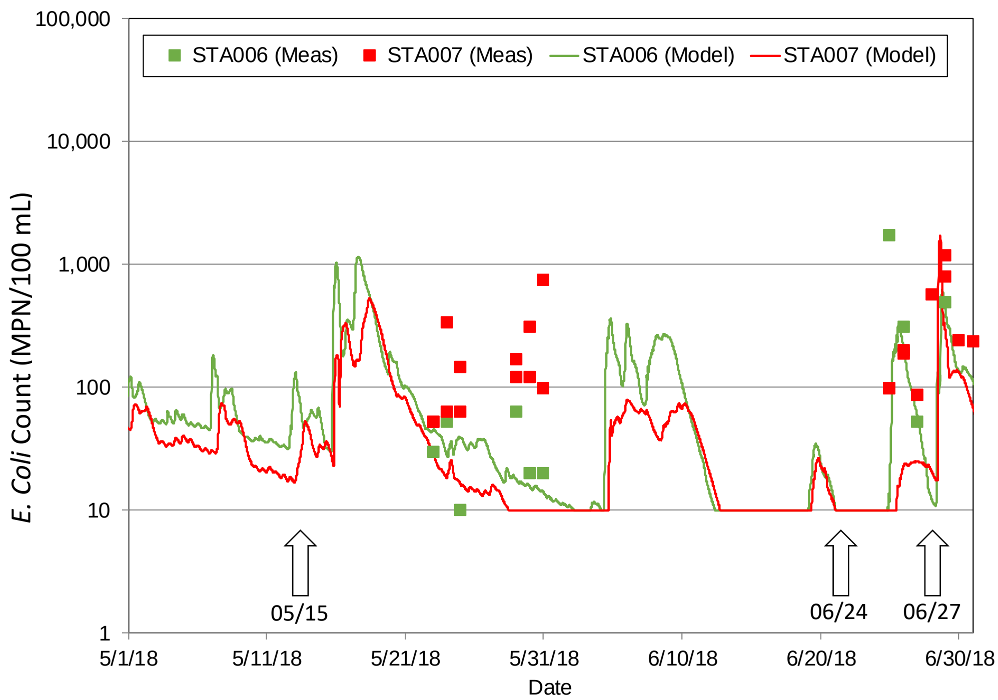
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station

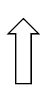




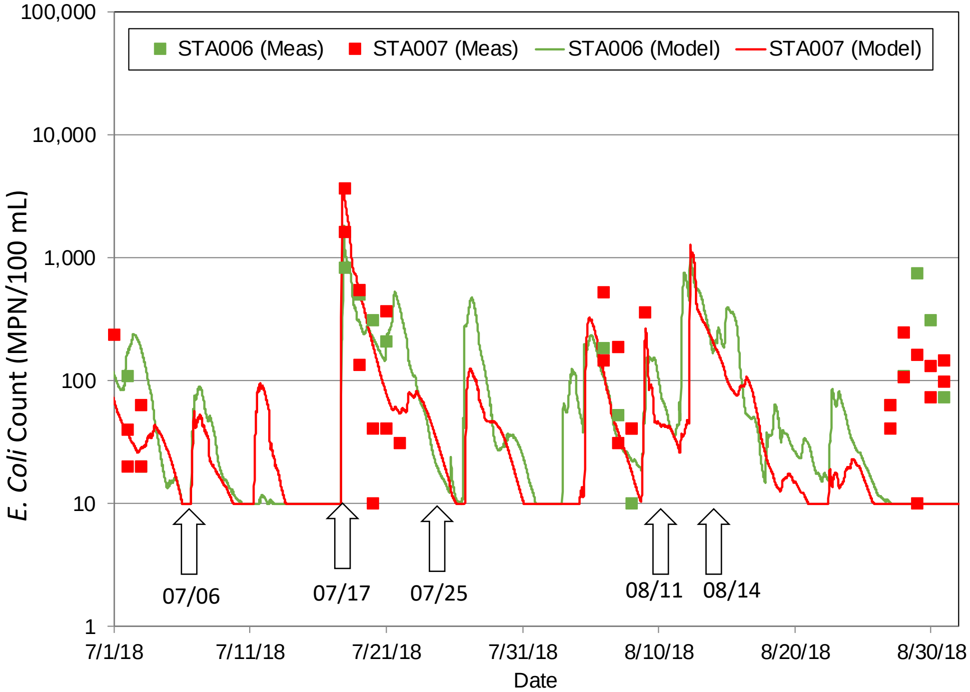
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station

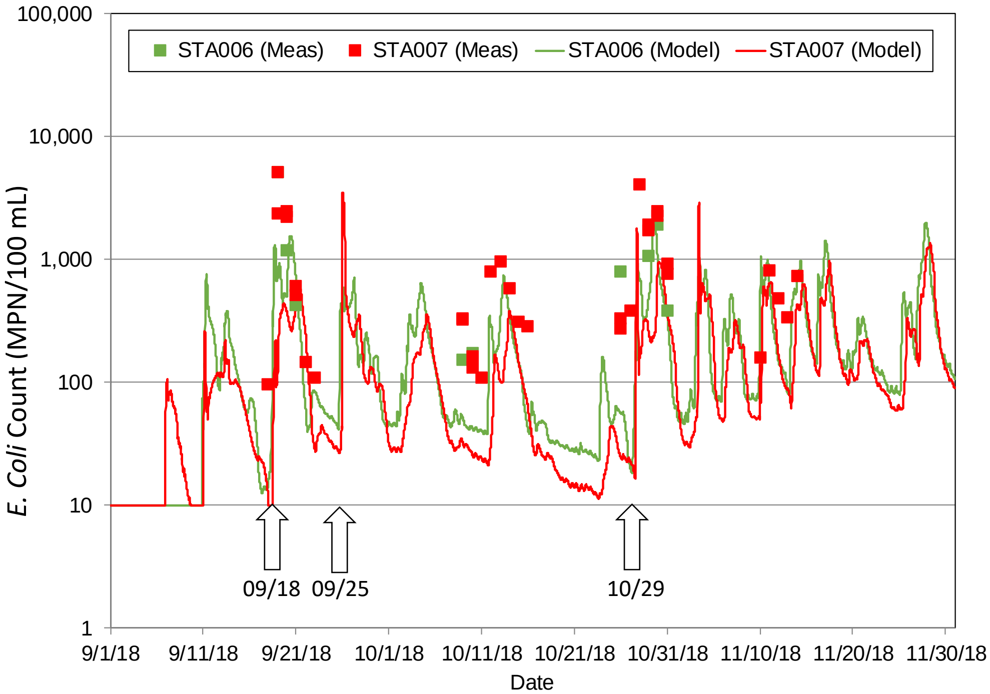




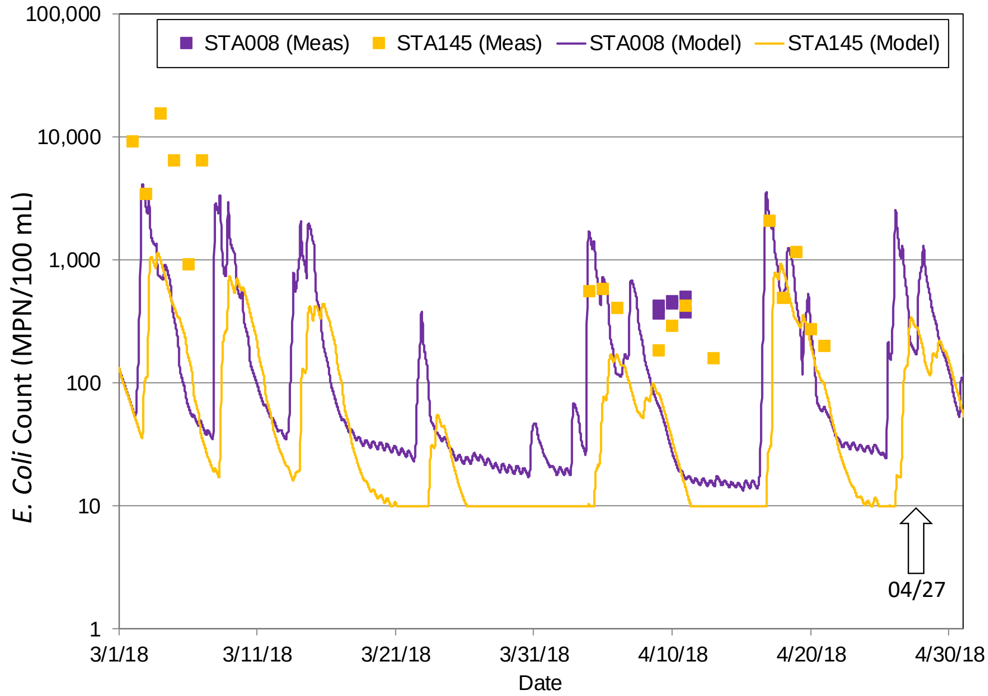


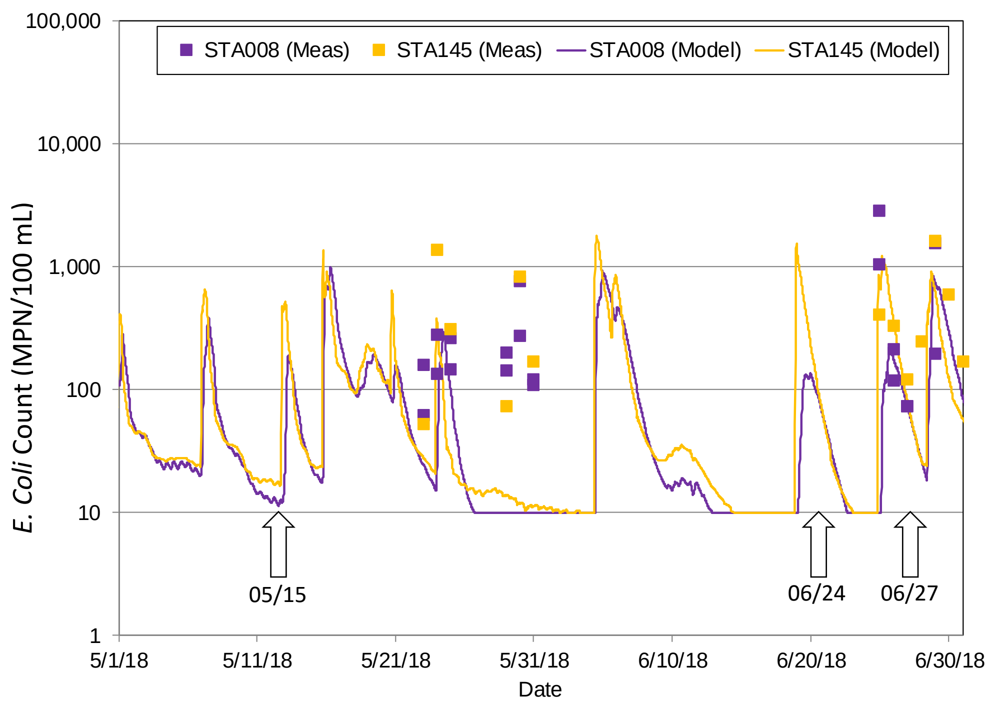
Date of model predicted CSO activation at a CSO located upstream of the sampling station



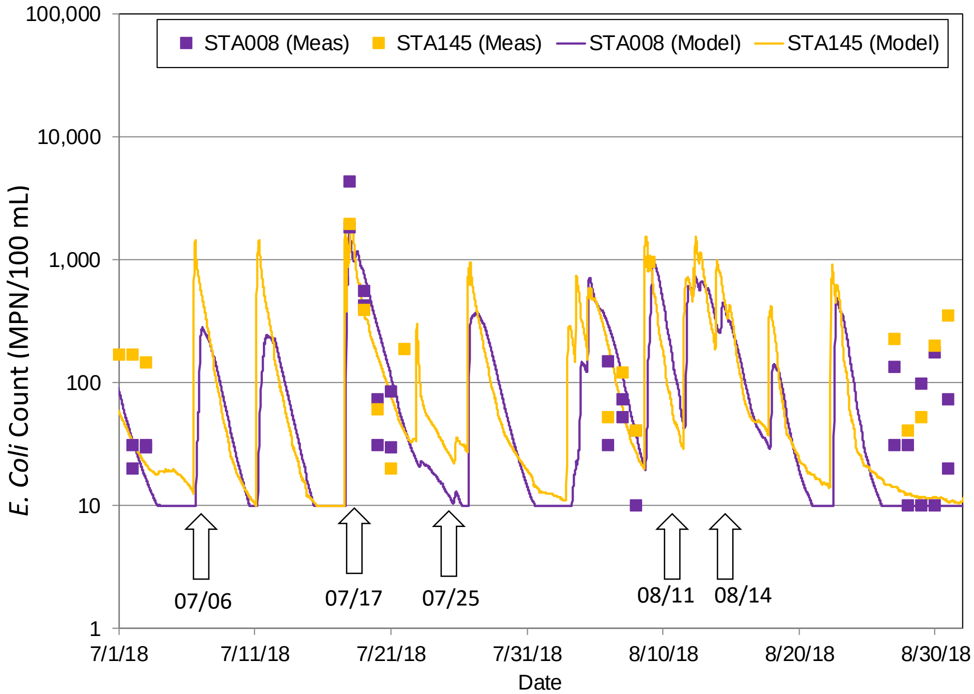


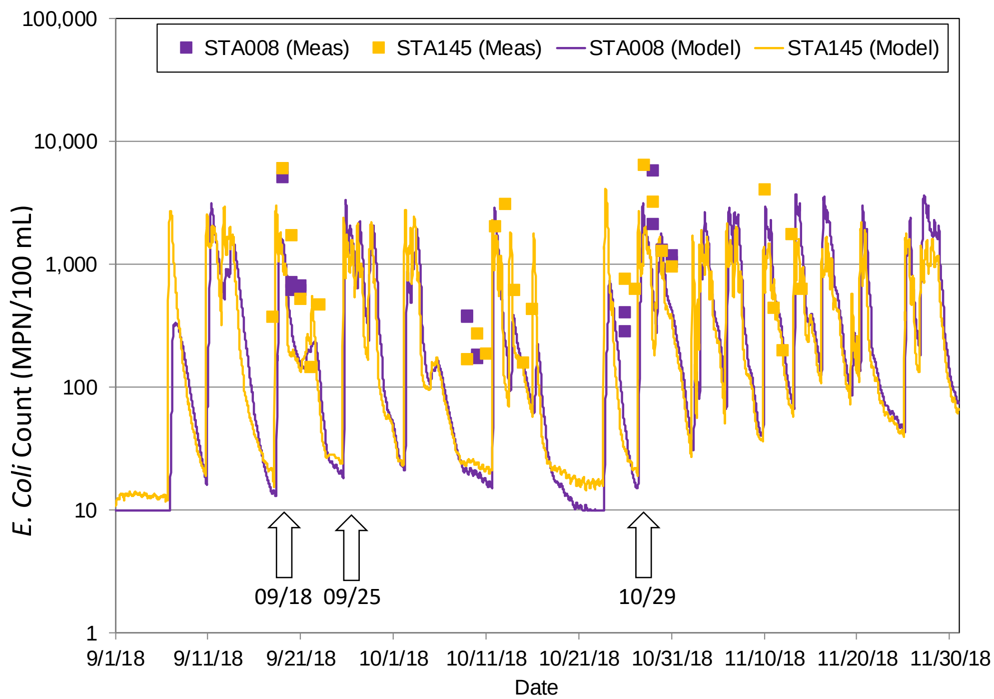
Date of model predicted CSO activation at a CSO located upstream of the sampling station



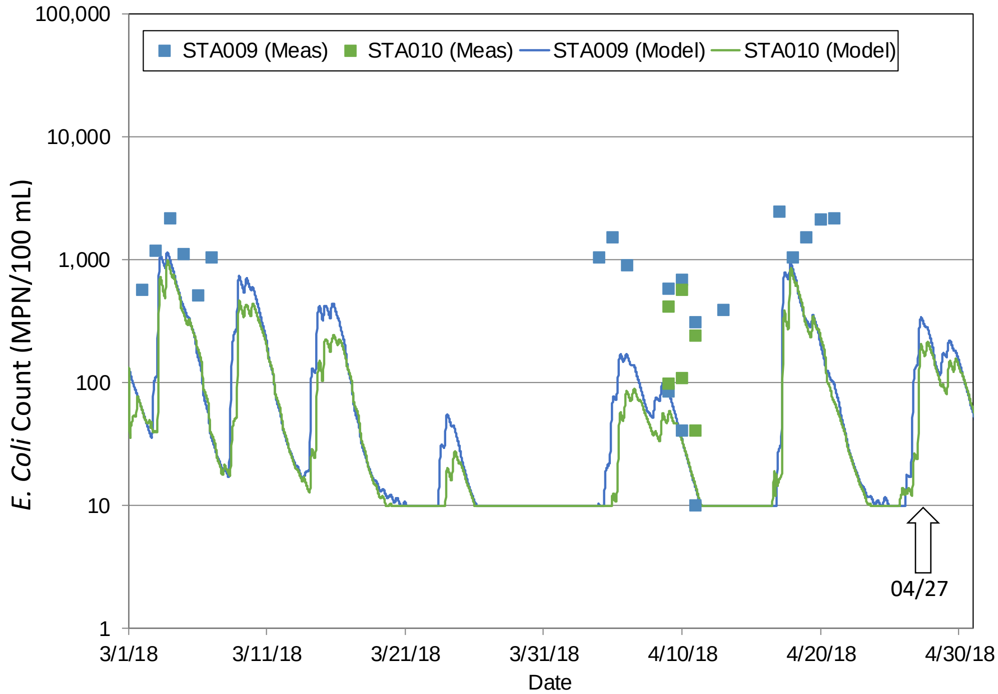


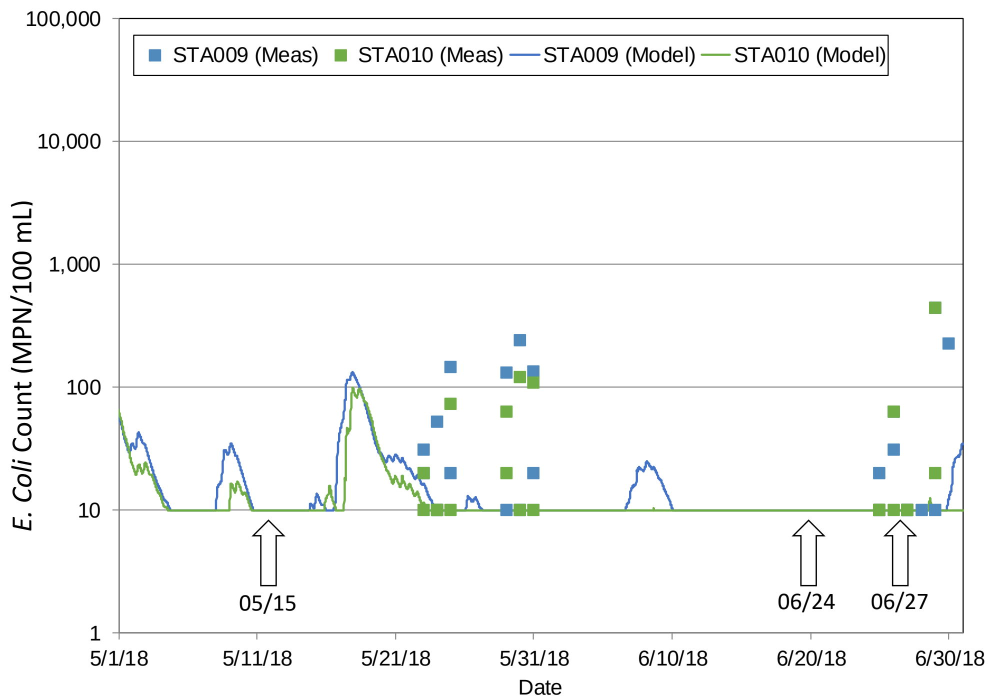
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



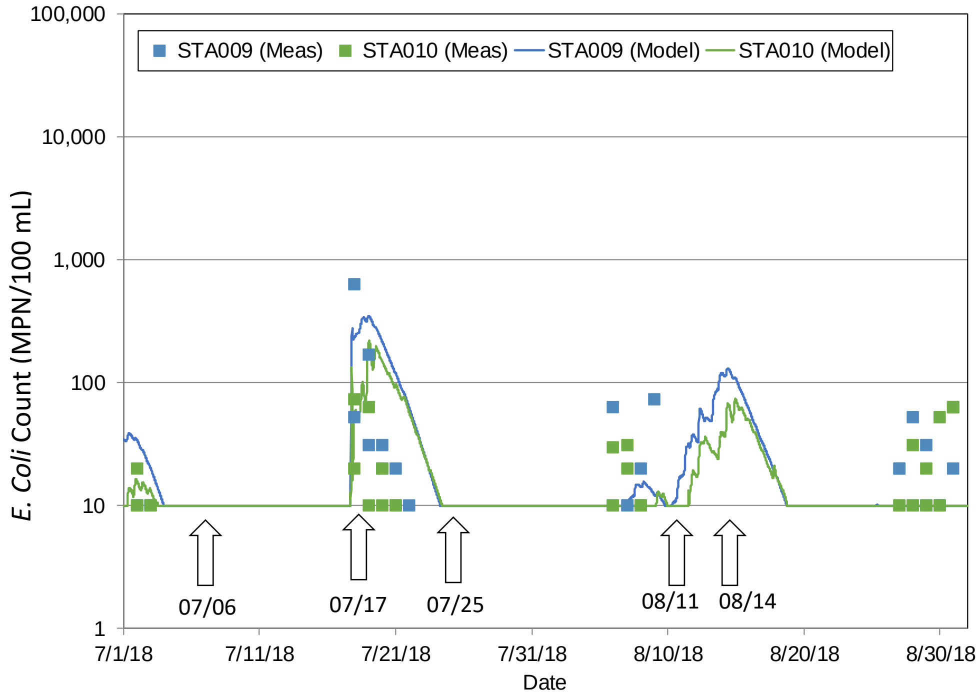


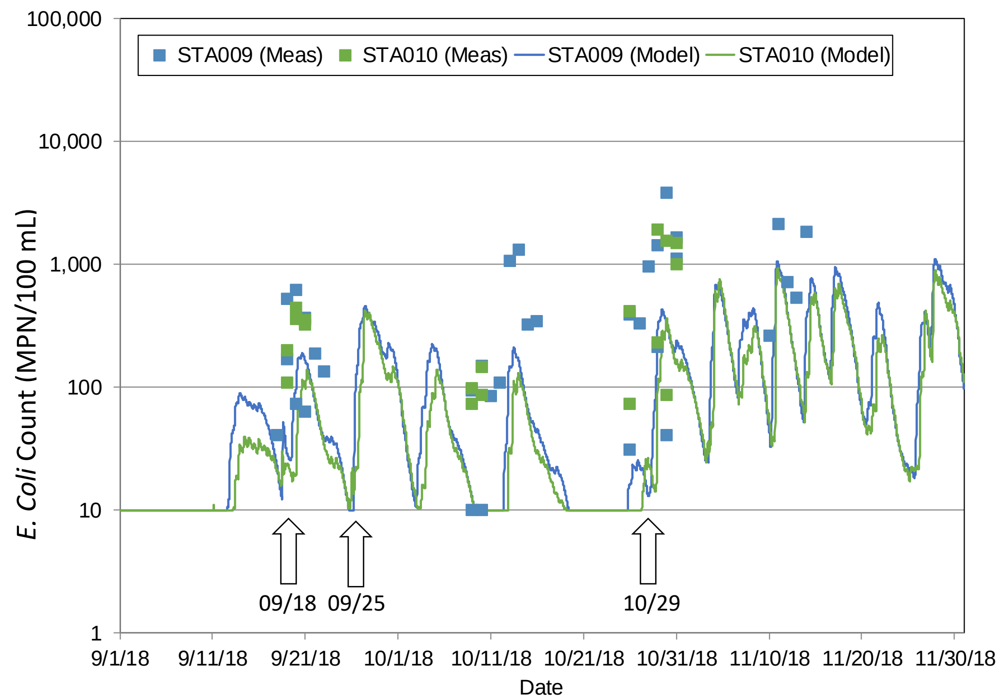
Date of model predicted CSO activation at a CSO located upstream of the sampling station



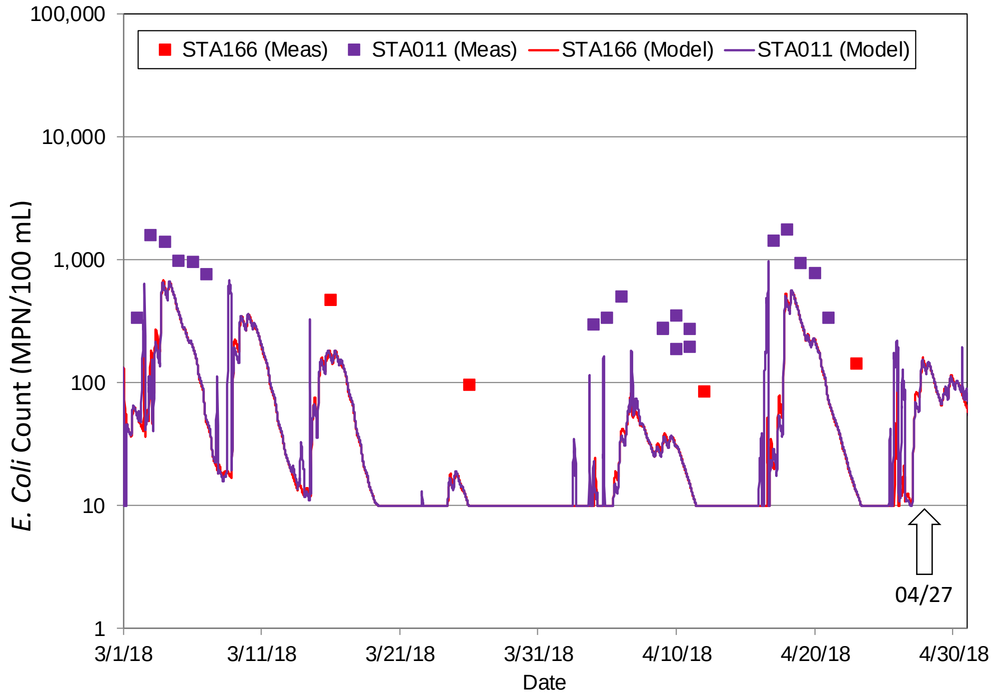


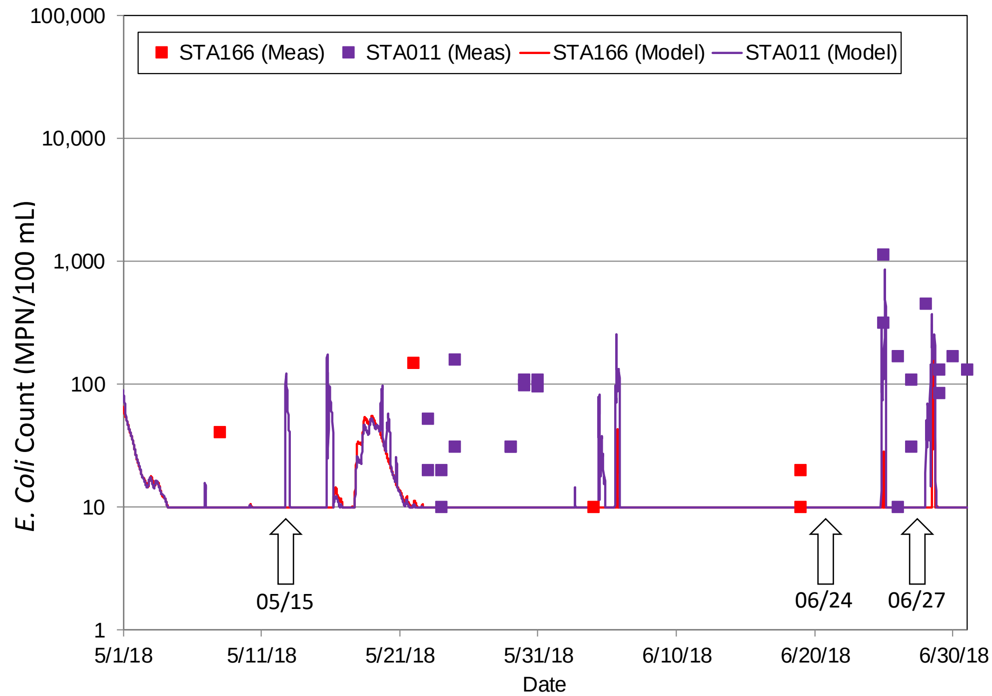
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station

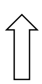




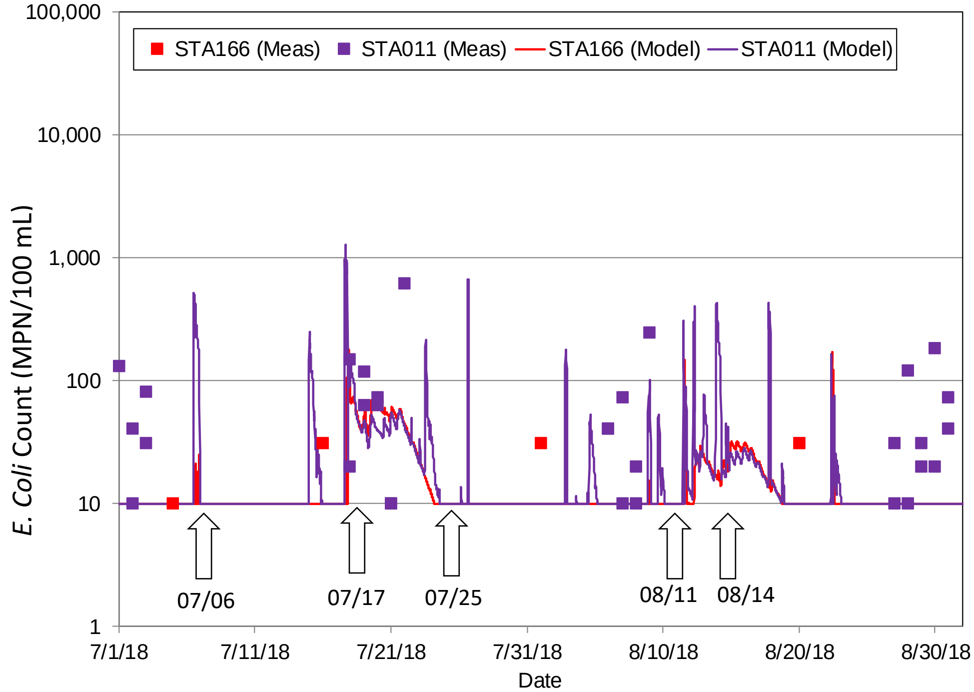

Date of model predicted CSO activation at a CSO located upstream of the sampling station

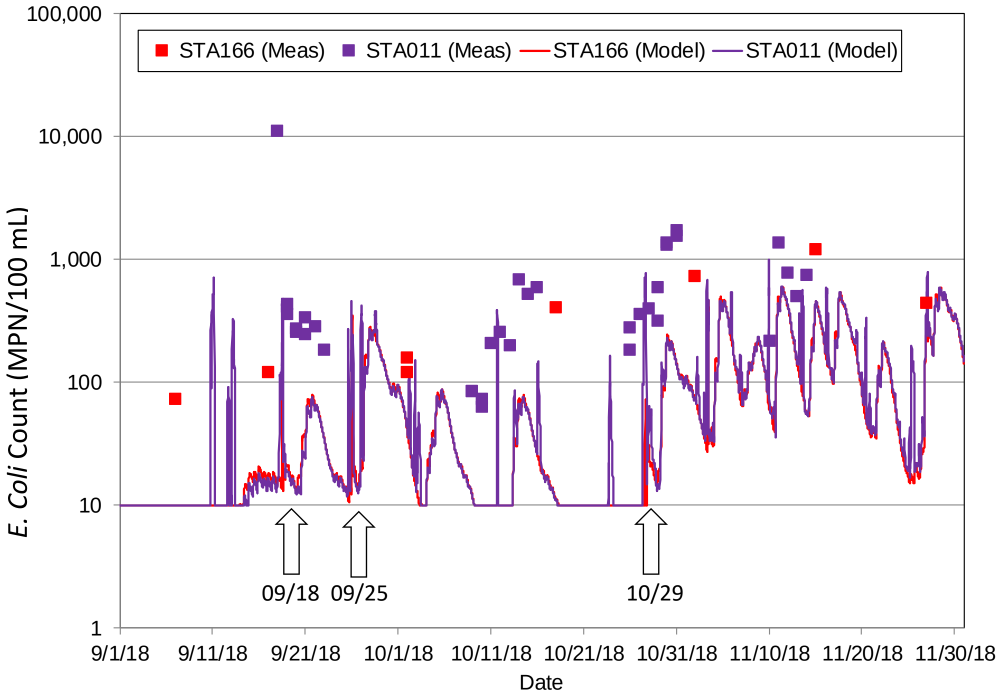


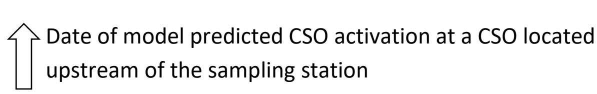




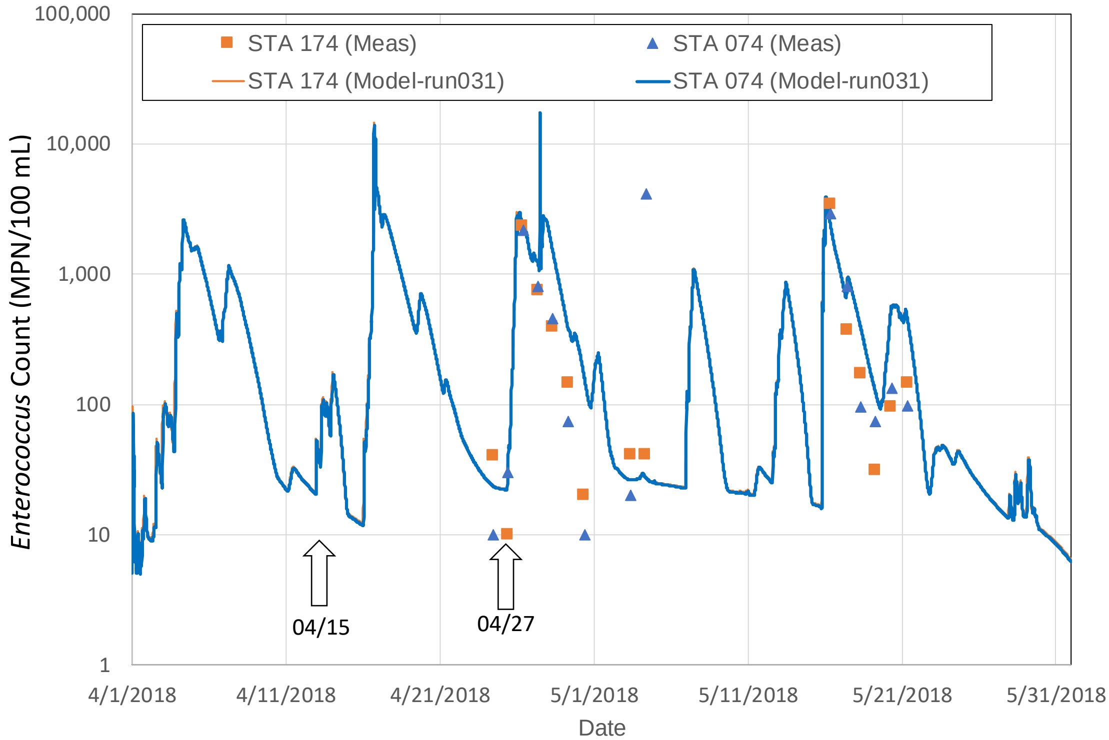
Date of model predicted CSO activation at a CSO located upstream of the sampling station

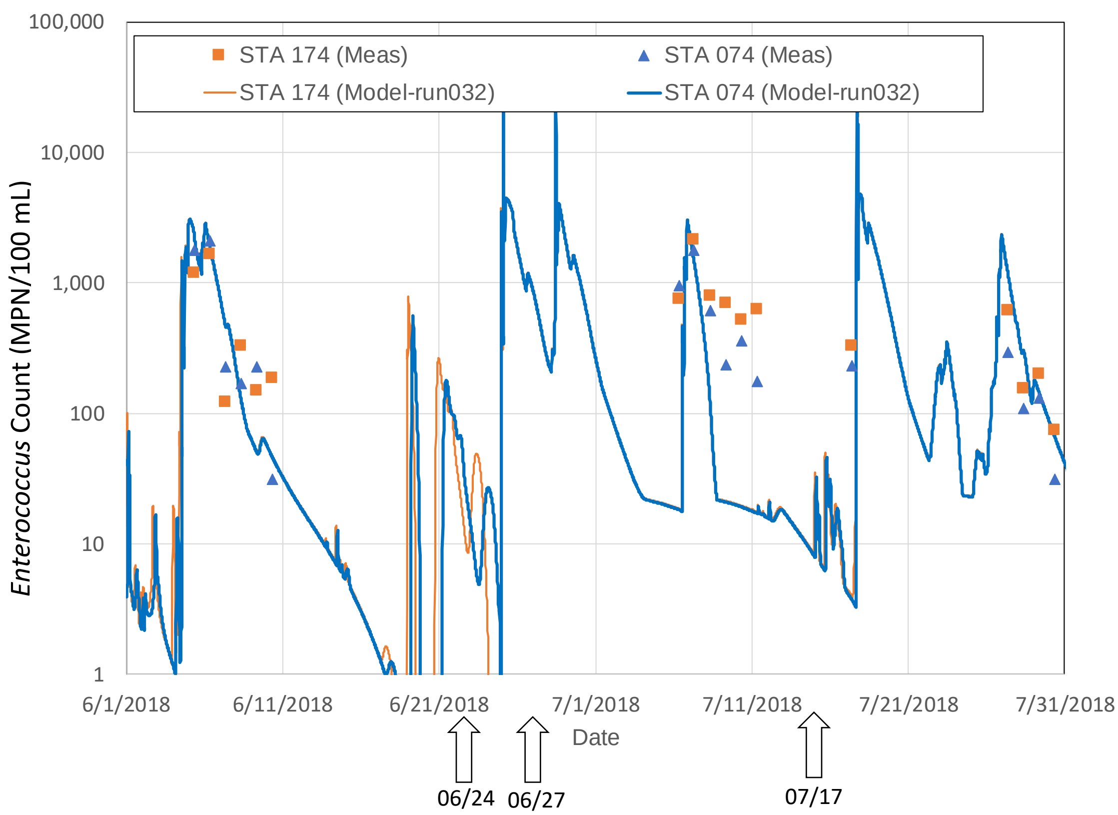

STA166 (Meas)
STA011 (Meas)
STA166 (Model)
STA011 (Model)
100,000
10,000
1,000
100
10
1
E. Coli Count (MPN/100 mL)
07/06
07/17
07/25
08/11
08/14
7/1/18
7/11/18
7/21/18
7/31/18
8/10/18
8/20/18
8/30/18
Date


STA166 (Meas)
STA011 (Meas)
STA166 (Model)
STA011 (Model)
100,000
10,000
1,000
100
10
1
E. Coli Count (MPN/100 mL)
09/18
09/25
10/29
9/1/18
9/11/18
9/21/18
10/1/18
10/11/18
10/21/18
10/31/18
11/10/18
11/20/18
11/30/18
Date

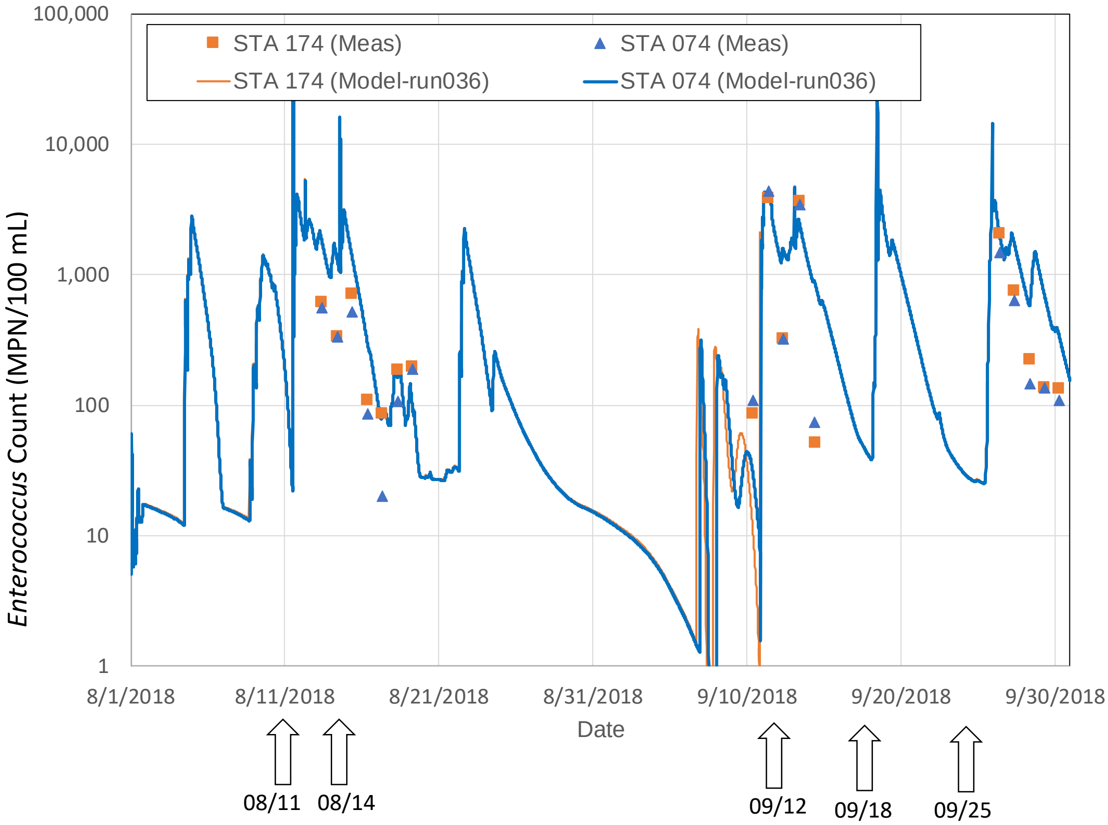

Date of model predicted CSO activation at a CSO located upstream of the sampling station

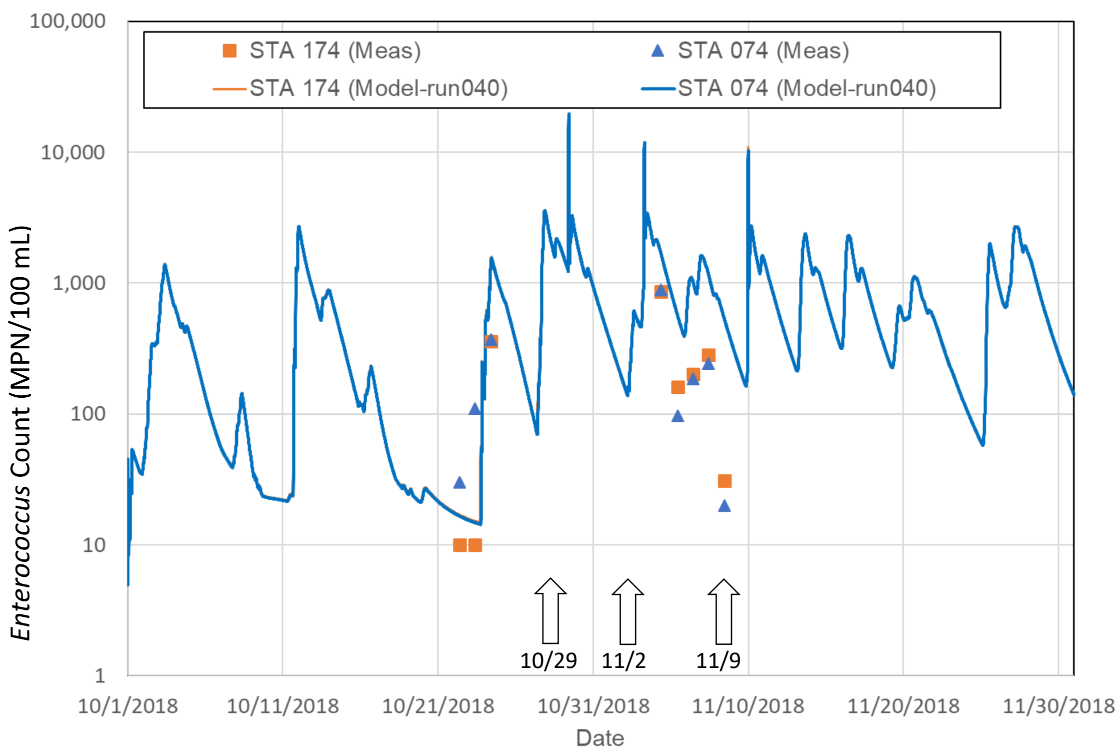
Appendix D – Alewife Brook/Upper Mystic River Model Calibration Plots – *Enterococcus*



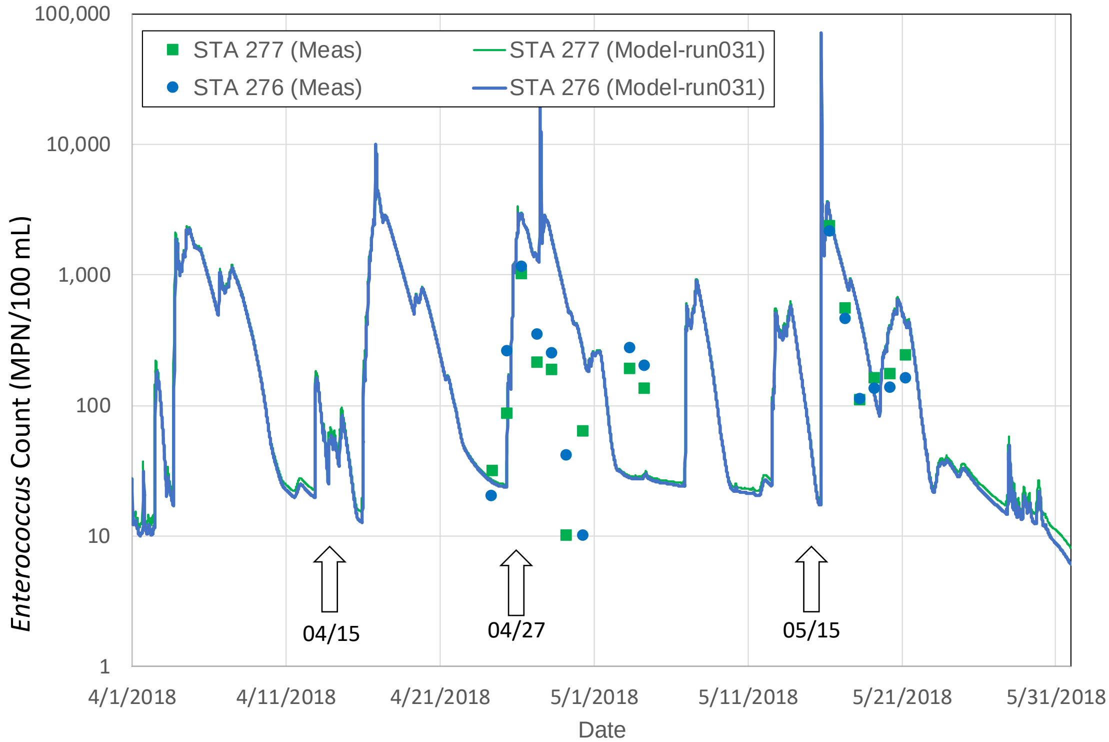


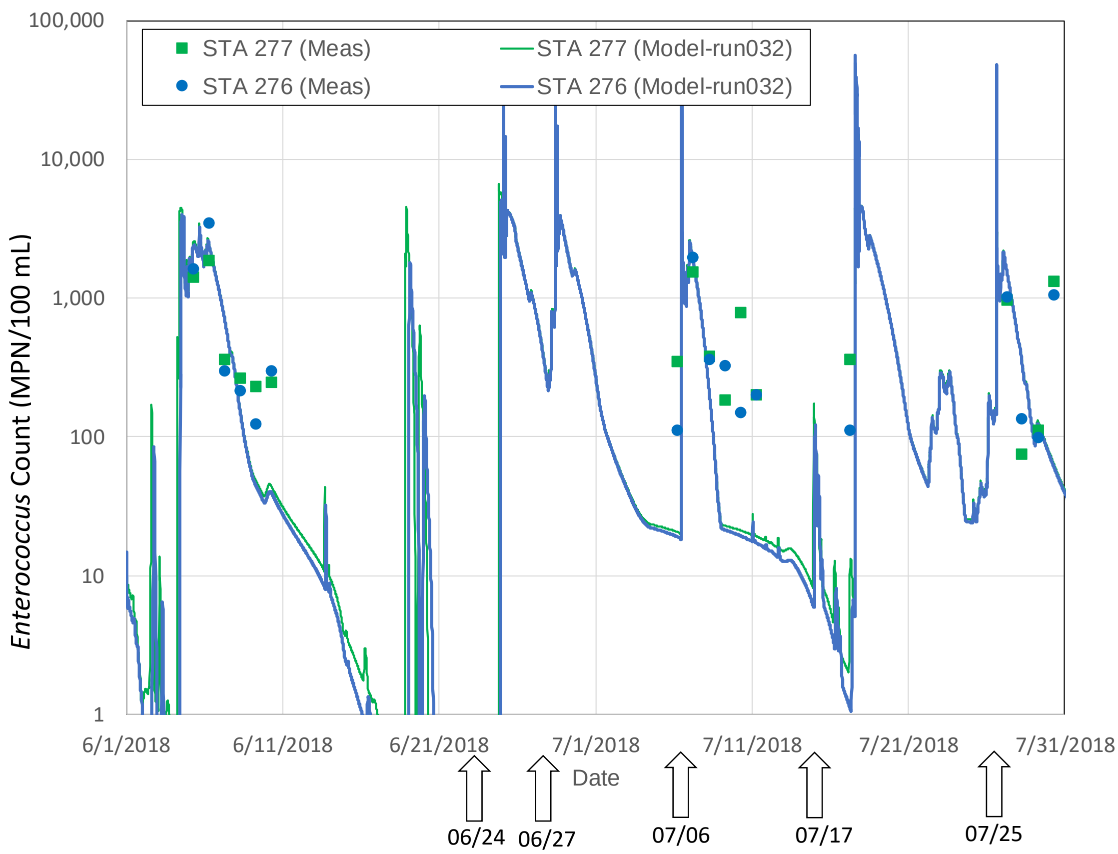
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



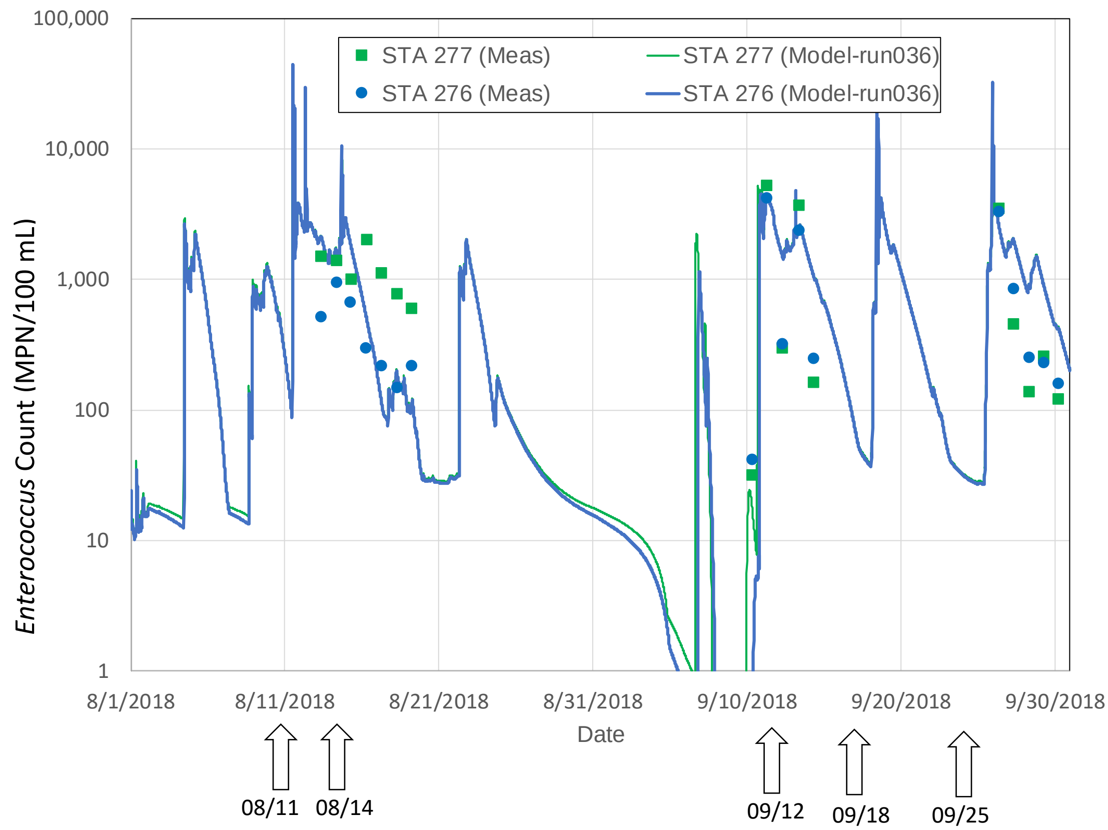


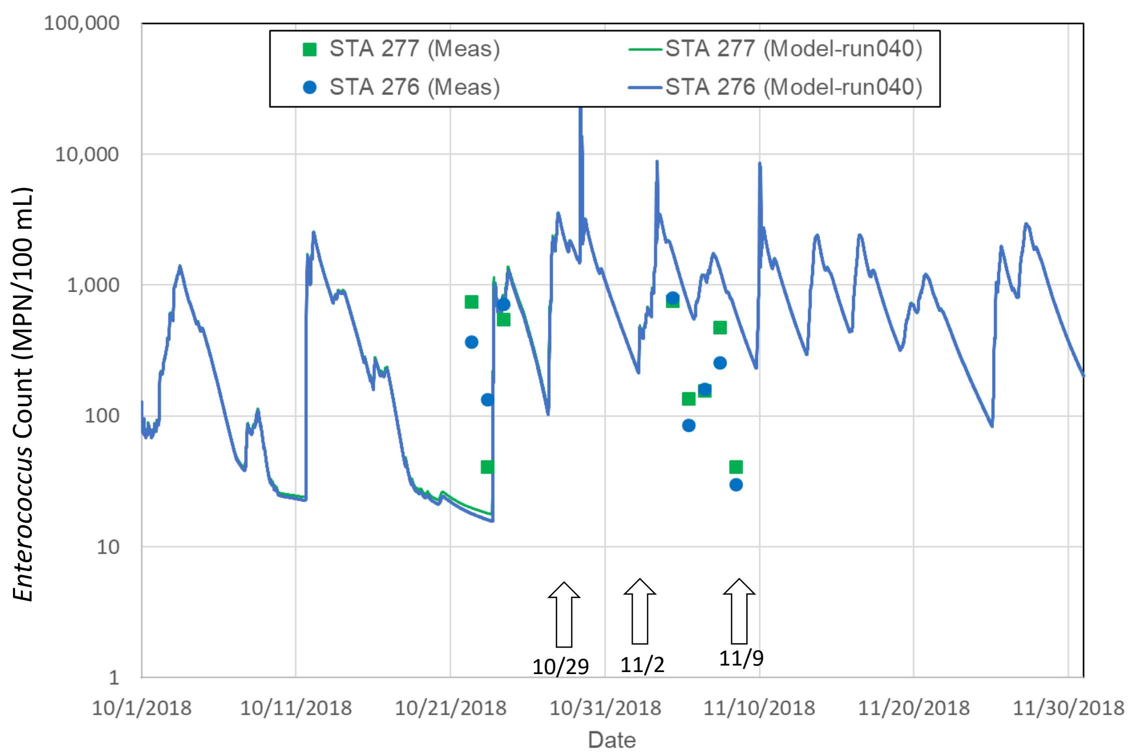
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



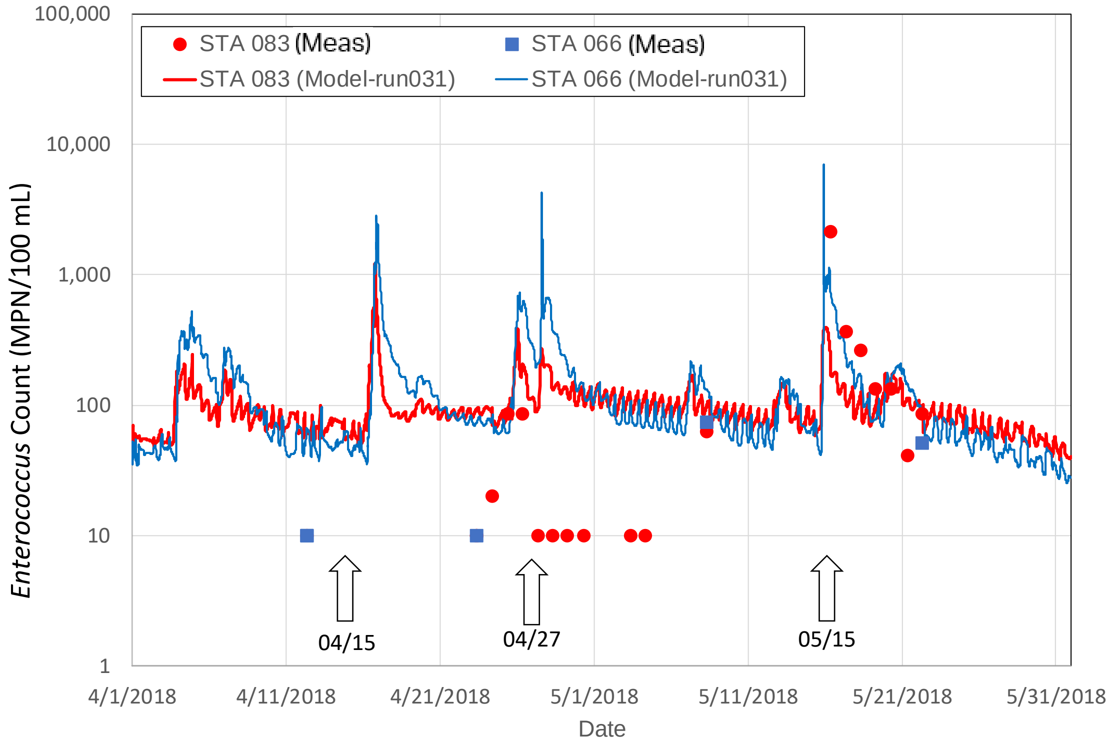


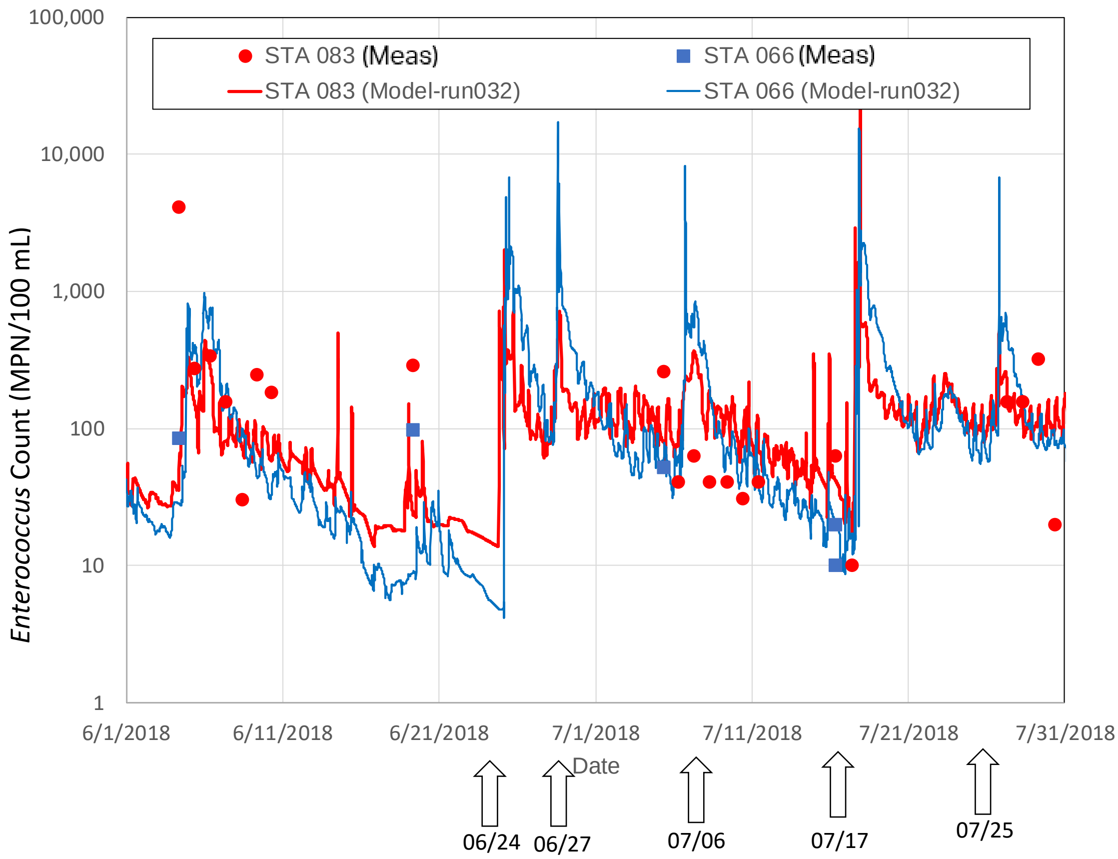
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



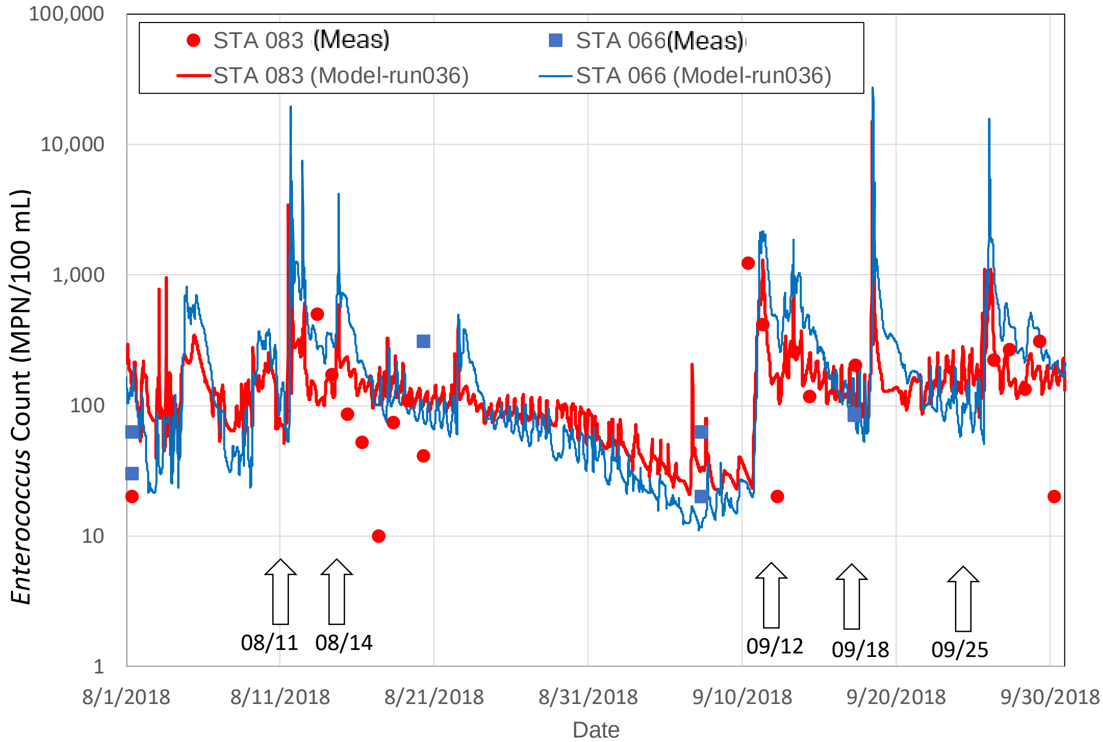


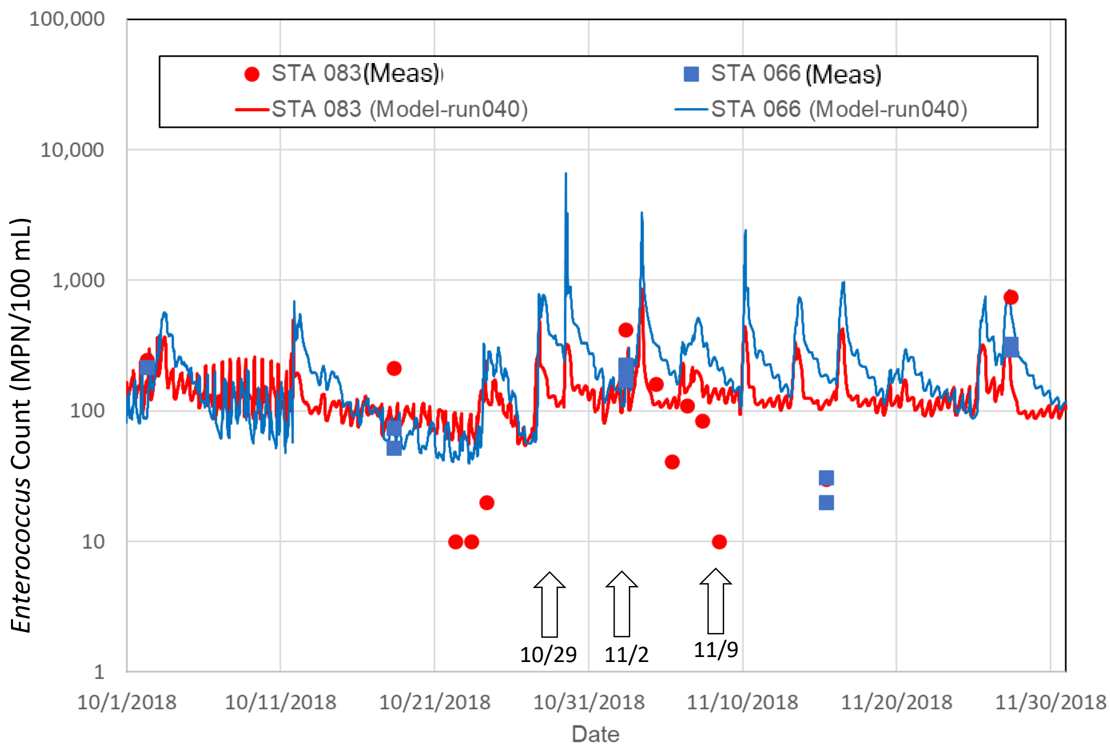
Date of model predicted CSO activation at a CSO located upstream of the sampling station





Date of model predicted CSO activation at a CSO located upstream of the sampling station





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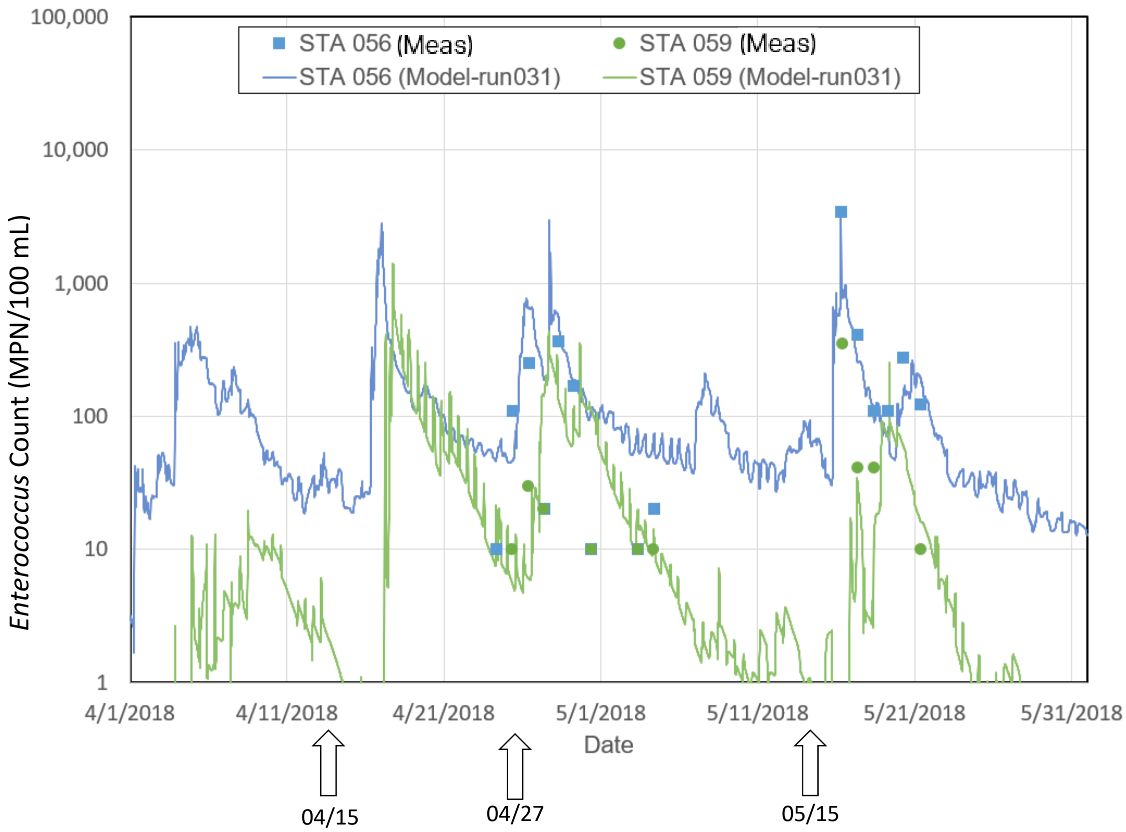

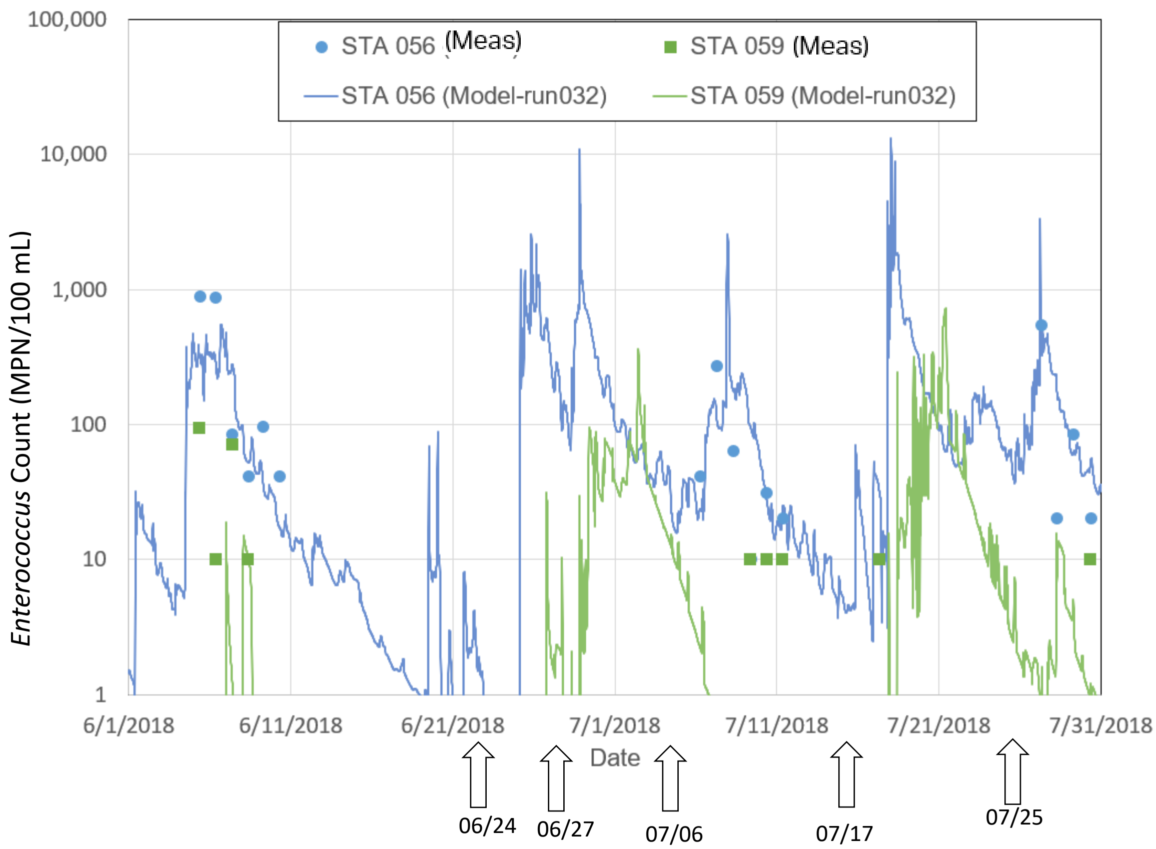

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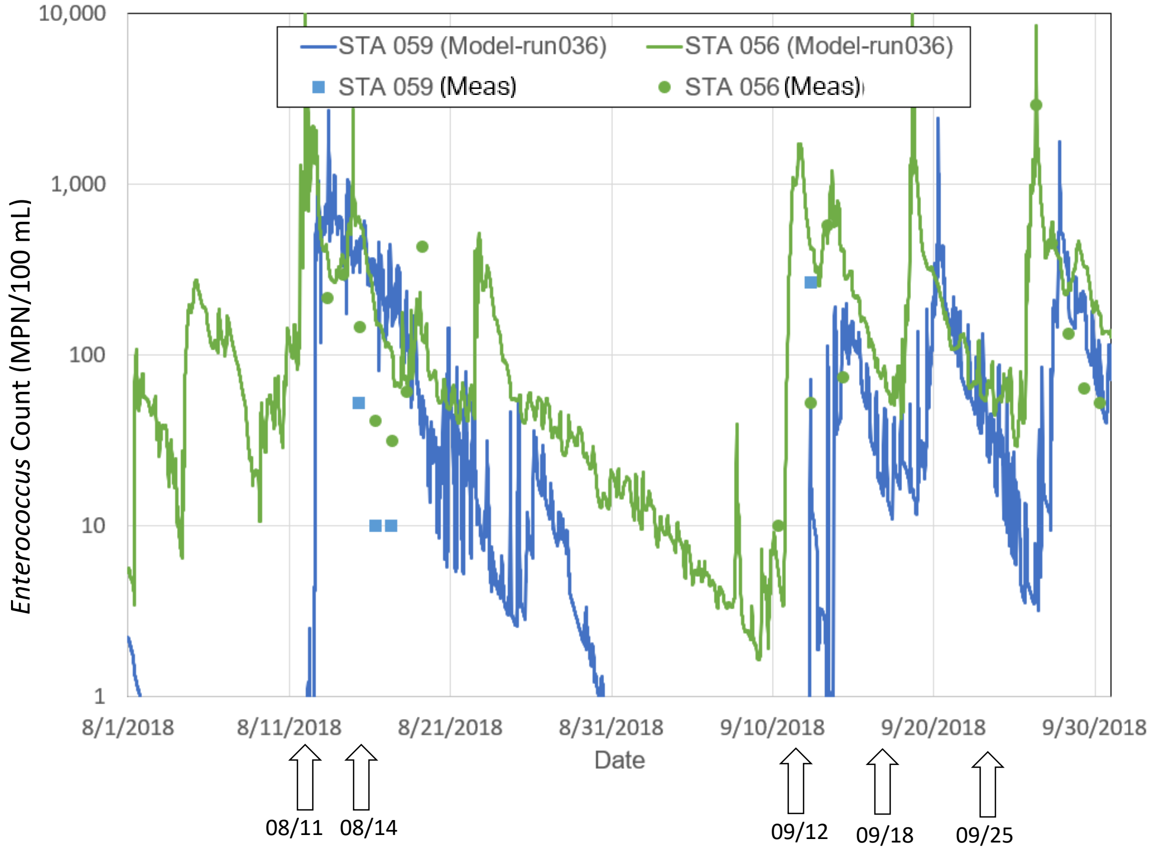

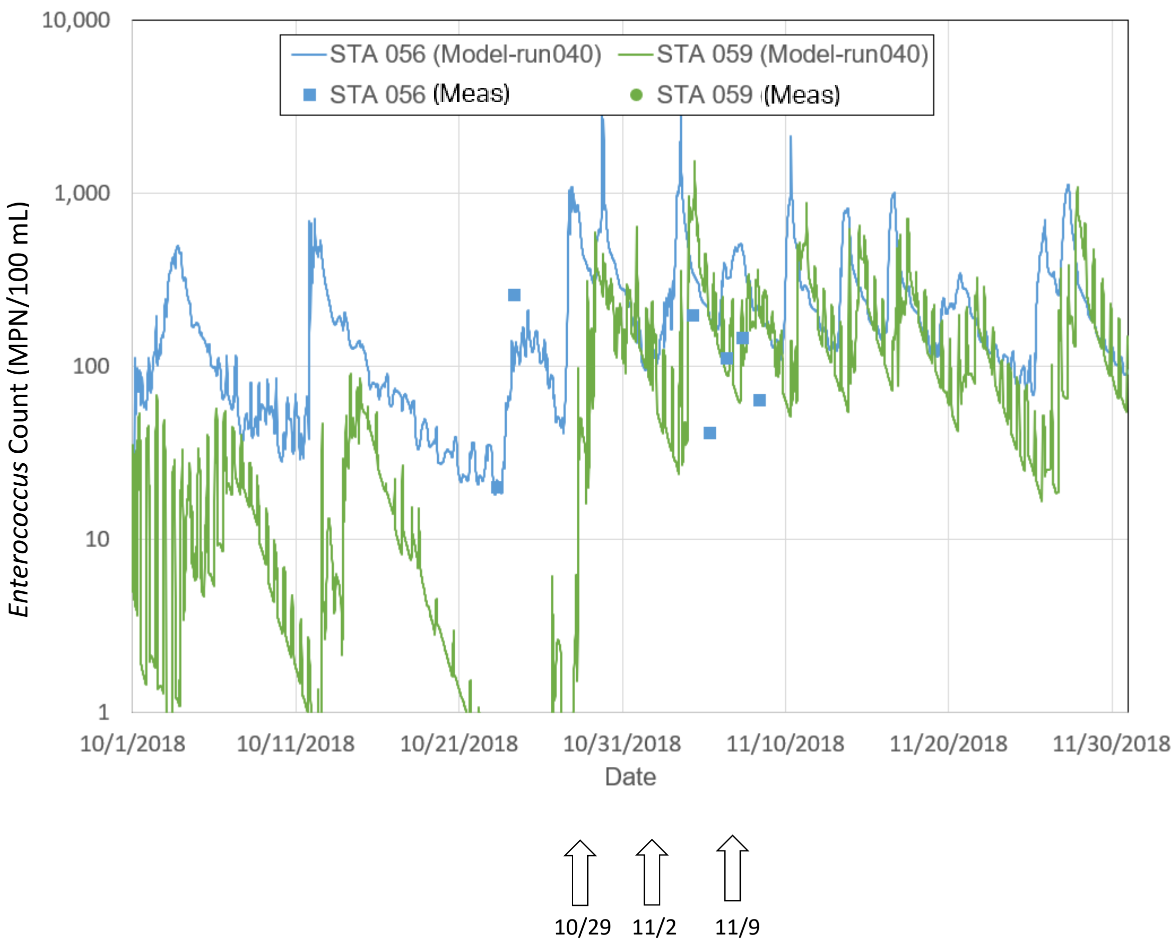

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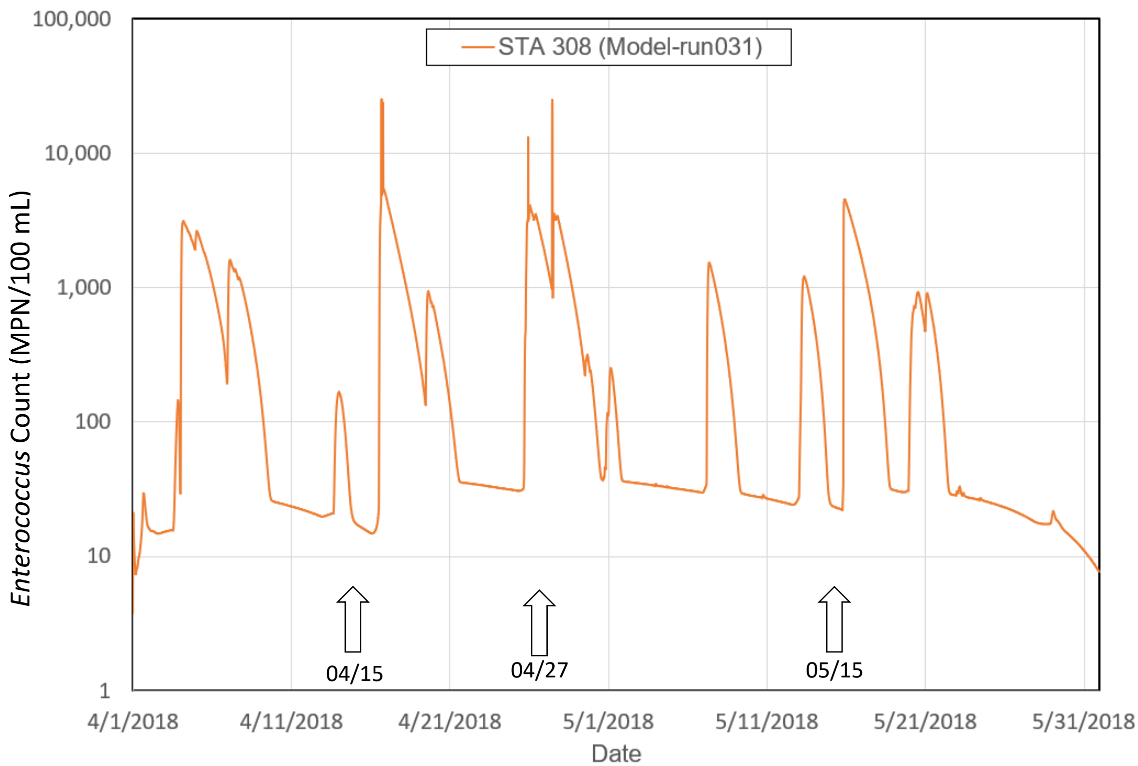
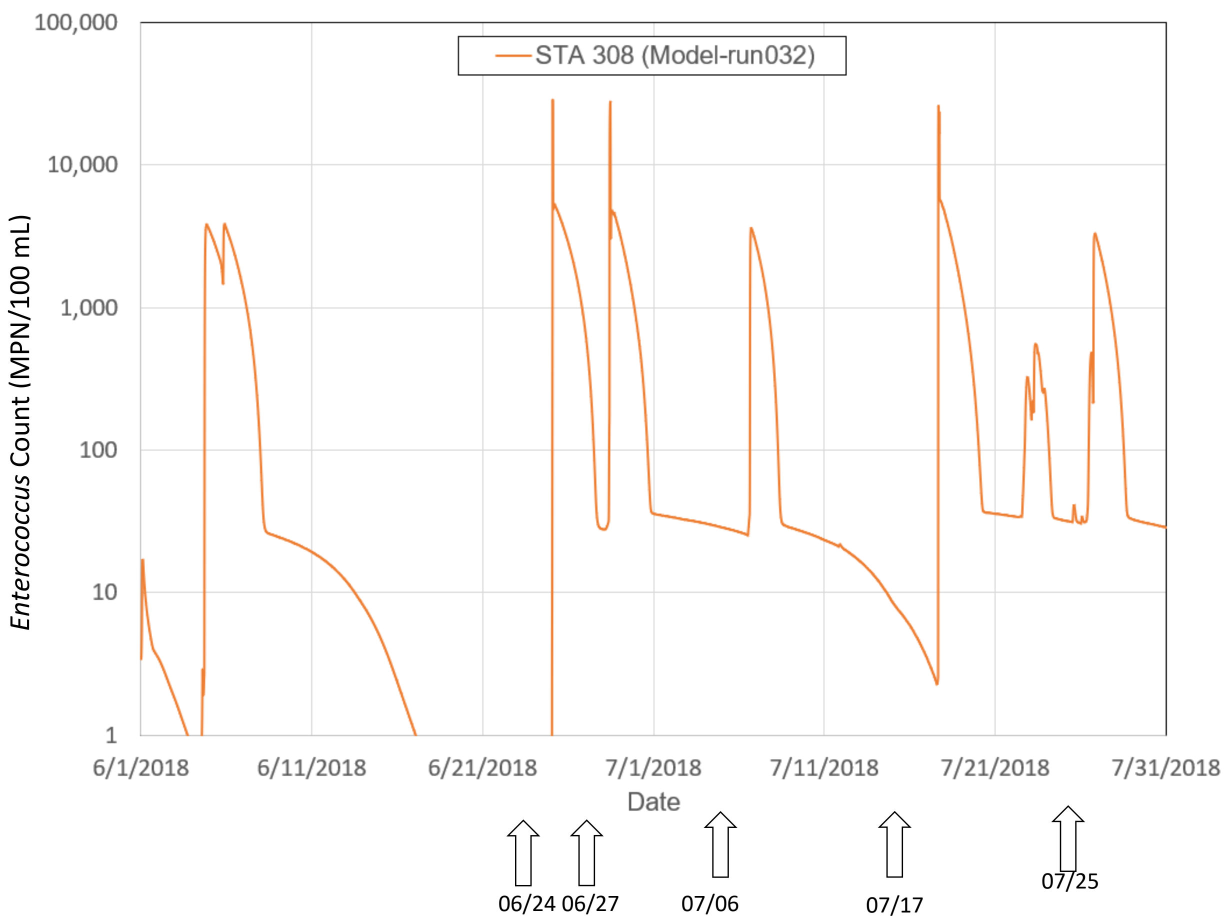
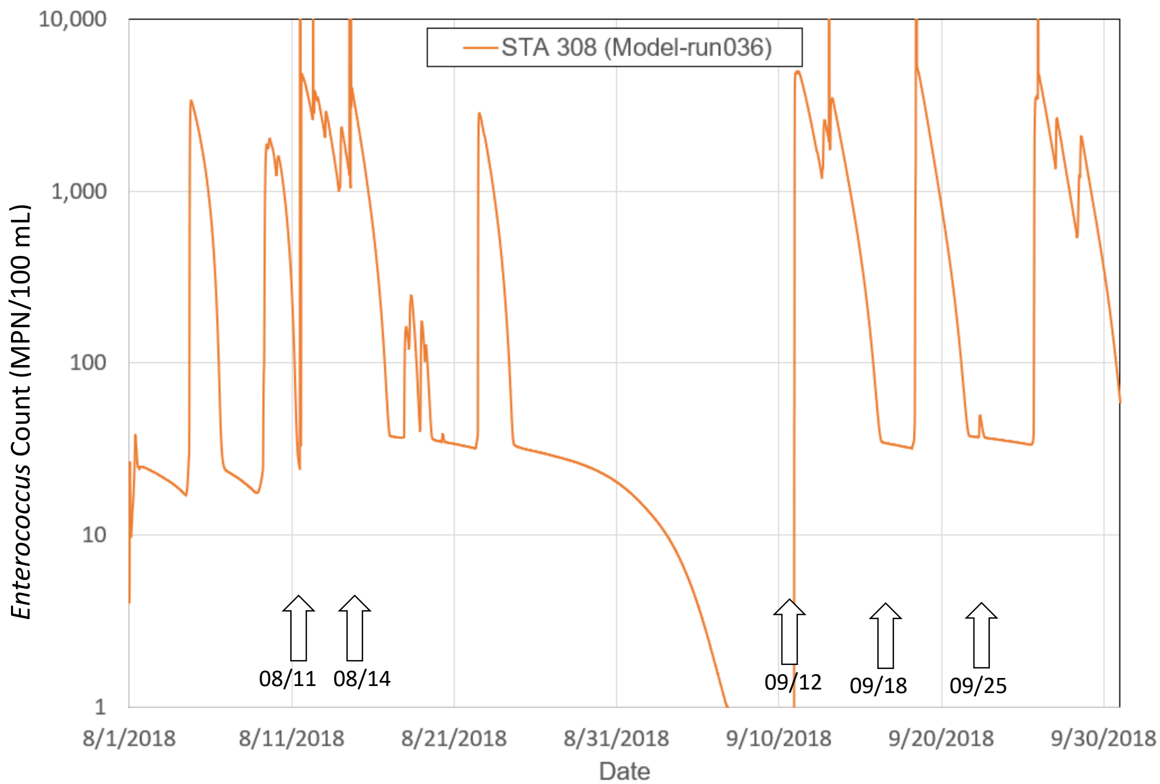
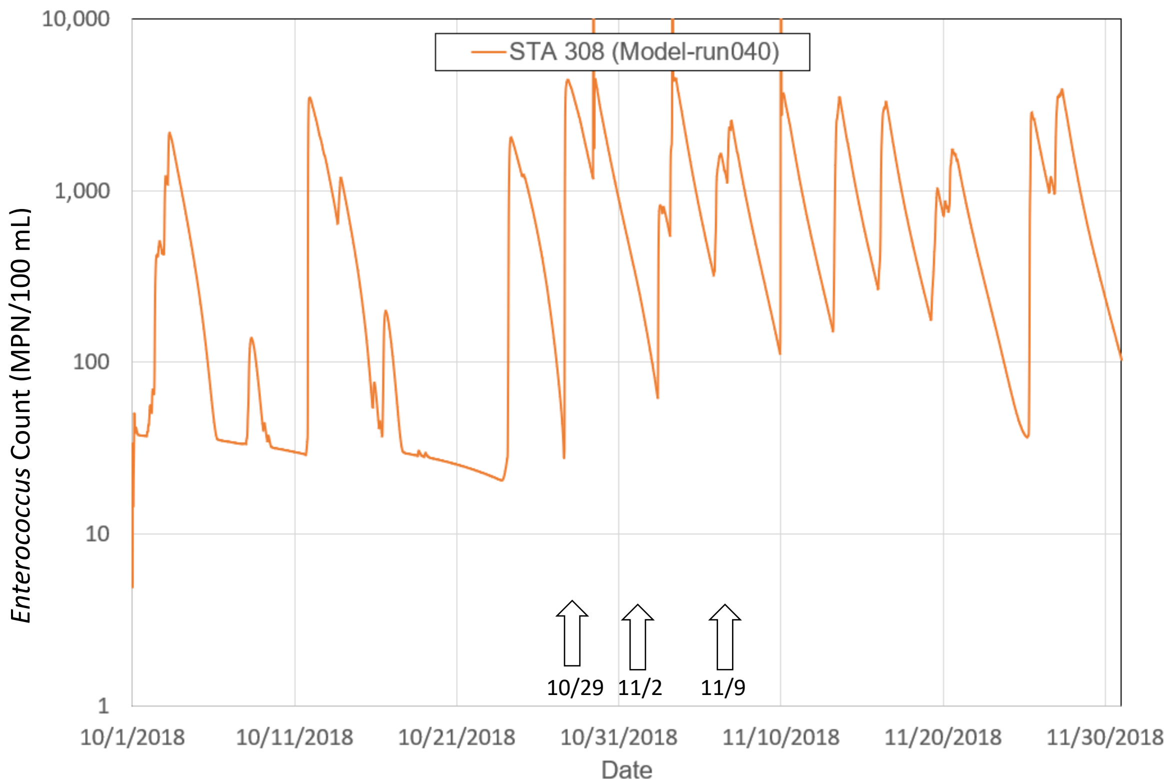




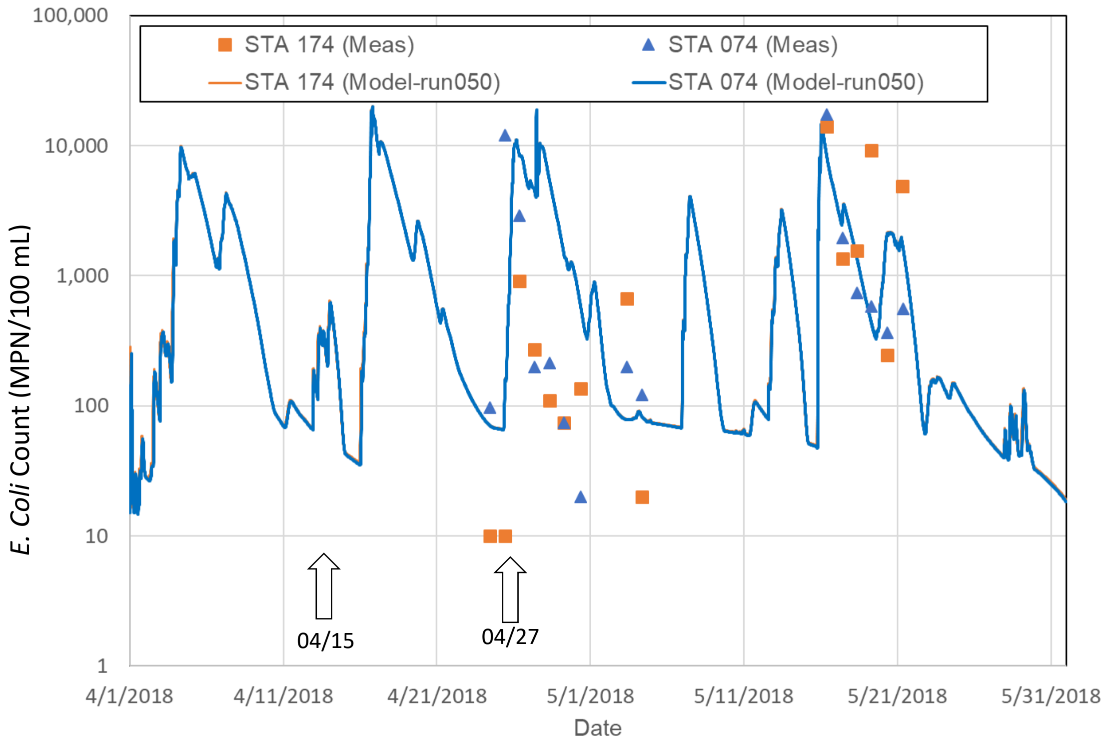
Date of model predicted CSO activation at a CSO located upstream of the sampling station

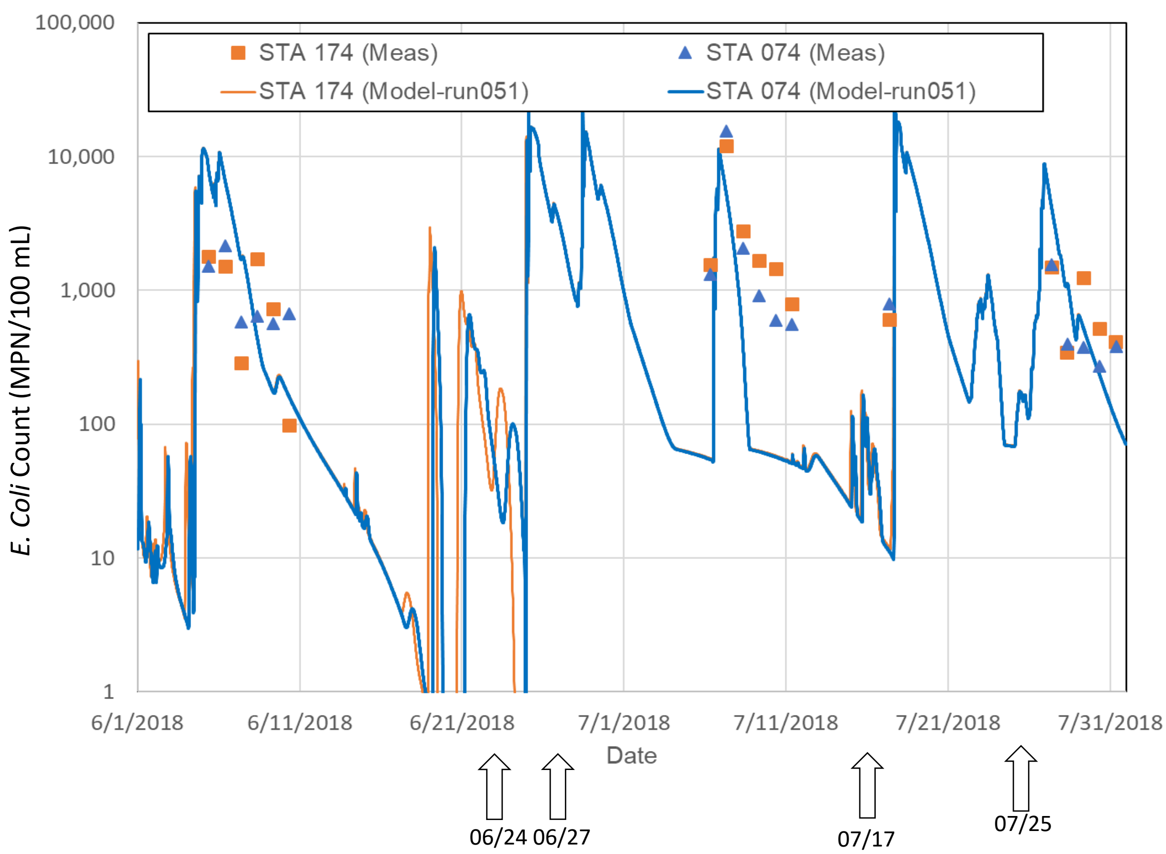




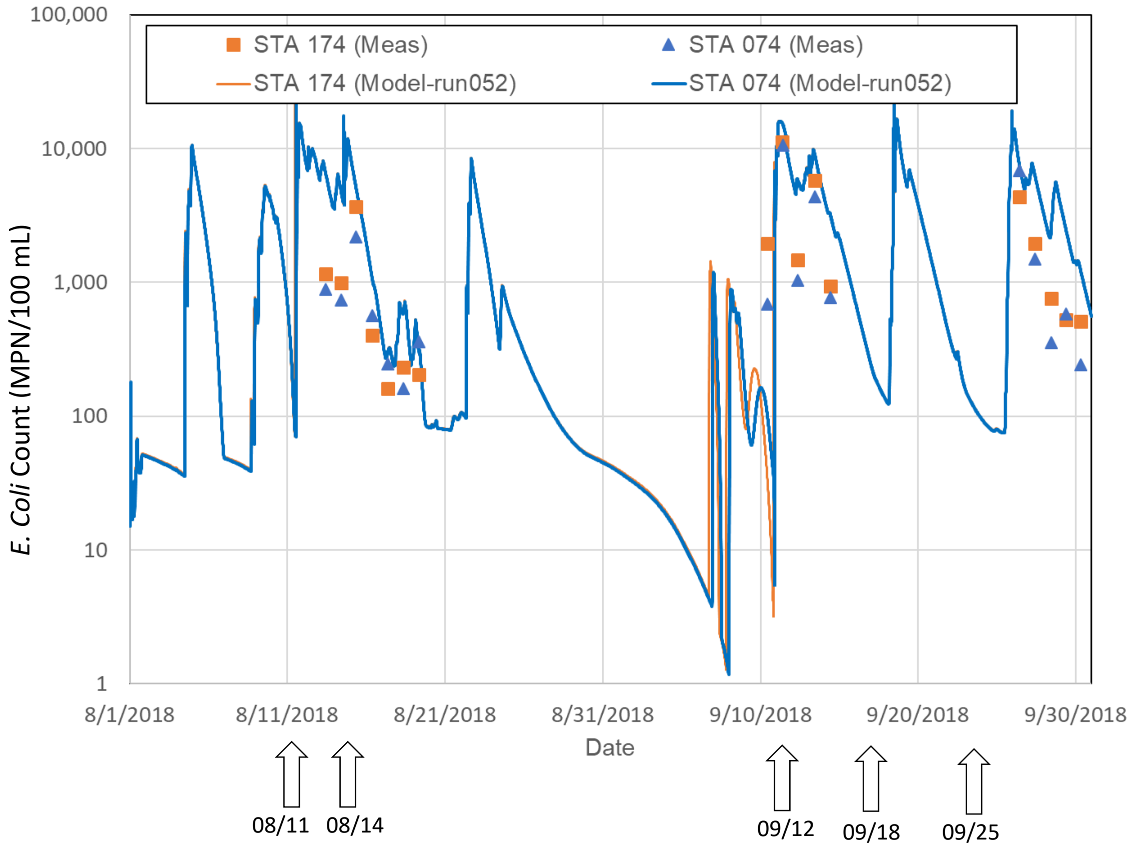
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station

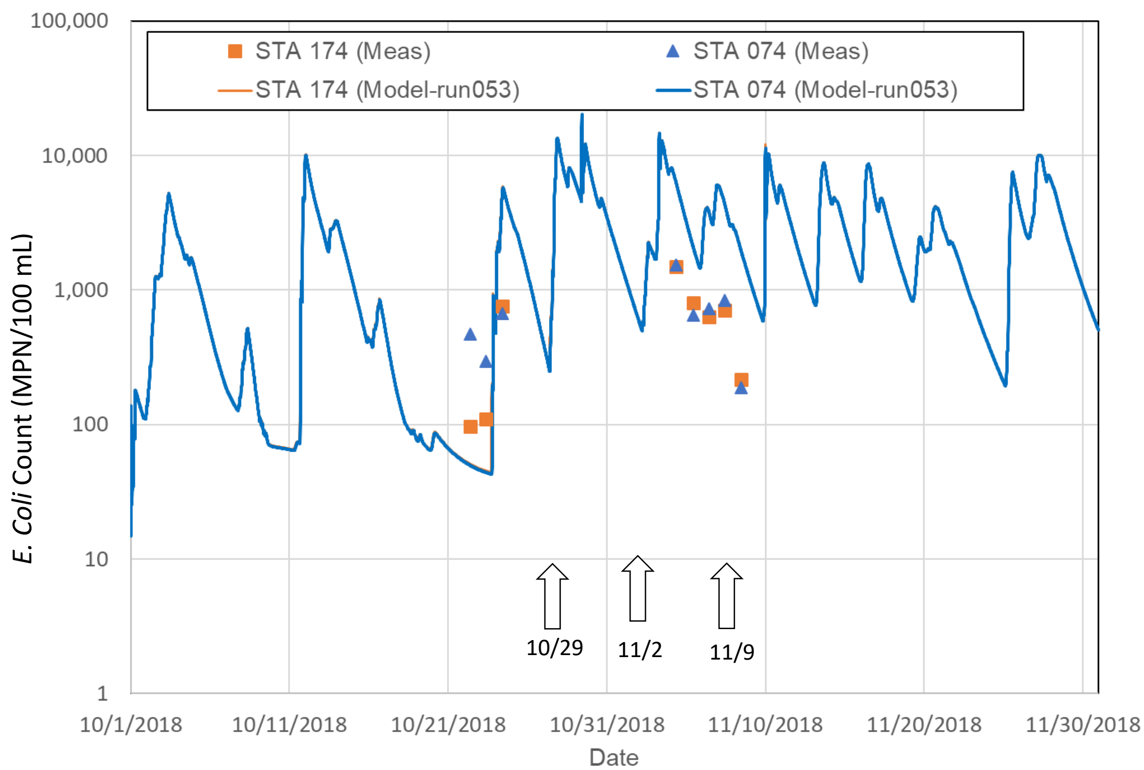
Appendix E – Alewife Brook/Upper Mystic River Model Calibration Plots – *E. coli*



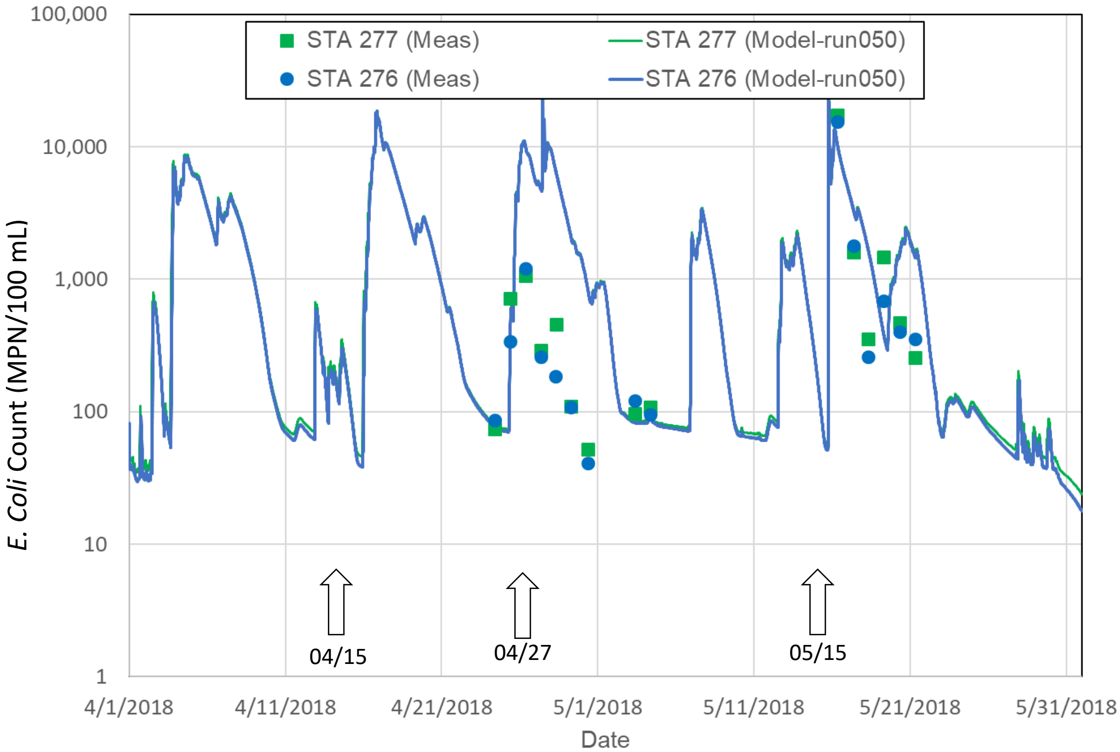


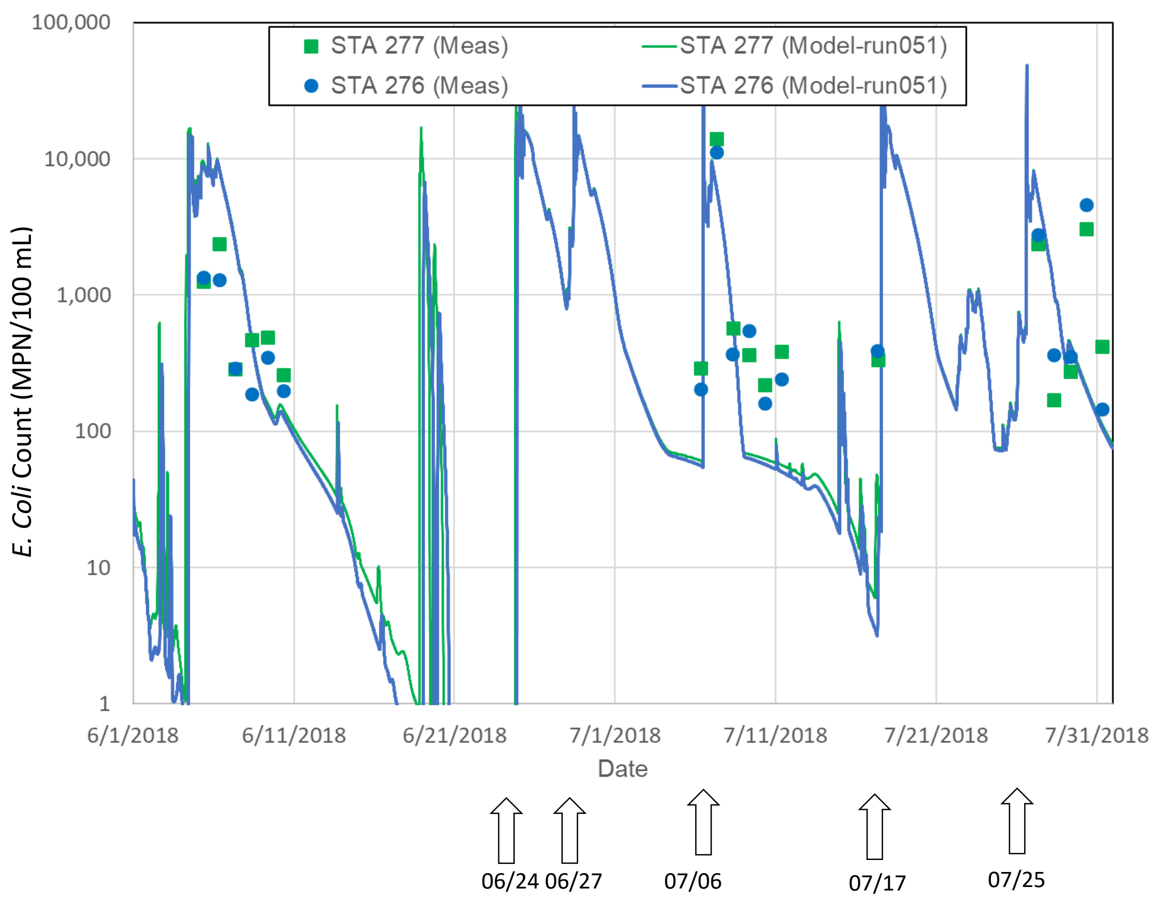
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



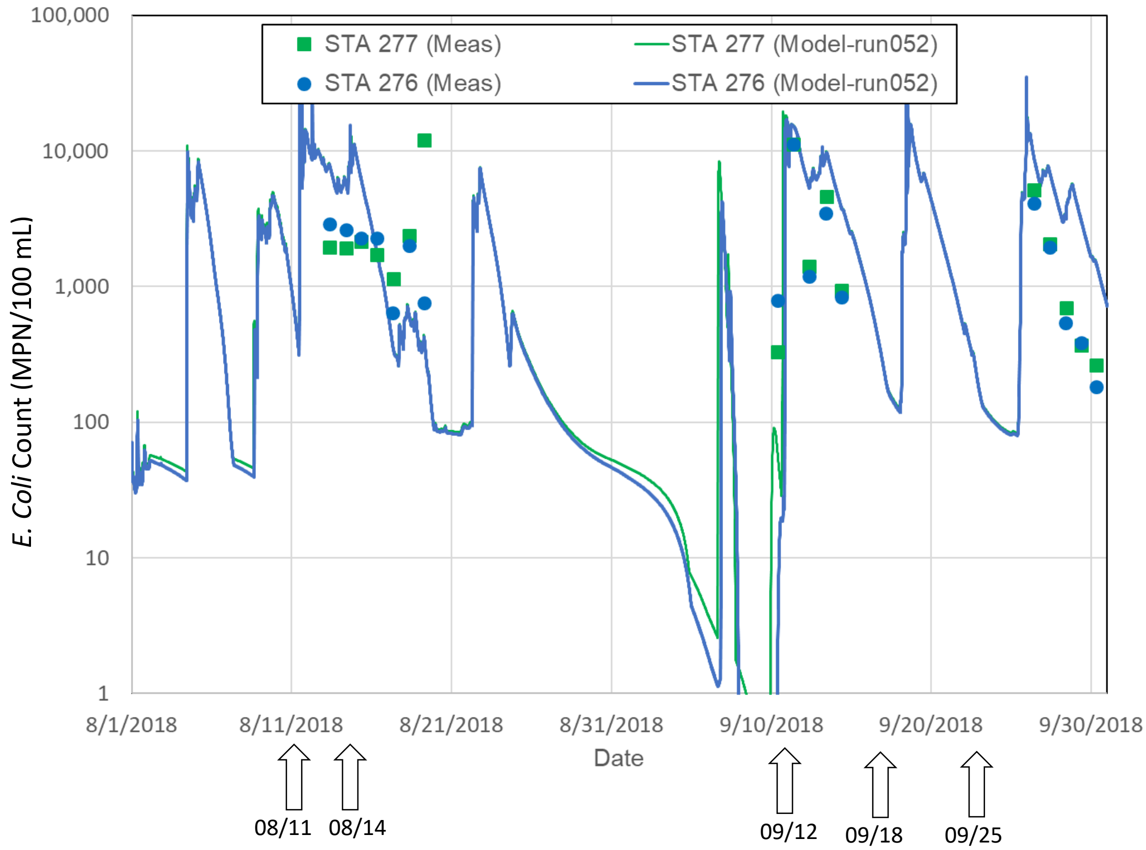


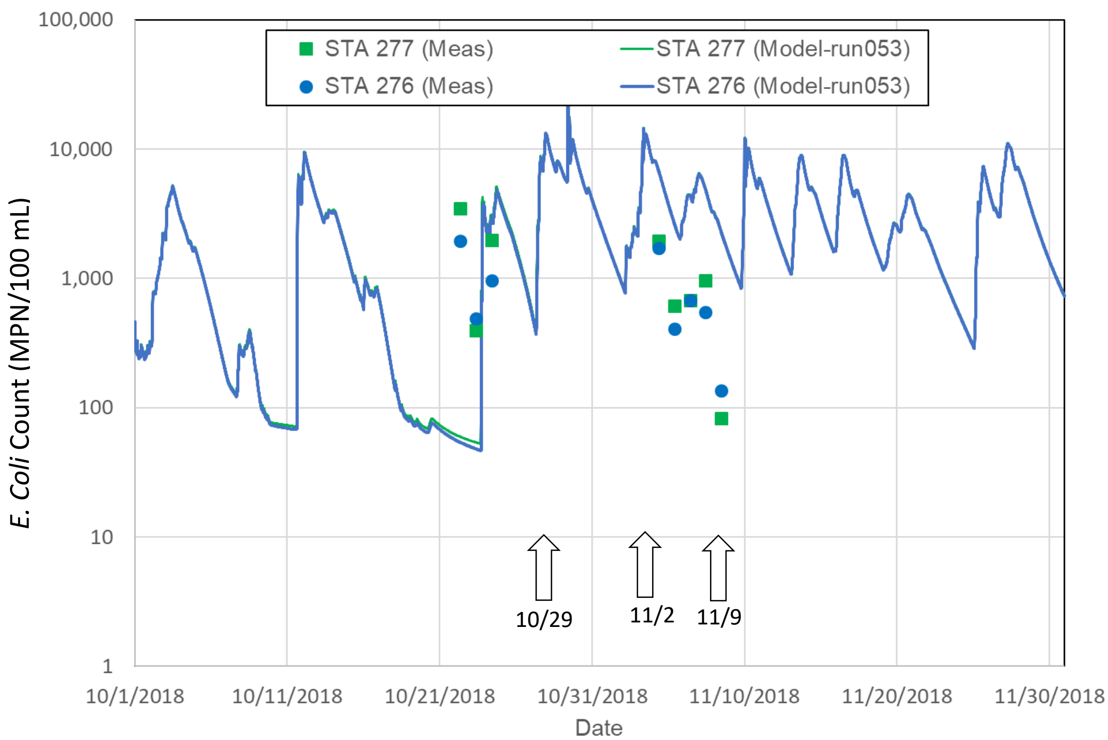
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



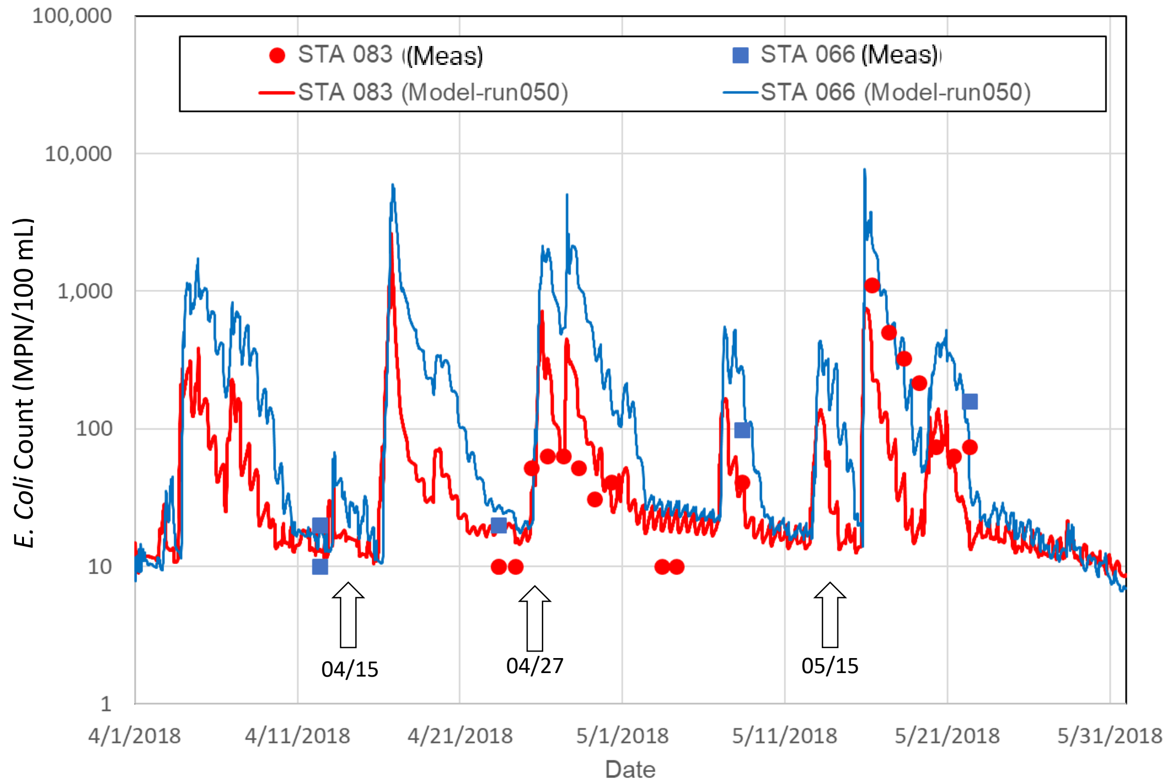


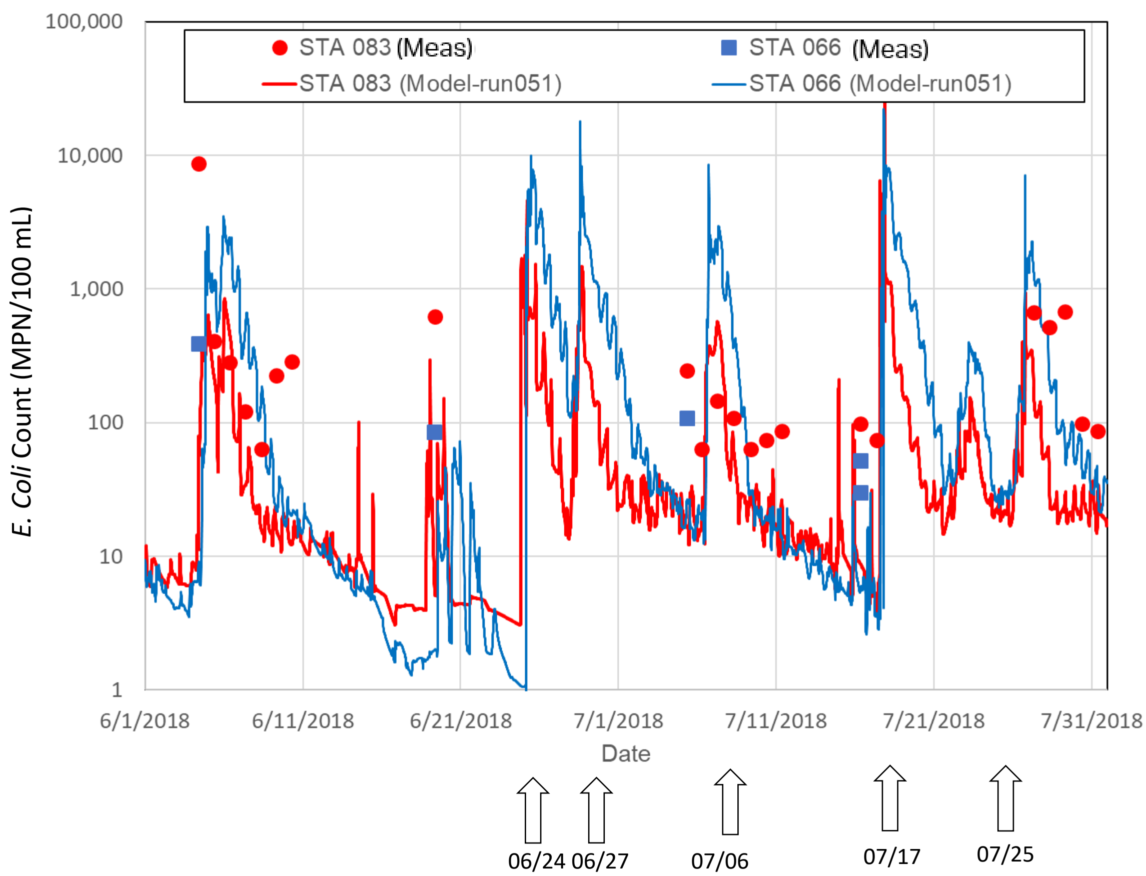
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



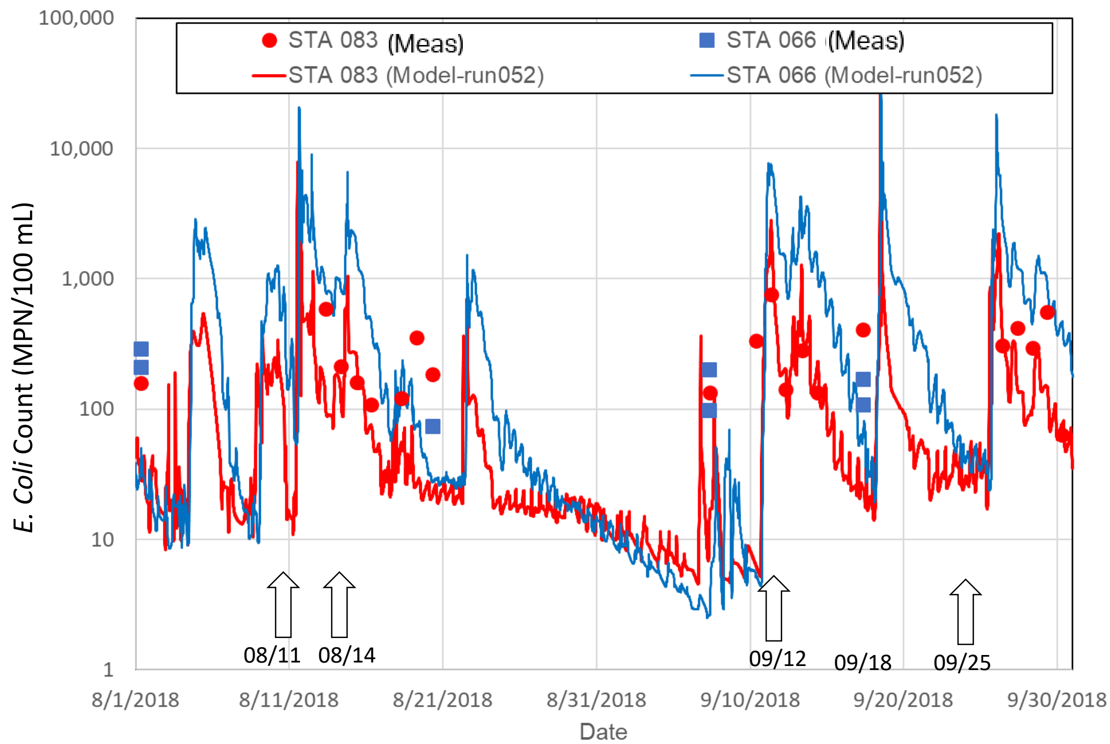


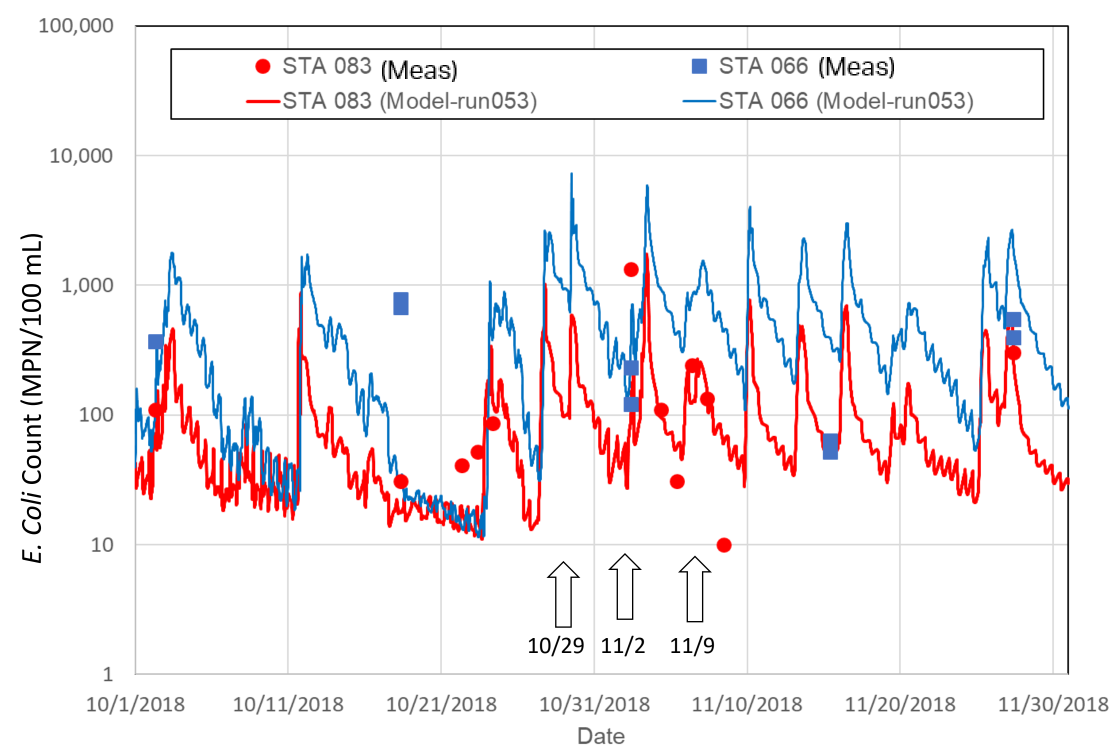
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



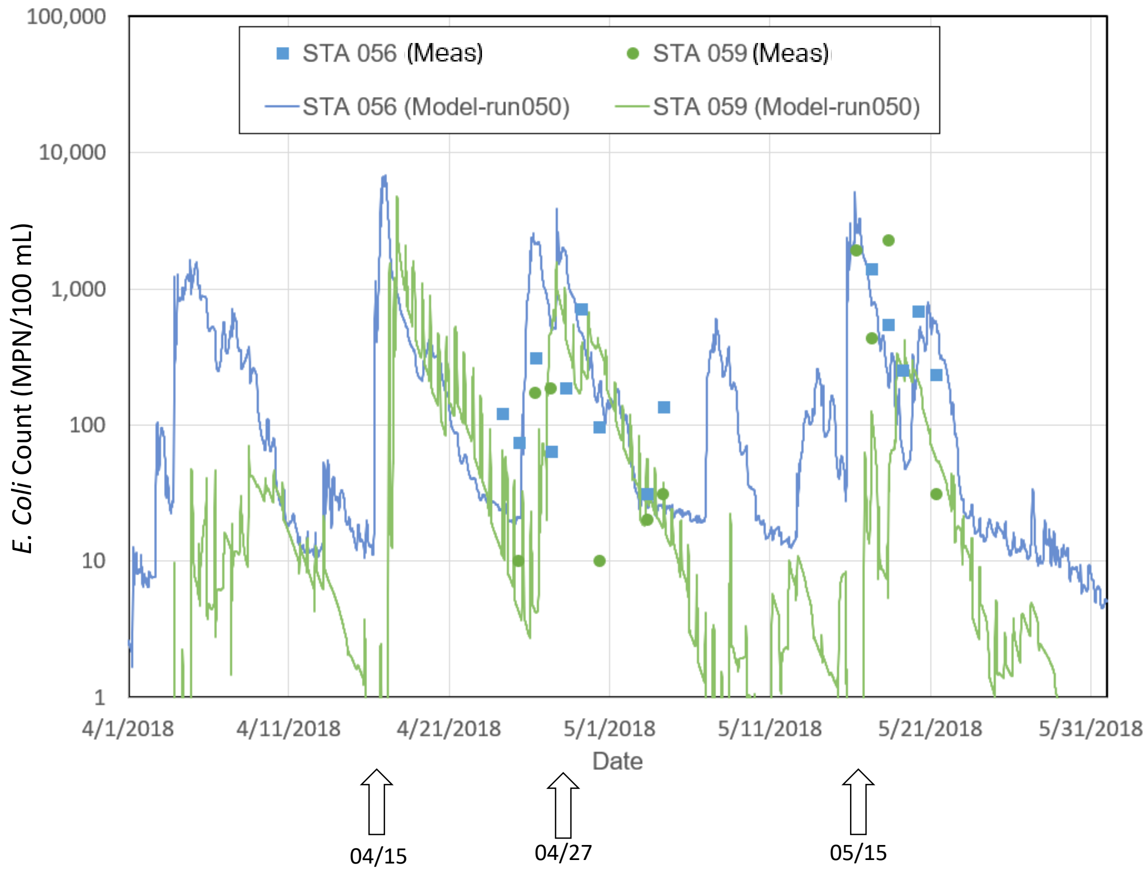


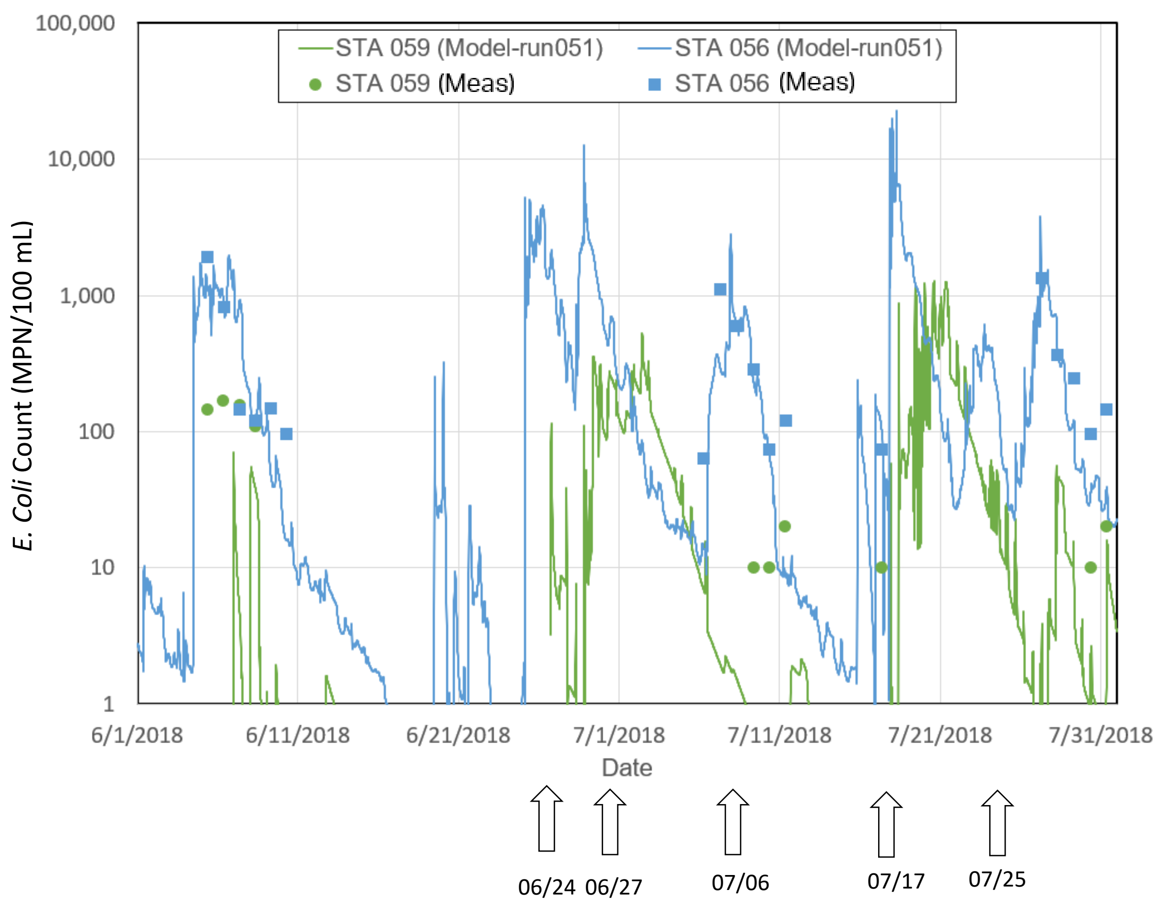
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



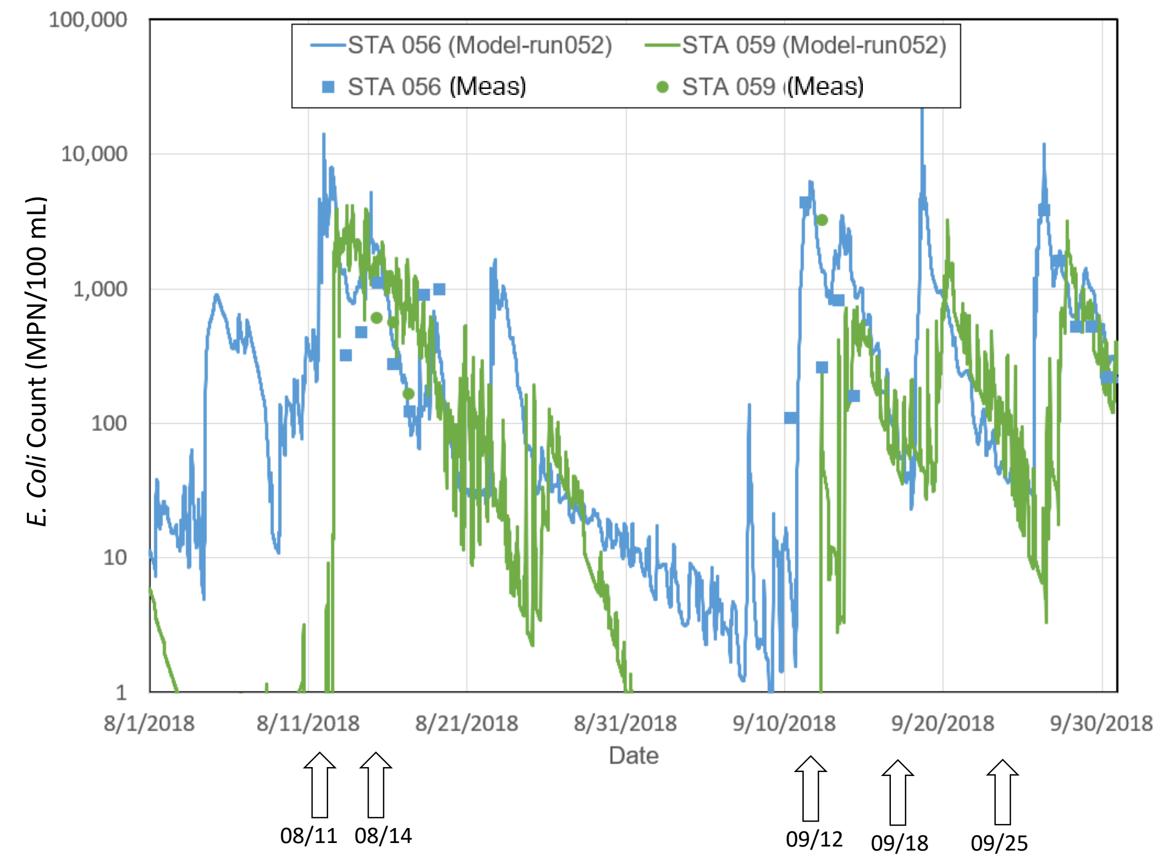


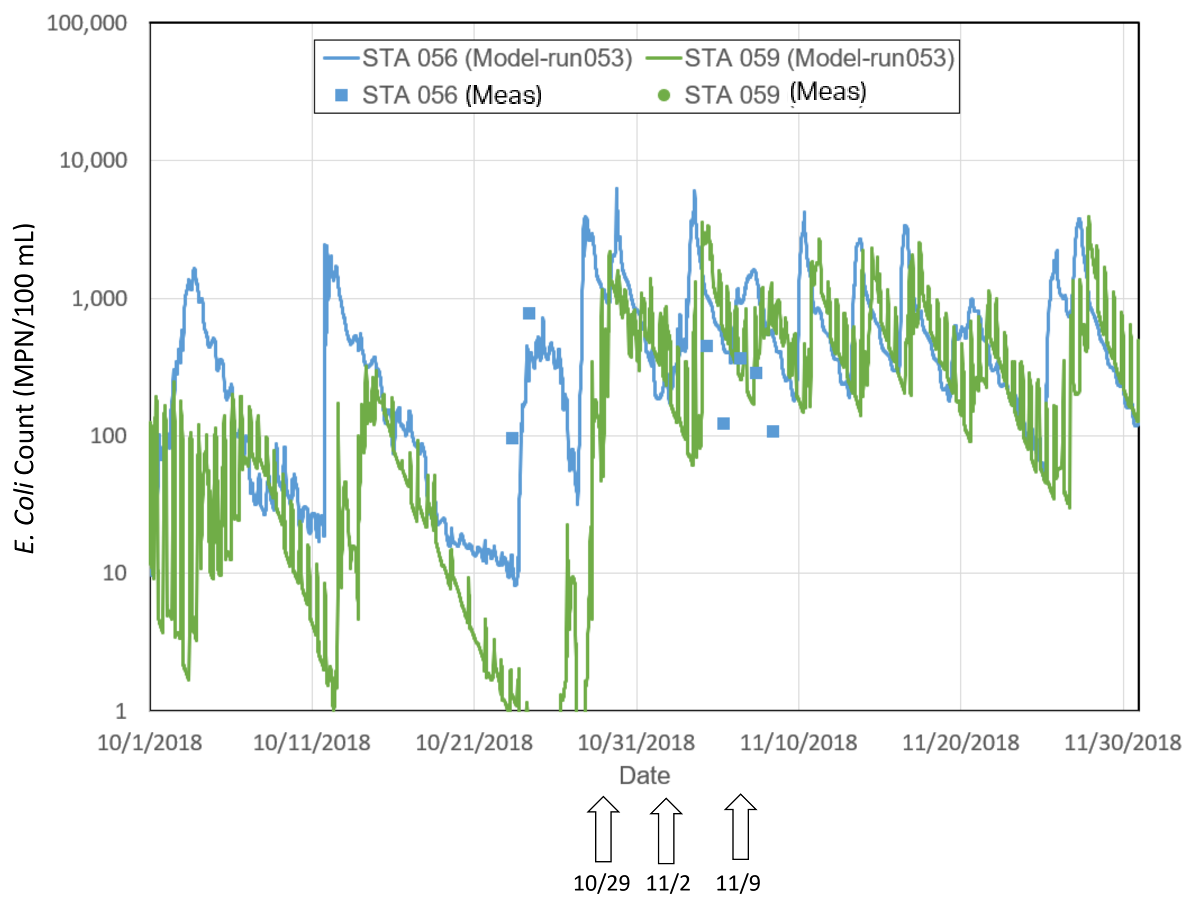
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station



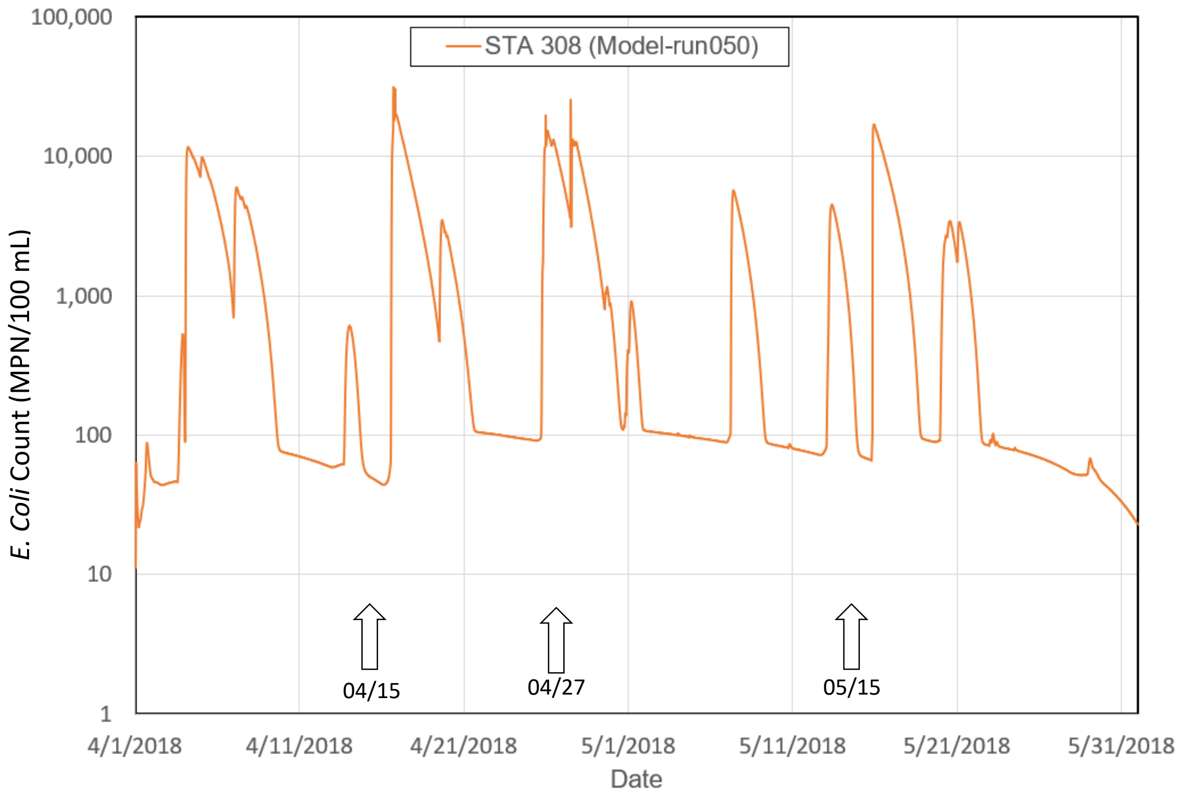


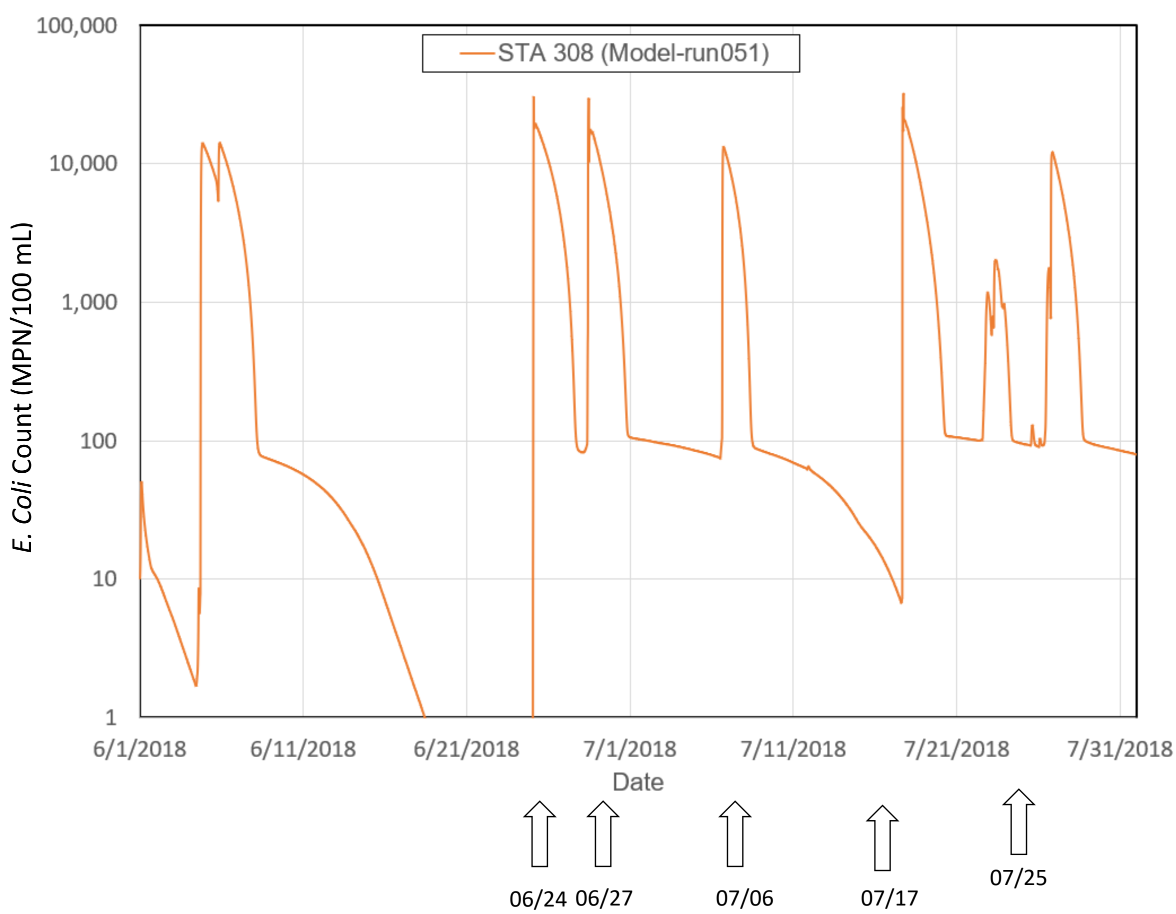
Date of model predicted CSO activation at a CSO located upstream of the sampling station



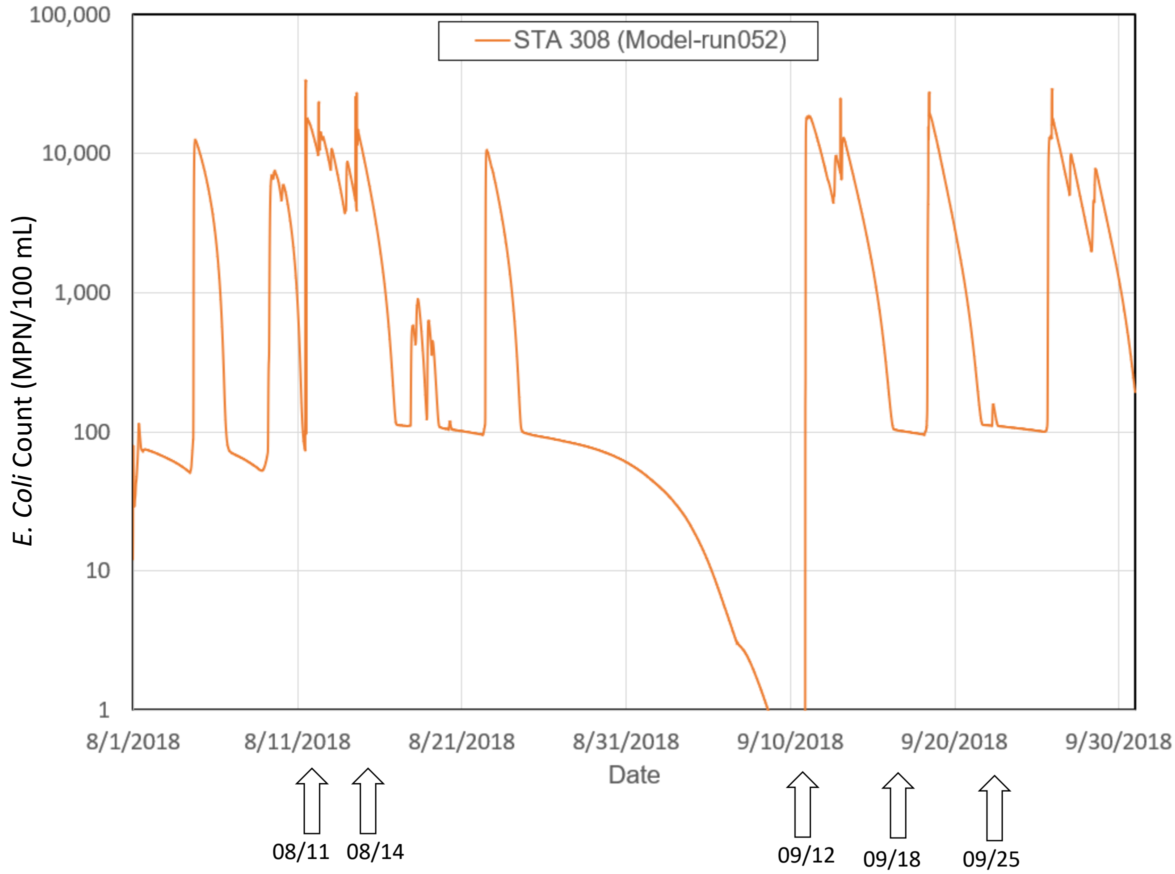


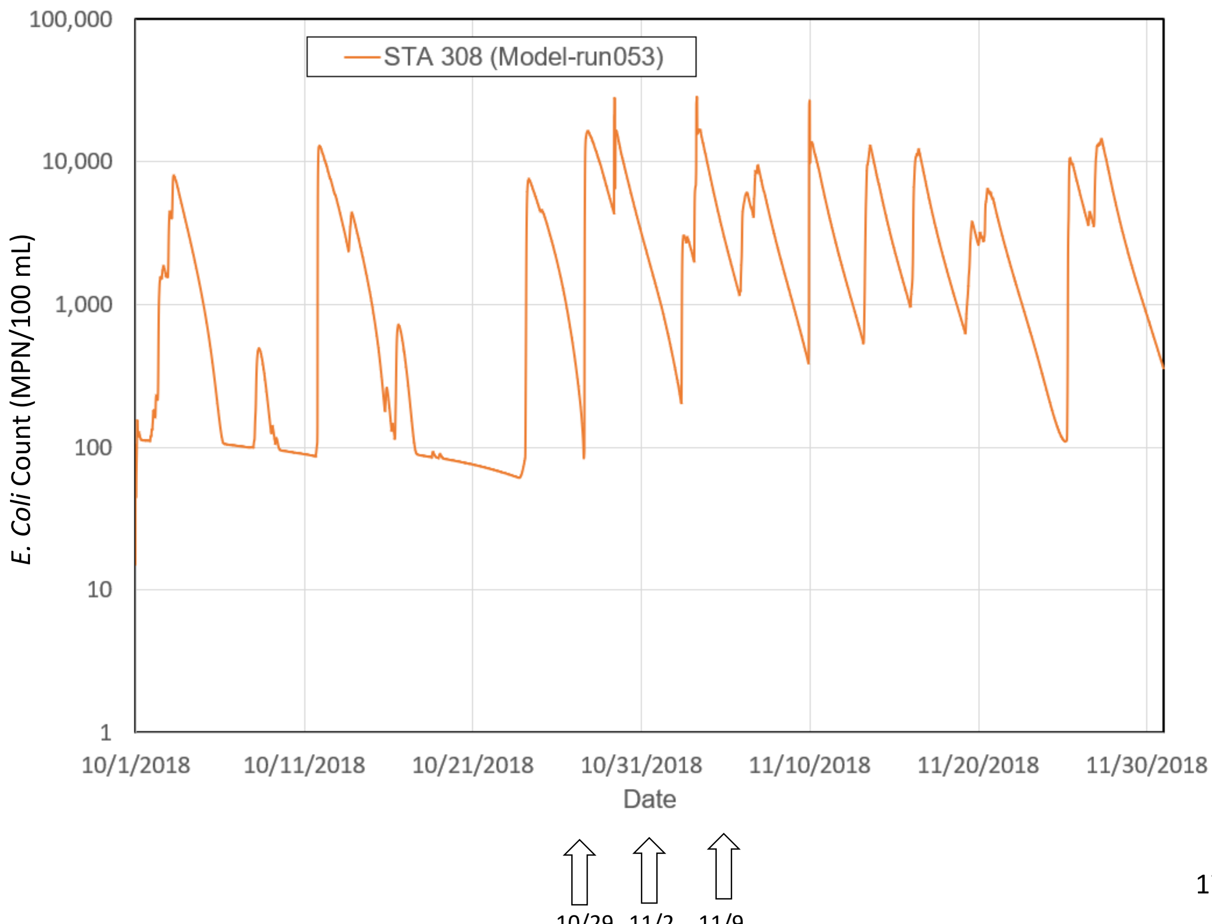
⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station





⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station





⇧ Date of model predicted CSO activation at a CSO located upstream of the sampling station

Appendix F – Correlations of Stormwater Bacterial Counts to Storm Characteristics and Catchment Land Use

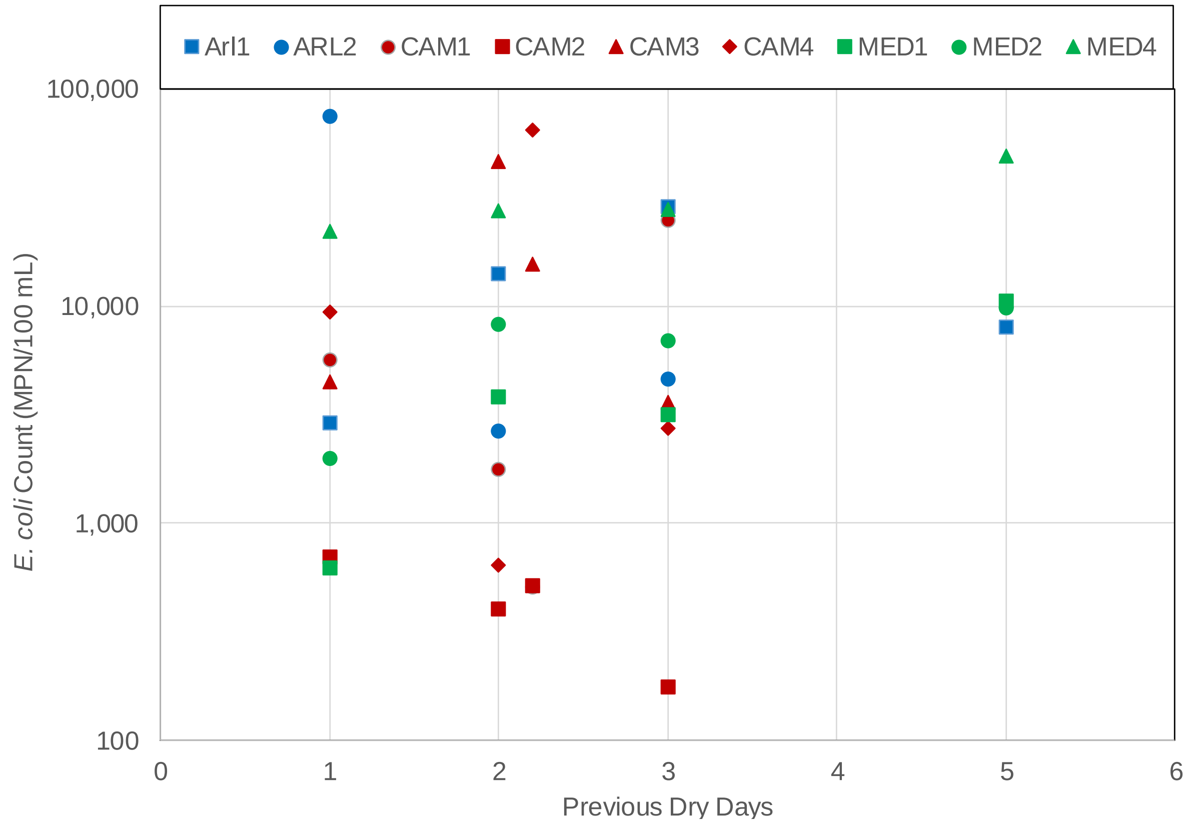


Figure F-1. Measured Stormwater *E. Coli* Counts versus Number of Prior Dry Days

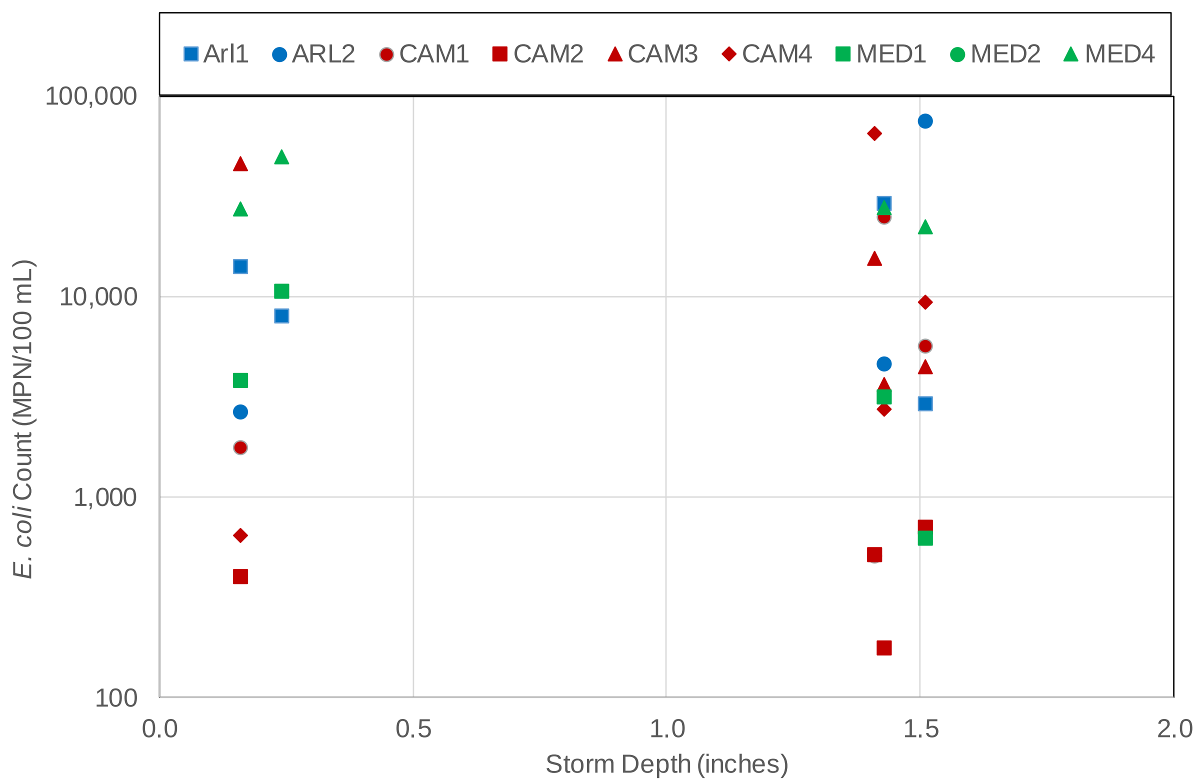


Figure F-2 Measured Stormwater *E. Coli* Counts versus Number of Prior Dry Days

Table F-1. Land Use in the Catchments Tributary to the Stormwater Monitoring Stations

Monitoring Station	Catchment Area (acres)	Land Use (Percent)			
		Industrial	Commercial	Residential	Undeveloped
ARL1	24	0	0	80	20
ARL2	49	0	5	60	35
CAM1	359	10	32	33	25
CAM2	23	0	35	38	27
MED1	433	0	13	54	33
MED2	317	1	16	31	52
MED4	337	0	5	57	38
SD04	28	0	1	68	31
SD08	23	0	0	44	56
SD10	23	0	2	44	54
SD26	15	0	0	44	56
SD28	14	0	0	55	45

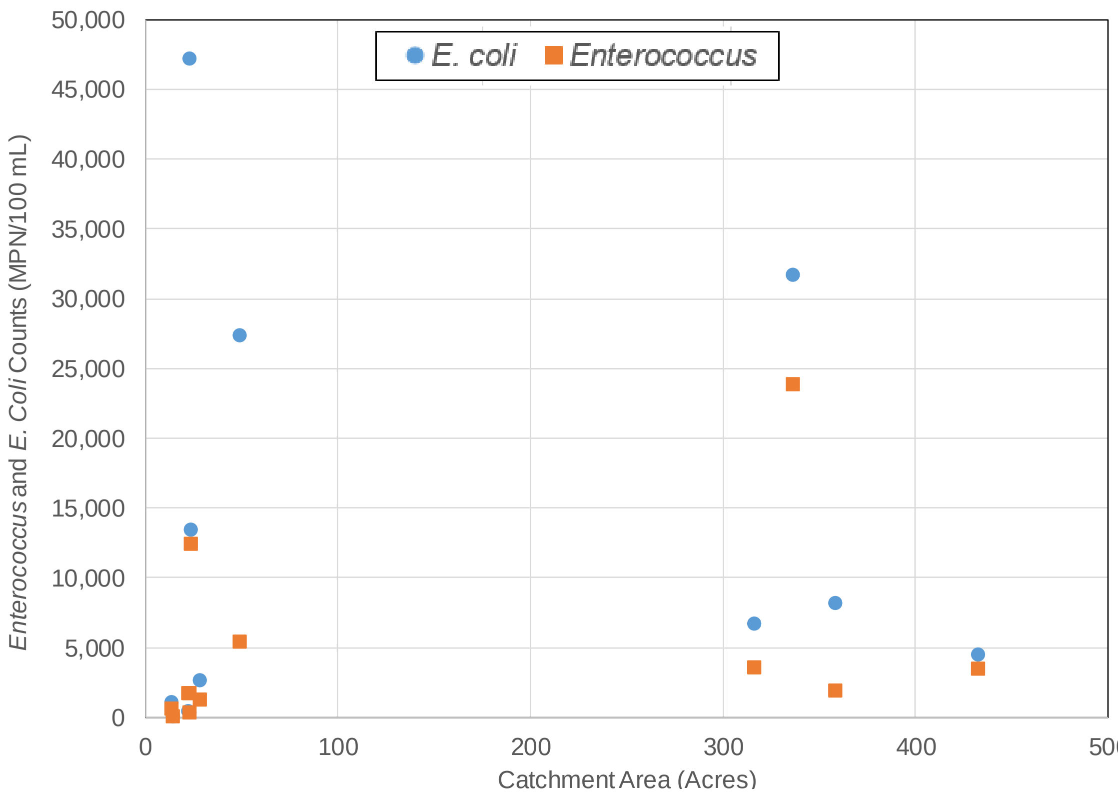


Figure F-3. *Enterococcus* and *E. Coli* Counts versus Catchment Areas

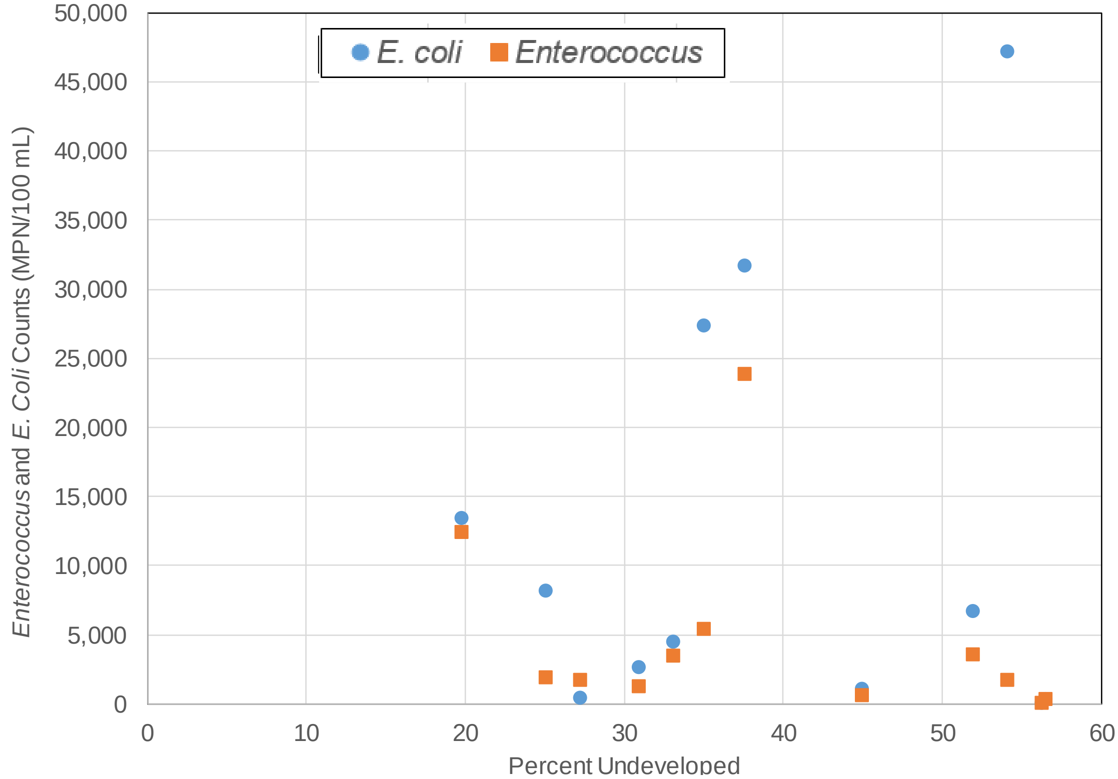


Figure F-4. *Enterococcus* and *E. Coli* Counts versus Percent Undeveloped

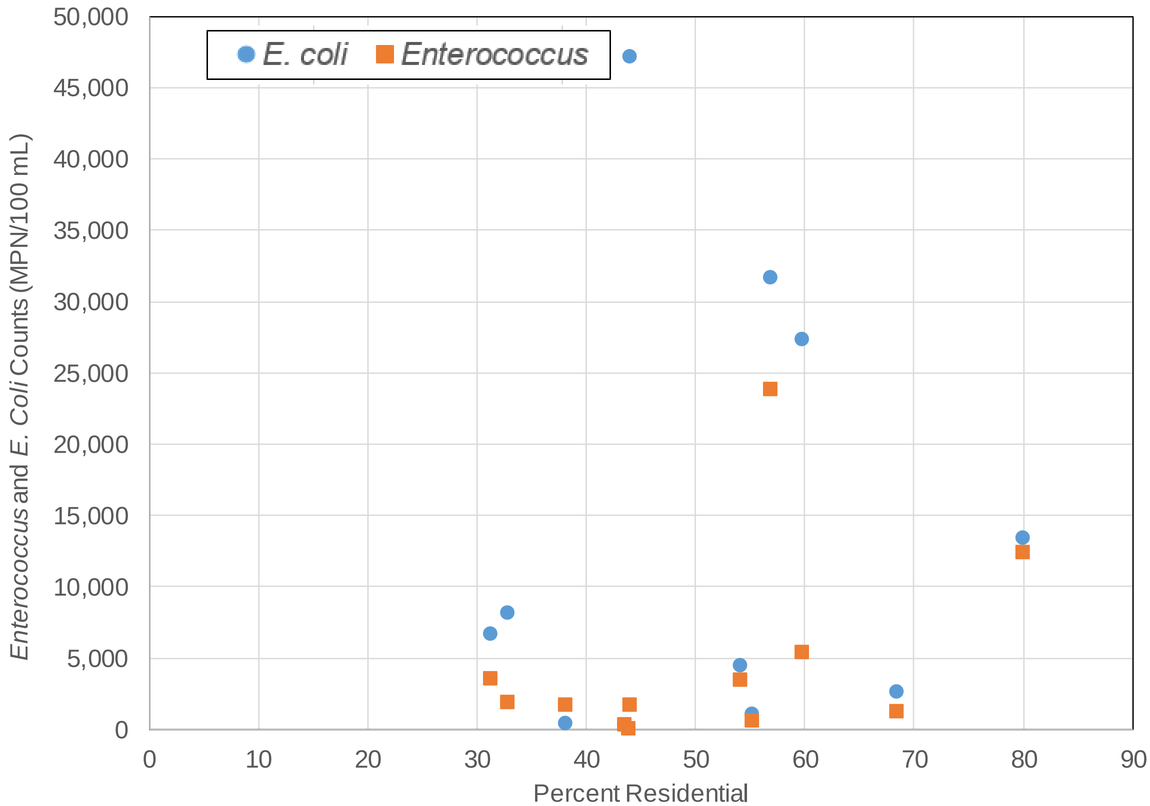


Figure F-5. *Enterococcus* and *E. Coli* Counts versus Undeveloped Area

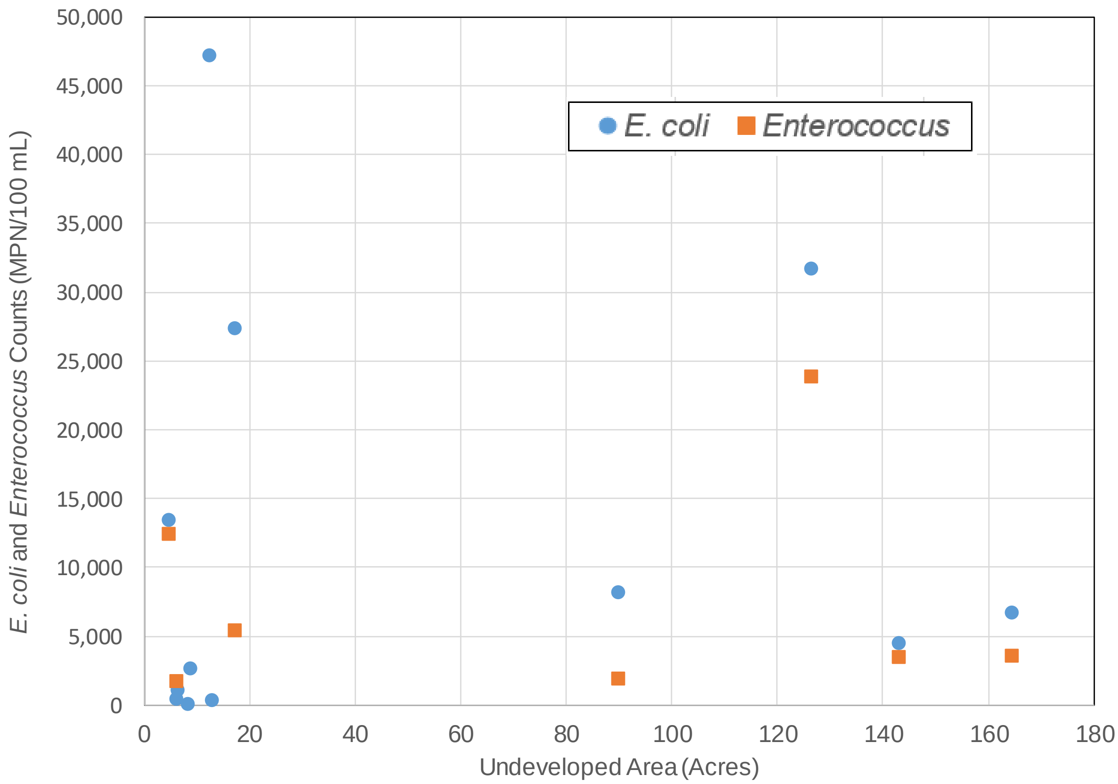


Figure F-6. *Enterococcus* and *E. Coli* Counts versus Percent Residential

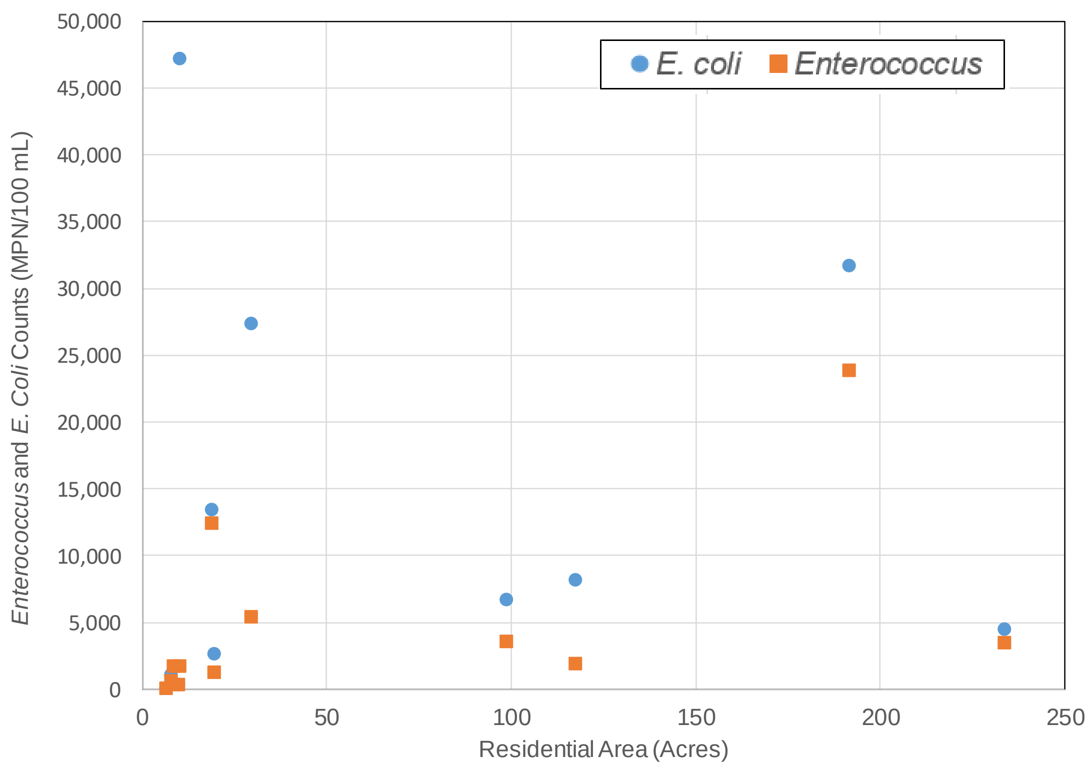


Figure F-7. *Enterococcus* and *E. Coli* Counts versus Residential Area