Appendix A

City of Burlington, Storm Water Management Model (SWMM) Update

1.0 Introduction

The purpose of this Appendix is to summarize the Storm Water Management Model (SWMM) update performed in support of the 1272 Order for the City of Burlington, VT. This Appendix will address the following items related to the SWMM update:

- Hydrologic Model Updates;
- Hydraulic Model Updates;
- Model Calibration;
- Model Validation;

The City's PCSWMM model was developed by Stantec during a previous model update in 2014. A document entitled *City of Burlington Domestic Model Development and Model Calibration, June 2016* summarized the model's development, calibration and validation. This model was reviewed by AECOM and several improvements were suggested. The City of Burlington then performed additional model updates, which involved subdividing some of the catchments and incorporating changes in the collection system that were discovered or occurred after 2016. This Appendix will focus on the modifications and updates performed since 2016. The advanced modeling software PCSWMM by Computational Hydraulics International (CHI) was used during the SWMM model update.

Based on the calibrated model, scenarios can be tested to predict how flow rates and volumes could change in response to infrastructure improvements and implementation of stormwater management practices. This model focuses on the Main Plant and will be used to predict how reductions in combined wastewater volume and peak flows (i.e., through sewer separation, in-line storage, or implementation of stormwater infiltration practices) might change annual peak flows, treated wastewater volume, and phosphorus loadings discharged from the Main Plant.
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2.0 Hydrologic Model

The 2016 version of the City's SWMM model consists of runoff catchments in the combined sewer areas and RTK unit hydrographs in the separated sewer areas. The combined subcatchments are used to generate wet weather runoff using the non-linear reservoir model in SWMM. The RTK unit hydrographs are used to generate inflow in the separated areas. As part of the model refinements, the RTK unit hydrographs were replaced with sanitary sewer subcatchments, which allowed the SWMM groundwater routines to be used to generate seasonal groundwater inflow where this was observed in the flowing metering data.

The subcatchment parameters (areas, slopes, lengths and widths) were adjusted using GIS tools. While the initial subcatchment properties were developed from GIS procedures, subcatchment properties were adjusted as needed during the calibration process. The subcatchment property modifications were generally slight adjustments to provide a closer match to the calibration data. The initial width of the catchment was based on the equivalent radius of the catchment, which was then adjusted based on the model calibration. The percentage of impervious area was calculated based on GIS data provided by the City. A portion of the impervious area was routed to pervious areas to account for some impervious areas, such as roofs that drain to pervious surfaces, such as backyards. The proportion of the impervious area that is routed to pervious surfaces was adjusted during model calibration. The revised combined subcatchments are shown on Figure 2-1.

In certain areas, the SWMM groundwater module was applied where the metering data appeared to show a significant groundwater component as indicated by a trailing source of inflow after the peak of the storm. The groundwater module applies a groundwater aquifer to its corresponding model subcatchment. The parameters of the flow interaction between the aquifer and the model network can be adjusted to achieve an adequate calibration.

The rainfall data used to run the models were provided by the City and verified against available National Oceanic and Atmospheric Administration (NOAA) rainfall data. The City collects rainfall data in fine increments (15-minute intervals) and the NOAA data are only available in hourly increments. The NOAA data were generally used to compare total rainfall amounts to the City data, but the resolution of the City data were preferred for the modeling. A summary of the calibration events used in the updated calibration is discussed in Section 4.

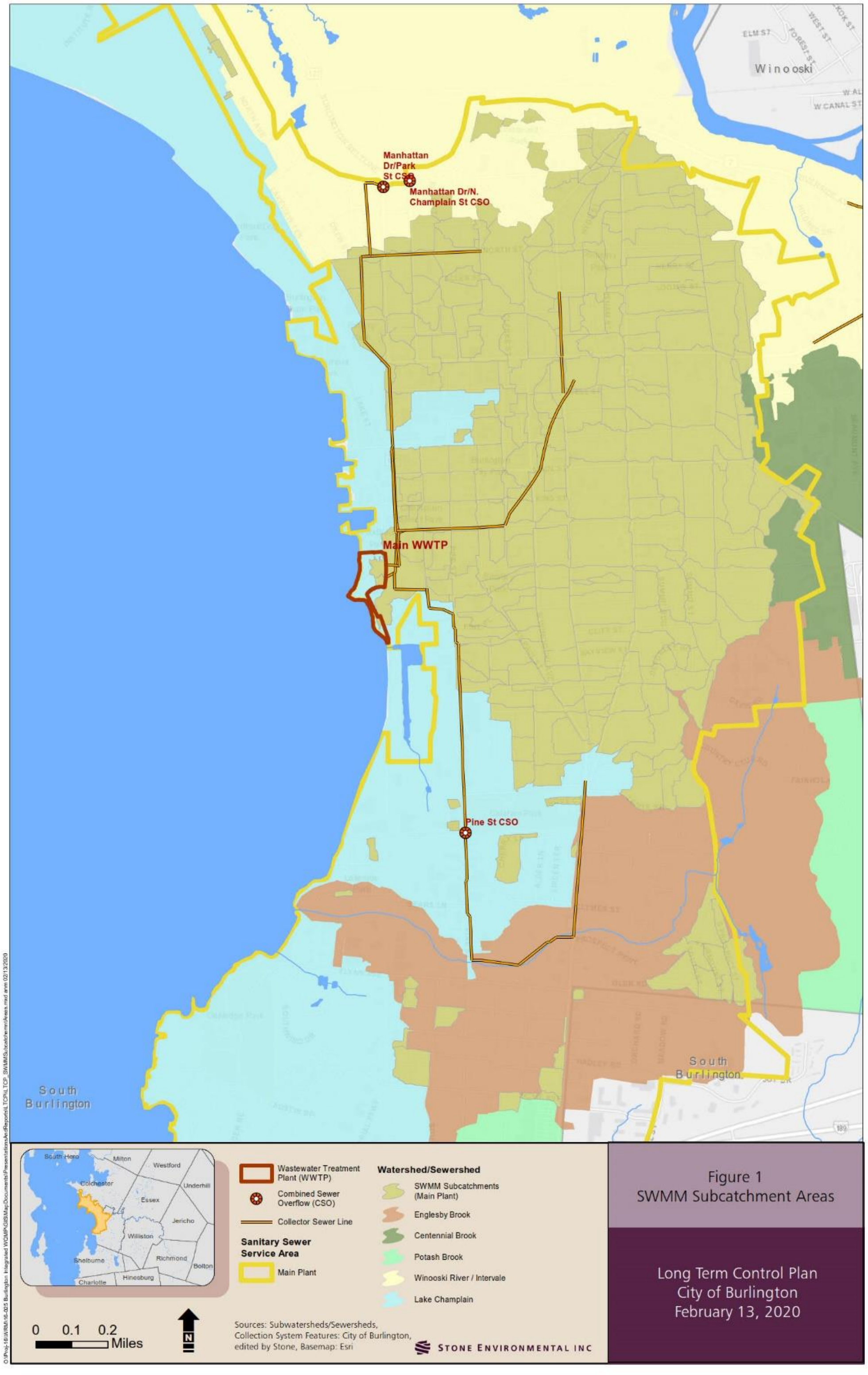

Figure 2-1. Combined Subcatchment Delineations

3.0 Hydraulic Model

The SWMM model's hydraulic network consists of conduits, nodes, storage, pump stations, controls (e.g., gates), weirs, orifices and outfalls. The following section summarizes the major changes made to the hydraulic model during the model update.

The model was updated based on the metering location schematics, and sketches provided by the City for specific locations as requested – typically at high point reliefs between subcatchments in the collection system. The model was updated to reflect the actual flows directed to the vortex at the WWTP.

The model time-steps used were 5 minutes for both wet and dry weather. For long-term model runs, the routing time step was 10 seconds which maintained an appropriate level of model stability.

4.0 Model Calibration

Model calibration is based on flow metering programs completed in 2014 and 2017-2018, as well as working with the existing model calibration completed by Stantec for the City in 2014. The Stantec model included an extensive water usage study to complete the dry weather analysis. Based on this extensive sanitary study, the sanitary baseflows were used in the 2020 model from the City of Burlington Domestic Model Development and Model Calibration, June 2016. Due to the level of detail associated with the dry weather calibration with the 2014 meters, the dry weather flow calibrations were minimally adjusted for the subcatchments. The Stantec model was then updated by the City including revisions to pipe network and subcatchment areas. The focus of the 2020 model update was wet weather calibration and replacing the RTK parameters with the groundwater module based on the flow metering.

Flow Metering:

> Flow metering of the Main WWTP collection system was conducted for the purpose of development and calibration of the collection system model. In addition, flow data established which areas of the City contribute relatively more or less flow, where infiltration and inflow may be disproportionately high, and how and where the timing of peak flows may contribute to CSO events.
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> A flow monitoring plan was developed by Stone Environmental for the purpose of identifying monitoring locations, schedule, and instrumentation to install. Stone's *Flow Monitoring Plan for Burlington's Combined Wastewater Collection Systems*, dated July 11, 2017 is presented in the 60% PER.
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> Flow data were collected at multiple points in the collection system and over a range of weather conditions, including summer and spring storm events and dry weather flows. The City previously installed six (6) flow monitors in the Main WWTP collection system in 2014. Five (5) additional Blue Siren flow monitor locations were identified, with multiple flow meters installed at each location for a total of 23 flow meters in 2017. The flow metering data collected in 2017 were reviewed and the quality of the flow data were questionable. It was recommended that additional flow monitoring continue through 2018 in order to collect higher quality data that could be used to calibrate the collection system model.

The meters were deployed in 2014 and 2017 to 2018 and locations are summarized in Table 4-1 and shown on Figure 4-1. Including the flow meter at the WWTP, there were a total of 8 flow meters deployed for 2014 and 25 for 2018.

Table 4-1 presents the following information for the 2014 and 2017 to 2018 metering periods:

- Meter name. For example, FM2014-1 designates flow meter (FM) 1, installed in 2014.
- Model node. This is the node (manhole or similar structure) in the model where the meter was located.
- Calibration storm events. While all metering data were used for dry weather calibration, select meter data were used for wet weather and groundwater calibration. Date ranges represent the dates for which particular meter data were used. Since 2017 to 2018 meter data do not cover the spring groundwater period, data from April 2014 were used. This column in the table also notes that certain meter data are considered not applicable (N/A) based on certain issues with the data.

The goal of the calibration update was to establish a single set of parameters that would be representative of collection system performance over the entire year. The previous model calibration adjusted certain parameters to calibrate on a storm by storm basis. The previous approach is suitable for analyzing discrete storm events but is not appropriate for long-term model simulations which are more appropriately based on a single set of input parameters.

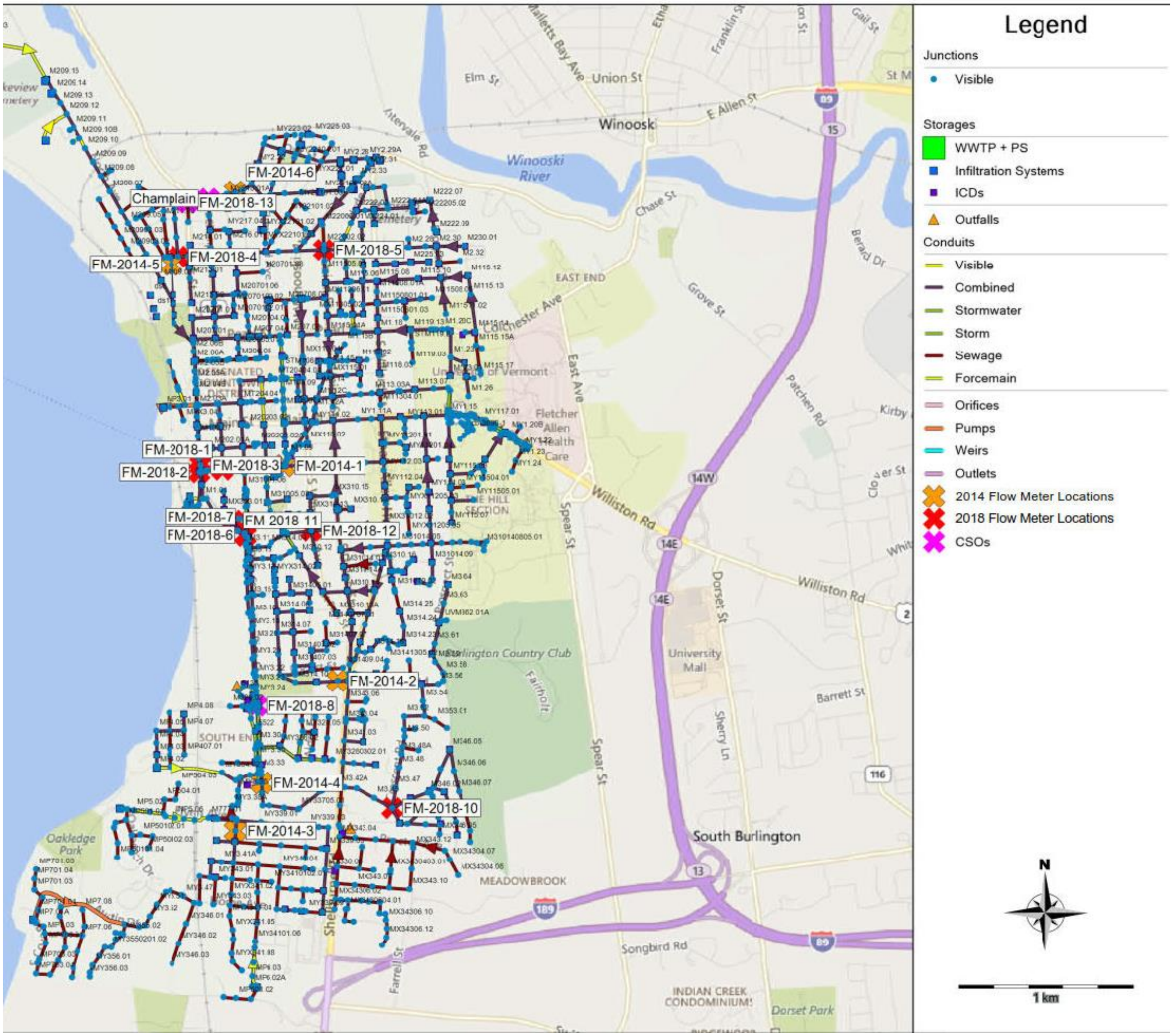


Figure 4-1. Flow Meter Locations

Table 4-1. Flow Metering Program

Meter Name	Model Node	Calibration Storm Events[1]
2014		
FM 2014-1	M1.09-_4	Used for groundwater calibration: 4/14/14-4/22/14 Used for wet weather calibration:6/24/14-6/26/14
FM 2014-2	M314.12-M314.11A	
FM 2014-3	MY3.40-MY3.39A	
FM 2014-4	M3.36-M3.35	
FM 2014-5	M2.10B-M2.10A	
FM 2014-6	MY2.21-MY2.20	
FM 2014-14	Main Plant Effluent	
FM 2014-15	Vortex Meter	
2017-2018		
FM2018-1a	M1.04 (12-inch influent)	N/A – Inconsistent data, and no clear velocity/depth relationship
FM2018-1b	M1.04 (12-inch influent)	N/A - Inconsistent base flow, and no clear velocity/depth relationship
FM2018-2	M103.04	9/5/18-9/12/18
FM2018-3a	M2.01 (30-inch influent)	9/5/18-9/12/18
FM2018-3b	M.201 (30x42 inch Effluent)	9/5/18-9/12/18
FM 2018-4a	M2.12 (24-inch Influent)	11/1/18-11/4/18
FM 2018-4b	M2.12 (18-inch influent)	N/A - Flow data vary significantly, and it appears that the velocity covers a wide range without a corresponding change in depth, likely a drifting velocity sensor.
FM 2018-5a	M2.21 (18-inch influent)	11/1/18-11/4/18
FM2018-5b	M2.21 (12-inch influent)	11/1/18-11/4/18
FM2018-6a	M.3.09 (21-inch influent)	N/A - Flow data do not seem reasonable and frequently drop to zero
FM 2018-6b	M.3.09 (24-inch effluent)	8/7/18-8/9/18
FM 2018-7a	M3.10 (24-inch effluent)	9/5/18-9/12/18
FM 2018-7b	M3.10 (15-inch overflow)	9/5/18-9/12/18
FM 2018-8a	M3.26 (Pine CSO DWF)	11/1/18-11/4/18

Meter Name	Model Node	Calibration Storm Events[1]
FM 2018-8b	M3.26 (Pine CSO WWF)	11/1/18-11/4/18
FM 2018-10a	M346.01-M3.46 (12-inch)	11/1/18-11/4/18
FM 2018-10b	M3.46 (12-inch influent No. 2)	11/1/18-11/4/18
FM 2018-10c	M.3.46 (10-inch influent)	11/1/18-11/4/18
FM 2018-11	M0303.01C (60-inch influent)	8/7/18-8/9/18
FM 2018-12a	M310.12 (12-inch influent #1)	N/A - Inconsistent base flow, and no clear velocity/depth relationship.
FM 2018-12b	M310.12 (12-inch influent #2)	11/1/18-11/4/18
FM 2018-13a	MY2.16 (Park CSO DWF)	N/A meter data issues- velocity issues
FM 2018-13b	MY2.16 (Park CSO WWF)	7/25/18-7/26/18
FM 2018-14	Main Plant Effluent	11/1/18-11/4/18
FM 2018-15	Vortex Meter	11/1/18-11/4/18

1) The date ranges presented are the dates for which meter data were used for calibration purposes

In addition to the flow metering program, other data sources included metering data at the WWTP and the vortex, and permanent CSO meters (i.e., meters used for reporting at the overflow structures).
Model parameters were adjusted to better match meter data, calibrating the model upstream first, then moving to the downstream meters.

Dry Weather Calibration Adjustments

As part of the dry weather calibration, the weekday diurnal curves assigned to junctions by Stantec were not modified. A new weekend diurnal pattern was created during calibration to more accurately represent metering results in the model. The average sanitary flow values originally assigned to junctions by Stantec were not modified. The base flows for each junction were modified as necessary during the dry weather calibration process.

Wet Weather Calibration

During the wet weather calibration process, the percentage of impervious areas routed to pervious surfaces was modified as the first calibration parameter. If further modifications were required to improve the calibration results, the soil group and percent imperviousness were adjusted to the extent that seemed reasonable for the given location.

Attachment A contains a sample of the updated calibration results based on the various data sources used in the calibration process. Two sets of calibration plots were produced based on the two different years of data and meter locations. The process was to complete the calibration of the 2014 meters and then update the model for the 2018 metering data. However, meters at the WWTF were common to both the 2014 and 2018 data sets. What was noted during the review of the meters at the WWTF was that there was significantly less flow in 2018 versus 2014. This was a trend that the City has also noticed between 2014 and 2018 in their monthly and yearly flow data. The City attributed the reduction in flow to several factors:

- Increased installation of low-flow fixtures, especially given relatively high (for VT) water & sewer rates.
- Annual relining of problematic sewer lines in the Main Plant collection system. The City has relined over 5,000 feet of sewer/combined sewer pipe in the Main collection system between 2014 and 2018.
- Climate change, which over the long-term increases periods of drought followed by intense rain events.

Groundwater Inflow Calibration
Flow meters deployed during 2014 were in place during the spring high groundwater season while meters deployed in 2018 were installed after the high groundwater season had ended. The model was therefore calibrated for groundwater conditions based on 2014 meter data. It was noted that FM2014-3 and 2014-4 meters were most impacted by groundwater in the overall system.

The groundwater module includes the following monthly evaporation data, which was used in the model:

Table 4-2. Monthly Evaporation Data for Burlington, VT

Month	Monthly Evaporation (in/day)
Jan	0.03
Feb.	0.06
March	0.10
Apr.	0.17
May	0.23
June	0.25
July	0.26
Aug.	0.22
Sept.	0.15
Oct.	0.11
Nov.	0.07
Dec.	0.05

5.0 Model Validation

The model was run for a continuous simulation period for the 2018 metering period from April 14, 2018 to December 16, 2018. The calibration update focused on selected metering locations for isolated storm events. The model over-predicted the number of overflows at CSO 1 and under-predicted the overflow at CSO 2. The number of overflows were generally reasonably predicted at CSO #3.

Table 5-1. Comparison of DEC Reported to Modeled CSO Volumes

CSO Location	2018 DEC Reporting		2018 SWMM Model Results	
	Event Date	Volume (gallons)	Event Date	Volume (gallons)
CSO # 1 Main S/N 003 Manhattan Drive/ Park Street	7/25/2018	14,397	7/25/2018 8/17/2018 9/26/2018	17,380 3,108(1) 594(1)
CSO # 2 Main S/N 004 Manhattan Drive/ hamplain Street	7/25/2018	>1,000 to 10,000	7/25/2018	No overflow
CSO # 3 Main S/N 005 Pine Street	1/12/2018	>10,000 to 100,000	Meter not installed(2)	Meter not installed(2)
	4/16/2018	>10,000 to 100,000	4/16/2018	1,511
	4/25/2018	No overflow	4/25/2018	2,914
	6/18/2018	Approx. 25,000 + Approx. 120,000 145,000 (2 events reported to DEC)	6/18/2018 (3)	153,580
	7/10/2018	No overflow	7/10/2018	6,830
	7/25/2018	65,705	7/25/2018	131,700
	8/7/2018	15,520	8/7/2018	9,334
	8/17/2018	Unknown(4)	8/17/2018	43,390
	9/6/2018	74,581	9/6/2018	19,170

	9/21/2018	89,100	9/21/2018	17,630
	9/26/2018	Approx. 300,000	9/26/2018	102,100
	10/11/2018	>10,000 to 100,000	10/11/2018	28,725

1) While only one overflow was reported to DEC three small-volume overflows were predicted by the model.

2) Model was run as a continuous simulation for the metering period of record. Since the metering period did not start until April the model run did not start until April.

3) Model results for June 18, 2018 are considered as one storm event and are reported together in the Table.

4) Meter/model results indicated OFs at Manhattan on August 17, 2018. City indicated block was caught and did not register as an OF and was not included by the City in 2018 DEC reports.

As noted above, the DEC-reported and model-predicted volumes are relatively small, in most cases the volumes are under 100,000 gallons or 0.1MG. The model as calibrated generally predicts overflows on dates when overflows were reported to DEC. There were two dates when the model predicted a small overflow (under 10,000 gallons) at CSO # 1 when overflows were not reported to DEC. While the model overflow volumes are different than the DEC-reported volumes; the overflow volumes are fairly small. Overall the model results appear to be reasonable given that the CSO volumes are fairly small and the model is generally predicting overflows on dates for which the City reported overflows to VT DEC.

6.0 Baseline Model Development

Updates to the model after 2018 Metering

Following the 2018 metering program, other projects were completed or slated to be completed prior to the review and implementation of the Integrated Planning Projects. The following is a list of the projects that were added to the calibrated 2018 model to create the Baseline model.

Baseline Modification 1

A catch basin located near South Burlington was plugged in April 2016 (see Figure 6-1). This area was included in the 2014 model calibration. The South Burlington interconnection flow was disconnected after the model calibration (see Figure 6-1). The entire sewer area from South Burlington was disconnected and directed to South Burlington via a pump station. This reduced the flow tributary to the Pine Street overflow.

Baseline Modification 2

1) Green Stormwater Infrastructure BMPs built in 2019
2) Green Stormwater Infrastructure BMPs that are scheduled to be built in 2020 to 2022

The location of these BMPs is shown in Figure 6-2.

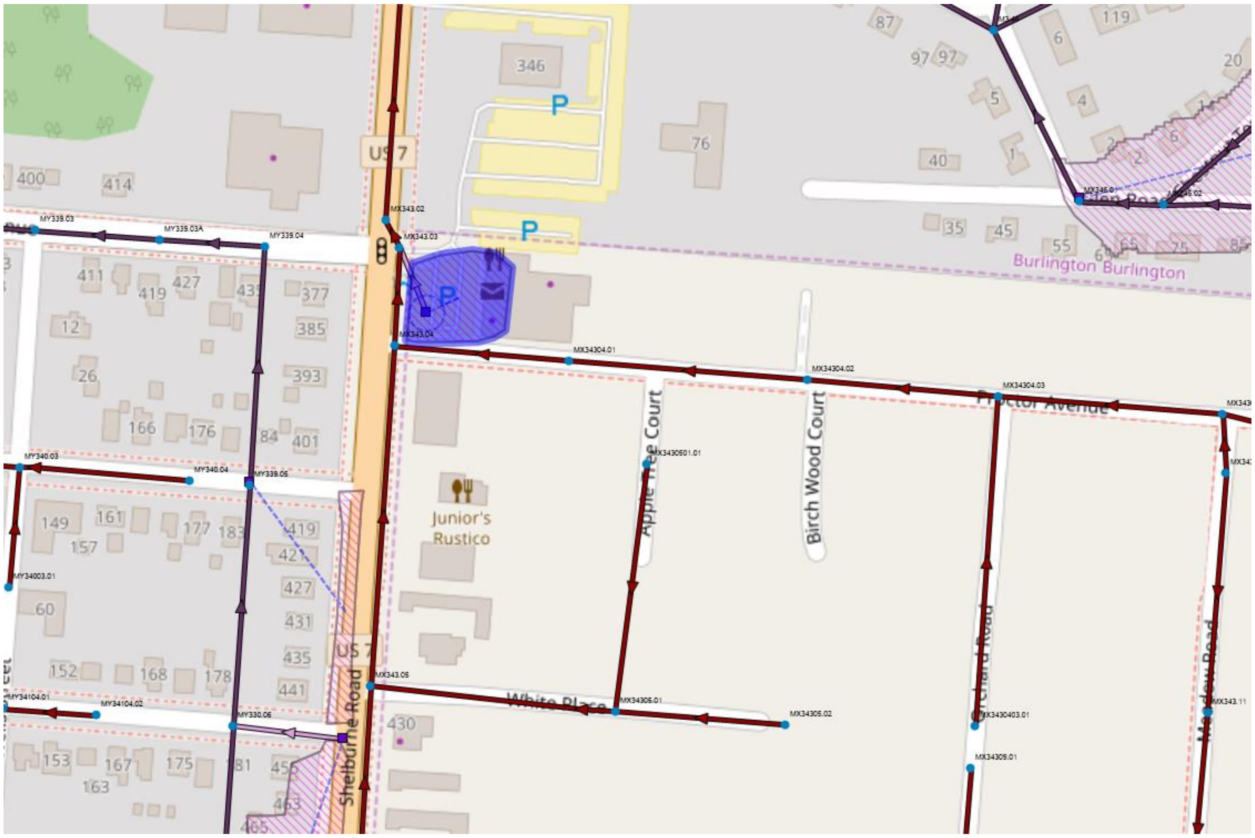
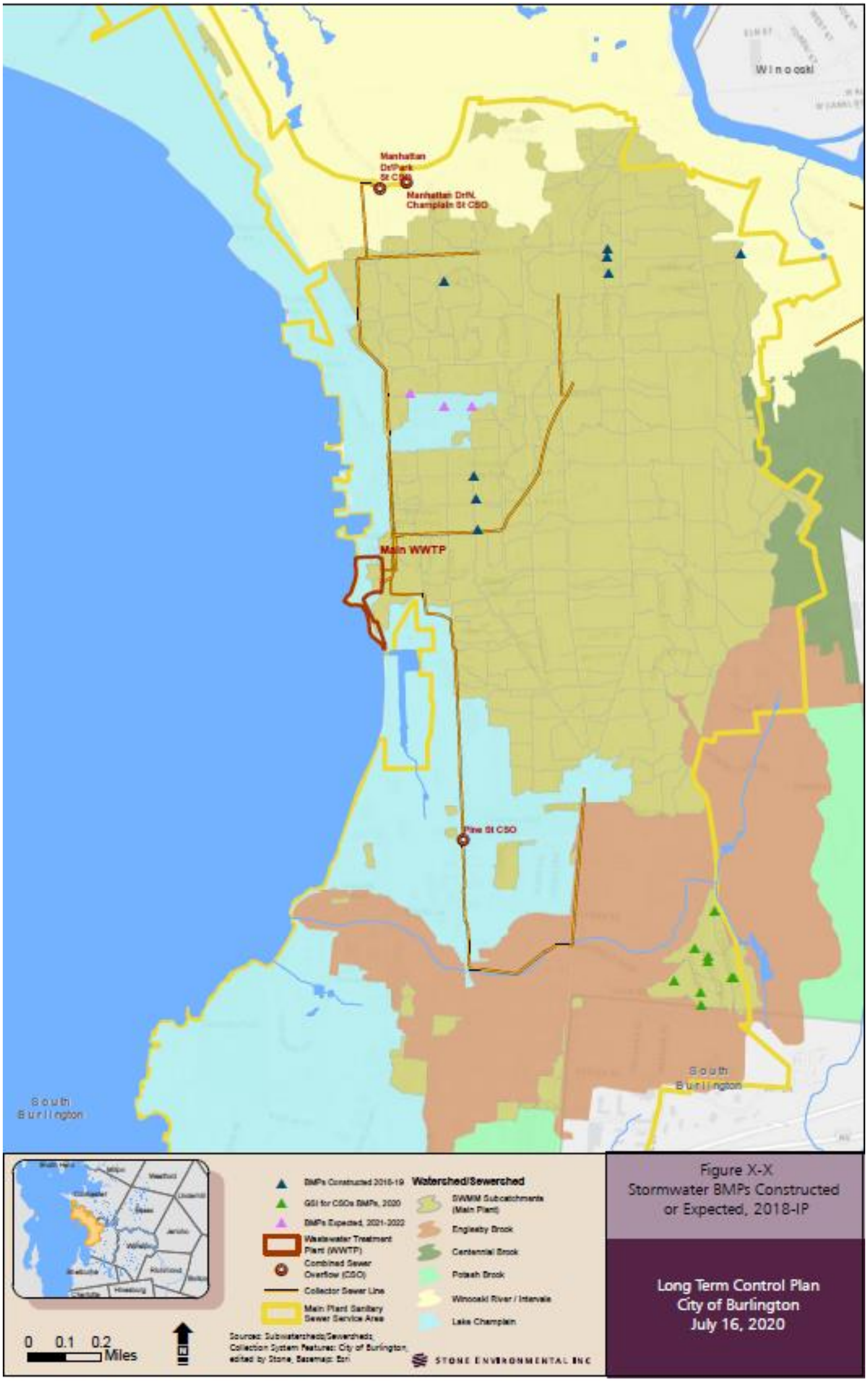


Figure 6-1. South Burlington Catch Basin Disconnection


Winooski
Manhattan Dr/Park St CSO
Manhattan Dr/N. Champlain St CSO
Main WWTP
Pine St CSO
South Burlington
South Burlington
BMPs Constructed 2018-19
GSI for CSOs BMPs, 2020
BMPs Expected, 2021-2022
Wastewater Treatment Plant (WWTP)
Combined Sewer Overflow (CSO)
Collector Sewer Line
Main Plant Sanitary Sewer Service Area
Watershed/Sewershed
SWMM Subcatchments (Main Plant)
Englesby Brook
Centennial Brook
Potash Brook
Winooski River / Intervale
Lake Champlain
0 0.1 0.2 Miles
Sources: Subwatersheds/Sewersheds, Collection System Features: City of Burlington, edited by Stone, Basemap: Esri
STONE ENVIRONMENTAL INC
Figure X-X
Stormwater BMPs Constructed or Expected, 2018-IP
Long Term Control Plan
City of Burlington
July 16, 2020

The South Burlington Flow Interconnection and the two phases of Great Streets BMPs were incorporated into the calibrated model to create the Baseline Model, which was used for development of CSO control alternatives.

The updated 2020 model was run for the 5-year level of control (i.e., the CSOs were evaluated to be controlled in up to a 5-year storm event) which is identified as an interim level of control in Burlington's 1272 Order and the VTDEC CSO Rule 2016 (§34-403 (8)). The 5-year event is a 2.7-inch, 24-hour storm, with a 1-hour peak intensity of 1.2 inches. VTDEC CSO Rule 2016 requires CSOs to meet VWQS at all times but recognizes that "financial capability is a significant factor in abating and controlling CSOs and meeting water quality standards." The City will evaluate progress towards meeting VWQS once the interim control target has been met. A 5-year level of control for CSOs is considered to be a high level of control. For that reason, the Baseline model was run for the 1, 2, and 5-year storm events to evaluate the magnitude of overflows within the Main Plant System over a range of design storm events. The statistics (total depth and peak intensity) for the 1, 2, and 5-year, 24-hour design storm events are included in Table 6-1

Table 6-1. Characteristics of 1, 2, and 5-year, 24-hour Design Storm Events

Recurrence Interval	Total Depth (in)	Peak 1-hour Intensity (in)
1-Year	1.92	0.76
2-Year	2.17	0.85
5-Year	2.70	1.2

CSO control alternatives were analyzed for the 1-year, 2-year, and 5-year events to provide a sense of incremental scope, size, and cost of each higher level of CSO control.

Baseline model results for the Main Plant System are summarized in Table 6-2.

Table 6-2. Main Plant System CSO Volume Predicted Using Baseline Model

	1-Year Design Storm Event	2-Year Design Storm Event	5-Year Design Storm Event
CSO Location	**CSO Volume (Gallons)**	**CSO Volume (Gallons)**	**CSO Volume (Gallons)**
CSO # 1 Main S/N 003 Manhattan Drive/ Park Street	0	0	22,920
CSO # 2 Main S/N 004 Manhattan Drive/ Champlain Street	0	0	0
CSO # 3 Main S/N 005 Pine Street	21,330	49,020	300,600
Main WWTF Bypass	0	0	2,388,000

Based on Baseline Model system conditions as presented in the above table, the Manhattan Drive/Champlain CSO will be controlled to a 5-year level of control (no overflow predicted in up to a 5-year design storm event). It is also noted that no overflows are predicted at CSO #1, CSO #2, or the Main WWTF Bypass in up to a 2-year design storm event.

The Baseline Model, and the overflow volumes tabulated above, were used to develop CSO control alternatives for CSO #1 (5-year level of control, only) and #3 (1, 2, and 5-year levels of control) The development and evaluation of these CSO control alternatives is presented in the Burlington Long Term Control Plan (LTCP).

Attachment A – Baseline 2014 Calibration Plots

As discussed in the text for Appendix A, some plots show better correlation than others between meter data and model predictions. This is typical for CSO modeling efforts. Some of the meter data indicate rapid rises and falls in values, which is considered "noise" in the data. The model will typically not replicate noise in the data and a more steady condition is generally predicted.

Table of Contents for Calibration Plots for 2014

34				WWF
35	Effluent	FM-2014-Effluent	Effluent	DWF
36				WWF
37	Vortex	FM-2014-Vortex	Vortex	DWF
38				WWF

Attachment B – Baseline 2018 Calibration Plots

As discussed above under Attachment A, some plots show better correlation than others between meter data and model predictions, and this is typical for CSO modeling efforts. Some of the meter data indicates rapid rises and falls in values, which is considered "noise" in the data. The model will typically not replicate noise in the data and a more steady condition is generally predicted.

Table of Contents for Calibration Plots for 2014

59			Pine St by Lakeside Ave intersection	WWF
60	M3.26-STM32602.02	FM-2018-8b	Pine St by Lakeside Ave intersection	DWF
61				WWF
62	M346.01-M3.46	FM-2018-10a	Intersection of Crescent Road and Prospect Parkway	DWF
63				WWF
64	M3.47-M3.46	FM-2018-10b	Crescent Road by Prospect Parkway intersection	DWF
65				WWF
66	MX346.01-M3.46	FM-2018-10c	Crescent Road by Glen Road intersection	DWF
67				WWF
68	M303.01D-M303.01C	FM-2018-11	Curtis Lumber Co. off Pine St	DWF
69				WWF
70	MX310.13-MX310.12	FM-2018-12b	Intersection of Spruce St and South Winooski Ave	DWF
71				WWF
72	MY2.16-MY2.15	FM-2018-13a	Intersection of Park St and Manhattan Drive	DWF
73				WWF
74	MY2.16-	FM-2018-13b	Intersection of Park St and Manhattan Drive	DWF
75				WWF
76	29	FM-2018-Effluent		DWF
77			Water Treatment Plant	WWF
78	4	FM-2018-Vortex	Railroad by Railway Lane	DWF
79				WWF