Model Refinement and Calibration Report

Stormwater System Modeling for Improved Communications and Development of Green Infrastructure

April 8, 2019

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City of Somerville

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Executive Summary

This document summarizes hydraulic model refinement and calibration performed under a Municipal Vulnerability Program (MVP) Action Grant obtained by Somerville to investigate the City's vulnerability to flooding on a street-by-street basis. The intent of the study is to use this data to learn where green infrastructure (GI) can best impact flood control and water quality management, and to identify vulnerable populations for risk and emergency communication.

Model enhancements were performed in areas selected by the City to represent a variety of neighborhood types. The selected areas encompass locations where the model was suspected to be missing critical information, areas of potential GI implementation, and areas slated for redevelopment. The hydraulic model was refined within these areas and calibrated using data from thirteen temporary flow meters. The newly refined and calibrated model is referred to as Refined Model moving forward.

Model Refinement. Model refinement was based on the City's most up-to-date GIS data, LiDAR data obtained from MassGIS, a manhole inspection report by Weston & Sampson, and field investigations performed by Stantec. Model refinement included adding missing conduits and nodes and adding network conduits of smaller sizes (<15" for combined and storm system and <10" for sanitary system). Figure ES-1 shows the model extents and added conveyance conduits in the City's Refined Model.

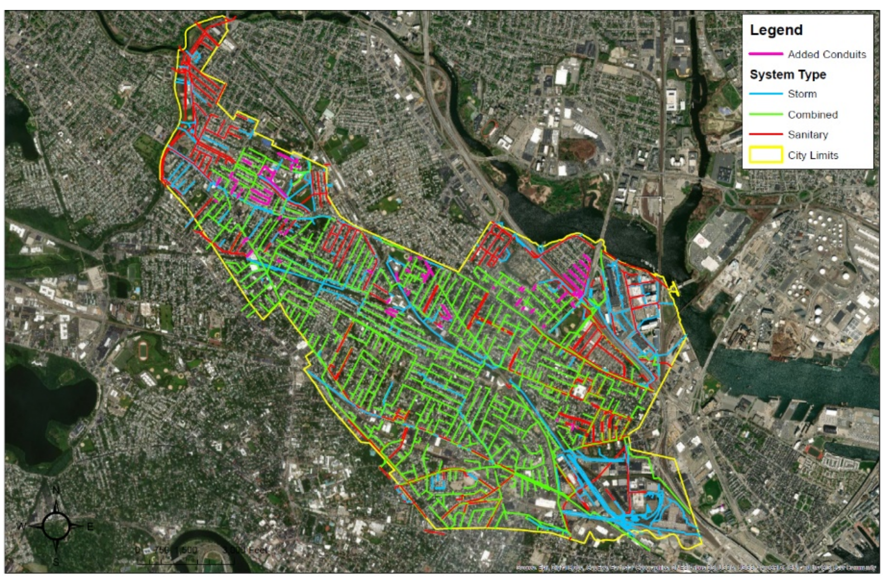

Figure ES-1 Refined Model Extent and Added Conduits

Model Calibration. The Refined Model was calibrated using measured flow data from temporary flow meters at thirteen locations identified in Figure ES-2. The calibration process consisted of adjusting the parameters associated with the hydrologic model to simulate and duplicate metered peak flow, flow volume, and hydrograph shape for dry weather and wet weather flow periods. Calibration was conducted in order to improve the ability of the model to simulate a range of storms with variable rainfall volume, duration, and intensity to increase confidence in model predictions to evaluate the impact of GI in the areas of interest as well as other future hydraulic improvements. Rainfall data obtained from a rain gauge installed at Somerville's DPW building during the flow metering period were reviewed in order to select calibration events.

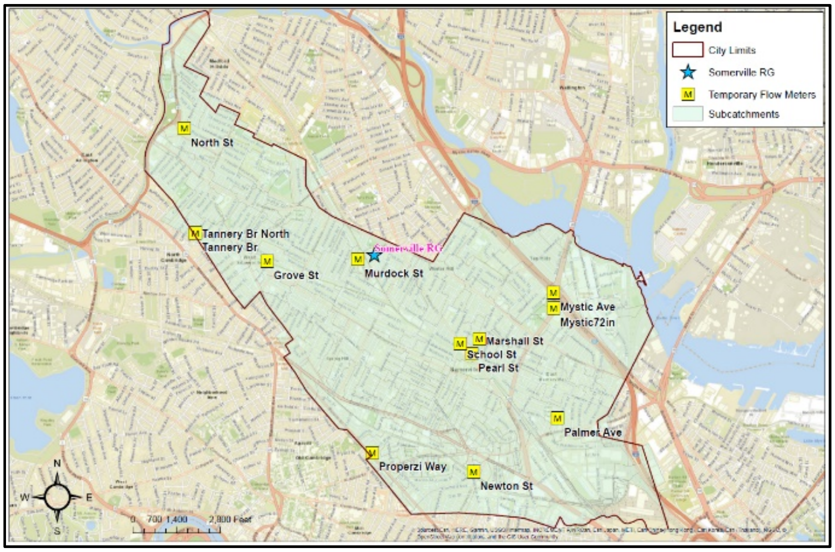

Figure ES-2 Location of Flow Meters and Rain Gauge

Dry Weather Flow Calibration. During dry weather, modeled peak flows and volumes fell, in most cases, within calibration standards for meters with clear and predictable diurnal patterns and meters with no dry weather flow. Two meters produced questionable dry weather flow data or had random flow spikes and the model could not be calibrated to meet calibration standards because the source of the flow spikes could not be identified with the information available.

Wet Weather Flow Calibration. The model was calibrated under wet weather conditions to ensure the model's ability to accurately estimate runoff, flow rates, and water levels across the sewer network system. Each meter area was calibrated based on one storm event and validated with a second storm event. Overall, the model was successful at replicating peak storm flows, but volumes could not always be kept within calibration standard limits. Several factors are suspected to be the potential sources of error:

Conveyance system uncertainty: Unknown collection system information such as pipe conditions, unknown blockages, sediment accumulation or cross-connections may cause the system to behave differently than anticipated.

Due to the limited flow monitoring period available for calibration, i.e. November 2018 – January 2019, the model was only tested for late fall and winter season soil moisture antecedent conditions.

The Refined Model after calibration and validation is deemed appropriate for planning purposes but further understanding of the system is necessary in certain areas, especially Tannery Brook and Mystic Ave, prior to proceeding with significant design of capital improvement projects.

Recommendations:

- In areas with known cross-connections and flow transfers such as Tannery Brook, School Street, and Murdock Street, and Union Square systems, perform exhaustive field investigations including CCTV to fully understand how the system works. Some detailed recommendations for CCTV are provided in Appendix A. Other locations outside of these study areas are also recommended for inspection, such as a bifurcation manhole on the School Street meter system and the Mystic Avenue system near the Marginal facility.
- At the Mystic Avenue meter location, the data from the January 24, 2019 storm shows sudden increases in peak flow which seem to be spikes in the flow data. The meter shows a high peak depth close to 6.5 ft. The reason for this is unknown; however, a possible cause maybe a temporary blockage or obstruction somewhere downstream in the system. Nevertheless, a good match between model and meter flow depth was achieved during the December 21, 2018 storm. It is recommended to complete CCTV in this area to observe pipe conditions and connectivity.
- The model over estimates peak depth at the Palmer Avenue meter during the January 24, 2019 storm the sewer surcharges. On the other hand, a reasonably good match between simulated and metered depth is achieved during the December 21, 2018 storm. It is recommended to complete additional metering in this area to capture additional representative storm events to enhance the ability of the calibrated model to reproduce observations.
- Continue to perform flow metering and pipe condition assessment on a routine basis that will help to continuously improve model detail and performance.

Next Steps. The Refined Model will be used to evaluate street-by-street flooding, evaluate the impact of different GI implementation scenarios, and quantify flood reductions in current and projected climate change conditions in an accurate and systematic way. The Refined Model will also be used for identifying vulnerable populations for risk and emergency communications.

Abbreviations

BSF	base sanitary flow
CCTV	closed-circuit television
CIWEM	Chartered Institution of Water and Environmental Management
DPW	Department of Public Works
DWF	dry weather flow
GI	Green Infrastructure
GIS	Geographic Information Systems
GWI	groundwater infiltration
ICM	Integrated Catchment Modelling
LIDAR	Light Detection and Ranging
MVP	Municipal Vulnerability Preparedness
RG	rain gauge
SWMM	Storm Water Management Model
WWF	wet weather flow

1.0 BACKGROUND AND PURPOSE

This document summarizes hydraulic model refinement and calibration performed under a Municipal Vulnerability Preparedness (MVP) Action Grant obtained by Somerville to investigate the City's vulnerability to flooding on a street-by-street basis. The intent of the study is to use this data to learn where green infrastructure (GI) can best impact flood control and water quality management, and to identify vulnerable populations for risk and emergency communication.

Model enhancements were performed in study areas selected by the City to represent a variety of neighborhood types and encompass locations where the model was suspected to be missing critical information, areas of potential GI implementation, and areas slated for redevelopment. The hydraulic model was refined within these areas, depicted in Figure 1, and calibrated using data from thirteen temporary flow meters.

The newly refined and calibrated model is referred to as the Refined Model moving forward. The Refined Model will be used to evaluate the impact of GI implementation scenarios and quantify flood reductions in current and projected climate change conditions in a more accurate and systematic way. The areas shown in Figure 1 were cut down to six neighborhood-scale opportunity areas ranging in size from 35 to 90 acres, for development of GI implementation scenarios. As the entire system is interconnected, model improvements outside the six neighborhood opportunity areas will still have an impact and improve results for those areas.

2.0 HYDRAULIC MODEL EXPANSION AND REFINEMENT

This task consisted of including missing conduits and nodes, if any, in the City's existing hydraulic model within the study areas of interest. During past projects, the City's hydraulic model had already undergone a first phase of model refinement by including combined and storm pipes with diameters equal or greater than 15 inches and sanitary conduits with a diameter equal or greater than 10 inches. As part of the present effort, storm and combined network conduits of smaller sizes were added to the model in the target (study) areas shown in Figure 1. Figure 2 shows the model extents and added conveyance conduits in the City's Refined Model.

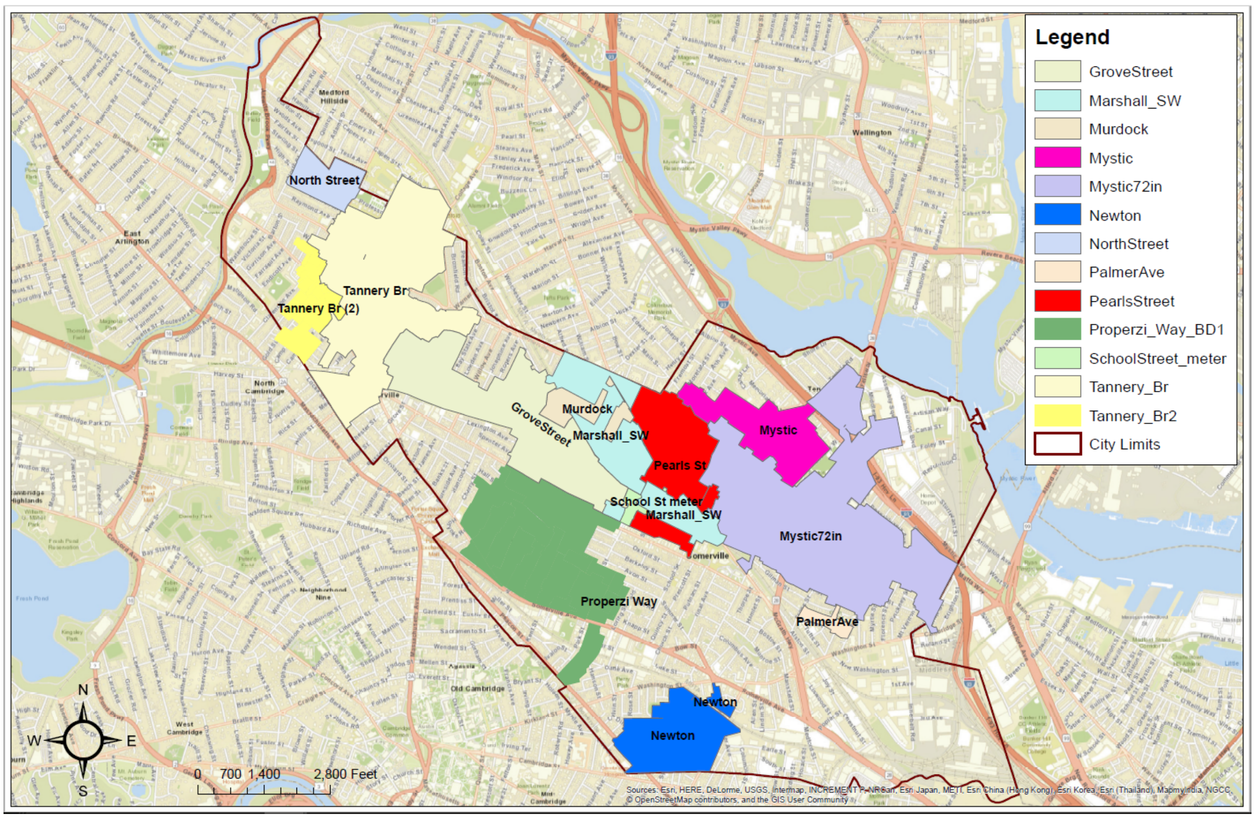

Figure 2 Flow Meter Areas of Model Refinement

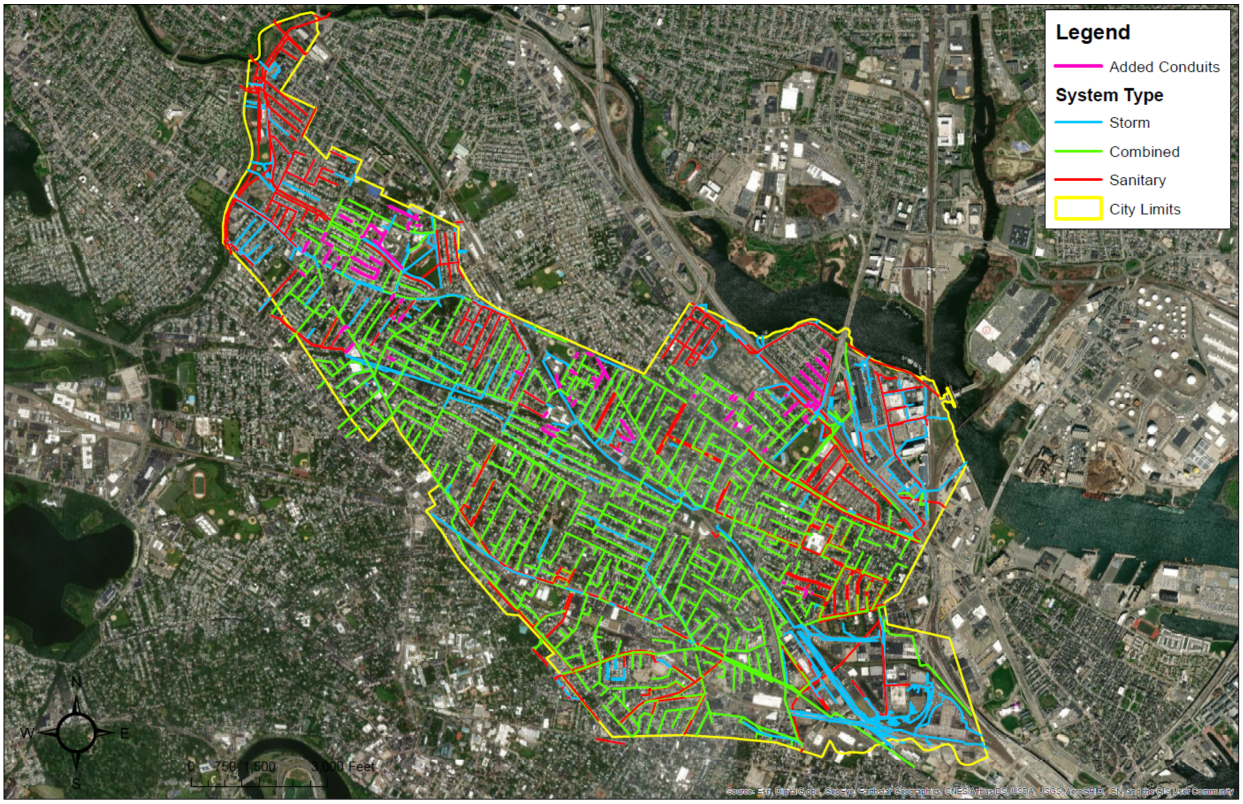

Figure 2 Refined Model Extent and Added Conduits

2.1 COMPARISON OF EXISTING MODEL AND REFINED MODEL

The table below shows a comparison of model elements between the existing and refined models. Note that all sub-catchments in the existing model were previously delineated in Arc-GIS with sizes ranging from 5 to 50 acres. In the Refined Model, large size sub-catchments city-wide were split to make them 3 to 5 acres in size.

Table 1 Comparison of Existing and Refined City Model

	Existing Model	Refined Model	% Difference
No. of Nodes	3,896	4,158*	7%
No. of Links	3,935	4,198*	7%
No. of sub-catchments	511	998	95%

*Increase is due to refinement within the thirteen areas of interest
** Increase is due to city-wide reduction in catchment size

2.2 SOURCES OF INFORMATION

The following sources of information were used for model refinement.

2.2.1 City's Geographic Information System (GIS)

The City's most up to date GIS data was used to obtain information on missing conduits and system nodes, when available. GIS data layers were extracted directly from the City's GIS on-line viewer, which reflects the most up to date information according to the City's GIS Department. These layers were downloaded and incorporated directly into the model.

2.2.2 LiDAR

Manhole rim elevations, where missing in GIS data, were updated based on 2013-2014 MassGIS Sandy Flyover LiDAR data. LiDAR data has a vertical and a horizontal resolution of 0.2 and 3 feet, respectively.

2.2.3 Other Data Sources

- Manhole Inspection Report by Weston & Sampson,
- Field investigations performed by Stantec staff October through December 2018. Please refer Appendix A for more details.

2.3 CONDUITS AND NODES WITH NO AVAILABLE DATA

Few nodes and links within city limits had no available data from any of the sources cited above. In those instances, the following methods were used to infer the data. (refer to the Appendix B - Data Gaps Analysis for a full description of how data gaps/issues were bridged in the model).

- Where GIS data for pipe invert elevations was missing, the InfoWorks ICM inference tool was used to obtain the invert elevations by regression between upstream and downstream available invert levels.
- Node rim elevations were filled based on LiDAR terrain elevations.
- Manning roughness coefficients (n) were assigned using pipe materials as shown in Table 2. When pipe material was not available, a default n value of 0.013 was assumed. However, since the roughness coefficient is subject to change with pipe age and factors such as sediment accumulation, this parameter was subject to change during the calibration process.

Table 2 Comparison of Existing and Refined City Model

Material in Sewer Layer	Actual Name	Manning's n*
CI	Cast Iron	0.012
CIPP	Cured in Place Pipe	0.011
CMP	Corrugated Metal Pipe	0.020
DIP	Ductile Iron Pipe	0.013
OTH	Other	0.014
PP	Plastic Pipe	0.012
PVC	Polyvinyl Chloride	0.010
RCP	Reinforced Concrete Pipe	0.013
St/Stone	Stone	0.019
VC/VCP	Vitrified clay pipe	0.013
Unknown		0.013
*Assuming pipe is in fair to aged condition		

3.0 HYDRAULIC MODEL CALIBRATION

The Refined Model was calibrated using measured flow data from temporary flow meters at thirteen locations. The calibration was performed for dry wet weather events. The purpose of the calibration was to increase the confidence in model predictions to evaluate the impact of GI infrastructure in the areas of interest as well as other future hydraulic improvements.

3.1 CALIBRATION PROCESS

The calibration process compared model predictions against measured flow meter data during individual dry weather and wet weather periods. During model calibration, adjustments of hydraulic and hydrologic parameters were made where necessary to achieve a better comparison between the metered and simulated peak flows, volume and peak depths for all flow meters.

For a successful calibration, dry weather flow (DWF) and wet weather flow (WWF) must be treated separately. DWF needs to be calibrated adequately before making adjustments to WWF parameters. The calibration process started by comparing metered data to model outputs and where significant differences occurred, the appropriate model parameters were adjusted while keeping the parameters within an acceptable range.

The DWF model calibration focused, for the most part, on the following elements:

- Estimates of DWF, comprised of base sanitary flow (BSF) and groundwater infiltration (GWI), including diurnal patterns.
- Manning's roughness coefficient (n-value) and friction loss coefficients in the system. Both parameters can affect depths of flow in the system and available system capacity.
- Physical system components such as hydraulic blockages and sediment.

The WWF model calibration focused, for the most part, on the following elements:

- Catchment runoff coefficients, initial loss values, contributing area, and rainfall derived infiltration parameters were changed for each area tributary to a flow meter.
- Runoff model Horton SWMM has been used during calibration. Its infiltration parameters have been changed during calibration.
- Details of runoff surfaces used in the Refined Model and their respective runoff parameters used in the Refined Model are shown in Table 3.

Table 3 Runoff Surfaces in Study Area

Meter Area	Runoff Surface ID	Description	Initial Loss Value (ft)	Runoff Coefficient	Horton Initial (in/hr)	Horton Limiting (in/hr)	Horton Max Infiltration volume (in)
Tannery Br North (2)	310	Tannery Br N (2) Impervious	0.0250	0.4			
	311	Tannery Br N (2) Impervious	0.0250	0.4			
	312	Tannery Br N (2) Pervious	0.0650		1	0.50	2
School St	320	School St Impervious	0.0100	0.4			
	321	School St Impervious	0.0100	0.4			
	322	School St Pervious	0.00350		0.250	0.010	2
Marshall SW	324	Marshall SW Impervious	0.0100	1			
	325	Marshall SW Impervious	0.0100	1			
	326	Marshall SW Pervious	0.0650		0.100	0.010	2
North St	340	North St Impervious	0.0250	0.5			
	341	North St Impervious	0.0250	0.5			
	342	North St Pervious	0.0656		2	0.25	2
Pearl St	345	Pearl St Impervious	0.0010	0.8			
	346	Pearl St Impervious	0.0002	0.8			
	347	Pearl St Pervious	0.0001		3	0.10	2
Newton St	350	Newton St Impervious	0.0100	0.8			
	351	Newton St Impervious	0.0100	0.8			
	352	Newton St Pervious	0.0035		1	0.0001	2
Murdock St	355	Murdock St Impervious	0.0035	0.4			
	356	Murdock St Impervious	0.0035	0.4			
	357	Murdock St Pervious	0.0035		1	0.1	2
Mystic Ave	360	Mystic Ave Impervious	0.0001	1			
	361	Mystic Ave Impervious	0.0001	1			
	362	Mystic Ave Pervious	0.0166		0.250	0.1	2
Grove St	364	Grove S Impervious	0.0035	0.6			
	365	Grove St Impervious	0.0035	0.6			

Meter Area	Runoff Surface ID	Description	Initial Loss Value (ft)	Runoff Coefficient	Horton Initial (in/hr)	Horton Limiting (in/hr)	Horton Max Infiltration volume (in)
	366	Grove St Pervious	0.0035		0.250	0.1	2
Palmer Ave	330	Palmer Ave Impervious	0.0250	0.85			
	331	Palmer Ave Impervious	0.0005	0.85			
	332	Palmer Ave Pervious	0.0100		4	0.1	2
Tannery Br	314	Tannery Br Impervious	0.0035	1			
	315	Tannery Br Impervious	0.0035	1			
	316	Tannery Br Pervious	0.0035		1	0.1	2
Mystic 72in	370	Mystic 72in Impervious	0.0001	0.7			
	371	Mystic 72in Impervious	0.0001	0.6			
	372	Mystic 72in Pervious	0.0001		1	0.1	2
Properzi Way	374	Properzi Way Impervious	0.00001	1			
	375	Properzi Way Impervious	0.00001	1			
	376	Properzi Way Pervious	0.0035		1	0.1	2

4.0 RAINFALL AND FLOW METER DATA

4.1 RAINFALL DATA SUMMARY

Rainfall data was available for model calibration and validation purposes from one rain gauge, (Somerville RG) installed at Somerville DPW building for the period October 23, 2018 through February 8, 2019. The rainfall data collected at the Somerville DPW rain gauge was available at 15-minute time intervals. The location of this rain gauge is depicted in Figure 3a. A summary of storms used for calibration and validation for each meter area are reported in Table 4. It is important to note that the same calibration events could not be used for all meters because not all of them were installed at the same time (refer to Section 4.2).

Table 4 Rainfall characteristics of the storm events used for calibration and validation

Date	Total Duration (hours)	Total Rain (in)	15-Minute Peak Intensity (in/h)
November 02, 2018	17.6	1.70	0.64
November 09, 2018	15.5	1.43	0.48
December 21, 2018	18.3	0.85	0.28
December 31, 2018	10.3	0.78	0.20
January 24, 2019	13.5	1.00	0.36

The first major snow storm of the season took place on January 19-20, 2019. Therefore, snow on the ground was not a factor for the first four calibration events which took place prior to this storm. There may have been snow on the ground during the January 24, 2019 calibration event, as a result of snowfall received January 19-20th (up to 5”).

4.2 FLOW METER DATA SUMMARY

A total of thirteen temporary flow meters were installed within Somerville City limits. Out of these thirteen flow meters, eight were operational between October 26 and December 16, 2018. The remaining five were installed at a later date and were operational between December 17, 2018 and February 8, 2019.

Flow, depth, and velocity observations were obtained and used to calibrate the Refined Model. Location of all flow meters are depicted in Figures 3a through 3j. Details of temporary flow meters used for model calibration are shown in Table 5.

Rainfall and Flow Meter Data
April 8, 2019

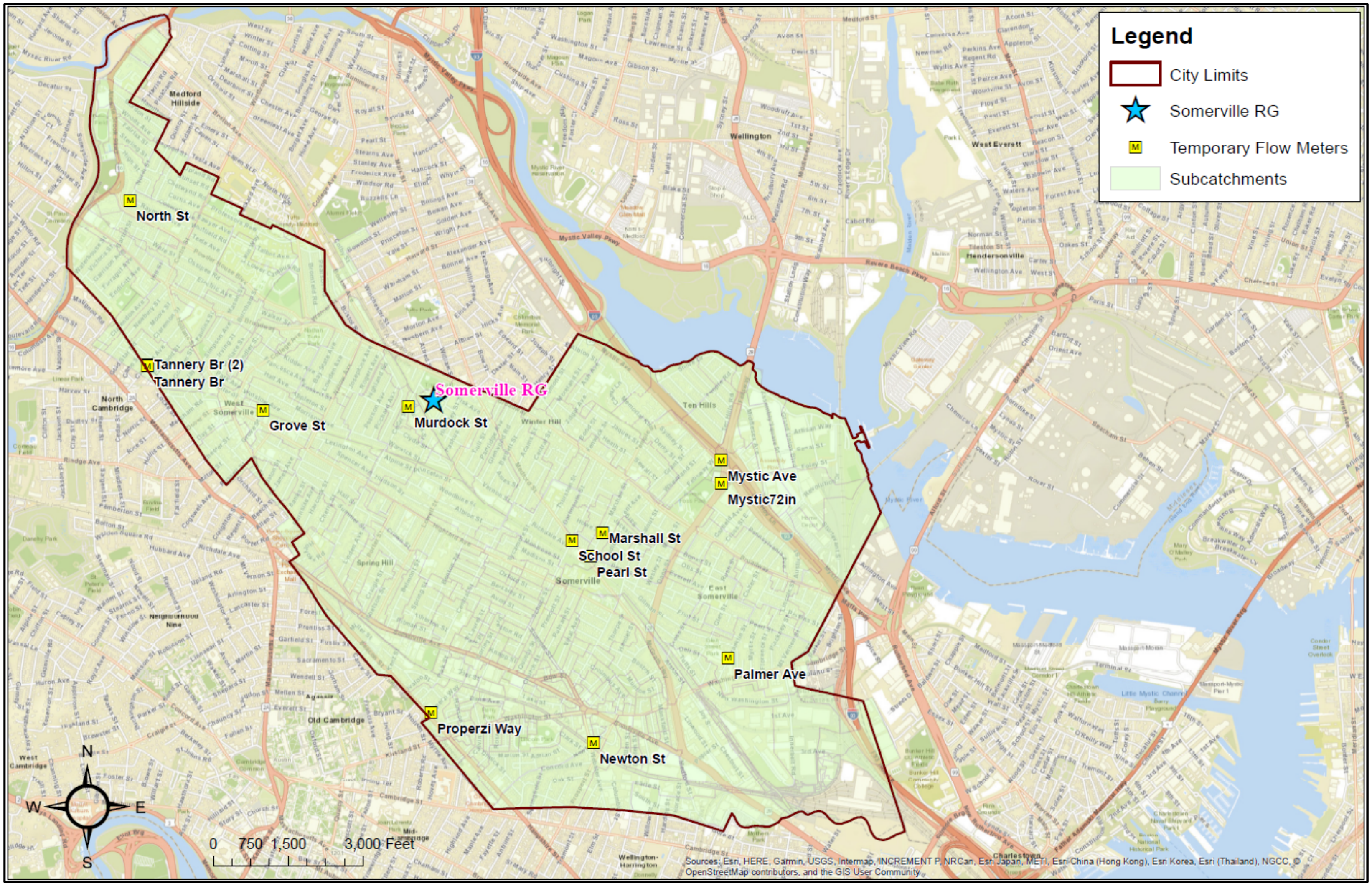

Figure 3a Location of Temporary Flow Meters, and Rain Gauges

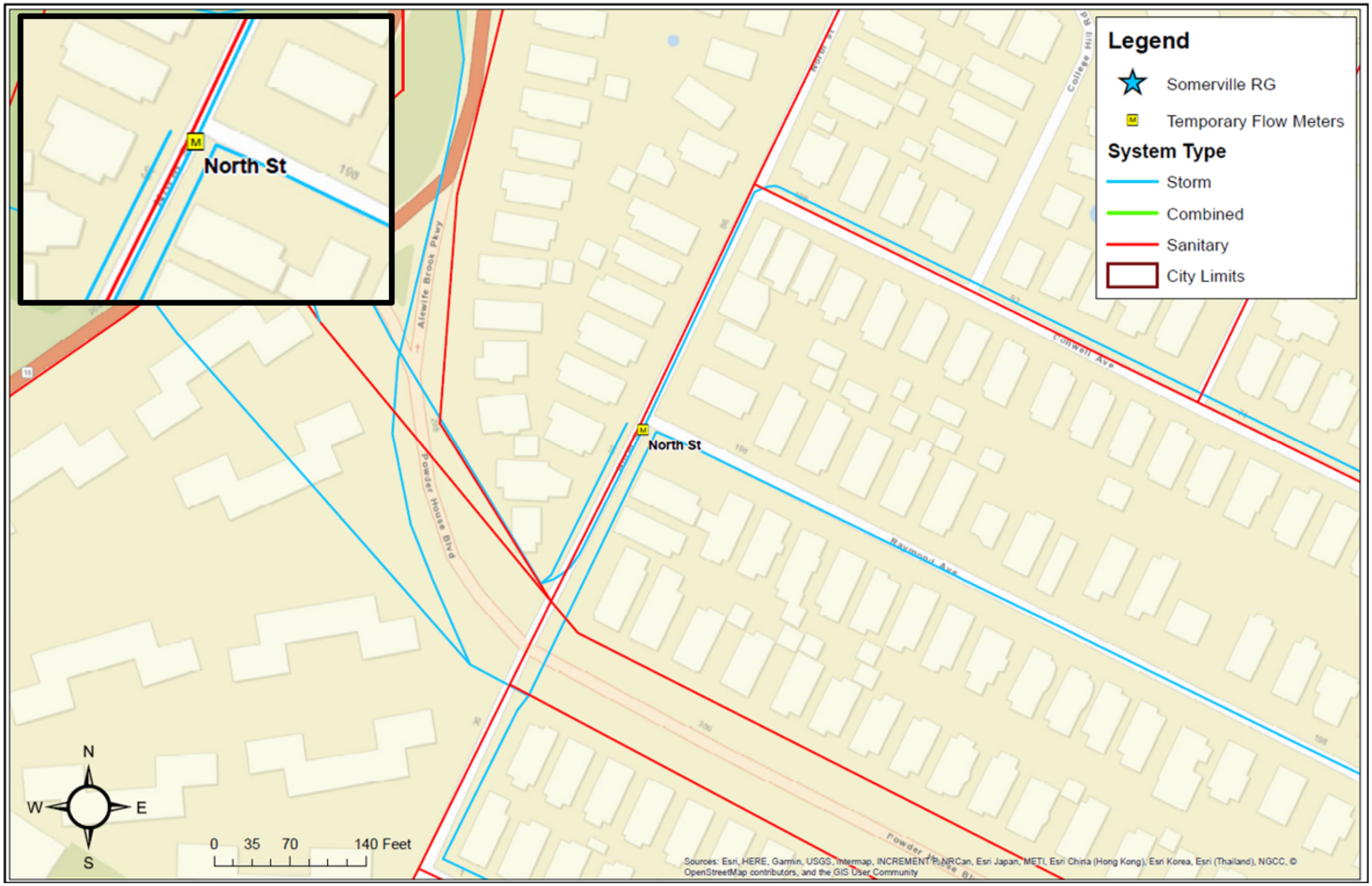

Figure 3b. Location of Temporary Flow Meters, and Rain Gauges (Closeup 1)

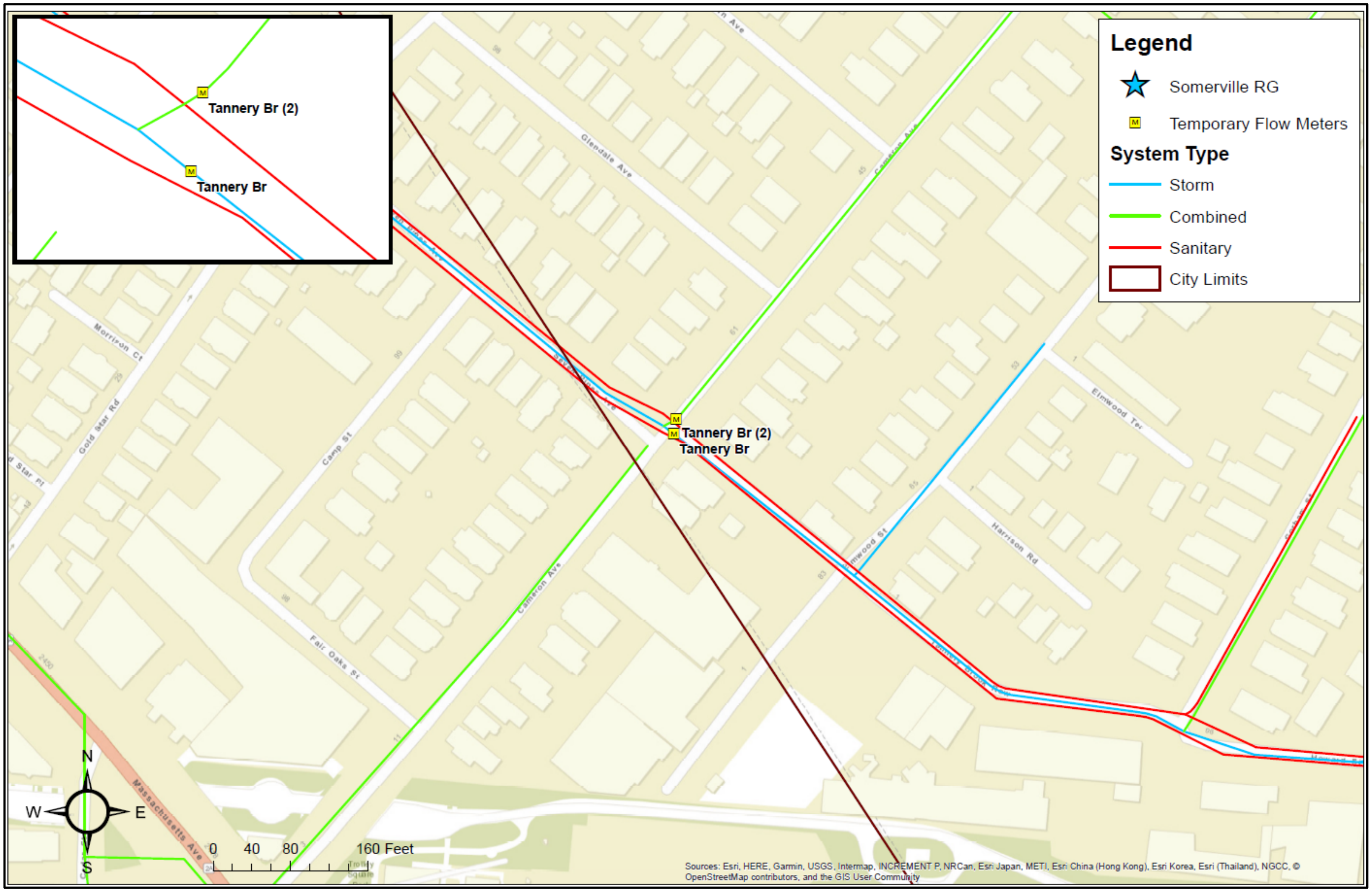

Figure 3c. Location of Temporary Flow Meters, and Rain Gauges (Closeup 2)

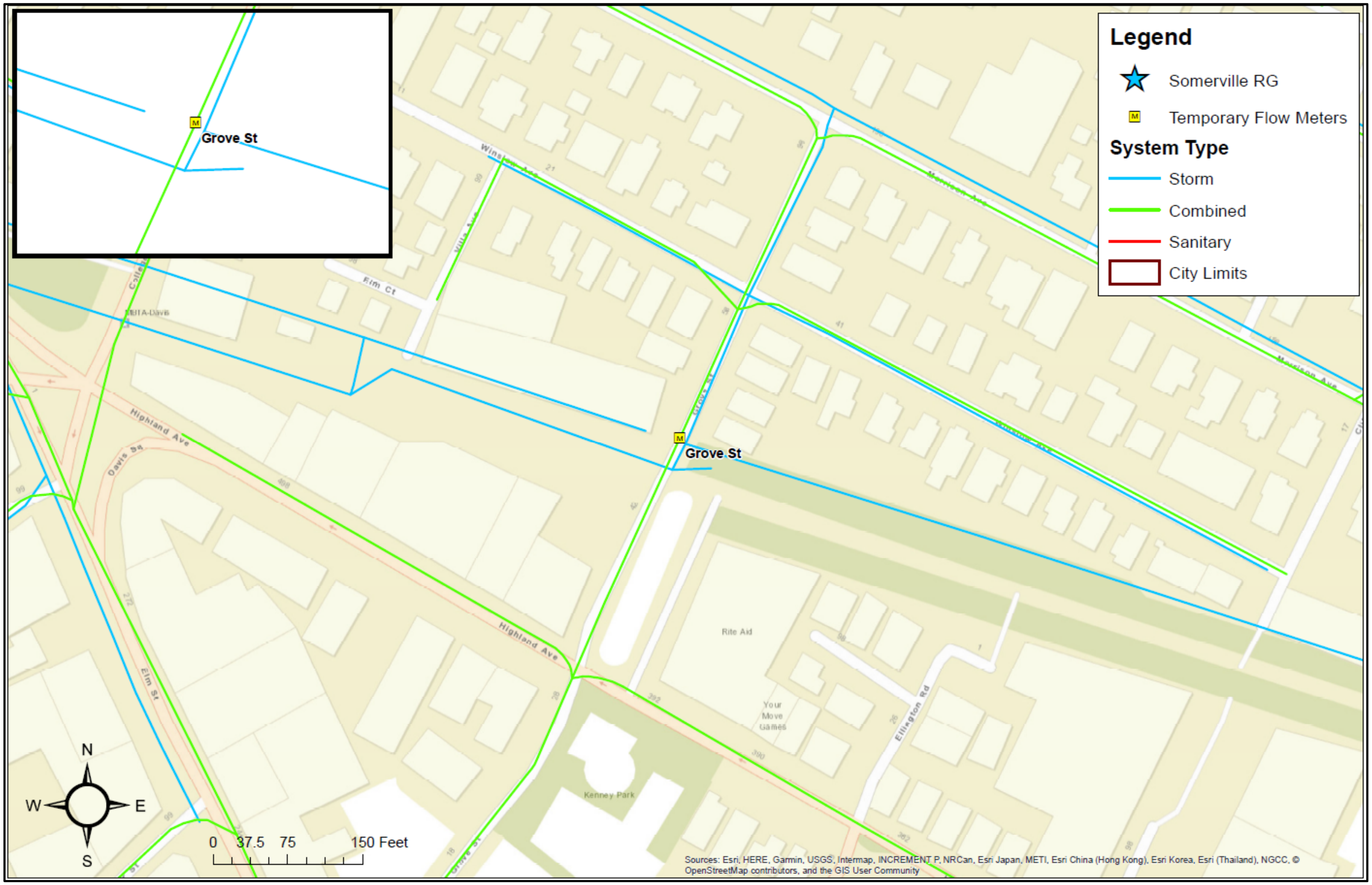

Figure 3d. Location of Temporary Flow Meters, and Rain Gauges (Closeup 3)

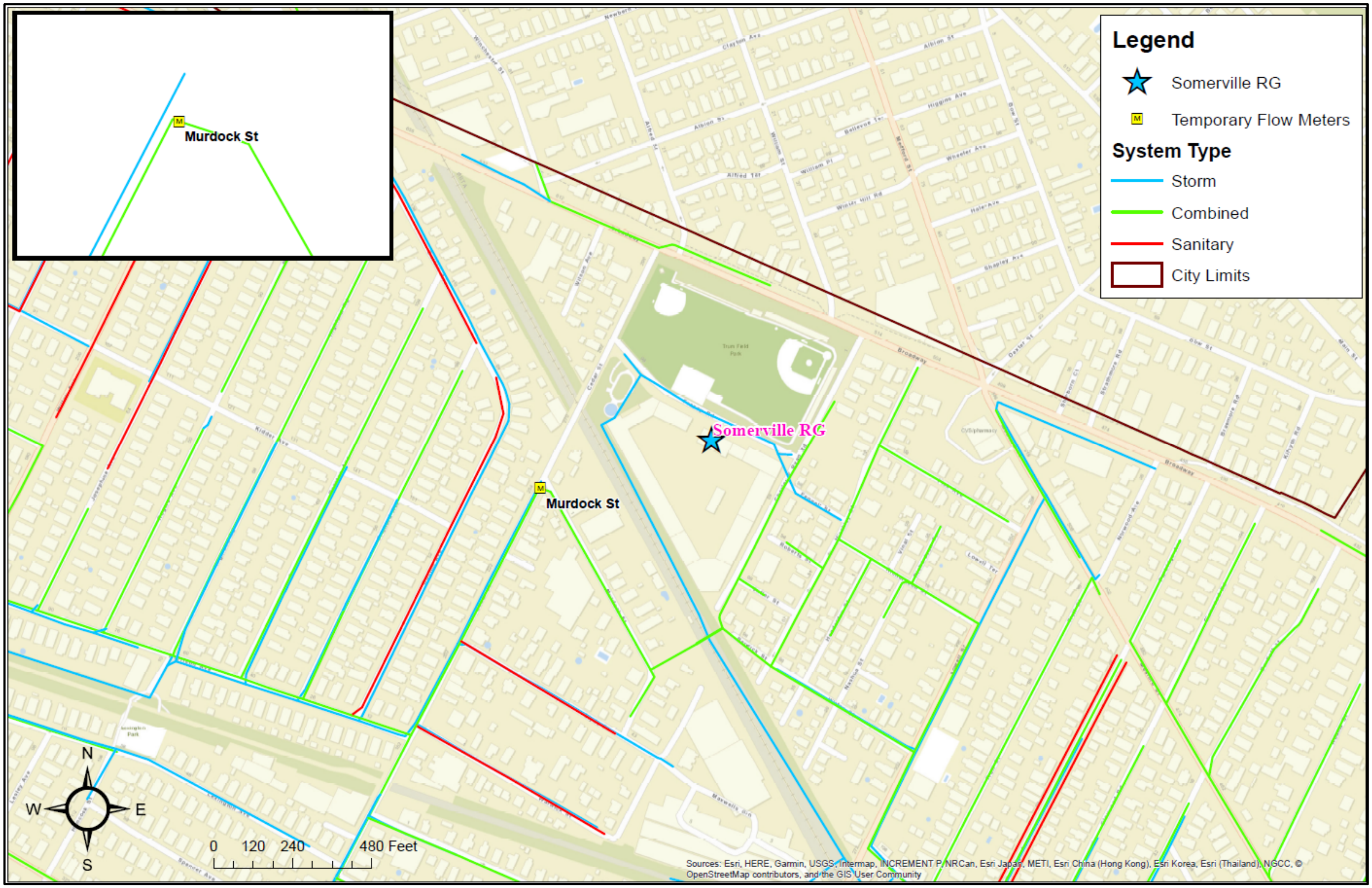

Figure 3e. Location of Temporary Flow Meters, and Rain Gauges (Closeup 4)

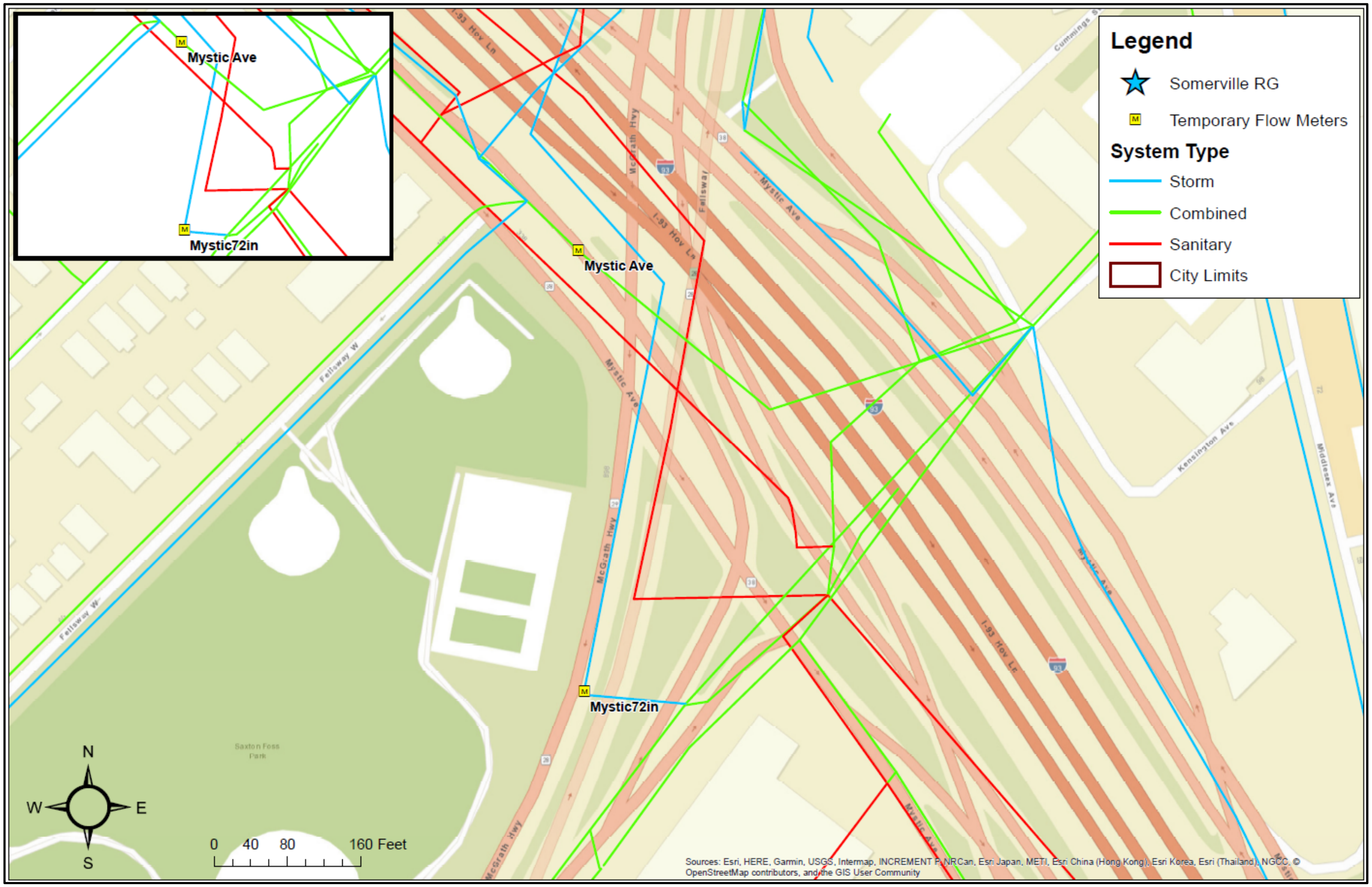

Figure 3f. Location of Temporary Flow Meters, and Rain Gauges (Closeup 5)

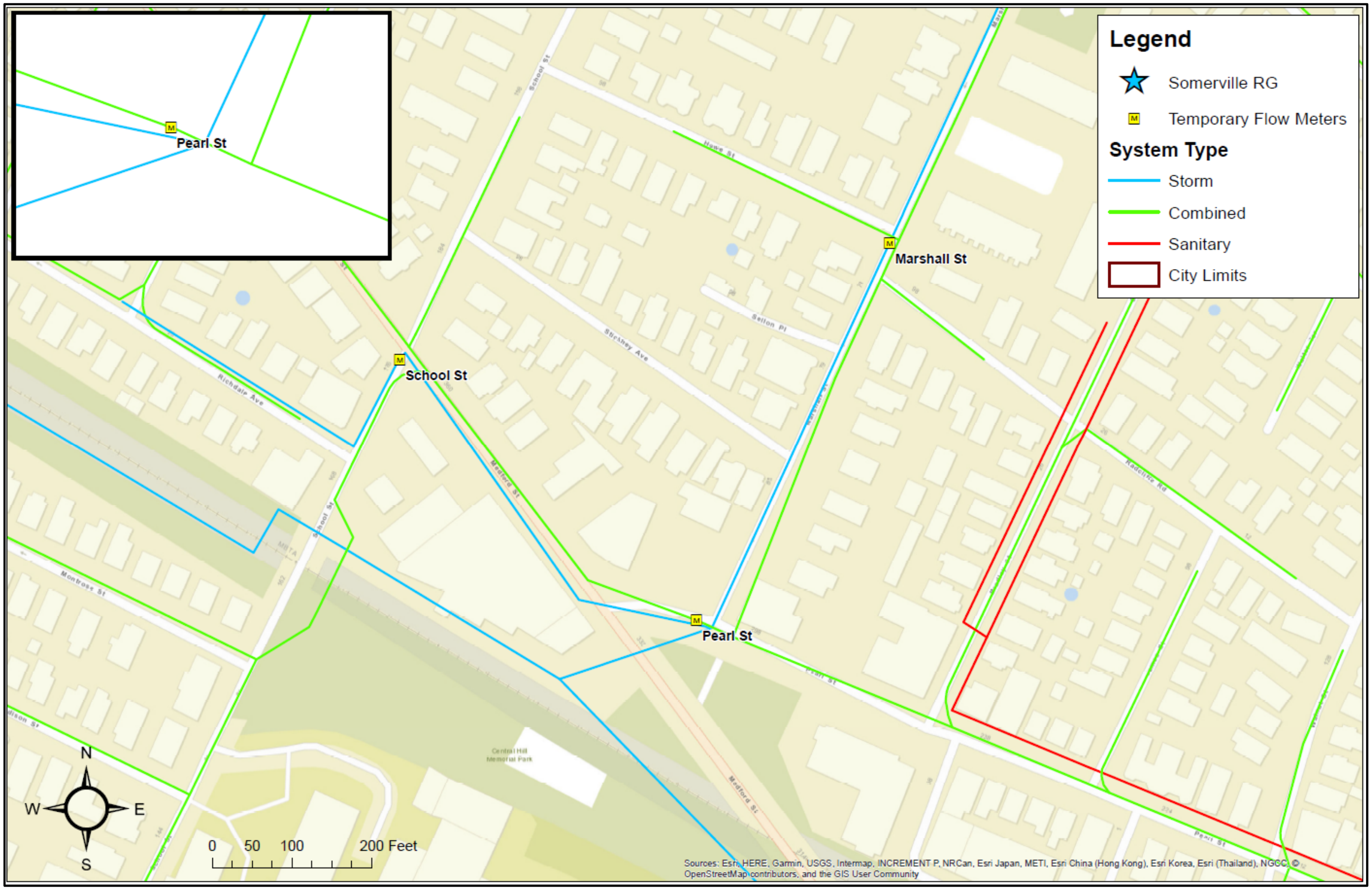

Figure 3g. Location of Temporary Flow Meters, and Rain Gauges (Closeup 6)

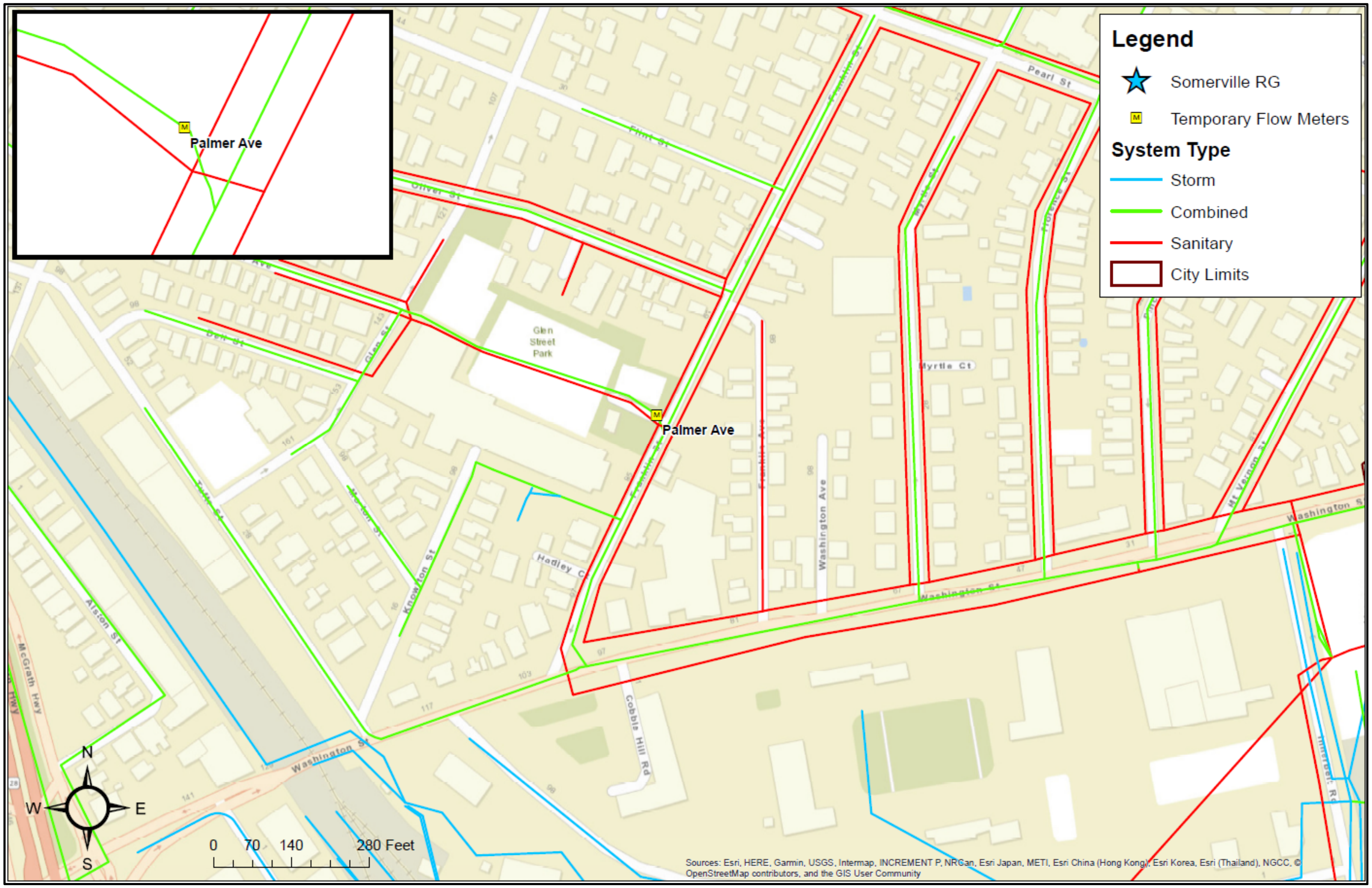

Figure 3h. Location of Temporary Flow Meters, and Rain Gauges (Closeup 7)

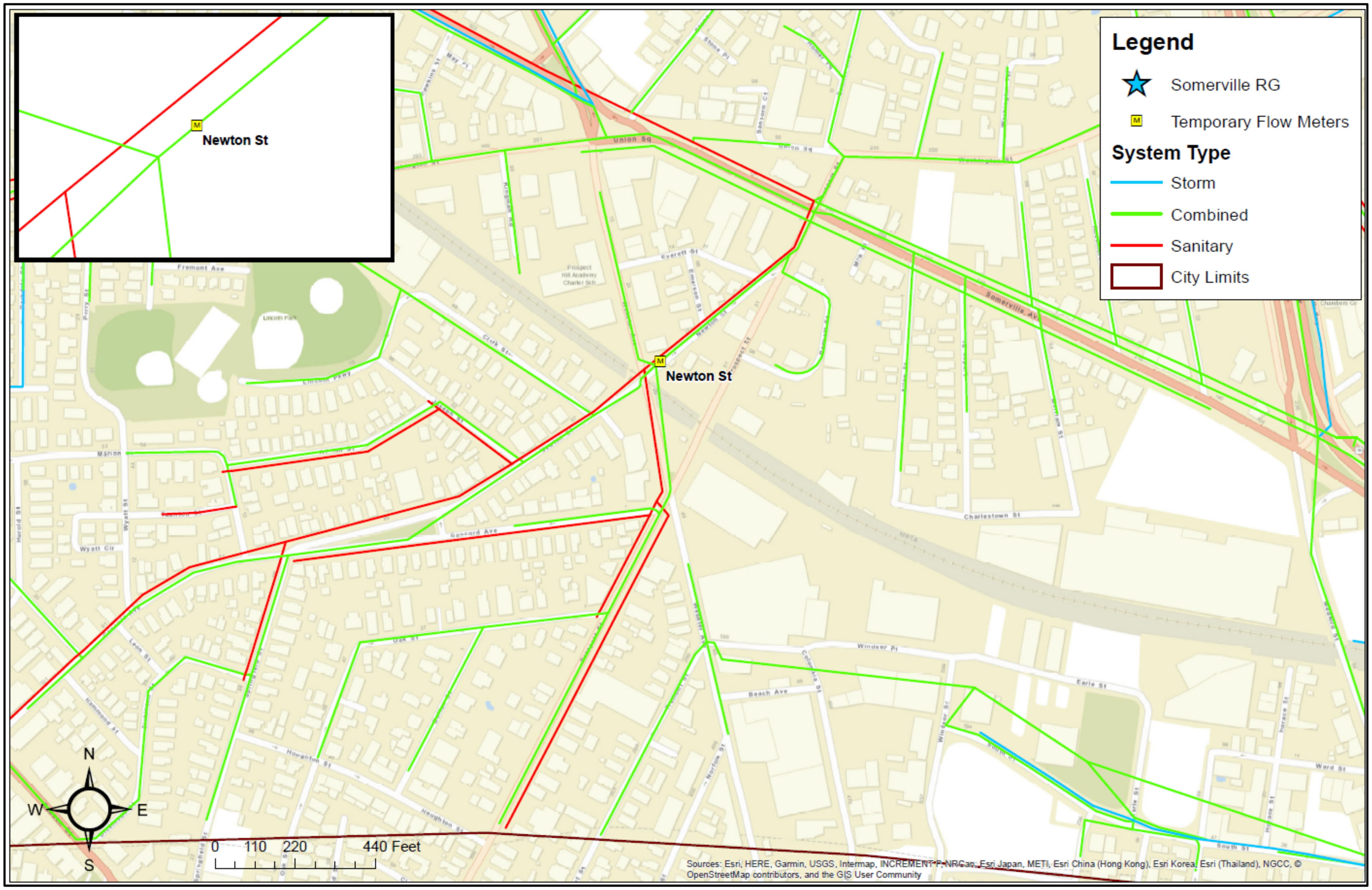

Figure 3i. Location of Temporary Flow Meters, and Rain Gauges (Closeup 8)

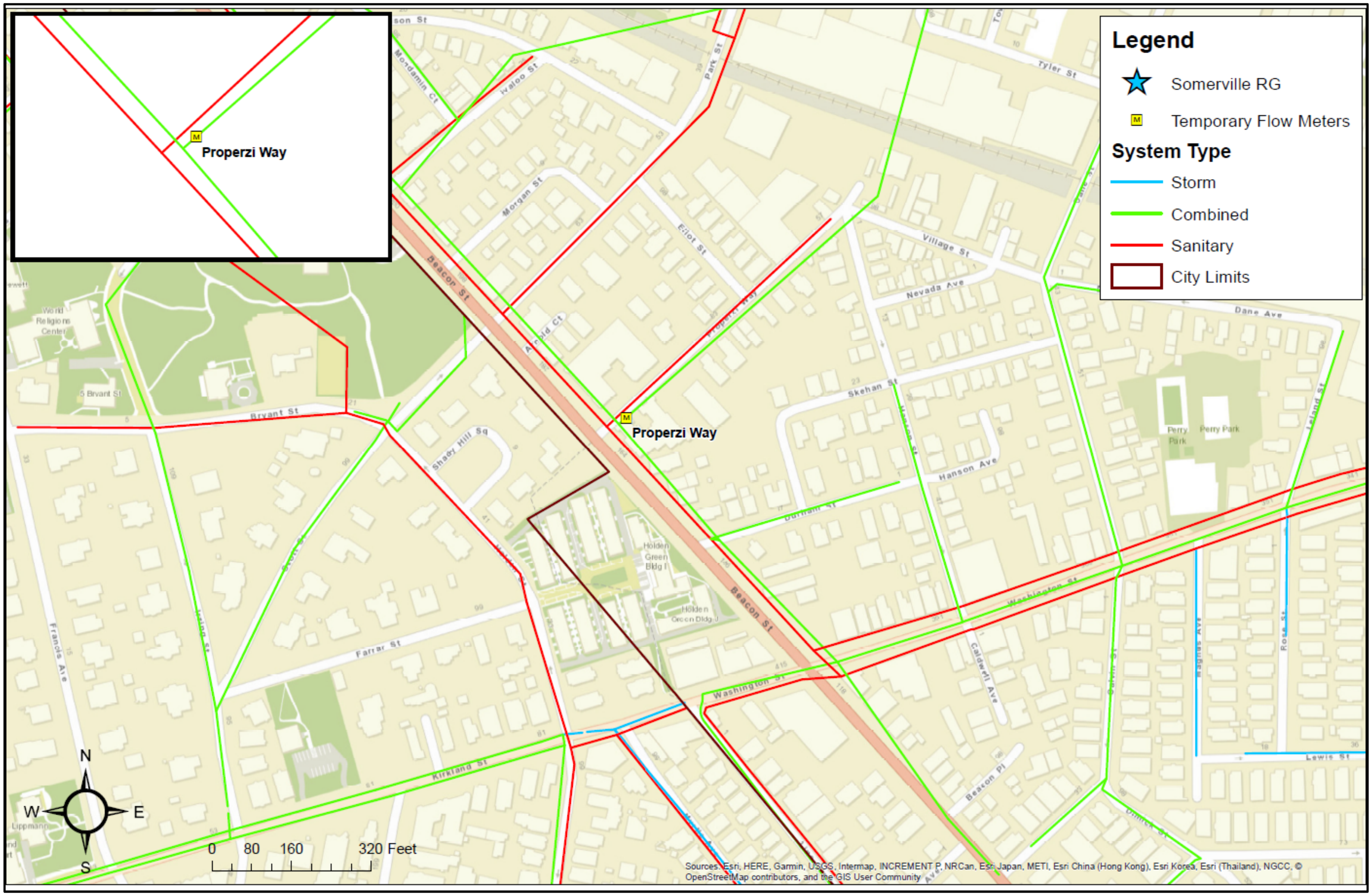

Figure 3j. Location of Temporary Flow Meters, and Rain Gauges (Closeup 9)

Table 5 Flow Meter Data Available for Calibration and Validation

Flow Meter No	Flow Meter Name	Record Period	Variables Recorded	Time Step (min)	Location (Street)	Pipe Size (in) (wxh)	System Type	Remarks
1	Tannery Br North (2)	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	Tannery Brook Row @ Cameron Avenue	30	Combined	Meter was installed in combined system to measure bifurcation flow. For dry day event there was no flow recorded. For storms reasonable data was observed.
2	School St	10/26/18 00:15 12/16/18 23:45	Flow, Depth, Velocity	15	School Street	18	Storm	Reasonable data** was observed during dry day and storm events
3	Marshall St	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	Marshall Street @ Howe Street	66	Storm	Good data was observed for dry and storm events
4	North St	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	North Street @ Raymond Avenue	20	Storm	Reasonable data** was observed for storm events.
5	Pearl St	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	Pearl Street@ Medford St	28	Combined	Low flows observed during storm 1 event. For storm 2, observed data shows backflow after peak rainfall.
6	Newton St	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	Newton Street @ Webster Avenue	36	Combined	Good data* was observed for dry day and storm events.
7	Murdock St	12/17/18 00:00 – 2/08/19 23:45	Flow, Depth, Velocity	15	Cedar Street @ Murdock Street	12	Combined	Good quality data* for two storm events. However, anomalous data was identified for 21st December 2018 and 24th January 2019 storms.
8	Mystic Ave	12/17/18 00:00 – 2/08/19 23:45	Flow, Depth, Velocity	15	Mystic Avenue	48	Combined	Reasonable data** was observed for two storm events. For storm 24 January 2019 observed data shows high depth 6.675 ft.

Rainfall and Flow Meter Data
April 8, 2019

Flow Meter No	Flow Meter Name	Record Period	Variables Recorded	Time Step (min)	Location (Street)	Pipe Size (in) (wxh)	System Type	Remarks
9	Grove St	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	Grove St @ Somerville Community Path	23 x 25	Combined	Good data was observed for dry day and storm events.
10	Palmer Ave	12/17/18 00:00 – 2/08/19 23:45	Flow, Depth, Velocity	15	Palmer Avenue @ Franklin Street	17x24	Combined	Good data* observed during storms. However, poor data was observed during DWF events. During DWF, flow data is not consistent. It's missing in intermediate periods.
11	Tannery Br	10/26/18 00:15 – 12/16/18 23:45	Flow, Depth, Velocity	15	Tannery Brook Row @ Cameron Avenue	60 x 48	Combined	Good data was observed for dry day and storm events.
12	Mystic 72in	12/17/18 00:00 – 2/08/19 23:45	Flow, Depth, Velocity	15	McGrath Way	72	Storm	Reasonable data** was observed for two storm events. For storm 24 January 2019 observed data shows high depth 6.5 ft.
13	Properzi Way	12/17/18 00:00 2/08/19 23:45	Flow, Depth, Velocity	15	Properzi Way @ Beacon Street	24	Combined	Reasonable data** was observed during dry day and storm events

*Good data refers to meter records (flow, depth and velocity) within expected ranges during storms with no missing time periods;

**Reasonable data refers to within expected flow response, but poor depth or velocity data were recorded or cases where some data are missing for part of the storm.

5.0 CALIBRATION STANDARDS

Model calibration standards from the Chartered Institution of Water and Environmental Management's (CIWEM) Code of Practice for the Hydraulic Modeling of Sewer Systems version 3.001 were adopted for this effort; these are described below.

5.1 DRY WEATHER FLOW CALIBRATION STANDARDS

- Observed versus predicted DWF calibration comparisons should closely follow each other both in shape and in magnitude.
- The flow hydrographs should meet the following criteria:
    - Timing of the peaks and troughs should be within 1 hr.
    - Peak flows should be in the range ±10%.
    - Volume of flow should be in the range ±10%.
    - Depth of flow shall be in the range ±0.33 ft.

5.2 WET WEATHER FLOW CALIBRATION STANDARDS

- Observed versus simulated WWF calibration comparisons shall closely follow each other both in shape and magnitude, until the flow has substantially returned to dry weather flow rates.
- Observed and simulated hydrographs shall meet the following criteria in at least two of the three events.
    - Timing of the peaks and troughs shall be similar in regard to the event durations.
    - Peak flows at each significant peak shall be in the range -15% to +25%.
    - Volume of flow shall be in the range -10% to +20%.
    - Surcharged flow depths shall be in the range -0.32 ft to +1.64 ft.
    - Un-surcharged flow depth shall be within the range ±0.33 ft.

Meeting all of the above standards would be a clear indication of a successful calibration. However, these are guidelines and not meeting some of them does not necessarily indicate a poor calibration or a model that is not 'fit for purpose.' Where calibration falls outside of the recommended range, the root causes are documented and recommendations to improve model performance are provided.

5.3 CALIBRATION DOCUMENTATION

The following were generated to show the acceptability of the calibration/verification efforts.

- Regression plots of model versus meter peak flow rates for calibration events.
- Regression plots of model versus meter total event volumes for calibration events.
- Time series plots of the individual events showing model and meter time series for flow and/or water depth/elevation as appropriate.

6.0 MODEL CALIBRATION PROCESS AND RESULTS

6.1 DRY WEATHER CALIBRATION

To calibrate the model for dry weather two DWF periods were selected. For the first eight flow meters the selected period for DWF calibration was the 3-day period ranging from 12/07/2018 through 12/10/2018. This period covers both weekday and weekend days. For the remaining five flow meters the selected period for DWF calibration was the 3-day period 01/11/2019 through 01/13/2019. This period covers both weekday and weekend days.

The model was calibrated under dry weather conditions to ensure the model's ability to replicate observed sanitary and base flows in the system. Sources of sanitary flow can be residential, industrial, or commercial. Sanitary flows typically follow weekday and weekend diurnal variations. Sub-catchment population and land use characteristics have the largest impact on the quantification of sanitary flows. On the other hand, base flow rate may vary seasonally based on ground water elevation that infiltrates into the collection system. Base flow is impacted by pipe age and condition, as well as groundwater levels surrounding the pipe. The current model calibration does not capture seasonal variations of base flow as flows meters were kept in the system for a period of only 8 weeks.

6.1.1 Dry Weather Flow Calibration Process

The following changes to the base model were necessary in order to achieve a satisfactory comparison between the observed and predicted hydrographs:

- Infiltration flows were reviewed as a base flow generated upstream of each flow meter site, based on observed low flow conditions data. Then observed base flow was subsequently distributed pro-rata by area to tributary catchments.
- A representative diurnal pattern based on measured flow data was developed for each meter separately. A sample of normalized weekday and weekend diurnal patterns from the flow meter in Newton Street are shown in Figure 4. The diurnal patterns were applied to sanitary and combined catchments tributary to each meter.
- An additional sanitary flow was assigned to the catchment tributary to each meter location and adjusted during calibration until the match between observed and modeled DWF hydrographs was within acceptable bounds.
- Pipe sizes and gradients, pipe roughness, and sediment representation were checked to resolve poor depth matches. Top and bottom roughness coefficients were also adjusted, if necessary.
- Head loss coefficients were changed when necessary to better the flow-depth match.

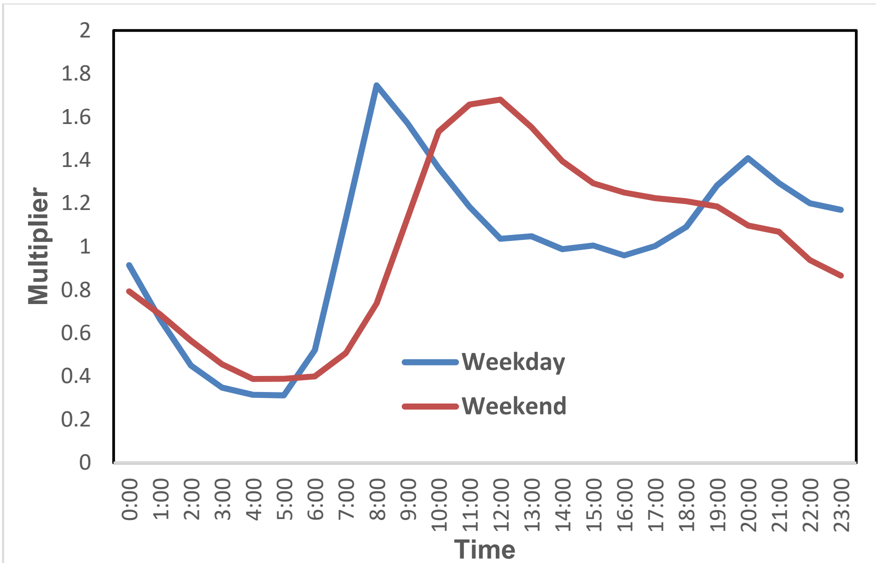

Figure 4 Diurnal patterns based on measured flow data at the Newton Street meter

6.1.2 Dry Weather Flow Calibration Results

In most cases the Refined Model replicated metered dry weather flows within calibration standards. Tables C.1 and C.2 in Appendix C summarize the results of the dry weather flow calibration for the December 7-10, 2018 and January 11-13, 2019 period. Peak flows and total volumes are reported along with percent differences between the metered and modeled values at each meter location. Only six out the thirteen locations had clear diurnal flow patterns. The remaining seven locations either had no flow or had random peak flow spikes that seem to indicate potential meter malfunctions (i.e. Tannery Brook (2) and Palmer Ave meters). Simulated peak flows and volumes at locations with predictable flows were within +-10% of the metered values at 10 out of 13 locations.

Figures 5 and 6 show regression plots of modeled versus metered peak flows and cumulative volumes under dry weather flow conditions for calibrated meters. A reasonable agreement between meter and model values is observed. As noted above, discrepancies between model and meter peak flow fall beyond the 10% range at only one meter location for volume.

Model and meter flow hydrographs are provided in Appendix C. Figure C.1 exhibits comparison of metered versus modeled flow charts at the thirteen meter locations listed above in Table 5. Modeled hydrographs closely match metered flow curves in terms of pattern and time to peak in most instances with predictable patterns.

Table C.3 lists simulated peak water depths compared to metered values during the DWF period. Differences at temporary flow meters are, for the most part, within the target ±0.33 feet under non-surcharged conditions. Larger differences in water depth are observed at Mystic Avenue meter locations under DWFs. For this meter, the data shows 0.880 ft depth. This sewer is 48” in diameter and it seems to get surcharged under dry weather flow conditions. The reasons why these conduits are submerged under dry weather conditions is unclear, but it may be due to pipe conditions (e.g. reverse pitch of some sections). It is recommended future field surveys are conducted in the area to verify sewer elevations and overall conditions.

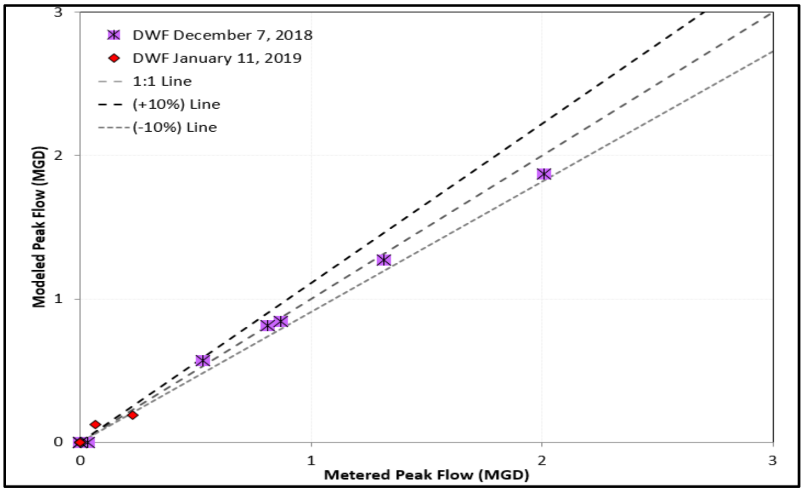

Figure 5. Comparison between modeled and metered peak flow under DWF

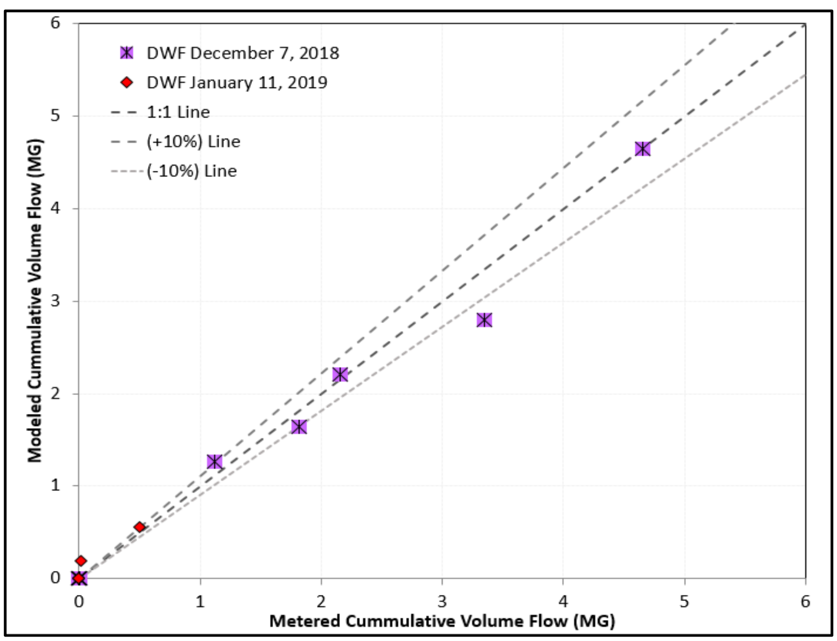

Figure 6. Comparison between modeled and metered cumulative volume under DWF

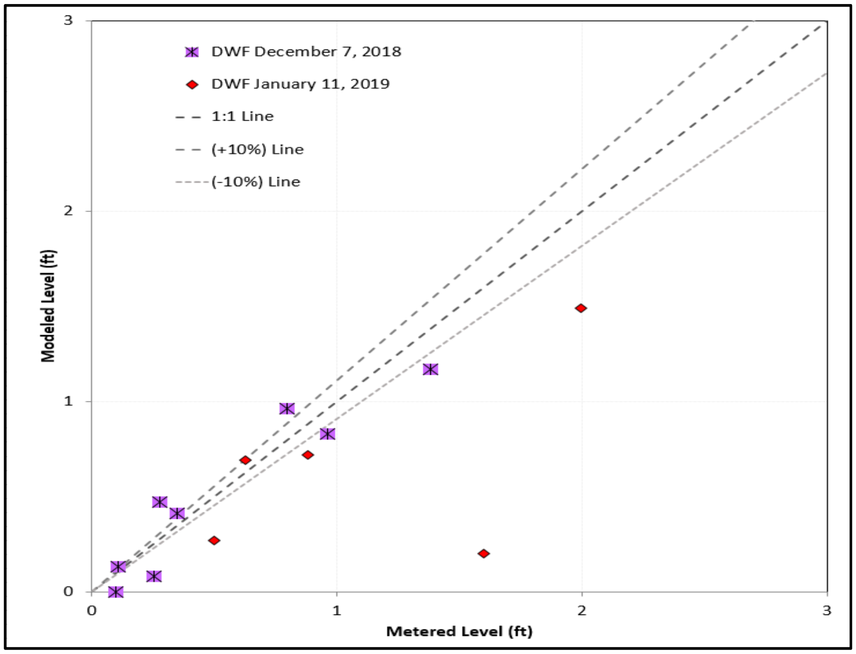

Figure 7. Comparison between modeled and metered peak depth under DWF

6.2 WET WEATHER CALIBRATION

For Somerville model calibration, a total of 13 temporary meters were installed in two phases. In the first phase, eight (8) meters were installed from October through December 2018. For these meters, the November 2, 2018 event was selected for calibration and the November 9, 2018 event was selected for validation.

In the second phase, five (5) meters were installed from December 17, 2018 through February 8, 2019. For these meters, the December 21, 2018 storm was selected for calibration.

Due to data quality issues, two different storms were used for validation for the second set of meters: the December 31, 2018 event was used for Properzi Way and Murdock Street meters and the January 24, 2019 event was used for the Mystic Avenue and Palmer Avenue meters.

6.2.1 Wet Weather Flow Calibration Process

The model was calibrated under wet weather conditions to ensure the model's ability to accurately estimate runoff, flow rates, and water levels across the sewer network system. The runoff calculations are influenced by catchment characteristics, including but not limited to catchment size and slope, soil infiltration properties, and whether the catchment has directly connected impervious areas. In the newly refined tributary areas, new land Runoff Surfaces defined in Table 3 were created and hydrologic parameters were then adjusted during the calibration process.

The most sensitive hydrologic parameters were initial loss value of pervious and impervious areas, contributing area of sub-catchments, runoff coefficients, and initial and final Horton infiltration rates. These parameters were adjusted during the calibration process at each flow meter. All these parameters were maintained within physically reasonable bounds.

Table 6 lists ranges of hydrologic parameters associated to sub-catchments after calibration was completed.

Table 6 Hydrologic Parameters before and After Refined Model Calibration

Parameter	Initial Range Value (Typical Values)	Range Value in Calibrated Model
Pervious Retention/Loss Depth (inches)	0.0001 – 0.065	0.0001 – 0.065
Impervious Retention/Loss Depth (ft)	0.00001 – 0.025	0.00001 – 0.025
Horton's Initial Infiltration Rate f_o (Inches/hour)	0.8 – 3.5	0.1 - 4
Horton's Final Infiltration Rate f_c (Inches/hour)	0.1 – 50	0.1 – 0.5
Runoff Coefficient	0.45 - 1	0.4 - 1
Horton's SWMM Decay Rate (1/hr)	2 - 10	2 - 7
Catchment Width (ft)	52 – 4,500	52 – 4,500
Catchment Slope (ft/ft)*	0 – 16	0 – 32.7
Catchment Imperviousness (%)	0 – 100%	0 – 100%
*Parameter not adjusted during calibration		

6.2.2 Wet Weather Flow Calibration Results

Tables D.1 through D.4 list percent differences between measured and simulated peak flows and volumes at the meter location with available measured flow data. The percent differences between metered and modeled flows for the calibrated models shows the overall performance of the model is good. The accuracy of the final model calibration is illustrated in Figures 8 and 9, which show a reasonable agreement between metered and modeled peak flows and total volumes for the two calibration events and for the validation events at most meter locations. Figure 8 shows that a large portion of the simulated peak flows fall within the +25% and -15% bounds for the two WWF storms. The model overestimated peak flows beyond the 25% upper bound at two locations but the largest over prediction was at the School Street meter during the calibration events. After multiple attempts to lower peak flow volumes in the School Street meter catchment area, it became apparent that flow transfers between adjacent systems occur within the catchment area and are not yet fully understood resulting in model overpredictions.

Figure 9 shows that the model is able to accurately estimate cumulative flows at most meter locations. As modeled values fall within the +20% and -10% bounds except at a few locations including Murdock Street, Pearl Street, and Palmer Avenue. Of interest is the fact that meter data showed no base flows during storm events at these locations. However, during DWF conditions meter data showed base flows for the first two and the model was successfully calibrated during DWF. These differences in base flow patterns is one of the reasons why the model overpredicted total volume during the calibration storm events.

Model versus meter comparison flow hydrographs are provided in Appendix D. Figure D.1 exhibits comparison of metered versus modeled flow charts for the calibration events at the thirteen (13) meter locations listed in Table 5.

Tables D.5 and D.6 show modeled against metered water depths during the calibration and validation WWF events. For most of the flow meters the model achieved a good peak depth against observed peak depth. At two meters, Mystic Avenue and Mystic 72in, the model underpredicts for peak depth by -2.7 ft. At the Mystic 72in meter, observed meter data shows surcharge conditions but the model does not predict it as the downstream trunk sewer has enough capacity to carry the storm flows. To achieve the observed depth, a few tests were performed such as adding silt, or changing gradient and headloss in the sewer but there was no improvement in the depth. Additional investigations are recommended to assess the root of the issue, which is suspected to be a sag in the line. Underpredicting on peak depth happened during one storm on January 24, 2019. It indicates there would be a temporary blockage/obstruction on downstream side of the meter.

For the storm on December 21, 2018 the model predicts a good match for peak depth against meter depth data.

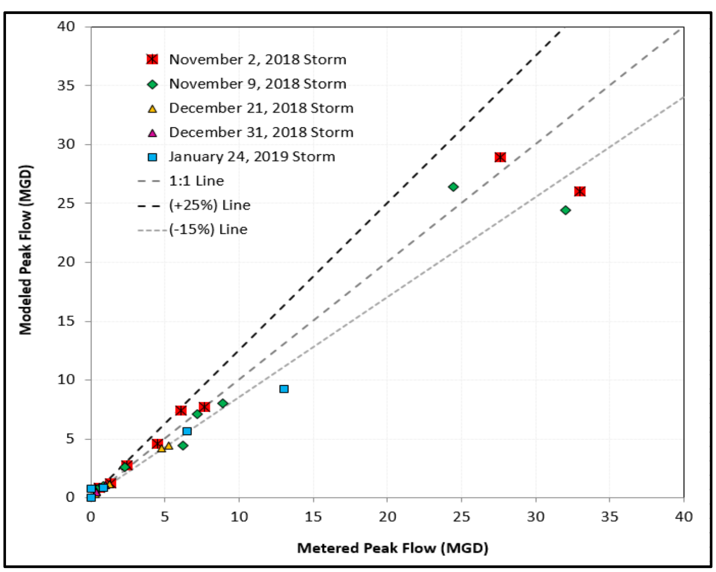

Figure 8. Comparison between modeled and metered peak flows during calibration events

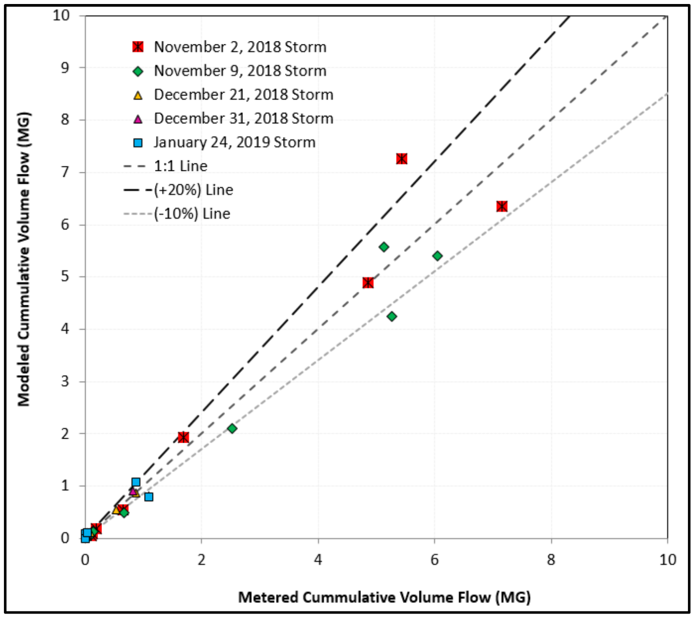

Figure 9. Comparison between modeled and metered cumulative volume during calibration events

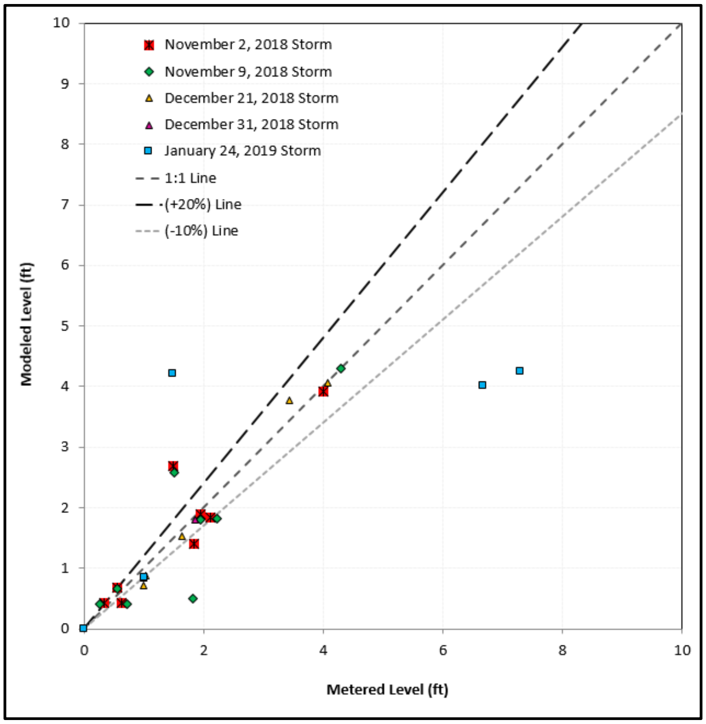

Figure 10. Comparison between modeled and metered peak depth during calibration events

7.0 SUMMARY AND CONCLUSIONS

Model calibration at thirteen temporary meters was completed. The calibration process consisted of adjusting the parameters associated with the hydrologic model to simulate and duplicate metered peak flow, flow volume, and hydrograph shape for dry weather and wet weather flow periods during the metering period. Calibration was conducted in order to improve the ability of the model to simulate a range of storms with variable rainfall volume, duration, and intensity. Rainfall data associated with the flow metering period were reviewed in order to select calibration events. Rainfall events were classified by peak rainfall intensity, total rainfall depth, antecedent dry period, duration, and equivalent recurrence interval.

7.1 DRY WEATHER FLOW MODEL CALIBRATION RESULTS:

During dry weather, modeled peak flows and volumes fell, in most cases, within CIWEM guidelines for meters with clear and predictable diurnal patterns or meters with no dry weather flow (i.e. Grove St, Newton St, Pearl St., Marshall St., Properzi Way, and Tannery Brook for the first and School St, North St., Mystic Ave, Mystic Ave_72in, and Murdock St for the latter). For meters with questionable dry weather flow data or with random flow spikes (i.e. Palmer Ave and Tannery Brook North (2)) the model could not be calibrated to meet CIWEM guidelines because the source of the flow spikes could not be fully understood with the information available.

7.2 WET WEATHER FLOW MODEL CALIBRATION AND VALIDATION RESULTS:

During the calibration and validation events, peak flows were within acceptable CIWEM bounds in all but five meters. The major source of flood overprediction during the calibration and validation events occurred at the School Street and Murdock street meter It is suspected that this overprediction is likely to be caused by potential flow transfers between pipes in the catchment area that are not well understood and need further investigations. In addition to this, the largest model peak flow underpredictions occurred at the Tannery Brook main conduit, which reinforces the theory that flow transfers between the Union Square and the Tannery Brook systems is not fully understood despite having detailed data on the main regulator structures. Additional cross-connections are suspected between these systems.

Cumulative flow volumes did not adhere to CIWEM standards in seven and nine occasions during calibration and validation, respectively. Most of these differences are due to the fact that differences in baseflows for some meters seem to behave differently between dry weather and wet weather flow calibrations but the model assumed same dry weather flows under both scenarios. Another source of volume difference is believed to be Rainfall Derived Infiltration Inflow (RDII) that prolongs the hydrographs post-storm in some meter areas such as Grove Street.

Overall, the model was successful at replicating peak storm flows, but volumes could not always be kept within CIWEM limits. Several factors are potential sources of error:

- Conveyance system uncertainty: Unknown collection system information such as pipe conditions, unknown blockages, sediment accumulation or cross-connections may cause the system to behave differently than anticipated.
- Due to the limited flow monitoring period available for calibration, i.e. November 2018 – January 2019, the model was only tested for late fall and winter season soil moisture antecedent conditions.

The Refined Model after calibration and validation is deemed appropriate for planning purposes but further understanding of the system is necessary in certain areas, especially Tannery Brook and Mystic Ave, prior to proceeding with significant design of capital improvement projects. Figure 11 depicts calibration results by geographic area.

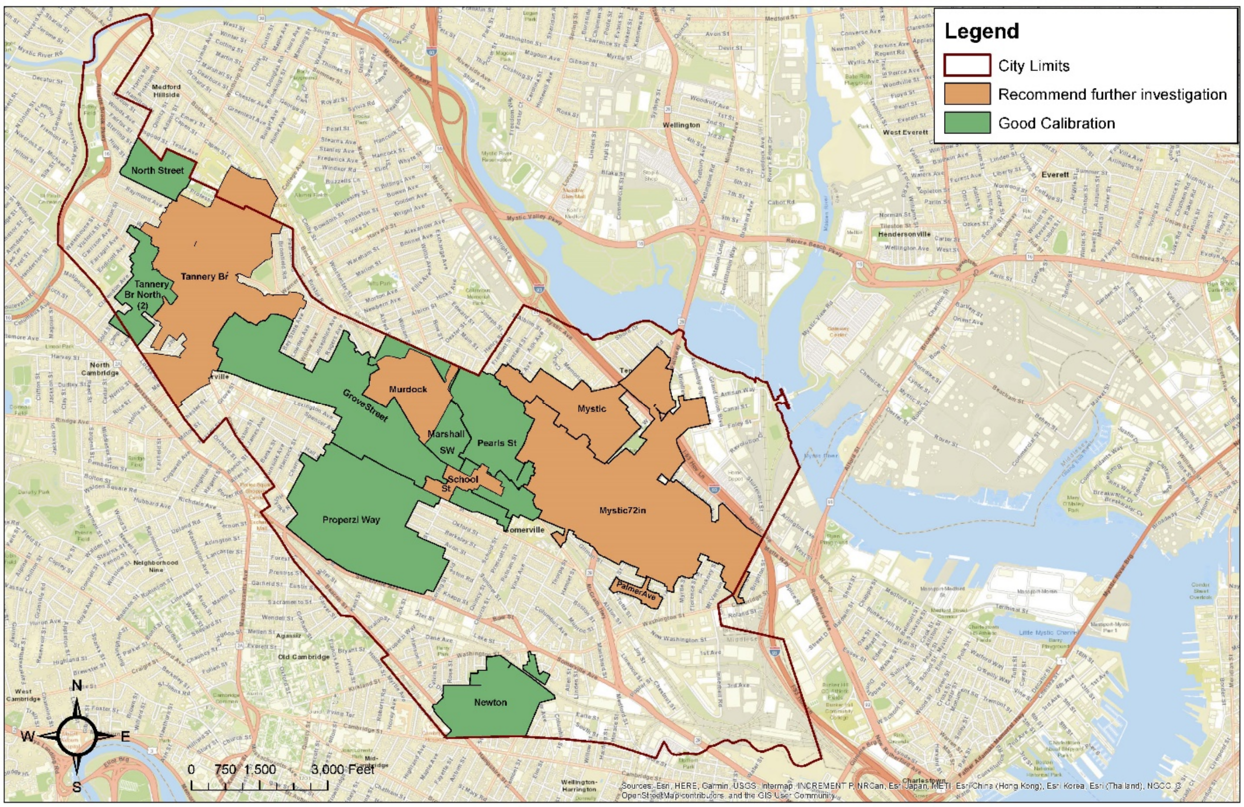

Figure 11. Calibration Status

8.0 RECOMMENDATIONS

- In areas with known cross-connections and flow transfers such as the Tannery Brook, School Street, and Murdock Street and Union Square systems, perform exhaustive field investigations including CCTV to fully understand how the system works. Some detailed recommendations for CCTV are provided in Appendix A. Other location outside of these areas are also recommended for inspection such as a bifurcation manhole on the School Street meter system and the Mystic Avenue system near the Marginal facility.
- At the Mystic Avenue meter location, the data from the January 24, 2019 storm shows sudden increases in peak flow which seem to be spikes in the flow data. The meter shows a high peak depth close to 6.5 ft. The reason for this is unknown; however, a possible cause maybe a temporary blockage or obstruction somewhere downstream in the system. Nevertheless, a good match between model and meter flow depth was achieved during the December 21, 2018 storm. It is recommended to complete CCTV in this area to observe pipe conditions and connectivity.
- The model over estimates peak depth at the Palmer Avenue meter during the January 24, 2019 storm the sewer surcharges. On the other hand, a reasonably good match between simulated and metered depth is achieved during the December 21, 2018 storm. It is recommended to complete additional metering in this area to capture additional representative storm events to enhance the ability of the calibrated model to reproduce observations.
- Continue to perform flow metering and pipe condition assessment on a routine basis that will help to continuously improve model detail and performance.

APPENDIX A

Field Investigation Report

Reference: Somerville Municipal Vulnerability Preparedness (MVP)

The following is a summary of the field investigations conducted as part of the City of Somerville's MVP Action Grant for stormwater system modeling to improve communications and development of green infrastructure. The investigations were conducted from October through December 2018 and included overseeing flow meter installation, manhole surface inspections, as well as confined space entries performed at select locations. The intent of this memorandum is to summarize the fieldwork and findings for the internal design team and to then utilize the content within the hydraulic technical memorandum for the City of Somerville.

Purpose

Field investigations were conducted to further refine the City's hydraulic model. The investigations were focused on structures hydraulically connected to known flooding areas as well as certain areas that required model refinement to enhance the overall accuracy of the model. As a result, a significant number of manhole inspections were concentrated within the Tannery Brook catchment area, with other locations scattered across the City.

Flow Metering

ADS Environmental Services installed thirteen (13) flow meters and one (1) rain gauge between October 2018 and December 2018. The meters were installed on October 23rd, October 24th, and December 13th. The structure identification number, according to the City's GIS, along with the installed date and pipe characteristics have been included in **Table A.1**.

Table A.1 Flow Meters

Structure ID	Structure Location	Installation Date	Meter Location	Pipe Size	Pipe Material
Rain Gauge	DPW Engineering Building	10/23/2018	Roof	NA	NA
MH 30-5112	School St / Medford St	10/23/2018	Outlet	18"	VCP
MH 30-5600	Pearl St / Marshall St	10/23/2018	Inlet	24"	CIPP liner
MH 30-5116	Marshall St / Stickney Ave	10/23/2018	Inlet	66"	Brick
MH CA-2401	Grove St (#48)	10/24/2018	Inlet	26"Wx24"H	Brick
MH 9-5186	North St / Raymond Ave	10/24/2018	Outlet	20"	VCP
MH 1-6432	Cameron Ave / Seven Pines Ave	10/24/2018	Inlet (Cameron Ave)	30"	Brick
		10/24/2018	Inlet (Tannery Brook)	60"Wx48"H 60"Wx53"H	Conc invert & sides w/ Brick wavy ceiling
MH C2-1994	Newton St / Webster Ave	10/24/2018	Outlet	36"	Brick
MH C2-1334	Properzi Way (#100)	12/13/2018	Inlet	25"Wx28"H	Brick
MH S2-3264	McGrath Highway / Foss Park	12/13/2018	Inlet	54"Wx48"H	Brick
MH 30-6204	McGrath Highway / Foss Park	12/13/2018	Inlet	72"	RCP
MH CA-453	Cedar St / Murdock St	12/13/2018	Inlet	10"	VCP
MH C1-1355	Palmer Ave / Franklin St	12/13/2018	Inlet	24"	PVC

Manhole Inspections

An asset management program was previously completed throughout the City, by another engineering firm, to update the City's GIS conveyance system. This included refinement of the location of manholes as well as collecting photographs of most manholes in the City. Stantec utilized this data to narrow down the structures that may contain cross connections, weirs, overflows, or bulkheads that required additional data gathering and then focused the investigations on these specific areas.

A total of (60) structures were inspected throughout the City with various levels of data collection. These included full manhole inspections, photographs only, and confined space entries. If a manhole cover was opened to confirm connectivity, but an inspection was not required, then only photographs were obtained.

A total of (42) manholes were inspected from the surface throughout the City. These included sewer, drain, combined sewer, and common manholes. An online ArcGIS database was setup using Esri's mobile application, Collector, to expedite work in the field with electronic data collection. A camera pole was also utilized to obtain information from within the structures. This allowed a camera to be extended down into the manholes and for the inspector to look around to obtain data while minimizing confined space entries. This was especially useful when pipes were bulk headed, but the bulkhead was recessed within the pipe and not seen from the ground surface.

A table has been included in **Appendix F** that summarizes all the structure inspections conducted. The structure identification number, location, manhole type, level of data collection, and comments related to findings have all been included in the table. **Appendix G** includes the manhole inspection reports along with the associated photographs.

Confined Space Entries

After conducting the manhole surface inspections, there were a few locations where additional information needed to be gathered that could not be obtained from the surface and could not be obtained using the camera pole. Confined space entries were conducted within (4) structures on December 20, 2018. The locations are further described below and notes from the entries have been included in **Appendix H**.

Broadway Street / Cross Street

Confined space entries were performed at manhole S2-2767 and S2-2141 at the intersection of Broadway Street and Cross Street. Manhole S2-2767 is lined along with the 36-inch outlet pipe on Broadway headed west. The inlet pipe into manhole S2-2767 is a 36-inch brick pipe and makes the bend from Cross Street. The 18-inch VCP in-line connection from Broadway was confirmed into the 36-inch brick pipe. A weir and overflow connection were observed from S2-2767 over to S2-2141 (See **Figure A.1**).

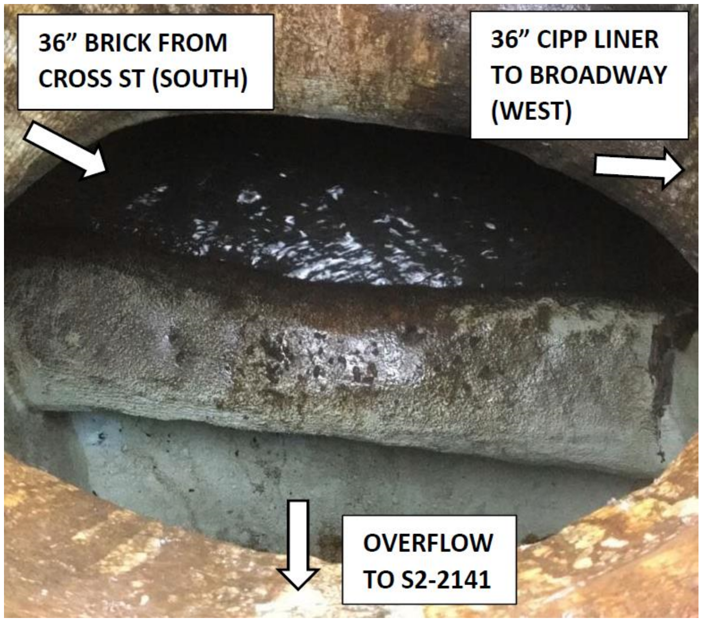

Figure A.1 – MH S2-2767 Weir and overflow to S2-2141

The overflow is a tapered brick channel measured to be 5.1’Wx1.4’H on the upstream end and then increases in height to 5’Wx2.3’H on the downstream end at manhole S2-2141.

Manhole S2-2141 is partially lined with the liner in poor condition at the manhole invert. The mainline inlet and outlet was measured to be a 41-inch brick pipe and sleeved inside the mainline is a 12-inch vitrified clay pipe that sits within the mainline invert. The 12-inch pipe has an open tee connection providing access within the limits of the manhole (See **Figure A.2**). There are also (2) inlets coming from the direction of Cross Street East. The source of these connections could not be determined.

Figure A.2 – MH S2-2141 36” Brick Inlet with 12” VCP sleeve at invert

Clarendon Avenue

A confined space entry was conducted within manhole S78CMH9500 to better understand the Tannery Brook conduit and the connectivity between the drain, sewer, and combined sewer on Clarendon Avenue. These inspections were conducted within the limits of Cambridge; however, this area has hydraulic impacts to the Somerville conveyance system upstream. The Somerville GIS system is not fully built out in this area, but the Cambridge GIS appears to match the connectivity observed in the field (See **Figure A.3**). The Cambridge structure identification numbers were used during the investigation along with the Somerville identification numbers if available.

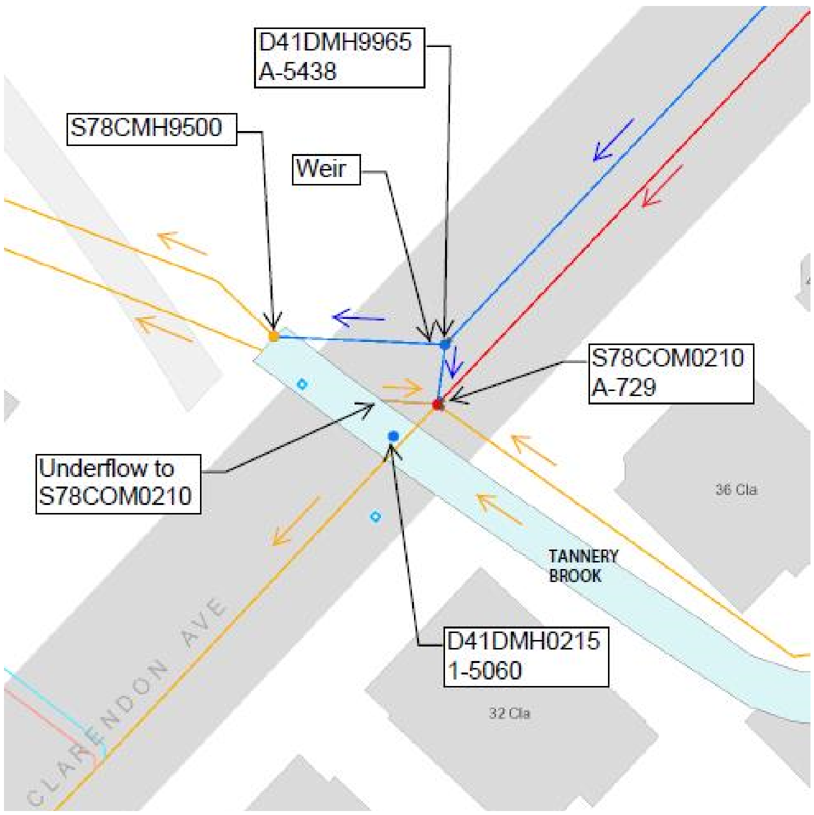

Figure A.3 – Clarendon Ave Tannery Brook Connectivity

The major findings included the observed 10-inch vitrified clay underflow connection from the Tannery Brook conduit over to A-729. This connection is approximately 6-inches below the Tannery Brook conduit directing base flows into S78COM0210 / A-729. In addition, a brick weir was observed within D41DMH9965 / A-5438 directing base flows into S78COM0210 / A-729. In this location, the Tannery Brook conduit is a rectangular channel and has a concrete invert with brick sides and a brick ceiling. The ceiling has consistent waves with varying heights. The conduit was measured to be 7.3'Wx4.1'H at its lowest point and 7.3'Wx4.4'H at its highest (See **Figure A.4**).

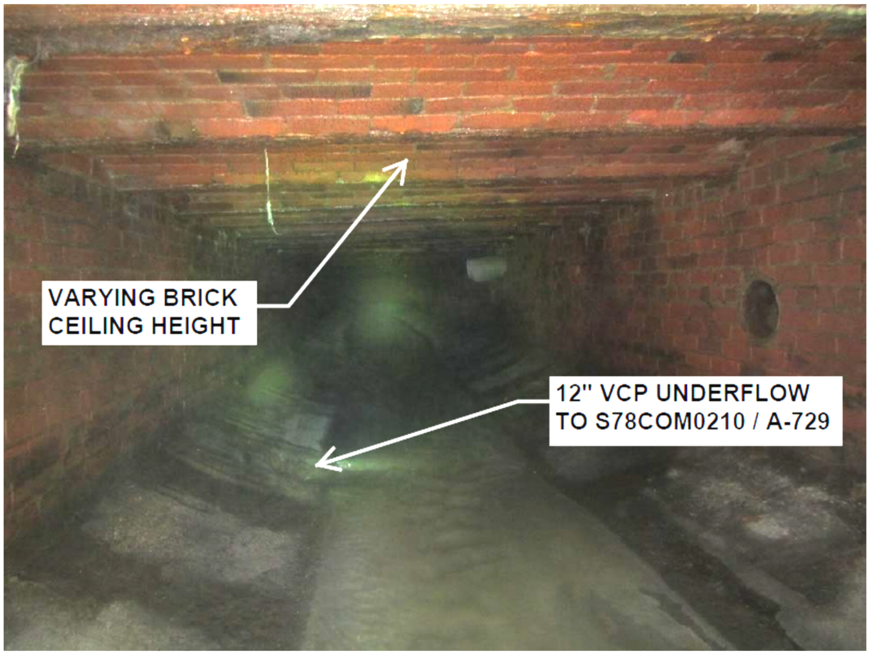

Figure A.4 – Clarendon Ave Tannery Brook Conduit (Inlet as observed from S78CMH9500)

The concrete invert of the Tannery Brook Conduit displayed signs of degradation with exposed aggregate and soil suspected to be from hydrogen sulfide corrosion (See **Figure A.5**).

Figure A.5 – Concrete invert corrosion within Clarendon Ave Tannery Brook Conduit

College Avenue

A confined space entry was conducted within drain manhole CA-5916 on College Avenue adjacent to the Davis Square MBTA entrance. The City GIS depicts a 30-inch drain on College Avenue ending at this manhole with no outlet. A large 10'Wx10'L concrete chamber was observed with a 5'Wx7'H concrete box culvert inlet and outlet going parallel to the MBTA tunnel from east to west (See **Figure A.6**). The College Avenue 30-inch ductile iron inlet was observed coming from the north in-line into the mainline box culvert along with an additional 24-inch corrugated metal inlet pipe coming from the south and connecting in-line. The source of the 24-inch inlet is unknown. In addition, a conduit passes through the chamber and it appears the structure was cast-in-place to allow for this crossing. This crossing is suspected to either allow for the combined sewer to pass through or a private utility.

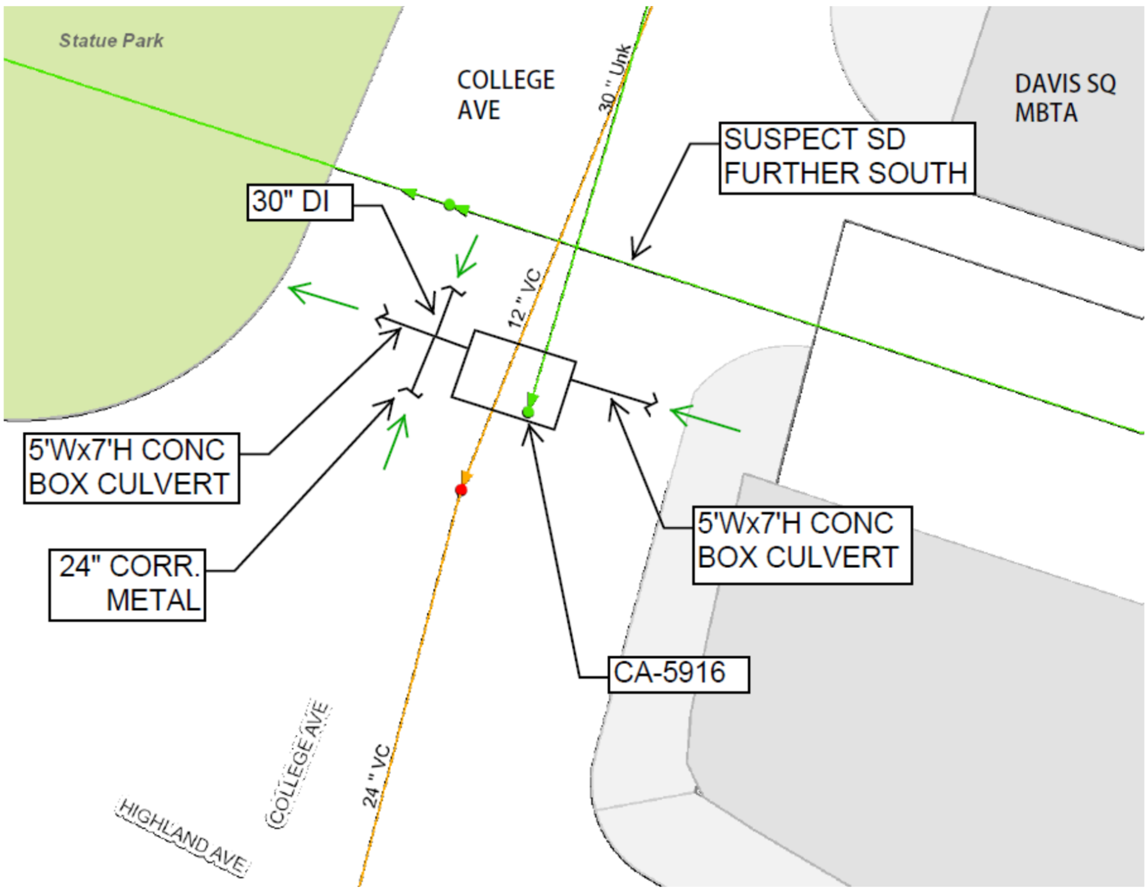

Figure A.6 – MH CA-5916 GIS Markup

Findings

Several discrepancies were found between the connectivity in the field as compared to the City's GIS. These include cross connections between the sewer and drain which greatly impacts the hydraulic model. Sketches have been included in **Appendix I** to depict these scenarios. In addition, common manholes, flap gates, bulkheads, structures requiring maintenance, and structures that were inaccessible have been identified and are summarized below.

A total of (11) common manholes were identified through the field investigations and have been tabulated in **Table A.2**. These are manholes that contain both a sewer and a drain within the same structure.

Table A.2 – Common Manholes

Structure ID	Structure Location
CA-3075	Day St / Elm St
A-532	Elmwood St / Elmwood Ter
A-533	Elmwood St / Harrison Rd
A-2331	Gorham St / Holland St
CA-2401	Grove St / Community Path
CA-254	Highland Rd / Kidder Ave
S2-3215	McGrath Highway / Foss Park
CA-2	Simpson Ave / Holland Ave
CA-3099	#15 Simpson Ave
CA-100	Simpson Ave / Cady Ave
CA-99	#47 Simpson Ave

A total of (3) flap gates or remnants of flap gates were observed within (2) structures and are summarized in **Table A.3**. The flap gates within CA-106 may have been partially removed or have corroded.

Table A.3 – Flap Gates

Structure ID	Structure Location	Pipe with Flap Gate	Condition
CA-106	Broadway / Paulina St	Inlet (From CA-5208)	Poor; portion may have been removed
		Inlet (From CA-5209)	Poor; portion may have been removed
CA-2752	Cedar St / Community Path	Inlet (SD)	Fair

A total of (3) bulkheads were confirmed and have been itemized in **Table A.4**. These bulkheads alter the pipe connectivity depicted in the City's GIS. The connectivity sketches have been included in **Appendix I**.

Table A.4 – Bulkheads

Structure ID	Structure Location	Pipe Found Bulkheaded	Updates to City GIS Required (Y/N)
CA-5209	Broadway St / Paulina St	Outlet to CA-106 bulkheaded; Inlet from CA-5208 not observed	Y
CA-2397	Holland St / Paulina St	Overflow towards Gorham St bulkheaded	N
C2-6439	Willow Ave / Lexington Ave	Connection to C2-270 bulkheaded	Y

Most manholes inspected appeared to be in good condition and did not appear to require cleaning. However, manhole A-533, at the intersection of Elmwood Street and Harrison Road, appeared to need cleaning due to suspected sanitary service weeping up through debris or potential groundwater infiltration (See **Figure A.7**).

Figure A.7 – MH A-533 in need of cleaning

A fracture was observed on the interior brick manhole wall within manhole S2-2686 at the intersection of Medford Street and School Street (See **Figure A.8**).

Figure A.8 – MH S2-2686 with interior fracture