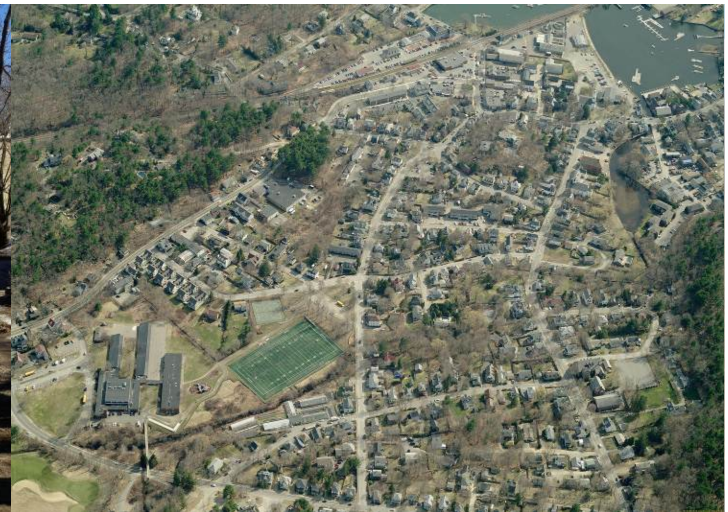


Tighe&Bond

Sawmill Brook Culvert and Green Infrastructure Analysis Task 4 Final Report: Evaluation of Locations for Flood Mitigation

Prepared For:

Town of Manchester-by-the-Sea
Manchester-by-the-Sea, Massachusetts

February 2016

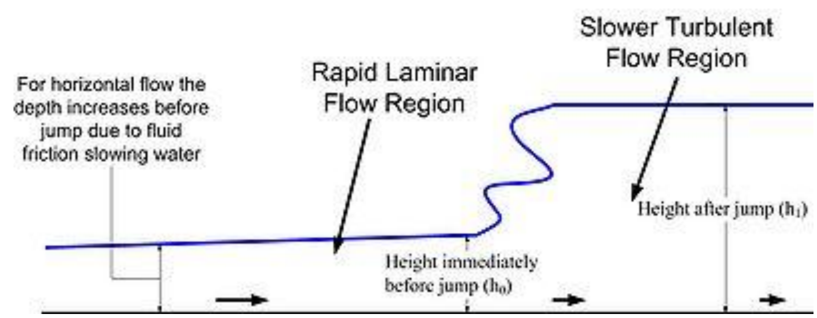
Table of Contents

Tables

Definitions

GIS: acronym for Geographic Information Systems; a system designed to store, analyze, manage, and present all types of geographical data

Hydraulic Jump is a phenomenon in the science of hydraulics which is frequently observed in open channel flow such as rivers and spillways. When water at high velocity discharges into a zone of lower velocity water, a rather abrupt rise occurs in the water surface. The rapidly flowing water is abruptly slowed and increases in height, converting some of the flow's initial kinetic energy into an increase in potential energy, with some energy irreversibly lost through turbulence to heat. In open channel flow, this manifests as the fast flow rapidly slowing and piling up on top of itself similar to how a shockwave forms. The following figure illustrates the behavior in a hydraulic jump.



A hydraulic jump is a region of rapidly varied flow and is formed in a channel when a **supercritical flow** transitions into a **subcritical flow**. In general, supercritical flows are shallow and fast and subcritical flows are deep and slow.[1]

Hydrologic Soil Group is a designation by the Natural Resource Conservation Service (NRCS). The NRCS publishes a soil survey for most counties in the United States that classifies the soils into one of four hydrologic soil groups based upon how quickly the soil drains. Soils classified as "A" are the fastest draining (and have the smallest runoff potential) and soils classified as "D" are the slowest draining (and have the greatest runoff potential).

Hydrograph is a graph that shows the relationship of flow vs. time for a particular location within the watershed.

Hyetograph: A plot of cumulative rainfall or rainfall intensity versus time for a particular precipitation event

Inundation: to be covered with water

Lag time is the time between when the peak of a precipitation event occurs, and when that runoff makes it to the outlet of the watershed.

[1] Source: Wikipedia.org

LiDAR: Light Detection and Ranging, is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. It is a state-of-the-art method for collecting accurate elevation information for large areas.

NAVD88: North American Vertical Datum of 1988 is the vertical control datum established in 1991 for vertical control surveying. NAVD88 consists of a leveling network on the North American Continent, affixed to a single origin point. NAVD88 replaced NGVD29 as the official vertical datum.

Return Frequency: likelihood, or probability that a rainfall event (specific to the magnitude and duration) will be equaled or exceeded in any given year.

Riverine: Associated with a river

Sea Level Rise: An increase in sea level caused by a change in the volume of the world's oceans due to temperature increase, deglaciation (uncovering of glaciated land because of melting of the glacier), and ice melt (Source: NOAA).

Stage Storage Discharge Curves: define the relationship between the depth of water and the discharge or outflow for the flood storage areas behind a culvert or impoundment.

Stillwater Elevation: The projected elevation of floodwaters in the absence of waves resulting from wind or seismic effects. In coastal areas, stillwater elevations are determined when modeling coastal storm surge: the results of overland wave modeling are used in conjunction with the stillwater elevations to develop Base Flood Elevations (Source: FEMA).

Storm Surge: Storm surge is the water, combined with normal tides that push toward the shore by strong winds during a storm. This rise in water level can cause severe flooding in coastal areas, particularly when the storm coincides with the normal high tides. The height of the storm surge is affected by many variables, including storm intensity, storm track and speed, the presence of waves, offshore depths, and shoreline configuration (Source: FEMA).

Tributary: a stream or channel that joins with a larger stream

Tailwater: The elevation of the water surface downstream from a dam or culvert. In coastal areas, such as Manchester-by-the-Sea, the tailwater elevation downstream of a dam is affected by tides, storm surge and sea level rise.

Time of Travel: The time interval required for water to travel from one point to another through a part (reach) of a watershed

Weighted Runoff Curve Number (CN): is a parameter used for predicting direct runoff or infiltration. The CN characterizes the runoff properties for each particular soil and groundcover in modeling applications. The CN method was developed by the USDA Natural Resource Conservation Services, formerly the Soil Conservation Service or SCS.

10-year Storm: A storm event having a 10% probability of occurring in any given year

25-year Storm: A storm event having a 4% probability of occurring in any given year

50-year Storm: A storm event having a 2% probability of occurring in any given year

100-year Storm: A storm event having a 1% probability of occurring in any given year

SECTION 1

Section 1 Introduction

1.1 Purpose of Study

This report describes the Sawmill Brook watershed modeling that was completed as part of the Coastal Zone Management Grant, **Manchester-by-the-Sea Sawmill Brook Culvert and Green Infrastructure Analysis**: Task 4 "Evaluation of Locations for Flood Mitigation". As part of the study existing conditions within the Sawmill Brook watershed were modeled and flooding impacts due to climate change, including increased levels of precipitation in combination with corresponding projections for sea level rise, were evaluated.

The modeling provides the data needed to evaluate adequacy of culvert sizing within the Sawmill Brook Watershed under climate change conditions and the mitigation value of proposed stormwater best management practices at specific locations, including green stormwater infrastructure, conveyance projects and flood storage. Additionally, the model will help determine projected flooding impacts upon important community assets identified as part of the Hazard Mitigation Plan enhancement under a Federal Emergency Management Agency (FEMA) Pre-disaster Mitigation Grant.

1.2 Project Methodology Overview

Tighe & Bond evaluated the existing hydrology and hydraulics within the study area under varying climatic events.

- **Existing watershed conditions were modeled** with HydroCAD and HEC-HMS (US Army Corps of Engineers, 2015) using information about soils, topography, ground cover (impervious cover and land uses), existing wetlands and waterbodies, water travel times, and existing structures that control discharges (e.g. Central Street tide gate, culverts, etc.). Existing conditions considered rainfall depths developed by the Cornell University Northeast Regional Climate Center and tidal influences using data from Flood Insurance Study for Essex County (July 2014). The existing conditions model was calibrated against the May 2006 storm (Mother's Day storm) that represent 25-year single day and 100-year consecutive day storm conditions.

- Building off the existing conditions model, **future watershed conditions** were predicted considering anticipated impacts from climate change and sea level rise in 2025, 2050, and 2100. For this model, precipitation estimates in the existing conditions scenario were replaced with estimates of future rainfall depths for 2025, 2050, and 2100 from the Oyster River Culvert Analysis project completed in Durham, New Hampshire (UNH, 2010). In addition, sea level rise and storm surge was incorporated into the model using data from the Inundation Risk Model (IRM) outputs developed by Keil Schmid (Geoscience, 2015).

- Using the future conditions model, the **potential impacts on existing infrastructure** (e.g. tide gate at Central Street, culverts, crossings) from storm surge, sea level rise, and future precipitation conditions in 2025, 2050, and 2100 were identified. The future condition model was also used to evaluate culvert sizes and needed upgrades, and the mitigation value of proposed stormwater best management practices including green stormwater infrastructure, conveyance projects, and flood storage.

Tighe & Bond partnered with organizations to obtain data necessary to complete the evaluation. Tighe & Bond walked the river on May 30, 2015, along with the Town's Stream Team and other volunteers, to become familiar with the river and identify critical locations for survey cross sections. Measurements and inventories of culverts were taken during this visit.

Town Staff and Volunteers making observations at the Lincoln Street Culvert

Tighe & Bond coordinated with Keil Schmidt of Geoscience to obtain elevations from the Inundation Risk Model (IRM) outputs for sea level rise and storm surge for incorporation into our modeling.

Tighe & Bond subcontracted with Doucet Survey of Newmarket, New Hampshire to survey the upstream and downstream ends of critical culvert locations. Tighe & Bond also utilized MassGIS LiDAR topographic data for overbank areas beyond the extent of the surveyed cross sections. LiDAR, which stands for Light Detection and Ranging, is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. It is commonly used to make high-resolution contour mapping of large areas.

1.3 Sawmill Brook Watershed

Sawmill Brook is the longest watercourse that flows through Manchester-by-the-Sea, and drains a majority of the Town. Please refer to **Figure 1** for the watershed's approximate boundaries. The watershed comprises a total of 4.8 square miles, most of which lies within Manchester-by-the-Sea, although portions of the watershed extend into Essex and Gloucester.

Sawmill Brook upstream of School Street, near its interchange with Route 128.

Main Stem of Sawmill Brook

The main stem of Sawmill Brook drains a circuitous route, beginning in the residential area just south of Interchange 16 of Route 128 (Pine Street). The watercourse passes north, beneath Route 128, discharging into Bayberry Swamp, where the brook receives runoff from the undeveloped, forested hills to the north of the swamp, which are characterized by a large number of rock outcroppings.

Main Stem of Sawmill Brook

The main stem of Sawmill Brook drains a circuitous route, beginning in the residential area just south of Exit 16 of Route 128 (Pine Street). The watercourse passes north, beneath Route 128, discharging into Bayberry Swamp, where the brook receives runoff from the undeveloped, forested hills to the north of the swamp, which are characterized by a large number of rock outcroppings.

The brook flows easterly through the swamp, roughly paralleling the north side of Route 128, accepting runoff from a small tributary that drains the valley located west of Milestone Hill. The brook then meets another small watercourse carrying the discharge from Millet's Swamp, and then turns northeasterly, draining through Cedar Swamp. The area contributing to Cedar Swamp is forested and largely undeveloped, with steep slopes and a number of outcroppings.

The brook flows northeasterly for approximately 2,400 feet, before turning abruptly eastward, passing beneath Old School Street and School Street into Beaverdam Swamp. The brook then curves southeasterly, then southwesterly around the eastern side of Shingle Place Hill. The surrounding contributory area is largely steep, undeveloped forested hills.

Sawmill Brook then passes beneath Route 128 again, flowing southerly where it meets with Cat Brook at river left, approximately 1,300 feet downstream of Route 128.

Immediately downstream of the confluence with Cat Brook, Sawmill Brook passes through land of the Essex County Club golf course, where the overbanks are grassed to the edge of the watercourse, and also include small man-made impoundments. The brook gently begins an arc to the southwest where it passes Manchester-Essex Regional Middle-High School on river right, and property of the golf course on the left before passing beneath Lincoln Street.

Almost immediately below Lincoln Street, Sawmill Brook is joined by Causeway Brook, and enters an area of significantly increased residential development density, passing between the backyards of numerous residences. Sawmill Brook continues to flow along a gentle arc before flowing westerly at School Street, immediately north of Brook Street. Before this crossing, the river left side of the watercourse is channelized with a stone masonry wall with the adjacent residential structures located near the wall.

Sawmill Brook just upstream of its crossing of School Street near Brook Street.

Downstream of School Street, both sides of the brook are channelized by stone masonry walls. Approximately 425 feet downstream of School Street, the watercourse makes a sharp turn to the left, emptying into Central Pond, which is regulated by the existing tide gate and dam structure at Central Street. Once the flow passes through the structure, it discharges into Manchester Harbor.

Millet Swamp Brook

The area roughly bounded by Old Essex Road, School Street, and Route 128 drains toward Millet Swamp, which is located between these roadways. The edges of the development area include steep forested hills that drop down to residential development along the roadways to the low lying area where the swamp is located.

The stream has a number of crossings at residential roadways, including Blue Heron Lane, The Plains, Millet Lane, and Old Essex Road.

The stream in this area generally has flat topography and is slow-moving due to its low gradient. The swamp outlets to the north, where it joins Sawmill Brook just upstream of Route 128.

Cat Brook

The source of Cat Brook are the undeveloped and forested hills lying south and east of Route 128, extending into Gloucester. Cat Brook begins as two separate watercourses that converge east of Mill Street. The western branch runs generally parallel with Route 128, while the eastern branch flows southwesterly then northeasterly before joining the western branch 700 feet upstream of Mill Street.

Downstream of Mill Street, Cat Brook passes along property of the Essex County Club along river left before discharging into Sawmill Brook.

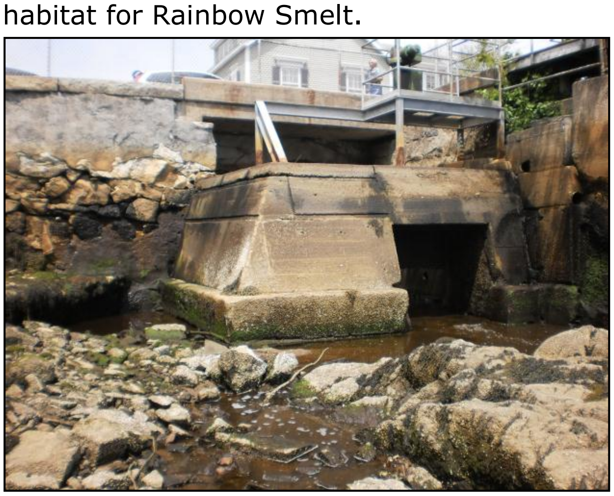
Causeway Brook

Causeway Brook begins as two separate watercourses that discharge from ponds on the eastern portion of the watershed, one of which is Dexter Pond. The two branches converge south of the MBTA railroad line, flowing westerly through a residential area along Summer Street, where it is briefly channelized, and passing through property of the Essex County Club before discharging beneath Lincoln Street. Causeway Brook discharges into Sawmill Brook just below Lincoln Street.

Causeway Brook downstream of Summer Street, showing the narrow channelized streambed

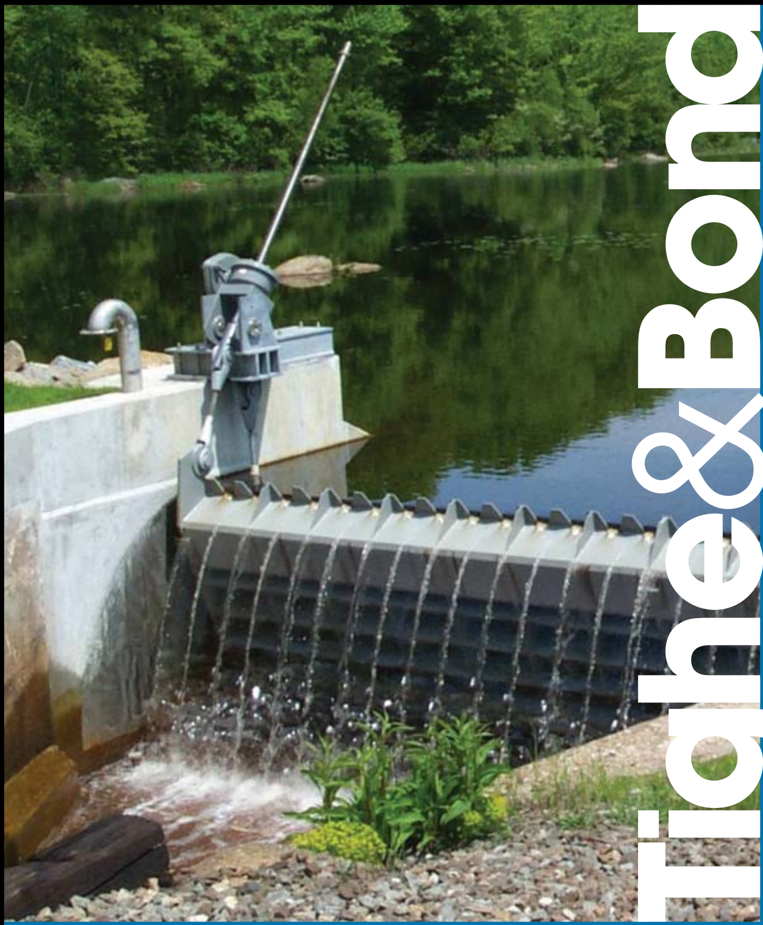
Culvert at Central Street

The Sawmill Brook culvert under Central Street consists of a seawall, tide gate structure, culvert and stream bed/weirs. Based on a review of documents available from the Town, it appears the tide gate was originally installed in the early 1900's for the purpose of creating a skating pond in the downtown area. This structure provides control for flooding caused by tides and maintains the elevation in Central Pond. The structure currently overtops during extreme storm events. Additionally, the tide gate design obstructs fish passage to upstream segments of Sawmill Brook that are known spawning habitat for Rainbow Smelt.



View of Tide Gate Structure from Harbor

View of Central Street tide gate towards the Harbor

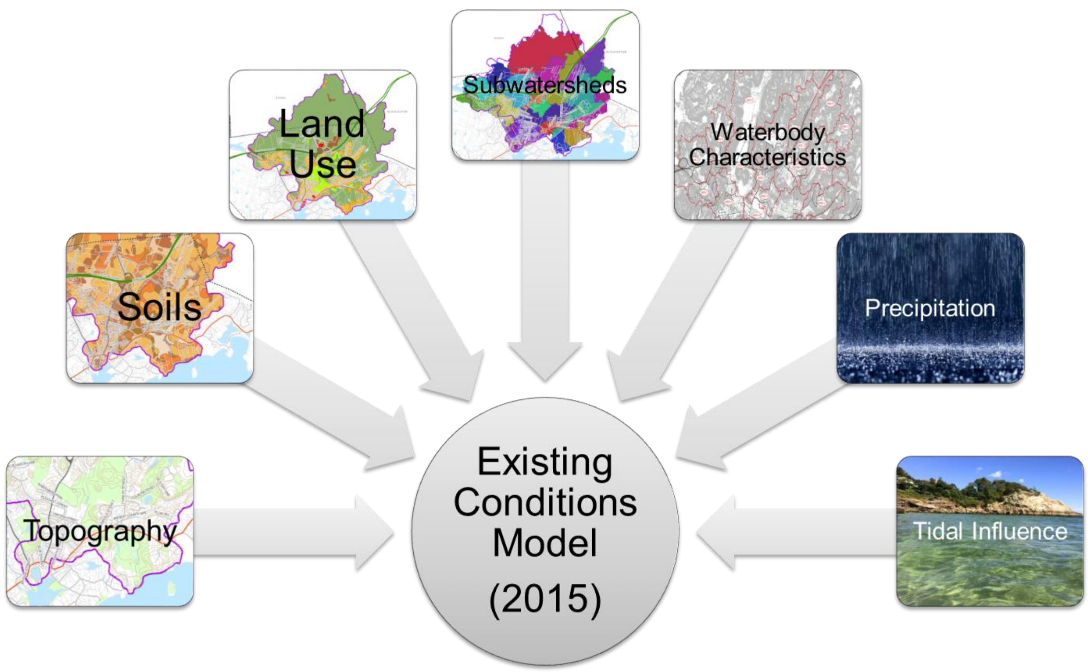


SECTION 2

Section 2
Modeling Existing Conditions

2.1 Overview

As part of the project, Tighe & Bond modeled existing conditions within the Sawmill Brook Watershed. The model considers information about soils, topography, ground cover (impervious cover and land uses), existing wetlands and waterbodies, water travel times, and existing structures that control discharges (e.g. Central Street tide gate, culverts, bridges, etc.). Existing conditions were based on rainfall depths developed by the Cornell University Northeast Regional Climate Center[2] and tidal influences using data from the Flood Insurance Study for Essex County (July 2014). The existing conditions model was calibrated against the largest storm in recent history, the May 2006 (aka "Mother's Day") storm.



2.2 Model Inputs

2.2.1 Watershed Conditions

The watershed contains steep topography in its upper reaches, which flattens out toward the main stem of the watershed as shown in **Figure 2.** Contours were developed using the LiDAR terrain and Digital Elevation Model (DEM) data available on the Massachusetts Geographic Information Systems (GIS) website.

---

[2] http://precip.eas.cornell.edu/

Soils within the watershed are classified by their Natural Resources Conservation Service (NRCS) Hydrologic Soil Group. Most of the soils within the swampy and steep areas of the watershed are slow draining, while the balance of the soils within the developed portion of the watershed are moderate to moderately well-drained. Please refer to **Figure 3** for the NRCS Hydrologic Soil Group (HSG) classifications of the watershed soils. **Appendix A-1** includes an NRCS Web Soil Survey report that provides further detail on the classifications.

Land uses within the watershed primarily consist of wetlands, forest, open space, and residential areas, along with small areas of industrial and commercial uses. Please refer to **Figure 4** for the distribution of land uses within the watershed and table describing the aggregation of categories from the MassGIS Land Use data for input into the model.

To facilitate the analysis of the stream, Tighe & Bond divided the watershed into 24 subwatershed areas to obtain a better understanding of the timing relationships between the numerous tributaries within the watershed. Please refer to **Figure 5** for the subwatershed mapping. Within each subwatershed, the land cover and underlying hydrologic soils group were evaluated and a lag time was developed in order to estimate the contribution of each subwatershed to Sawmill Brook.

In a complex watershed with a number of tributaries, such as Sawmill Brook, the time it takes various tributaries in the watershed to have peak flow can vary greatly from tributary to tributary depending on a number of factors, such as topography, impervious coverage, soil types and storage areas (reservoirs). Therefore, the timing of the peak flow from the tributaries could be different enough that they do not impact the receiving river simultaneously.

Tighe & Bond utilized available GIS mapping and data to develop the data inputs for the hydrologic analysis. Using the Soil Conservation Service (SCS) methodology in the HydroCAD software package, each subwatershed was routed through downstream subwatersheds and combined as necessary to develop a hydrograph of the main channel flow. The hydrographs were routed through the riverine network all the way to Manchester Harbor.

The weighted runoff curve number (CN) values for each of the subwatersheds were calculated based upon the land uses and hydrologic soil groups within the watershed. The lag time was computed based upon land cover, flow regime and basin topography. Please refer to **Appendix A-2** for the computation worksheets for both the weighted CN value and the lag time for each subwatershed.

2.2.1 Watershed Storage

The hydrologic model accounts for areas of flood storage within the watershed. Typically, these areas of storage can be found behind dams or behind culverts. As part of the hydrologic analysis, Tighe & bond developed stage-storage-discharge curves using Autodesk's Hydraflow for Hydrographs software program. The curves define the relationship between the depth of water and the discharge or outflow for the flood storage areas behind the existing culverts.

Appendix A-3 provides a summary table of the culverts within the watershed. More detail on these culverts can be found in the Tighe & Bond report titled "Manchester-by-the-Sea, Massachusetts, Stream Crossing Evaluation, Sawmill Brook Watershed" dated July 30, 2015. Please refer to **Figure 6** for the culvert locations.

In addition, the following locations in the watershed were modeled as storage areas:

- Pine Street (Pond 1)
- School Street north of Route 128 (Pond 2)
- Atwater Avenue (Pond 3)
- Mill Street (Cat Brook) (Pond 4)
- Lincoln Street (Causeway Brook) (Pond 5)

Please refer to **Appendix A-4** for the stage-storage-discharge computations for the storage areas.

2.2.2 Precipitation

The hydrologic model uses rainfall totals from the Northeast Regional Climate Center (NRCC) at Cornell University to develop the hydrographs. In the recent past, many flood studies historically used the climatic data published by the U.S. Weather Bureau in Publication TP-40, issued in 1961. The NRCC data is a more current data set and incorporates the increase in annual precipitation and storm intensity that has been documented by a number of studies since the 1961 publication of TP-40. **Table 2-1** lists the rainfall depths from a 24-hour duration storm that were used in the model.

Table 2-1
2015 Rainfall Depths for the Sawmill Brook Watershed (24 hour storm)

Frequency Storm	Annual Probability	Rainfall Depth (inches)
25-year	4%	6.16
50-year	2%	7.36
100-year	1%	8.76

This report refers to storm events by their return frequency, such as a 25-year storm, 50-year storm, and 100-year storm. The return frequency is the likelihood, or probability, that a rainfall event (specific to the magnitude and duration) will be equaled or exceeded in any given year. The reference will help the general public better understand the typical probability associated with a storm event. However, it is possible to have multiple 100-year storms in consecutive years, and it is also possible to have 50 years pass without a 25-year storm. Notable storm events for Manchester-by the Sea measured at the Town’s Wastewater Treatment Facility include a near 100-year storm event of 8.27 inches recorded on October 20, 1996, and a 25-year storm event of 6.56 inches recorded on May 13, 2006, during the Mother’s Day Storm.

Please refer to the Extreme Precipitation Tables in **Appendix B-1** for the completed data set for Manchester-by-the-Sea.

2.2.3 Surge and Tidal Influence

There is a tide gate structure that regulates the mouth of Sawmill Brook at Central Street. The structure normally limits the tidal influence of Manchester Harbor on the Sawmill Brook. Based on the current effective Flood Insurance Study (FIS) for Essex County, Massachusetts, dated July 16, 2014, the tidal stillwater surface elevations (that include storm surge) at the mouth of Sawmill Brook just downstream (ocean side) of Central Street are outlined in **Table 2-2** for existing conditions. Values presented in Table 2-2 are elevations associated with an annual probability (e.g. for the 1% annual probability, there is a 1% annual chance of the high tide influenced by storm surge to reach an elevation of 9.90 feet NAVD88 at the mouth of Sawmill Brook) shown in the

FIS.[3] The Base Flood elevation at this location is 10.6 ft NAVD 88, which includes the stillwater elevation and the effects of wave setup.

Table 2-2
2015 Stillwater Elevations at Central Street

Frequency Storm	Annual Probability	Elevation (NAVD88) (feet)
25-year	4%	9.15
50-year	2%	9.40
100-year	1%	9.90

The values in Table 2-2 were used as starting water surface elevations in the hydraulic (HEC-RAS) model to account for tidal influence and storm surge on Sawmill Brook. Based on the Inundation Risk Model (IRM) outputs for 2015, Sawmill Brook is tidally influenced to the School Street culvert under existing conditions. See Section 3.2.2 for additional detail on the IRM model.

The town is currently in the process of requesting a revision of the July 16, 2014 FEMA FIS based on an August evaluation by the Woods Hole Group. A Letter of Map Revision has been submitted by the Town. The revised 100-year still water level is 9.00 ft NAVD, and the Revised Flood Zone and Base Flood Elevation for the Central Street location is AE 10, one foot lower than the current effective FIRM. As the planning progresses, this information should be taken into consideration.

2.3 Modeling Approach

2.3.1 Hydrologic Modeling

Hydrologic analysis of existing and post-development conditions was carried out by generating a computer model using the HEC-HMS Computer Program developed by the U.S. Army Corps of Engineers at the Hydrologic Engineering Center in Davis, California.

The hydrologic equations used in the computer model are described in the U.S. Army Corps of Engineering publication "Hydrologic Modeling System, HEC-HMS User's Manual, Version 3.5", dated August 2010. The data requirements for the HEC-HMS computer model include the following categories:

1. Soil Cover
2. Ground Cover
3. Ground Slopes
4. Degree, Density and Type of Development
5. Location and extent of wetlands, including swamps and ponds
6. Time of concentration, travel time, lag time
7. Controlled discharge structures, pipes and channel

[3] See Table 11 – Transect Data. Transect 38 was used to represent Manchester Harbor.

The results of the HEC-HMS for existing conditions are included in **Appendix B-2.**

2.3.1 Hydraulic Modeling

Once hydrographs had been developed for the various watersheds, the next step was to build a model using the U.S. Army Corps of Engineers Hydraulic Engineering Center's HEC-RAS software to analyze the resultant water surface elevations. The HEC-RAS model evaluates stream gradient, cross section, and land cover within the channel and overbanks. It also accounts for energy losses through friction, and expansion and contraction at hydraulic structures, such as bridges and culverts.

The geometry of the HEC-RAS model was based upon a digital terrain model extracted from MassGIS LiDAR data, and then extrapolated cross sections from that data. The LiDAR data was supplemented by survey from third-party culvert surveys.

2.4 Model Calibration

In developing the existing conditions model, past storm events were examined to confirm if channel geometries, land use coverages and lag times used in the model can duplicate observations recorded during past rainfall events. Calibration efforts were focused on a historic storm in May 2006. The storm lasted over a 4-day period and dropped nearly 11 inches of rain on the area.

Table 2-3
May 2006 Rainfall Event recorded at Beverly Municipal Airport

Date	Precipitation (inches)
May 13, 2006	4.32
May 14, 2006	4.95
May 15, 2006	1.15
May 16, 2006	0.56
Total	**10.98**

Based on information provided by the NRCC, 11.29 inches of rain over a 4-day period is equivalent to a 100-year storm event, while 4.95 inches of rain in a 24 hour period is equivalent to a 25-year storm event.

Please refer to **Appendix C-1** for the precipitation data from Beverly Municipal Airport.

The May 2006 event was preceded by a wetter than normal weather pattern, which increased the moisture conditions in the ground. Therefore, the weighted runoff curve number (CN) values were adjusted in the calibration model to reflect the higher level of moisture in the soil at the time of the May 2006 rainfall event. The calculations for the CN values appear in **Appendix C-2.**

In order to calibrate the hydrology, observations of flooding elevations reported by the Town during the May 2006 flood event were compared to the elevations calculated by the HEC-HMS model for the storm event.

Please refer to **Table 2-4** for a comparison of observations and model predictions for the May 2006 flood event. The observations for the storm event come from the document titled "Hydrologic Study, Millets Brook and Sawmill Brook Watersheds" (Metcalf & Eddy, February 2008).

Table 2-4
May 2006 Flood Observations Compared to HEC-RAS Model Output

Location	Cross Section Number	Observed Elevation (NAVD 88) (feet)	HEC-RAS Model Prediction (NAVD 88) (feet)
School Street north of Route 128	11191	45.1	43.04
Mill Street at Cat Brook	2359	39.6	38.03

Note: Observed elevations presented in Table 2-4 are from Table 5 in the 2008 Metcalf & Eddy report. The survey from the 2008 report used vertical datum reference NGVD 29 (FT). They have been converted to NAVD 88 in Table 2-4 for consistency. An error was identified in Table 5 of the 2008 Metcalf & Eddy report. Table 5 indicates the observed elevation at School Street north of Route 128 was 48.75 feet (downstream) and 45.8 feet at Old School Street (upstream). To correct this error, the two points were swapped, and Table 2-4 includes the Metcalf & Eddy value for Old School Street, adjusted for NAVD88.

2.5 Model Output

After calibrating the model, existing conditions were simulated for the 25-year, 50-year and 100-year storm events. **Appendix D** provides the data outputs from the existing conditions modeling runs. To assist in interpretation of the results Table 2-5 provides a cross reference for each culverts and bridges in the model including identifying culvert number from the Task 2 culvert inventory, and their cross section number in the HEC-RAS model. Cross section numbering is based upon distance from the mouth of Sawmill Brook at Manchester Harbor for the main stem of Sawmill Brook, and from the distance with the confluence of the main stem of Sawmill Brook for the tributaries. **Figure 7** shows the existing conditions model results, where culvert overtopping may occur.

For the 2015 25-year storm, the existing conditions models indicate that 48% of the culverts overtop the roadway. For the 50-year storm, this number increases to 52%, and with a 100-year storm, 59% of culverts overtop.

Comparing the model existing conditions to the historic experience of culvert overtopping gives the reader an idea of where the model may be conservative. The model is consistently predicting the areas of historic flooding from the intersection of Causeway Brook to the Harbor, but may be conservative for culverts along Route 128 (culverts 33 and 35) and in the area of Old School Street at the Cedar Swamp, and Conservation Area on Winchester Drive. There are additional areas outside of Sawmill Brook that flood, so it is important to realize the limitations of the model extent and accuracy. The model can continue to be refined with observed flood elevations. It is an excellent screening tool to evaluate the impact of future flood conditions as discussed in Section 4 and the combined effect of flood mitigation projects, discussed in Section 5.

Table 2-6
Cross Reference for Hydraulic Structure Identification in HEC-RAS Model

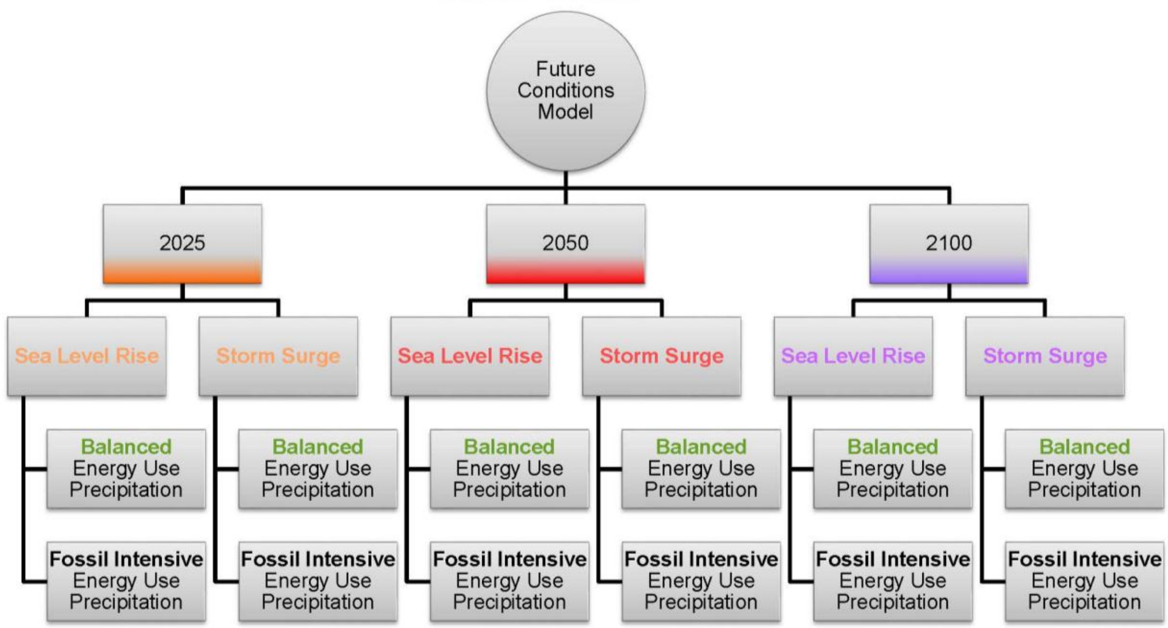
Stream	Culvert Inventory Identification Number	Street Crossing	HEC-RAS Section Number
Sawmill Brook	25	Central Street	199
	23	School Street	1629
	22	Norwood Avenue	2653
	17	Lincoln Street	3686
	16	Golf Course Driveway	5192
	27	Mill Street	7533.5
	26	Route 128	7686
	36	Route 128 Ramp	8131.5
	4	Atwater Avenue	9168
	3	School Street	11161
	2	Old School Street	11479.5
	5	Old Essex Road	13499
	34	Route 128	14218
	31, 33	Route 128	15106
	32, 35	Route 128	16328
	28, 29	Route 128	17648
Causeway Brook	18	Lincoln Street	378
	19	Golf Course Driveway	1280
	20	Summer Street	1757
Cat Brook	11	Mill Street	1869
Millet Brook	12	Millet Lane	1777
	13	The Plains	1570
	15	Blue Heron Lane	1111

SECTION 3

Section 3
Modeling Future Conditions

3.1 Overview

As part of the project, future flooding conditions within the Town were projected as a result of anticipated climate change and sea level rise at three different points in the future: 2025, 2050 and 2100. Data on climate change was obtained from two sources. Future conditions precipitation relied upon the Oyster River Culvert (UNH, 2010) analysis, while the future conditions sea level utilized projections along the Manchester-by-the Sea coastline prepared by Kiel Schmid (GeoScience, 2015).



3.2 Inputs for Future Conditions Model

3.2.1 Precipitation

The Oyster River Culvert Analysis University of New Hampshire (2010) was utilized to project precipitation depths for future conditions. The Oyster River Culvert Analysis extreme precipitation model was developed based upon recent peer-reviewed studies for statistical analysis of climate change effects. The model focuses on fall precipitation events (September, October, November) since 25-year events for this time period were consistently greater than events for late spring (April, May, June)

The Oyster River watershed is located in Durham, New Hampshire, approximately 60 miles north of Manchester-by-the-Sea along the New Hampshire coast. The two areas have a similar climate and elevation, and therefore would experience similar precipitation patterns.

The rate of increase in future precipitation events is anticipated to be dependent upon the use of fossil fuels and the corresponding impacts on greenhouse gases. If a transition to a more balanced use of renewable and fossil fuel energy sources is used, the expectation is that the rate of increase in precipitation would be less than it would if fossil fuels continue to be a primary source of energy.

The Oyster River study model predicts a range of possible climate change outcomes by considering two peer-reviewed greenhouse gas emission scenarios [4]:

1. One scenario assumes a "balanced" global energy mix; i.e. an equal ratio of fossil fuel use to less greenhouse gas intensive sources of energy. This balanced scenario can be viewed as the more optimistic view of climate change's potential impacts in which the atmosphere has approximately 700 ppm of carbon dioxide equivalents by the year 2100.

2. The second scenario assumes a "fossil intensive" global energy mix; i.e. fossil fuels continue to be the primary fuel source. The fossil intensive scenario is the more pessimistic view of climate change's potential impacts in which the atmosphere has approximately 970 ppm of carbon dioxide equivalents by the year 2100.

The data in the Oyster River Culvert Analysis was utilized to project future precipitation in 2025, 2050, and 2100 for the balanced and fossil intensive scenarios, with the results shown in **Tables 3-1a** and **3-1b**. Data points from the 1964 U.S. Weather Bureau, the 2015 NRCC data, and the mid-century (2050) Oyster River Study precipitation estimates were plotted, and a logarithmic trend line was used to establish data points for balanced and fossil intensive energy use conditions in 2025 and 2100.

Table 3-1a
"Balanced Energy Use" Rainfall Depths for the Sawmill Brook Watershed
(inches, 24-hour storm)

Frequency Storm	2025	2050	2100
25-year	6.36	6.86	7.84
50-year	7.42	7.58	7.88
100-year	8.85	9.31	10.69

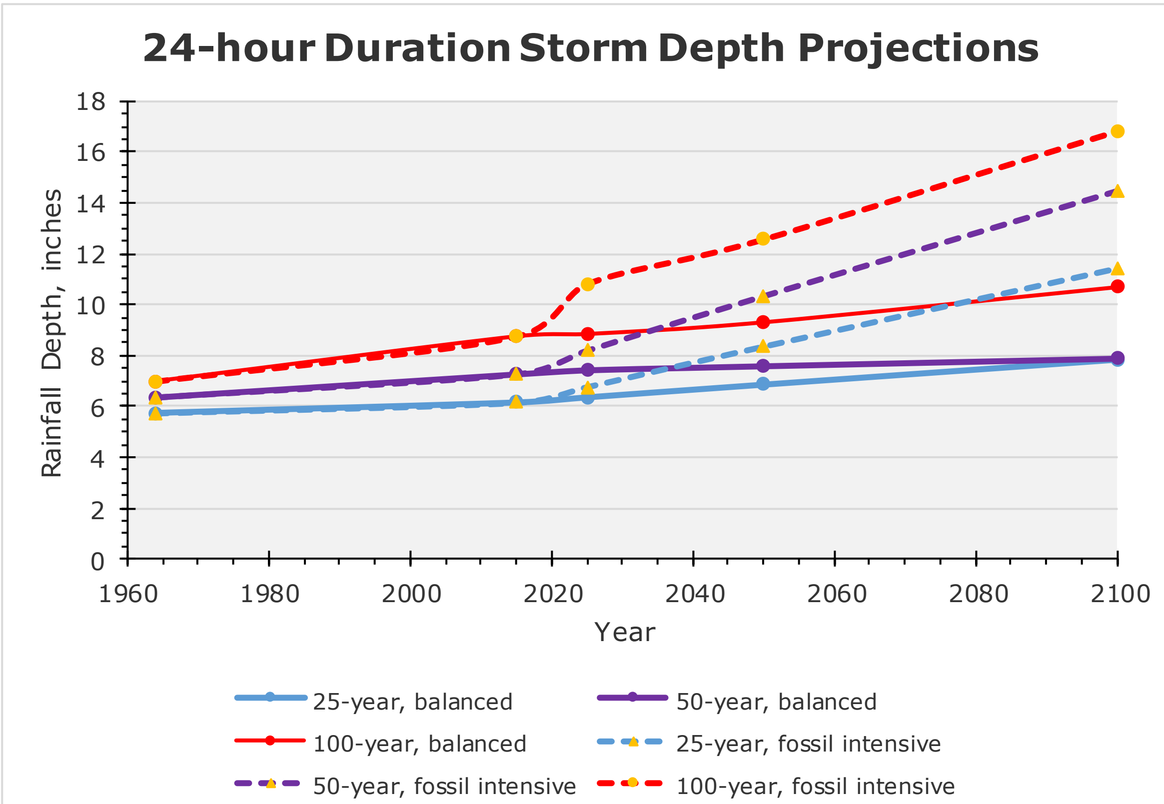
Table 3-1b
"Fossil Intensive Energy Use" Rainfall Depths for the Sawmill Brook Watershed
(inches, 24-hour storm)

Frequency Storm	2025	2050	2100
25-year	6.77	8.35	11.39
50-year	8.19	10.34	14.48
100-year	10.82	12.58	16.82

[4] Intergovernmental Panel on Climate Change's (IPCC) 4th Report developed in 2007

Chart 3-1 offers a graphic representation of the changing rainfall depths for a 24-hour duration storm over time, beginning with the U.S. Weather Bureau Technical Paper-40 data from 1964, through the 2015 Northeast Regional Climate Center data, and also the balanced and fossil intensive energy use projections for 2025, 2050, and 2100. Please refer to **Appendix C-3** for the calculations of the precipitation values in 2025, 2050 and 2100.

Chart 3-1
Precipitation Depths Over Time, 24-hour Duration Storm



3.2.2 Coastal Climate Change Model

Potential sea level rise and future storm surge predictions for Manchester-by–the-Sea were obtained from the Inundation Risk Model (IRM). The IRM model was developed by Keil Schmidt of Geoscience Consultants in 2015 for the Salem Sound Coast Watch communities in Northeast Massachusetts, including Manchester-by-the-Sea. Tighe & Bond reviewed a number of coastal models with the Town and the Town's Coastal Resilience Advisory Group (CRAG) and elected to use the IRM model because of its balance of simplicity and detail. More information on the model selection may be found in a Tighe & Bond Technical Memorandum "Potential Climate Change Impacts to Manchester-by-the-Sea", September 30, 2015. Tighe & Bond worked with the model developer to refine data specific for Manchester-by-the-Sea.

The IRM is an expanded version of the National Oceanic and Atmospheric Administration (NOAA) Sea Level Rise (SLR) viewer, which considers present and future inundation from SLR at mean higher high water (MHHW), shallow coastal flooding, Category 1 hurricanes, and stillwater annual storm surge (including coastal storms other than hurricanes, i.e. Nor'easters). The goal of the model is to provide easily understandable and self-contained information for decision makers and citizens that incorporates a probabilistic handling of the uncertainties involved in documenting future coastal hazards.

Model outputs are shown as risk of inundation presented in percent risk of occurrence ranging from 1% highly unlikely to 99% certain risk. The model outputs do not show water levels or depth of inundation. Data sets include sea level rise at mean high high water, shallow coastal flooding, Category 1 hurricanes and still-water annual storm surge for selected timeframes (2015, 2025, 2050 and 2100). The output, description of risk and data sources are included in **Table 3-2.**

Table 3-2
IRM Model Outputs, Descriptions and Data Sources

Output	Description of Risk	Data Sources
Sea Level Change	Level is mean higher high water (MHHW). Risk describes chance of being inundated at least once per day.	Sea Level Change NOAA curves are source for future water levels.
Shallow Coastal Flooding	Risk describes chance of area being flooded several times a year, where inundation becomes a deterrent to development.	
Storm Surge	Risk describes the chance of an area being inundated once a year from coastal storms other than hurricanes (i.e. Nor'easters).	Historic still water surge data (Boston gauge) is used to define surge height.
Hurricane/ Category 1	Risk describes chance of area being inundated if a Category 1 hurricane is predicted to strike in the area. Rare occurrence.	Data from SLOSH model defines hurricane surge height for grid cells.

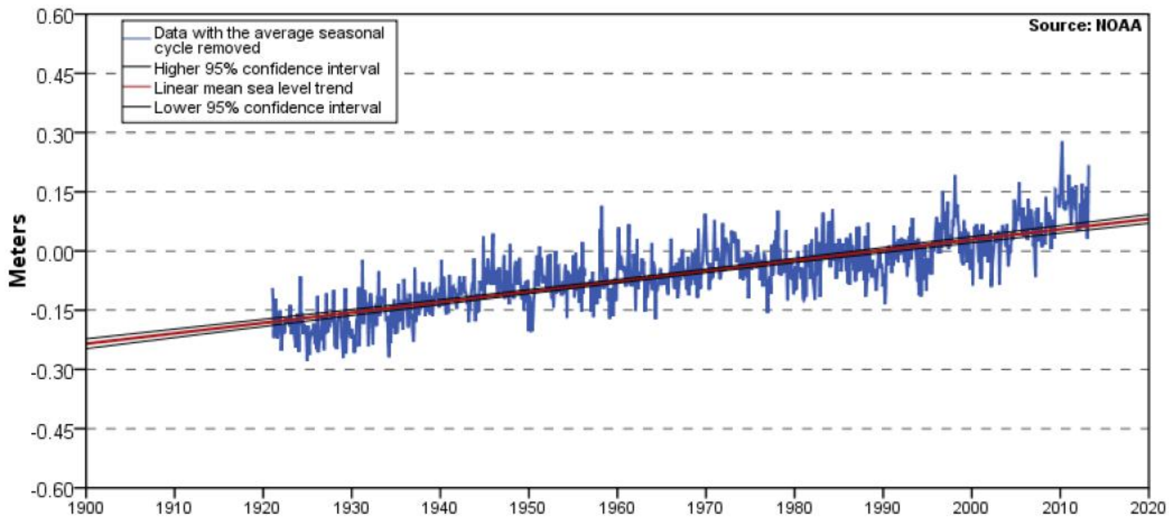
Keil Schmidt of Geoscience Consultants provided elevation values for use as model inputs to the HEC RAS software for future coastal tailwater conditions. The image on the left, below, shows the output of all probability values for areas impacted by sea level rise for a particular time period, from 1% in dark green as the least likely to occur to 99% in red as the most likely to occur. The right image shows the area covered by the 50 percent probability output, defined by the IRM author "flooding that is as likely to occur as not". Elevations provided by Keil Schmidt are based on the 50 percent output.

3.2.3 Sea Level Rise

Climate scientists are predicting a rise in sea level caused by a change in the volume of the world's oceans due to temperature increase, deglaciation (uncovering of glaciated land because of melting of the glacier), and ice melt. It is anticipated that as a result of sea level rise, the tidal influence of Manchester Harbor will exert a greater effect than it does today, and the boundary of tidal influence will shift further up Sawmill Brook.

NOAA has documented that the average sea level has been slowly increasing in Boston Harbor, and has increased by approximately 2 millimeters on average per year since 1920, for a cumulative increase of 0.67 feet (**Chart 3-2**) to the present.

Chart 3-2
Observed Mean Sea Level, Boston, MA
Source: NOAA



Keil Schmidt of Geoscience Consultants extracted the tidal elevations just downstream of the existing tide gate from the 50% probability of the IRM MHHW model output for sea level rise in 2025, 2050 and 2100 (**Table 3-3**). These elevations were utilized to evaluate tailwater impacts on the watershed flood model due only to sea level rise. The sea level rise flood elevations would impact affected properties on a daily basis, likely twice each day corresponding to the high tides.

Table 3-3
IRM Mean High High Water (Sea Level Rise) Tailwater Conditions for HEC-RAS Modeling
50% probability, approximate location 42° 34' 30.6664" N, 70° 46' 22.4346" W

Year	MHHW (Sea Level Rise) Feet Above Sea Level (NAVD88)
2025	5.1
2050	5.8
2100	8.0

3.2.4 Storm Surge Influence

Keil Schmidt of Geoscience Consultants provided elevation data interpreted from the 50% probability contours of IRM model just outside of the existing tide gate for annual stillwater flood scenarios, which include annual storm surge, as the governing elevation for the tailwater impact of coastal flooding. The annual stillwater scenarios were used because the stillwater methodology is consistent with what FEMA uses for determining backwater for riverine analyses. The annual flood elevation would impact affected properties on an annual basis.

Table 3-4 shows tidal elevations extracted from the 50% probability of the IRM stillwater output for storm surge in 2025, 2050 and 2100. It is interesting to note that these model outputs bracket the 25-, 50- and 100-year FIRM stillwater elevations presented in Table 2-2.

Table 3-4
IRM Mean Storm Surge Tailwater Conditions for HEC-RAS Modeling
50% probability, approximate location 42° 34' 30.6664" N, 70° 46' 22.4346" W

Year	Annual Stillwater Storm Surge Feet Above Sea Level (NAVD88)
2025	8.2
2050	8.9
2100	11.1

3.3 Future Conditions Modeling Approach

3.3.1 Hydrology

The rainfall depths presented in Section 3.2.1 were entered into the HEC-HMS model of the watershed to determine flow rates (discharge) along the river. The results of the HEC-HMS under future conditions is included in **Appendix B-3**. **Table 3-5** summarizes the discharge at Central Street comparing balanced energy use (A1b) and fossil intensive use (A1fi) greenhouse gas emissions scenarios as described previously in Section 3.2.1. for present and future time periods. Table 3-5 illustrates that the flow rates increase dramatically under the fossil intensive uses and by 2100, under the fossil intensive scenario, flow rates will be nearly 2.5 times greater than they are today

Table 3-5
Summary of Flow Rates (cubic feet per second) at Central Street

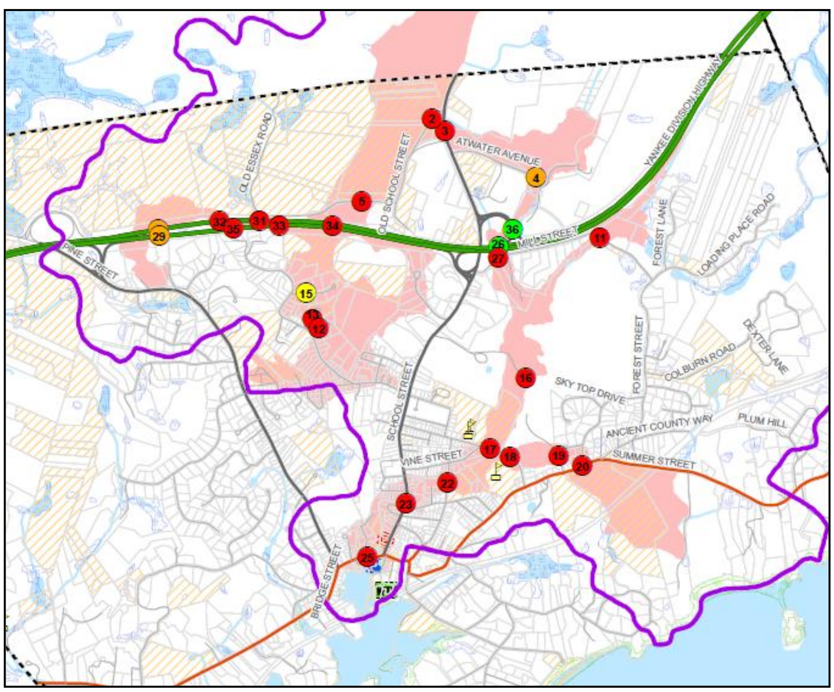
Frequency (years)	2015	2025		2050		2100	
		Bal.	Intensive	Bal.	Intensive	Bal.	Intensive
25	1,437	1,513	1,674	1,706	2,261	2,073	3,437
50	1,897	1,919	2,202	1,978	3,039	2,088	4,642
100	2,427	2,450	3,222	2,630	3,868	3,174	5,924

3.3.2 Future Conditions Hydraulics

The riverine flow data obtained from the hydrologic analysis was entered and combined with two different tailwater elevations (storm surge and sea level rise) to model the watershed under future climate change scenarios in 2025, 2050, and 2100 for the balanced and fossil intensive energy use precipitation projections. As anticipated, the floodplain expands considerably, especially under the fossil intensive energy use scenarios. HEC-RAS model data for future conditions appears in **Appendix D**.

3.4 Impact on Existing Infrastructure

Based upon the results of the HEC-RAS model, the impact on the existing culverts and bridges in the watershed was assessed based on the 50% probability for both stillwater (annual storm surge) and sea level rise. By 2100 almost all of the culverts in the watershed will be overtopped for storms more frequent than the 100-year event due to either tailwater condition (see inset below). **Table 3-6** shows where, when and how culverts in the Sawmill Watershed will be impacted with climate change conditions. For example, using the Balanced Energy Use projection, the culvert at Mill Street on Sawmill Brook will overtop under the Balanced Energy Use in the years 2025 and 2050 during a 50-year storm; and under both Balanced and Fossil Intense Energy Use, it will overtop in the year 2100 during a 25-year storm. Overtopping results with sea level rise tailwater conditions alone versus storm surge conditions does have overall lower surface elevations. For project specific applications, the data provided in Appendix D should be referenced.



Shown above are culverts that will overtop during specific flood events in the year 2100 with a fossil intensive precipitation scenario and storm surge. Culverts shown in red will overtop during a 25 year storm, orange will over top during a 50 year storm, yellow will overtop during a 100 year event and culverts in green will not overtop even with a 100 year storm event. Areas of surficial flooding are shown in pink.

Table 3-6
Storm Frequency at which Hydraulic Structures Overtop-
Storm Surge or Sea Level Rise

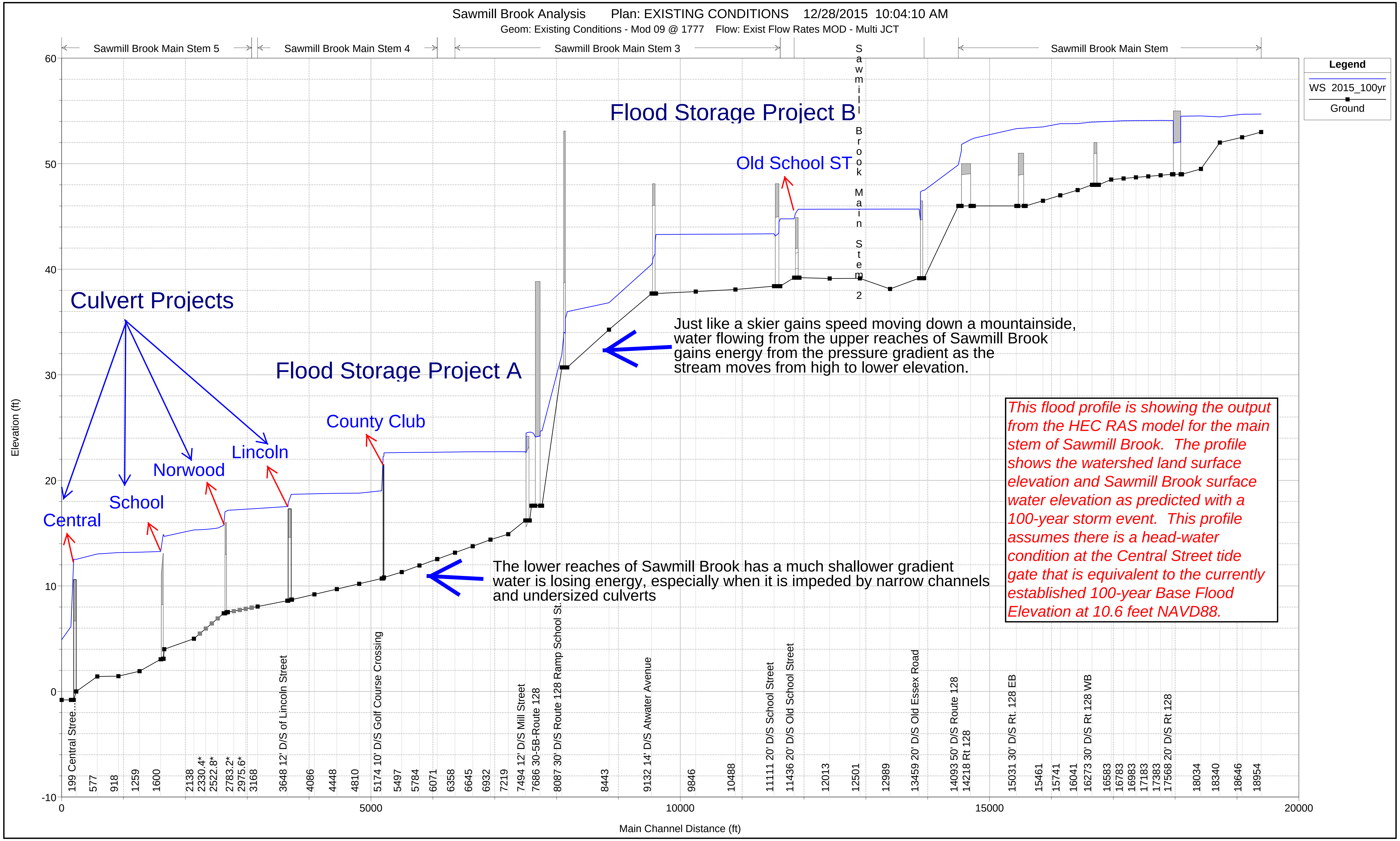
Stream	Culvert Crossing		Balanced Energy Use			Fossil Intense Energy Use		
	Location	Number	2025	2050	2100	2025	2050	2100
Sawmill Brook	Central Street	25	25-year	25-year	25-year	25-year	25-year	25-year
	School Street	23	25-year	25-year	25-year	25-year	25-year	25-year
	Norwood Avenue	22	25-year	25-year	25-year	25-year	25-year	25-year
	Lincoln Street	17	25-year	25-year	25-year	25-year	25-year	25-year
	Golf Course Driveway	16	50-year	50-year	25-year	50-year	25-year	25-year
	Mill Street	27	50-year	50-year	25-year	50-year	25-year	25-year
	Route 128	26	>100-year	>100-year	>100-year	>100-year	>100-year	>100-year
	Route 128 Ramp	36	>100-year	>100-year	>100-year	>100-year	>100-year	>100-year
	Atwater Avenue	4	>100-year	>100-year	>100-year	>100-year	100-year	50-year
	School Street	3	>100-year	>100-year	100-year	100-year	100-year	25-year
	Old School Street	2	25-year	25-year	25-year	25-year	25-year	25-year
	Old Essex Road	5	25-year	25-year	25-year	25-year	25-year	25-year
	Route 128	34	100-year	100-year	100-year	50-year	25-year	25-year
	Route 128	31, 33	25-year	25-year	25-year	25-year	25-year	25-year
	Route 128	32, 35	>100-year	100-year	100-year	100-year	50-year	25-year
	Route 128	28, 29	>100-year	>100-year	>100-year	>100-year	>100-year	50-year
Causeway Brook	Lincoln Street	18	25-year	25-year	25-year	25-year	25-year	25-year
	Golf Course Driveway	19	25-year	25-year	25-year	25-year	25-year	25-year
	Summer Street	20	25-year	25-year	25-year	25-year	25-year	25-year
Cat Brook	Mill Street	11	>100-year	>100-year	100-year	100-year	50-year	25-year
Millet Brook	Millet Lane	12	25-year	25-year	25-year	25-year	25-year	25-year
	The Plains	13	>100-year	>100-year	>100-year	>100-year	>100-year	25-year
	Blue Heron Lane	15	>100-year	>100-year	>100-year	>100-year	>100-year	100-year

Precipitation Storm Event Frequency

25-year	red
50-year	orange
100-year	yellow
>100-year	green

Another way of examining the model output is to look at flood profiles created by the HEC RAS model. The profiles across the Sawmill Brook Watershed are shown in Chart 3-3 for existing conditions. The chart shows the graphic output directly from the HEC-RAS model including the elevation profile of the land surface, the water table elevation resulting from a 100 year storm event in 2015, and the location of the 27 culverts that were included in the model. Locations are highlighted for Central Street, School Street, Norwood Avenue and Lincoln Street where culvert projects are proposed. The County Golf Course and Old School Street are highlighted where flood storage projects are proposed. These mitigation projects are further described in Section 4- Modeling Improvements for Flood Mitigation.

CHART 3-3 FLOOD PROFILE FOR EXISTING CONDITIONS SAWMILL BROOK MAIN STEM
2015 100-YEAR FLOOD



SECTION 4

Section 4 Modeling Improvements for Flood Mitigation

The watershed modeling was expanded to look at potential improvements to flooding by relieving channel restrictions at Central Street, providing additional flood storage north of Route 128, managing flooding through culvert rightsizing, and utilizing green infrastructure best management practices at a variety of pre-screened locations. Modeling for the flood mitigation scenarios was based on conditions in the year 2050, assuming precipitation based on a balanced energy use and the 50 year storm event. This section provides a description of the specific flood mitigation projects considered, the model iteration process to evaluate the impact of different project combinations, and the resulting improvements.

4.1 Central Street Culvert and Tide Gate

The Town of Manchester-by-the-Sea has recognized that the Central Street tide gate, dam and related structures are in need of modification to provide better functionality with respect to drainage and fish passage. This location has been identified for many years as a source of flooding upstream due to this hydraulic restriction, particularly during large rainfall events. The elevated water behind the tide gate is also putting pressure on the seawall at Central Street, causing seepage though the rock voids in the wall.

Reviewing the flood elevations and profiles from Chart 3-3 in the previous section, the flood elevations change significantly across the Central Street Bridge and tide gate area, indicating that this location is a significant bottleneck along the channel. The structures were observed by Tighe & Bond in July 2015, and improvements were identified to address safety, drainage and fish passage.

Looking upstream (low tide) toward tide gate and Central St culvert

The options for the Central Street crossing and tide gate are presented in Table 4-1, while stream restoration options are presented in Table 4-2.

Table 4-1
Sawmill Brook Central Street Design Concept Alternatives

Option	Design Element
Option 1	Remove tide gate Rehabilitate existing bridge/culvert/seawall structure Restore Sawmill Brook at Central Pond
Option 2	Remove tide gate Replace and widen culvert /restore seawall and guard rail Restore Sawmill Brook at Central Pond

Table 4-2
Sawmill Brook Stream Restoration and Flood Stage Alternatives

Design Element	Purpose
Widen bottleneck	Improve hydraulic flow through system, decrease upstream impounding
Augment instream vegetation	Stabilize sediment, reduce downstream deposition, provide wildlife habitat
Build up island and augment instream vegetation	Stabilize sediment, reduce downstream deposition, provide wildlife habitat
Connect islands and augment instream vegetation	Direct stream flow into main channel, provide wildlife habitat
Dredge central channel	Improve hydraulics, improve fish passage
Dredge sediment from central pond	Remove fines and sources of nutrients, increase flood storage
Maintain shallow channel	Minimize sediment management requirements, accommodate spawning areas
Build up rock outcrop at mouth	Increase aeration, improve fish passage, naturalize transition between harbor and stream
Create rock riffles	Improve fisheries/spawning habitat
Stabilize banks	Minimize sedimentation of stream channel and harbor, protect adjacent land uses
Flood bank storage	Improve flood storage capacity, reduce downstream flooding severity

Water seepage (flow) coming from the stone culvert side wall

The HEC-RAS model was used to evaluate Option 2, removal of the tide gate, and widening the current dimensions of the Central Street culvert to maximize the cross sectional area available for flow. Stream restoration options will be considered in the conceptual design phase of the project.

Tables 4-3 and 4-4 summarize modeling runs for widening the culvert and removing the tide gate. The tables compare combinations of flooding and emissions scenarios for the years 2015-2100 to evaluate the range of conditions under which flooding would be mitigated. The results indicate that the improvements will substantially improve capacity for most storm events, even with sea level rise, however with the addition of storm surge, the roadway would be overtopped after the year 2050. Although water elevations are lowered significantly, improvements are only achieved near term under 25-year and 50-year storm events. In addition, the modeling runs with only Central Street improvements lowered water elevations in the stream reach immediately upgradient from Central Street, but did not alleviate flooding problems further upstream. Culverts continued to overtop for School Street, Norwood Street, Lincoln and other locations upstream.

Removal of the tide gate has two additional benefits beyond flood mitigation. The gate is set with a partial opening, which is not conducive for smelt migration due to the head pressure and high velocity of water exiting the gate. Removal of the tide gate will significantly improve the ability of fish to migrate upstream, particularly Rainbow Smelt, who cannot jump up the existing weirs.

In addition, removal of the tide gate will alleviate the hydraulic pressure on the Central Street Seawall. With the tide gate in place, the seawall is technically define by the state as dam because the water impounded behind the wall exceeds five feet in height at a 100-year design storm. With removal of the tide gate, the technical definition will no longer apply, along with any jurisdictional responsibilities.

Table 4-3
Overtopping at Central Street with Tide Gate Removed and Culvert widened, Balanced Energy Use with Sea Level Rise

Year	25 yr		50 yr		100 yr	
	Exist.	Prop.	Exist.	Prop.	Exist.	Prop.
2015	Overtops	Capacity	Overtops	Capacity	Overtops	Overtops
2025	Overtops	Capacity	Overtops	Capacity	Overtops	Overtops
2050	Overtops	Capacity	Overtops	Capacity	Overtops	Overtops
2100	Overtops	Capacity	Overtops	Capacity	Overtops	Overtops

Table 4-4
Overtopping at Central Street with Tide Gate Removed and Culvert widened, Balanced Energy Use with Storm Surge

Year	25 yr		50 yr		100 yr	
	Exist.	Prop.	Exist.	Prop.	Exist.	Prop.
2015	Overtops	Capacity	Overtops	Capacity	Overtops	Overtops
2025	Overtops	Capacity	Overtops	Overtops	Overtops	Overtops
2050	Overtops	Overtops	Overtops	Overtops	Overtops	Overtops
2100	Overtops	Overtops	Overtops	Overtops	Overtops	Overtops

Enlarging the culvert and eliminating the tide gate would result in significant reductions in water surface elevation. Although the water surface elevation would drop in comparison with existing conditions if the proposed improvements were undertaken, the roadway would still eventually overtop because the surge elevation exceeds the roadway centerline elevation for 2050 and beyond. When only sea level rise is taken into account, the improvements have a larger impact on reducing water surface elevations.

Given the existing constraints in the area of the existing roadway elevation and development on both banks of the river, options to improve the situation at Central Street will need to included additional upstream culvert improvements and flood storage. Reducing storm surge might be achieved with some sort of hurricane barrier. A hurricane barrier might be situated at the mouth of Manchester Harbor.

4.2 Increasing Flood Storage

Four locations were evaluated for potential flood storage:

- Old School Street north of 128;
- Municipal land near Knights Circle;
- Land abutting the Coach Field Playground, and
- The Essex County Golf Course.

Modeling involved adjustment of model parameters at the project site to simulate potential flood attenuation. The model was run to determine the change in stream discharge for a 50-year storm, in the year 2050 using a balance energy emission scenario.

The land next to Coach Field Playground consists of municipally owned area abutting Sawmill Brook upstream of Norwood Avenue. This area is lightly vegetated (with some large diameter trees) with opportunity to create flood storage on the bank of the stream. A project would include re-grading the area and installing natural plantings while leaving the large diameter trees. Approximately 13,000 square feet of area could potentially be utilized.

Municipal land upstream of the School Street culvert, across from Knight's Circle, includes a potential opportunity to create a flood storage area to the left side of the Sawmill Brook looking upstream from School Street culvert. The project would include re-grading the bank area to allow for storage of flood waters by increasing the floodplain. It was assumed that the area on the north bank would be excavated beginning at 12 inches above the bottom of the stream in order to maintain a low-flow channel.

Tighe & Bond modeled these potential flood storage opportunities by modifying the corresponding cross sections in the HEC-RAS model. Because these two areas manage such small areas of floodwater compared to the overall Sawmill Brook watershed, they did not produce any discernable benefit. Two sites for flood storage, Old School Street and the Essex County Golf Course, produced discernable benefits and are described in more detail below.

4.2.1 Upstream of Old School Street

There is a significant area of storage upstream of Old School Street north of Route 128. If the road centerline of Old School Street were raised, additional stormwater could be impounded behind it. Increasing the storage behind Old School Street attenuates storm discharge and reduces the frequency and amount of instances where culverts overtop downstream. Providing flood storage at the top of the Sawmill Brook Watershed would provide greatest benefit for locations immediately downstream of Route 128, where flooding occurs frequently. The conceptual design included replacing the three existing culverts with two reinforced concrete box culverts with natural bottoms and one reinforced concrete pipe culvert. The road elevation of Old School Street would be raised by approximately 4 feet to elevation 46 feet NAVD88.

Inlet of one of Old School Street Culverts

In order to model the raising of Old School Street, the stage-storage-discharge table at Old School Street was updated to account for the additional flow attenuation. The revised tabular data was then entered the into the HEC-HMS model to measure the flood attenuation that would result along the watercourse with the proposed modification.

To assess the benefit of increasing storage behind Old School Street, flow rates on the main stem of Sawmill Brook downstream of Old School Street were modeled for a 50-year storm event in the year 2050, utilizing a balanced energy emission scenario. Flows were entered into the HEC-RAS model to determine the resultant water surface elevations downstream and to demonstrate the impact of the proposed additional flood attenuation capacity at select locations on the river..

Increasing the storage behind Old School Street reduces the flow rates downstream and reduces the frequency and amount of instances where culverts overtop downstream. The flood reduction benefit is limited to a stream reach of approximately one mile. The flood storage project has the potential to reduce flows by 16% to 85% in the area south of Old School Street before the Essex County Club, but by 1% or less downstream from the County Club, particularly in the downtown area.

4.2.2 Golf Course

Essex County Club flood plain area

The golf course was selected based on opportunities to manage flooding on both municipally owned or privately owned portions of the Essex County Club. Projects would include increasing flood storage areas abutting the stream channel by generally increasing the cross sectional area of the waterbody. In addition, restoring the channel to a more natural orientation would improve aesthetics. Improvements to this location would require coordination with the golf course and considerations for public safety.

Tighe & Bond looked at increasing flood storage on the course by re-grading an area abutting the stream channel to create approximately 6.6 acre-feet of storage. This would alter approximately 13.8 acres on the golf course property.

Providing flood storage within the golf course by increasing the cross sectional area of the existing stream channel will attenuate flood waters below

Route 128, reducing downstream flooding severity.

Restoring the channel to a more natural orientation would improve aesthetics. This public location presents an excellent opportunity for a public education kiosk describing how open space parcels can help flood attenuation.

Based on the HEC-RAS watershed modeling completed, this project has limited potential to reduce water surface elevations and water flows during the 50 year storm in 2050, due to the extensive size of the watershed.

4.3 Culvert Rightsizing

Flooding can be managed by changing the dimensions of (i.e. "rightsizing") culverts throughout the watershed. Using the HEC-RAS model, Tighe & Bond evaluated culverts throughout Manchester-by-the-Sea to identify the preliminary impact on downstream and upstream flooding. Based on our evaluation, increasing the cross-sectional area of the following culverts has the most benefit to reducing overall watershed flooding:

- Culvert 23, School Street
- Culvert 22, Norwood Avenue
- Culvert 17, Lincoln Street

Inlet of School Street Culvert

4.3.1 Culvert Improvements at School Street

Several design concepts were evaluated for culvert improvements at School Street to maximize flood mitigation. Additional HEC-RAS modeling runs were performed using a 50-year future design storm for the year 2050 under a balanced energy precipitation scenario, incorporating parameters for several sizes of culverts, and channel widening. After carefully evaluating the physical environment, site constraints and HEC-RAS modeling results, the following project elements were proposed to re-size the culvert at School Street to accommodate existing and future flood conditions.

- Remove the existing School Street culvert and replace with 6.6 foot tall by 16 foot wide box culvert
- Widen and lower limited segments of Sawmill Brook.
  - At School Street, lower stream channel by approximately 1.2 feet.
  - Downstream of School Street, widen by approximately 4 feet until Central Pond.
  - Upstream of School Street to Norwood Avenue, widen by approximately 4 to 8 feet depending on location and conflicts with private property.

Outlet of School Street Culvert

Enlargement of the School Street culvert and limited widening of Sawmill Brook stream channel will improve hydraulic capacity of the stream channel and limit backwater flooding to alleviate flooding of private properties adjacent to Sawmill Brook. Improvements to stormwater drainage will benefit water quality. Sediment removal and stabilization of the streambank as part of the stream widening will improve rainbow smelt habitat.

Based on the HEC-RAS modeling completed, increasing the size of this culvert, widening and lowering of limited segments of Sawmill Brook, in addition to improving the downstream Central Street Culvert and upstream Norwood Avenue culvert, will decrease water surface elevations in flood conditions by approximately 5% upstream of School Street and approximately 13% downstream of School Street. Without making channel improvements, the downstream water surface elevations will only be reduced by only approximately 8%. It should be noted that some channel improvements are necessary for culvert widening.

4.3.2 Culvert Improvements at Norwood Avenue

Several design concepts were evaluated for culvert improvements at Norwood Avenue to maximize flood mitigation. Additional HEC-RAS modeling runs were performed using a 50-year future design storm for the year 2050 under a balanced energy precipitation scenario, incorporating parameters for several sizes of culverts, and channel widening. After carefully evaluating the physical environment, site constraints and HEC-RAS modeling, the following project elements were proposed to re-size the culvert at Norwood Avenue to accommodate existing and future flood conditions.

- Remove existing Norwood Avenue culvert and replace with 7’ tall by 20’ wide box culvert
- Widen Sawmill Brook stream channel downstream of Norwood Avenue by approximately 4 to 8 feet depending on location and conflicts with private property.
- Lower Sawmill Brook channel by approximately 3.1 feet at Norwood Avenue Culvert

Enlargement of the Norwood Avenue culvert and limited widening of Sawmill Brook stream channel will improve hydraulic capacity of the stream channel and limit backwater flooding to alleviate flooding of private properties and municipal facilities adjacent to Sawmill Brook.

Based on the HEC-RAS modeling completed, increasing the size of this culvert, widening and lowering of limited segments of Sawmill Brook, along with improving the downstream School Street and Central Street culverts, will decrease water surface elevations in flood conditions by approximately 6% downstream before School Street and approximately 13% downstream of School Street. As noted for the School Street culvert, some channel improvements are necessary for culvert widening.

Outlet of Norwood Avenue Culvert

4.3.3 Culvert Improvements at Lincoln Street

Several design concepts were evaluated for culvert improvements at Lincoln Street to maximize flood mitigation. Additional HEC-RAS modeling runs were performed using a 50-year future design storm for the year 2050 under a balanced energy precipitation scenario, incorporating parameters for several sizes of culverts. After carefully evaluating the physical environment, site constraints and HEC-RAS modeling, the following project elements were proposed to re-size the culvert at Lincoln Street to accommodate the 50-year storm for existing and future flood conditions.

- Remove existing Lincoln Street culvert and replace with 6.5 foot tall by 20 foot wide box culvert
- Full-depth roadway reconstruction including guardrail replacement.
- Sediment and organic debris removal in vicinity of culvert.

Enlargement of the Lincoln Street culvert will increase the hydraulic capacity of Sawmill Brook and reduce backwater flooding impacting the High School property and Lincoln Street Wellfield upgradient of the site, which has flooded in previous storm events. The stone culvert is aging, and replacement will eliminate safety concerns, especially during large flood events which are currently undercutting the banks at the culvert sidewalls.

Based on the HEC-RAS modeling completed, increasing the size of this culvert along with improving the downstream Norwood Avenue, School Street, and Central Street culverts, will decrease water surface elevations in flood conditions by up to 10% in the upstream segment, by approximately 3% directly downstream of Lincoln Street, almost 10% downstream of Norwood Avenue and School Street.

Stone Arch Construction of the Lincoln Street Culvert

4.4 Green Infrastructure

Tighe & Bond conducted an assessment of the potential benefit of installation of green infrastructure practices also known as Low Impact Development Best Management Practices (LID BMP's). For a complete description of the Green Infrastructure BMP Analysis, please refer to the Tighe & Bond Report, "Opportunities for Flood Mitigation within Sawmill Brook", July 30, 2015. As described in this report, opportunities to install green infrastructure throughout the watershed included the following locations:

- Parking lot abutting the Town Fire Station at 12 School Street;
- Parking lot for the Coach Field Playground;
- High School; and
- Elementary School.

Green infrastructure practices manage small areas of runoff compared to the overall Sawmill Brook watershed. Tighe & Bond evaluated these locations as part of the HEC RAS modeling. For example, for the Elementary School, we assumed that all of the existing pavement would be converted to permeable pavement, approximately 39,000 square feet. The curve number calculation for this location was adjusted for the land use coverage assuming that the area would be converted to permeable pavement. The runoff curve number dropped from 74 to 73, which is not significant. Additional model runs were performed to account for the reduced runoff curve number. We found that, under all modeling conditions, there was only a slight reduction (generally 2 cfs) in the flow rate downstream of the elementary school and that culvert overtopping was not reduced (i.e. the project would not have a significant impact on the water surface elevations).

Of the areas identified as potentially feasible for green infrastructure installation, the Coach Field Parking Area was selected by the Town to further explore the flood benefits from installation of porous pavement or LID BMPs.

4.4.1 Recommended Project - Porous Asphalt for Coach Field Parking

HEC-RAS modeling was evaluated for the potential benefit of installing porous asphalt in the Coach Field parking lot. Because the parking area is small (approximately 0.4 acres) in comparison to the overall watershed (approximately 3,400 acres), this improvement will have limited benefit to reducing flows during larger precipitation events (e.g. the 25, 50, and 100 year storms in 2025, 2050, and 2100 that range from 6.3 inches to almost 11 inches in a 24-hour storm). However, it will have some benefit during small storm events. In addition, installing porous aspahlt on the parking area will improve water quality and reduce thermal loading to Sawmill Brook. This project would consist of the following elements:

View of parking area from Norwood Avenue

- Construction of a porous asphalt parking area to replace existing gravel parking, including excavation of existing parking lot and installation of sub-base.
- Installation of small bathroom facilities as part of project
- Project would include a public education component through signs and displays.

Water quality improvements would be attained with the implementation of this project. Sediment routinely migrates from the unpaved parking area to Sawmill Brook, negatively impacting smelt habitat. Porous asphalt, the green stormwater infrastructure recommended for the site, has the ability to reduce total suspended solids up to 80%. Porous asphalt will also help reduce runoff to Sawmill Brook during smaller storms. The public location of the parking area, and high use volume makes this an ideal spot for a public education kiosk, to inform the public about impacts of stormwater runoff on Sawmill Brook and the benefits of green stormwater infrastructure.

4.5 Storm Surge Barrier

A storm surge barrier would be an option to protect Manchester Harbor and vicinity from moderate storm surge, some sea level rise, wave action and if closed during low tide, a way to hold a low tail-water condition to minimize back-watered river flooding. These types of structures can range from large structures, such as the New Bedford Hurricane Barrier (right), to smaller tidal dikes, lower right. From the existing topographic land height limitations in Manchester Harbor, a surge barrier would likely be a structure size in between these two example photographs.

The site of the conceptual surge barrier illustrated in Figure 1 was selected as a balance between vicinity protected (most of the harbor area) and finding an area with adjacent high shoreline and relative shallow water depths to minimize structure costs. Several sites were considered, including the railroad bridge that benefits from the existing railroad fill, and were viewed and discussed with town officials. The preferred site from a technical perspective is the harbor entrance between Tucks Point and Proctor Point. This site is just inshore of mapped/historical eelgrass beds, thus avoiding sensitive benthic habitat.

View of Manchester Harbor

The conceptual design of the surge barrier is a traditional stone armored dike/breakwater with a navigation opening aligned with the harbor entrance channel. A boat navigation opening at least 60 feet wide would be provided in the barrier, aligned with the channel, formed by side walls and a hinged steel gate, typically open, lying on the seabed. The opening end walls might consist of steel sheet pile cells, or concrete structures. The concept layout is based on a 12 foot wide crest path that would likely be needed for periodic maintenance and a crest elevation about 21 feet above mean lower low water, based on the present FEMA 100 year velocity zone elevation. The barrier structure might also need to include submerged tunnels with gates, normally open, to maintain good tidal water exchange and water quality in the harbor. The existing town sewer outfall pipe is buried along the edge of the existing navigation channel and this would need to be investigated to see if modifications including armoring and a back flooding prevention valve might be needed.

4.6 Evaluation of Combined Projects

To achieve optimal flood reduction benefits, a combination of culvert resizing projects and flood storage is desirable. HEC-RAS modeling runs were completed for a series of combined projects as shown below in **Table 4-5** to evaluate the potential benefits from cumulative flood mitigation. **Appendix E** provides a summary of the HEC-RAS modeling iterations with the project combinations. This information will be used in combination with other considerations to refine and prioritize projects for the final Task 6 memo.

Table 4-5
Summary Table of Combined Flood Mitigation Projects

Project Elements	**Modeling Iterations**												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Culvert Improvements*													
Central Street	X		X			X	X	X	X	X	X	X	X
School Street	X		X			X	X	X	X	X	X	X	X
Norwood	X		X			X	X	X	X	X	X	X	X
Lincoln						X	X	X	X				
Channel Improvements													
School –Norwood Widen	X		X			X					X	X	X
School-Norwood Widen and Deepen												X	X
Flood Storage													
Essex County Golf Course				X	X								
Old School Street		X	X		X	X		X					

The following presents notes on the various model iterations:

- Iteration 1: Includes increasing dimension of culverts at Central Street to 19' wide 8' tall, School Street to 20' wide by 7.5' tall, and Norwood Avenue to 20' wide 7' tall (all three are proposed box culverts) and widening the Sawmill Brook channel between School Street and Norwood Avenue by eight feet on each side of the stream channel.

- Iteration 2: Includes only flood storage by raising Old School Street by approximately 4 feet to elevation 48.1.

- Iteration 3: Includes increasing dimension of culverts at Central Street to 19’ wide 8’ tall, School Street to 20’ wide by 7.5’ tall, and Norwood Avenue to 20’ wide 7’ tall (all three are proposed box culverts) and widening the Sawmill Brook channel between School Street and Norwood Avenue by eight feet on each side of the stream channel, and raising Old School street by approximately 4 feet to elevation 48.1 to create flood storage (Iteration 2).

- Iteration 4: Includes only flood storage at the Essex County Club by expanding area by 38 acre-feet at elevation 18.

- Iteration 5: Combines flood storage using Old School Street and the Essex County Club (Iterations 2 and 4).

- Iteration 6: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 20’ wide by 7.5’ tall, Norwood Avenue to 20’ wide 7’ tall, and Lincoln Street to 20’ wide by 6’ tall (all four are proposed box culverts) and widening the Sawmill Brook channel between School Street and Norwood Avenue by ten feet on each side of the stream channel.

- Iteration 7: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 20’ wide by 7.5’ tall, Norwood Avenue to 20’ wide 7’ tall, and Lincoln Street to 20’ wide by 6’ tall (all four are proposed box culverts) along with using flood storage at the Essex County Club (Iteration 4).

- Iteration 8: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 20’ wide by 7.5’ tall, Norwood Avenue to 20’ wide 7’ tall, and Lincoln Street to 20’ wide by 6’ tall (all four are proposed box culverts) along with raising Old School Street to create flood storage (Iteration 2).

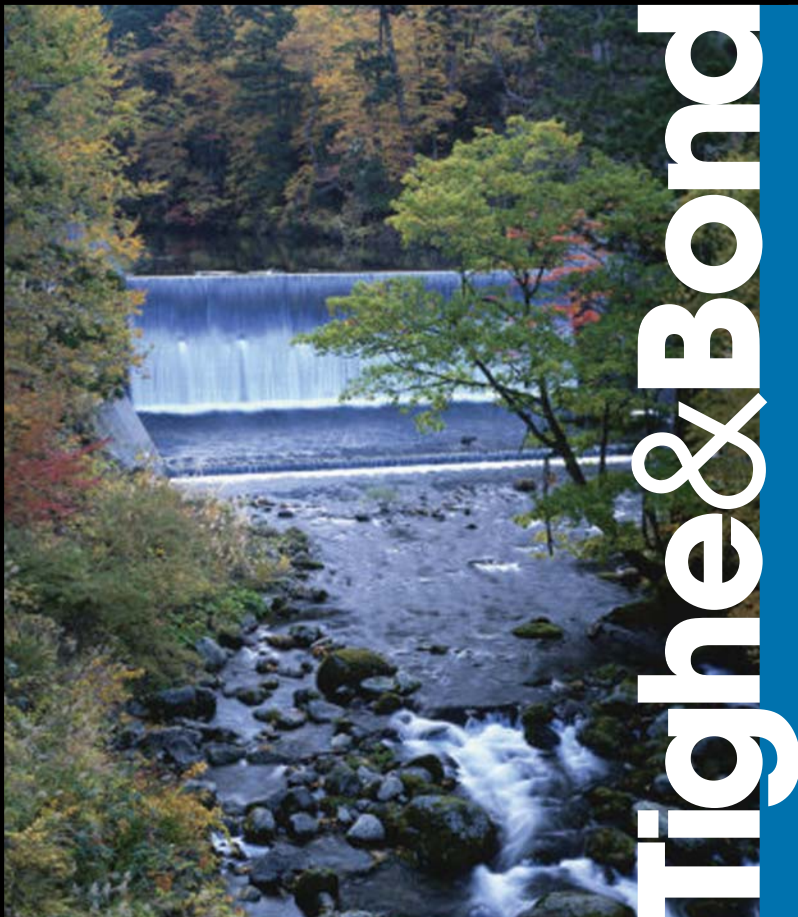
- Iteration 9: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 20’ wide by 7.5’ tall, and Norwood Avenue to 20’ wide 7’ tall (all three as box culverts) and reducing the Lincoln Street to 10’ wide by 5.9’ tall (as an arch culvert) for creation of upstream flooding in Essex County Club.

- Iteration 10: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 20’ wide by 7.5’ tall, and Norwood Avenue to 20’ wide 7’ tall (all three are proposed box culverts), with no other channel improvements.

- Iteration 11: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 14’ wide by 5.64’ tall, and Norwood Avenue to 20’ wide 4.65’ tall (all three are proposed Con/Span® culverts), with widening Sawmill Brook by approximately four feet on each side in the vicinity of School Street, ten feet on each side in the vicinity of Norwood Avenue, and seven feet on each side in the area between School Street and Norwood Avenue.

- Iteration 12: Includes increasing dimension of culverts at Central Street to 20’ wide 8’ tall, School Street to 16’ wide by 8’ tall, and Norwood Avenue to 20’ wide 7’ tall (all three are proposed Con/Span® culverts), with widening Sawmill Brook by approximately four feet on each side in the vicinity of School Street, ten feet on each side in the vicinity of Norwood Avenue, and seven feet on each side in the area between School Street and Norwood Avenue. This also includes deepening Sawmill Brook by approximately 1.9 feet at School Street, 2.3 feet at Norwood Avenue, and up to 2 feet in the channel between the two culverts.

- Iteration 13: Includes increasing dimension of culverts at Central Street to 20' wide 8' tall, School Street to 16' wide by 8' tall, and Norwood Avenue to 16' wide 7' tall (all three are proposed Con/Span® culverts), with widening Sawmill Brook by approximately four feet on each side in the vicinity of School Street, ten feet on each side in the vicinity of Norwood Avenue, and seven feet on each side in the area between School Street and Norwood Avenue. This also includes deepening Sawmill Brook by approximately 1.9 feet at School Street, 2.3 feet at Norwood Avenue, and up to 2 feet in the channel between the two culverts.



SECTION 5

Section 5
Project Summary & Recommendations

5.1 Summary

Tighe & Bond evaluated the existing and future hydrology and hydraulics within the Sawmill Brook watershed under varying climatic events. Evaluation including modeling existing watershed conditions using information about soils, topography, ground cover (impervious cover and land uses), existing wetlands and waterbodies, water travel times, existing structures that control discharges (e.g. Central Street tide gate, culverts, etc.), rainfall depths developed by the Cornell University Northeast Regional Climate Center, and tidal influences using data from Flood Insurance Study for Essex County (July 2014). The existing conditions model was calibrated against the May 2006 storm (Mother's Day storm) that represent 25-year single day and 100-year consecutive day storm conditions.

Future watershed conditions were modeled to build off the existing conditions model and consider anticipated impacts from climate change and sea level rise in 2025, 2050, and 2100. For the future conditions model, precipitation estimates from the existing conditions scenario were replaced with estimates of future rainfall depths for 2025, 2050, and 2100 from the Oyster River Culvert Analysis project completed in Durham, New Hampshire (UNH, 2010). In addition, sea level rise and storm surge were considered using data from the Inundation Risk Model (IRM) outputs developed by Keil Schmid (Geoscience, 2015).

Using the future conditions model, we evaluated potential impacts on existing infrastructure (e.g. Central Street tide gate, culverts, crossings) from storm surge, sea level rise, and future precipitation conditions in 2025, 2050, and 2100. The future condition model for the year 2050 using a 50-year storm and a balance energy emission scenario was also used to evaluate right sizing culverts sizes and needed upgrades, and the mitigation value of proposed stormwater best management practices including green stormwater infrastructure, conveyance projects, and flood storage.

In general, the floodplain will continue to expand over time for the proposed climate change scenarios, and as a result of the increased flow and higher tailwater elevations exerted by tidal forces, by 2100, under a fossil intensive projection, 60% of the culverts in the watershed will overtop during a 25-year storm, and 70% will overtop during a 100-year storm under both storm surge conditions and sea level rise conditions.

Tighe & Bond expanded the modeling to look at potential improvements to flooding by relieving channel restrictions at Central Street, providing additional flood storage north of Route 128, rightsizing culverts, and utilizing green infrastructure best management practices at a variety of pre-screened locations. Based on the modeling results looking at individual projects, the scenario with resizing the culvert at Central Street has by far the largest improvement in the watercourse's flood carrying capacity.

To achieve optimal flood reduction benefits, a combination of culvert resizing projects and flood storage is desirable. HEC-RAS modeling runs were completed for a series of combined projects. This information will be utilized to make recommendations for prioritizing projects as part of Task 6.

5.2 Recommendations

Tighe & Bond met with Town staff on October 26, 2015, to review the modeling effort and preliminary results and to identify projects for further evaluation under Task 5, conceptual designs and preliminary permitting evaluation. Based on discussions at this meeting, conceptual designs will be prepared for the following nine projects:

1. Removing channel restrictions at Central Street (Option 1) consists of removing the tide gate and keeping the configuration of the culvert, potentially with a rock riffle to keep Central Pond full of water
2. Removing channel restrictions at Central Street (Option 2) consist of removing the tide gate, opening the culvert, removing the dam, and changing the entire crossing to be a bridge, and restoring the historic stream channel
3. Increasing the dimensions of the School Street culvert (23) with modifications to the channel of Sawmill Brook to account for increased culvert sizing
4. Increasing the dimensions of the Norwood Avenue culvert (22) with modifications to the Sawmill Brook channel to account for the increased culvert dimensions
5. Increasing the dimensions of the Lincoln Avenue culvert (17)
6. Flood storage in the Essex County Club Golf Course.
7. Flood storage upstream of Old School Street culvert (2)
8. Development of a hurricane barrier located in Manchester Harbor to manage overtopping from storm surge and hurricanes
9. Installation of a green infrastructure practice, porous pavement, at the Coach Field parking lot

Removing Channel Restrictions at Central Street & Installation of a Hurricane Barrier

- When only sea level rise is taken into account, the Central Street improvements have the largest impact on reducing water surface elevations upstream. Due to the locations of business on the east bank of the river, and the roadway on the west bank, any widening of the river approach would be difficult, but eliminating the tide gate would result in reductions in water surface elevation. Culvert enlargements would also result in significant reductions in water surface elevation upstream, and would restore the stream crossing to historic conditions. Both improvement alternatives will improve smelt passage and spawning potential.

- Under worst case future storm conditions, even with modifications to the Central Street Bridge, the roadway would still overtop because the surge elevation exceeds the roadway centerline elevation for 2050 and beyond. This may be addressed with use of a hurricane barrier or raising the elevation of Central Street. A hurricane barrier might be located at the mouth of Manchester Harbor.

Removing Channel Restrictions at Culverts

- Improving conveyance of Sawmill Brook in the "downtown" area of Manchester (i.e. culverts at School Street, Norwood Avenue, and Lincoln Street) will reduce the overall watershed flooding.

Increasing Flood Storage at the Golf Course

- The golf course is located at approximately the halfway point in the watershed, includes Town-owned land, and has a large area for flood management before Sawmill Brook flows into Manchester's downtown area. These reasons make the golf course an excellent candidate for managing floodwaters with limited impacts to abutters.

Improving Flood Storage behind Old School Street

- Increasing the storage behind Old School Street (north of Route 128) reduces the flow rate for the stretch of stream channel between School Street and the confluence of Causeway Brook at Lincoln Street for large storm events. Most improvement would be between School Street and Mill Street. Further downstream, flows from other areas in the watershed combine, increasing flow in the watershed, so the contribution of the storage decreases until it disappears by the time the brook meets Causeway Brook.

Installation of Green Infrastructure at the Coach Field Playground Parking Area

- The Coach Field Playground parking area was identified as a priority over the Elementary School parking area due to proximity to Sawmill Brook and planned improvements at the Elementary School. While installation of porous pavement at the Coach Field Playground parking area does not reduce flood elevations in Sawmill Brook, it does have an excellent opportunity to improve water quality and result in localized reductions in discharge from the parking lot. This is also an excellent location for public education.

References

University of New Hampshire (2010). The Oyster River Culvert Analysis.

Schmidt, Keil. Integrated Risk Model Website: http://www.geosciconsultants.com/projects/2015/5/27/coastal-risk-mapping-in-salem-sound

Tighe & Bond (6/2015). Memo to Mary Reilly, "Manchester-by-the-Sea, Grants Coordinator, Sawmill Brook Central St Seawall, Tide Gate & Culvert Observations".

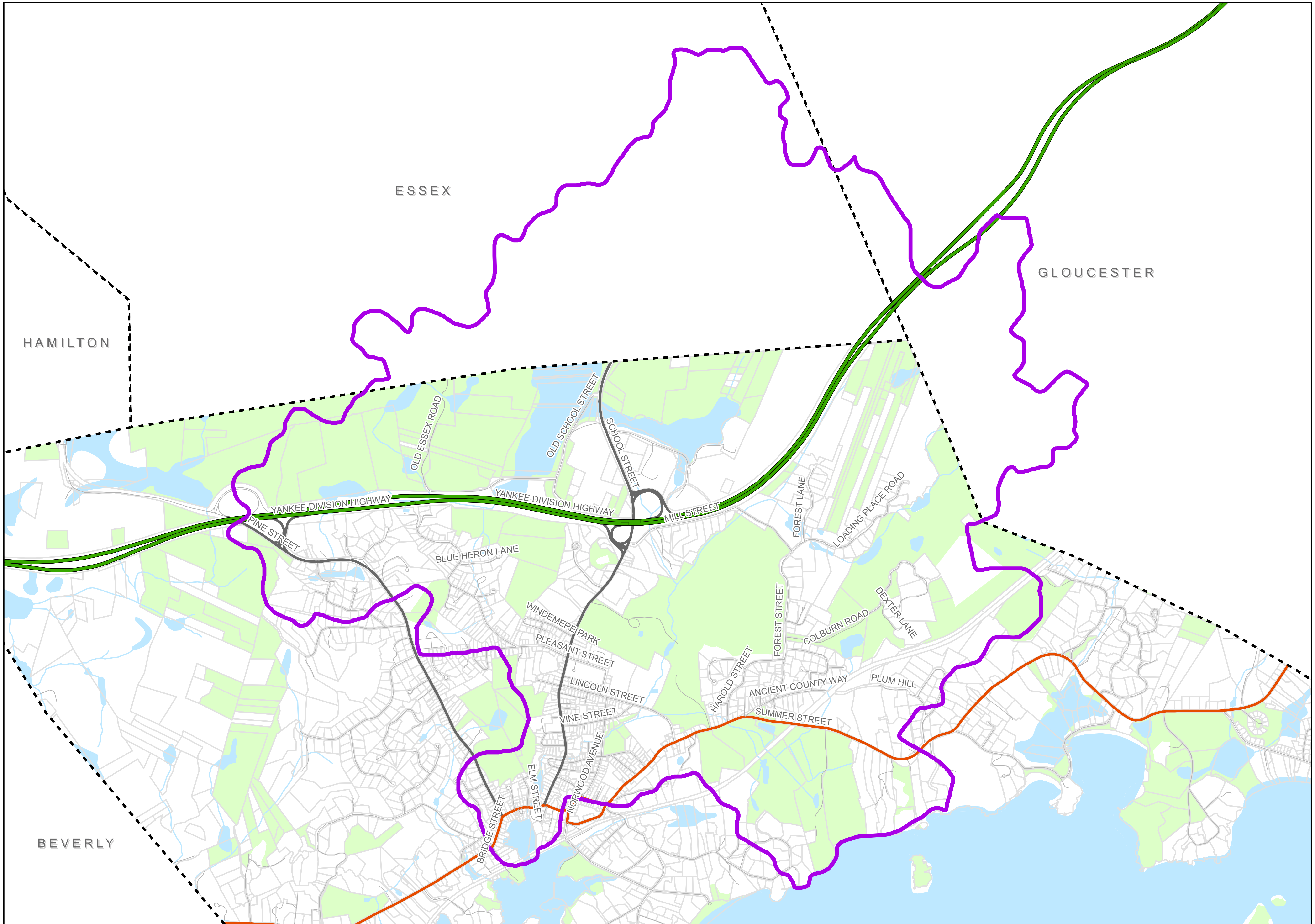
Tighe & Bond (7/2015). Report, "Opportunities for Flood Mitigation within Sawmill Brook

Tighe & Bond (7/2015). "Manchester-by-the-Sea, Massachusetts, Stream Crossing Evaluation, Sawmill Brook Watershed".

Tighe & Bond (9/ 2015). Technical Memorandum "Potential Climate Change Impacts to Manchester-by-the-Sea".

FIGURES

SAWMILL BROOK WATERSHED



LEGEND

Sawmill Brook Watershed

LOCUS MAP

N

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

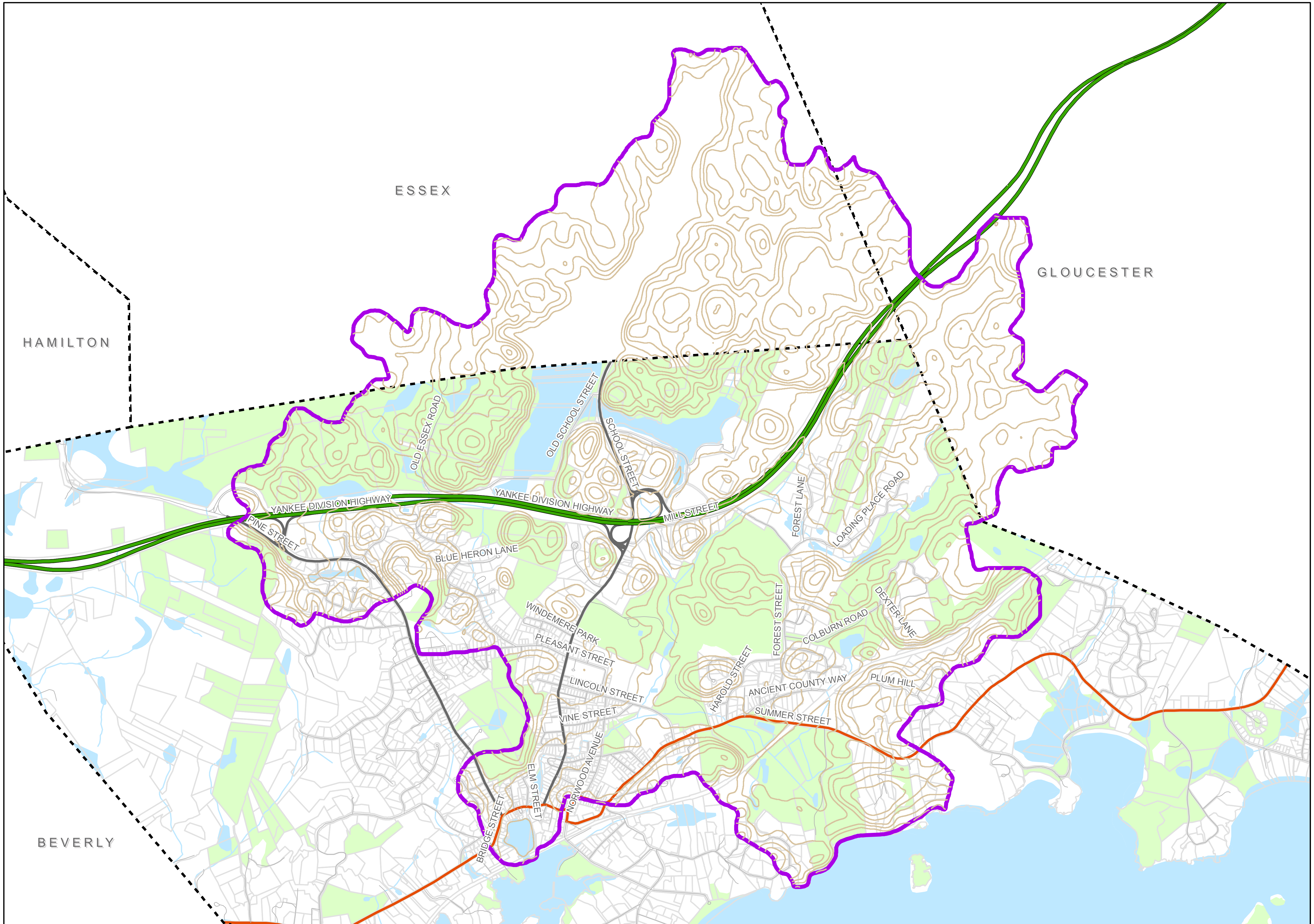
Figure 1

Sawmill Brook Culvert & Green Infrastructure Analysis
Manchester-by-the-Sea, Massachusetts
September 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\WatershedBoundary.mxd

M-1476



SAWMILL BROOK TOPOGRAPHY

LEGEND

20' Contours

Sawmill Brook Watershed

LOCUS MAP

N

0 875 1,750

Feet

1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 2

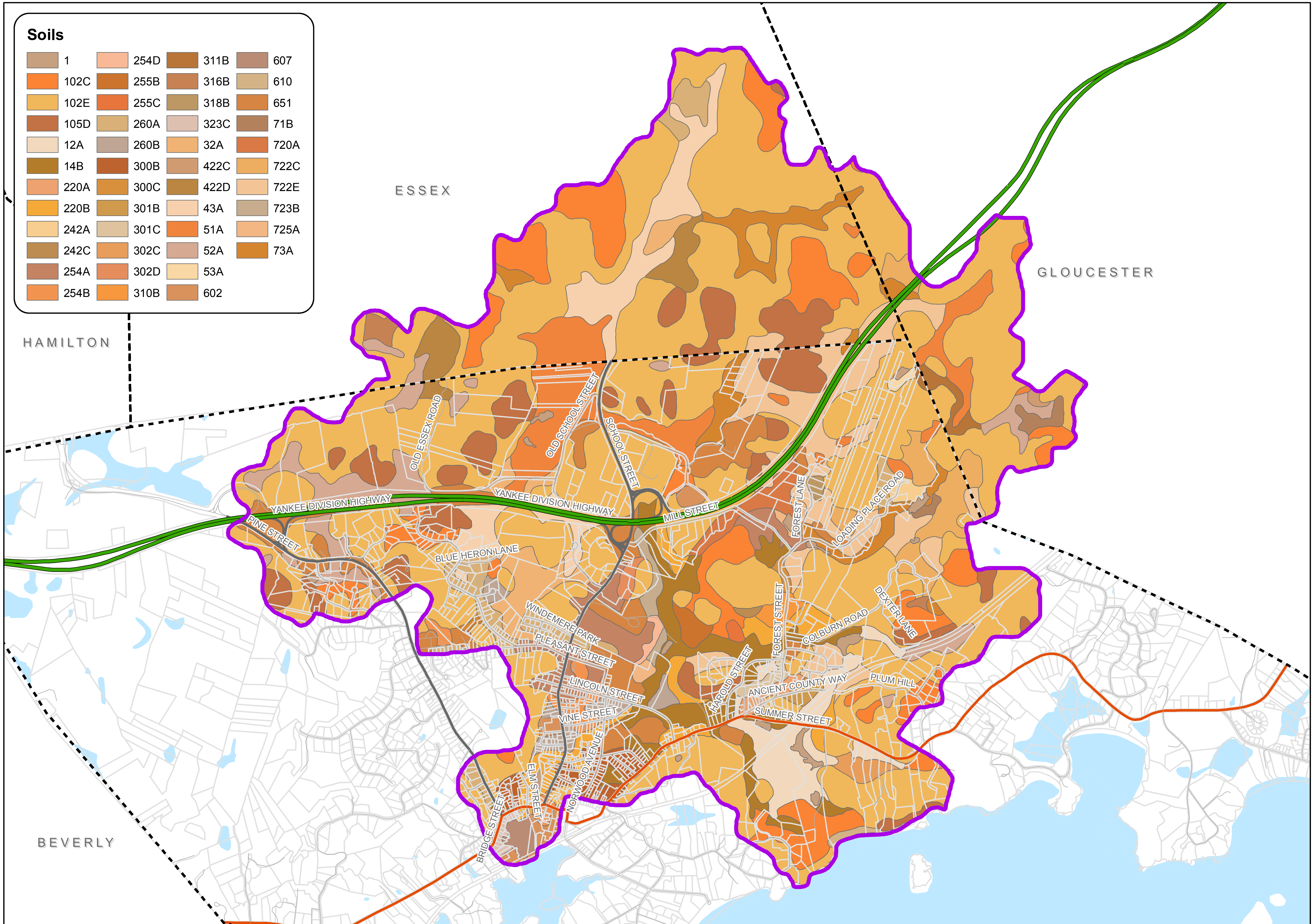
Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

September 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\WatershedTopography.mxd

M-1476



SAWMILL BROOK SOILS

LEGEND

Sawmill Brook Watershed

LOCUS MAP

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 3

Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

September 2015

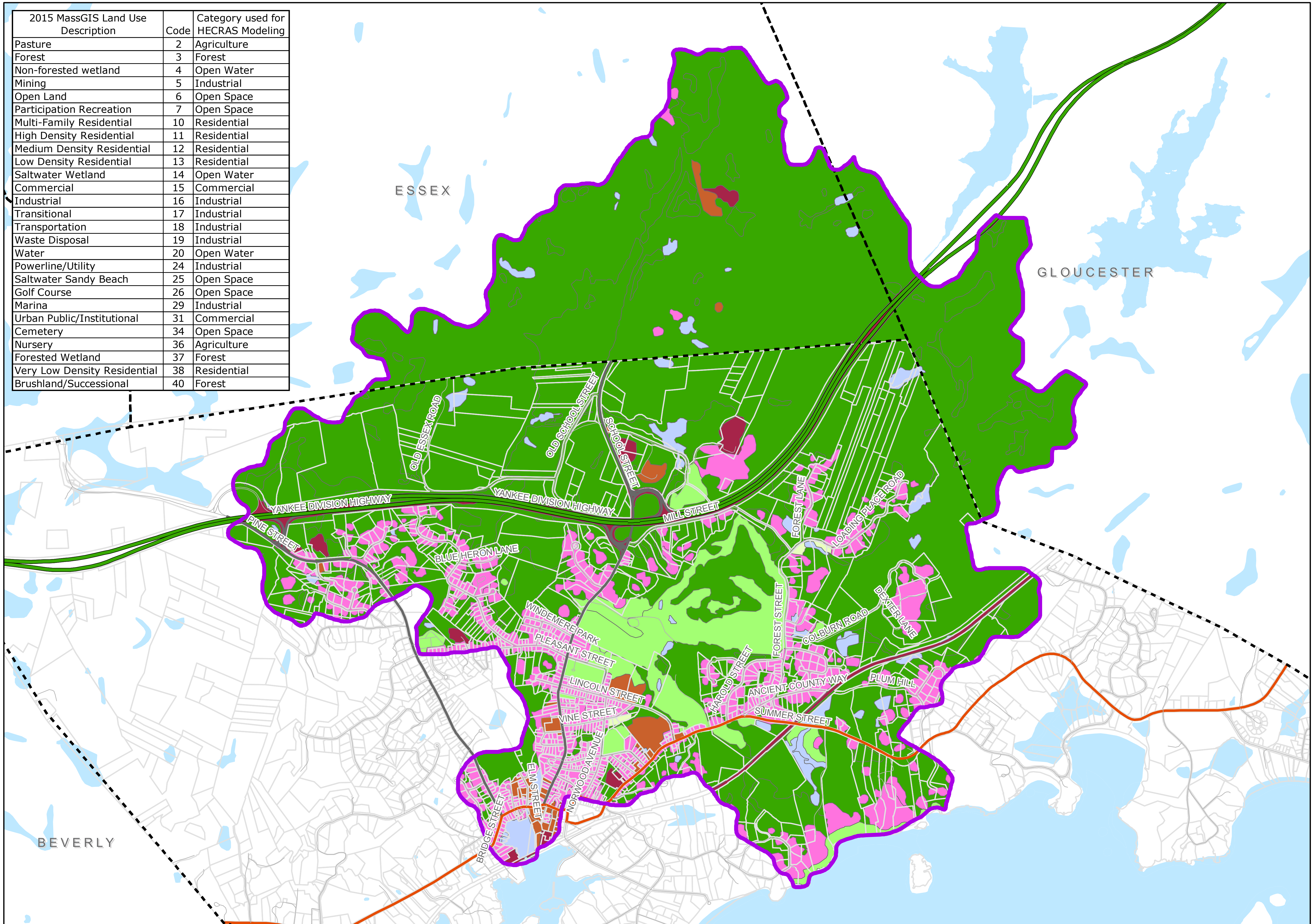
Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\WatershedSoils.mxd

M-1476

SAWMILL BROOK LAND USE

2015 MassGIS Land Use Description	Code	Category used for HECRAS Modeling
Pasture	2	Agriculture
Forest	3	Forest
Non-forested wetland	4	Open Water
Mining	5	Industrial
Open Land	6	Open Space
Participation Recreation	7	Open Space
Multi-Family Residential	10	Residential
High Density Residential	11	Residential
Medium Density Residential	12	Residential
Low Density Residential	13	Residential
Saltwater Wetland	14	Open Water
Commercial	15	Commercial
Industrial	16	Industrial
Transitional	17	Industrial
Transportation	18	Industrial
Waste Disposal	19	Industrial
Water	20	Open Water
Powerline/Utility	24	Industrial
Saltwater Sandy Beach	25	Open Space
Golf Course	26	Open Space
Marina	29	Industrial
Urban Public/Institutional	31	Commercial
Cemetery	34	Open Space
Nursery	36	Agriculture
Forested Wetland	37	Forest
Very Low Density Residential	38	Residential
Brushland/Successional	40	Forest



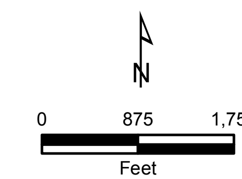
LEGEND

- Sawmill Brook Watershed

Aggregated Land Use

- Agriculture
- Commercial
- Forest
- Industrial
- Open Space
- Open Water
- Residential

LOCUS MAP



1:21,000

NOTES

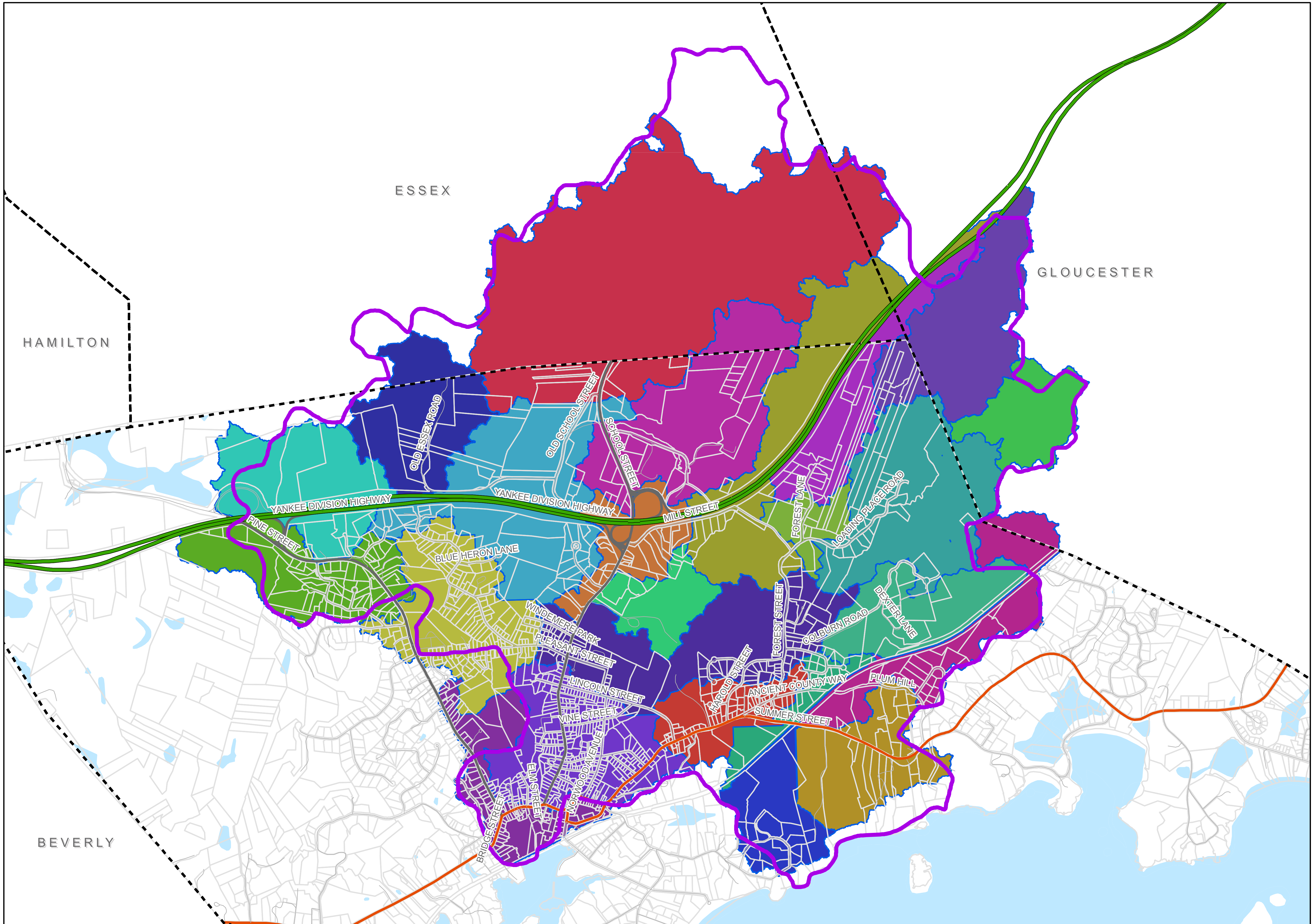
Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 4

Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists



SAWMILL BROOK SUBAREAS

LEGEND

Sawmill Brook Watershed

Watershed Subareas

LOCUS MAP

N

0 875 1,750

Feet

1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 5

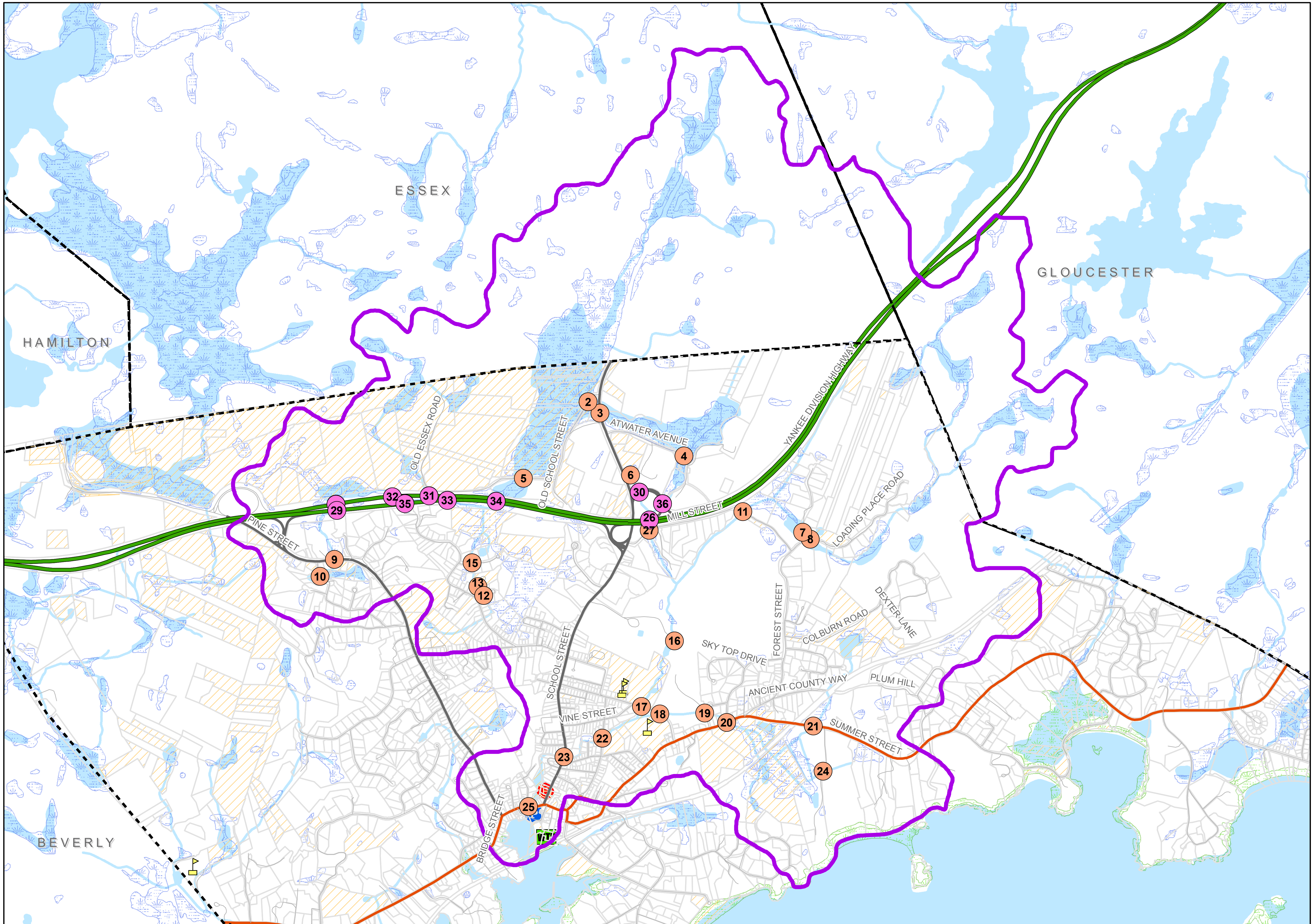
Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

September 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\WatershedSubAreas.mxd

M-1476



SAWMILL BROOK CULVERT LOCATIONS

LEGEND

- Sawmill Brook Watershed
- Town Boundary
- MassDOT Culvert
- Culvert
- Fire Station
- Police Station
- Wastewater Treatment Plant
- Schools (PK - High School)
- Town Owned Property
- Inland Wetlands
- Coastal Wetlands
- Waterbodes

LOCUS MAP

N

0 875 1,750

Feet

1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 6

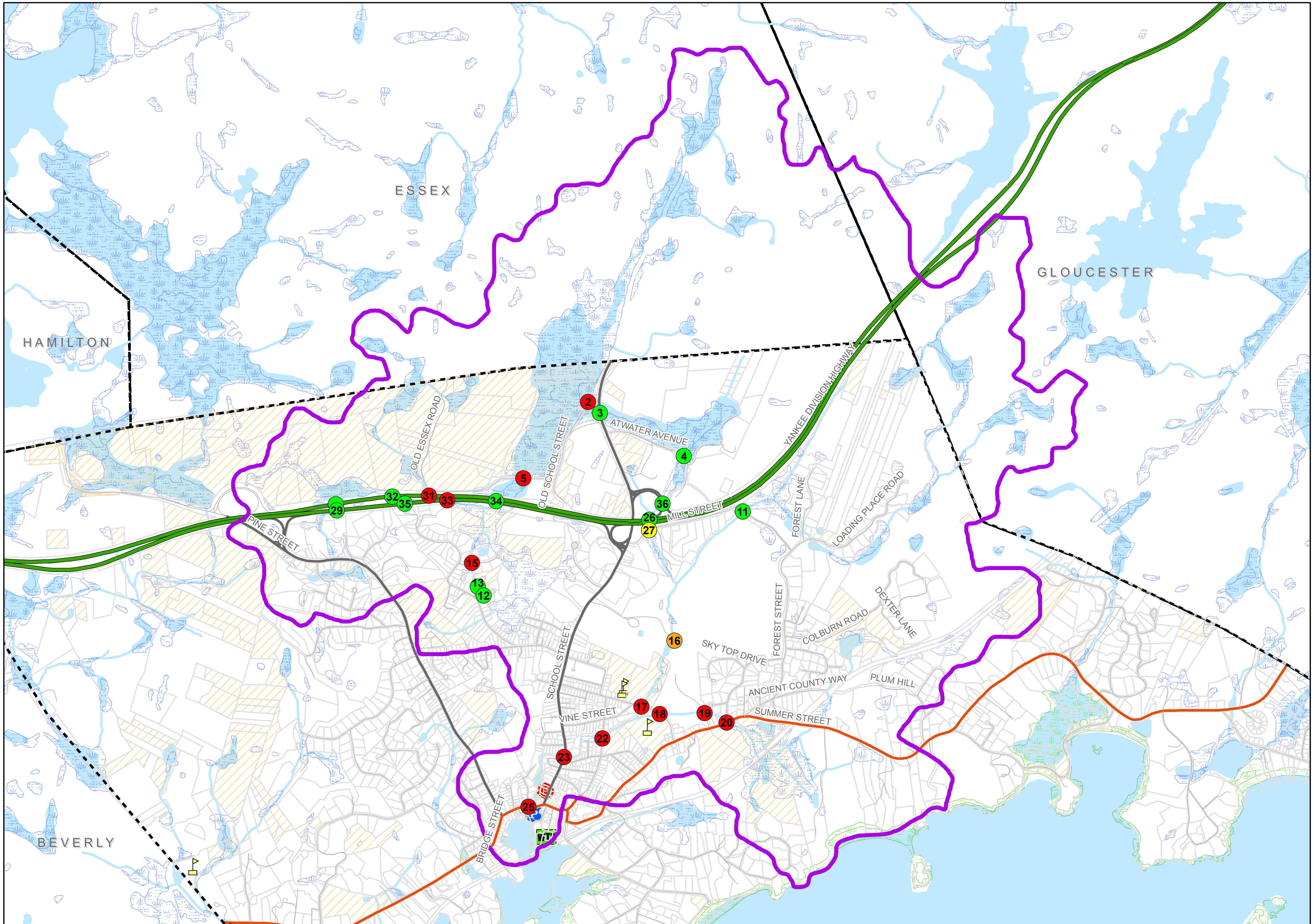
Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\WatershedCulvertLocations.mxd

M-1476



2015 STORM FREQUENCY CAUSING OVERTOPPING Existing Conditions Model

LEGEND

Culvert Overtopped

- >100 Year
- 25 Year Storm
- 50 Year Storm
- 100 Year Storm
- Sawmill Brook Watershed
- Town Boundary
- Town Owned Property
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

N

0 875 1,750

Feet

1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 7

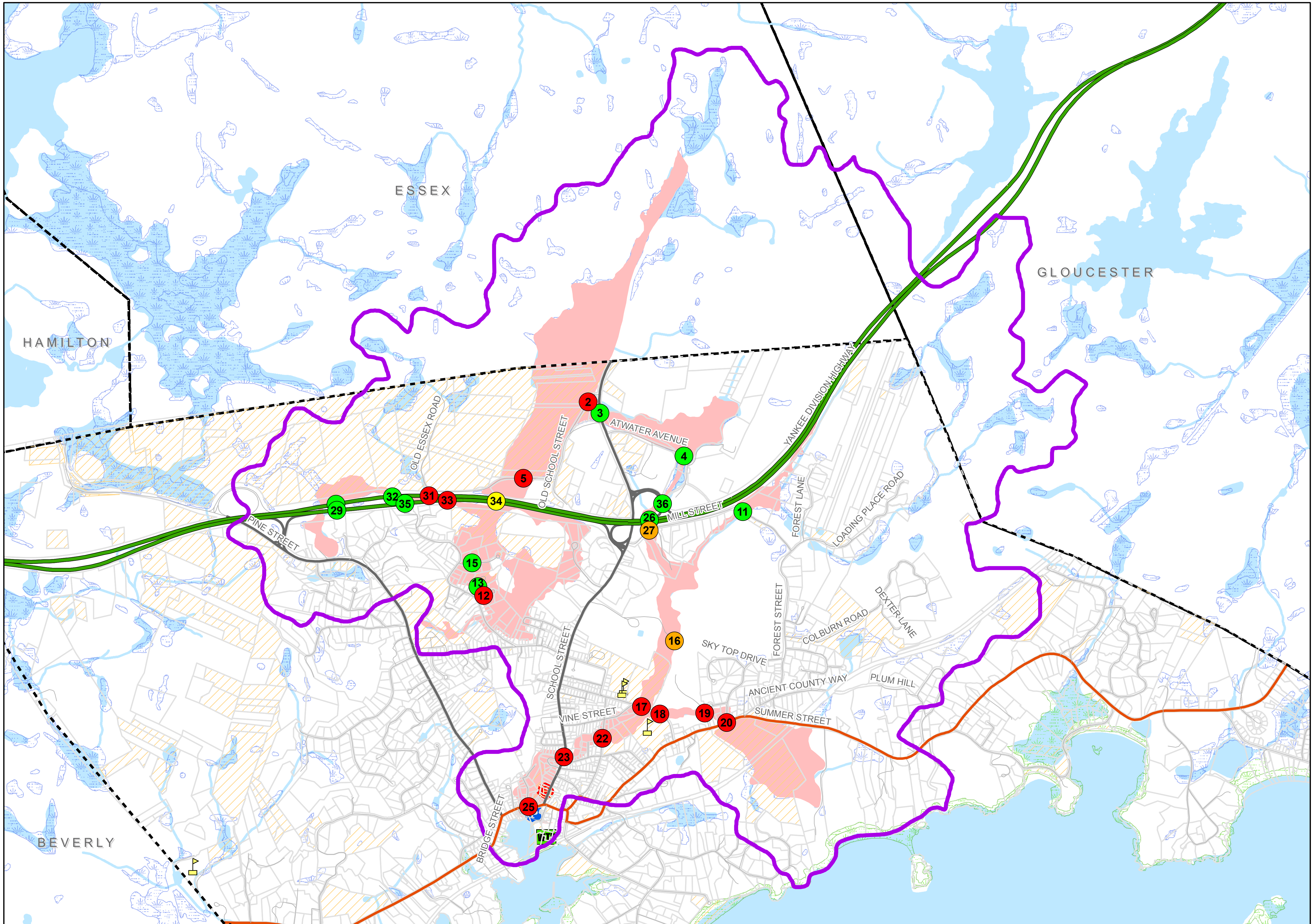
Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\CulvertOvertopping_2015.mxd

M-1476



2025 STORM FREQUENCY CAUSING OVERTOPPING
Balanced Energy Use,
Storm Surge or Sea Level Rise

LEGEND

Storm Frequency Causing Overtopping

- 25 Year Storm
- 50 Year Storm
- 100 Year Storm
- >100 Year Storm
- Sawmill Brook Watershed
- Town Owned Property
- Sea Level Rise Balanced
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

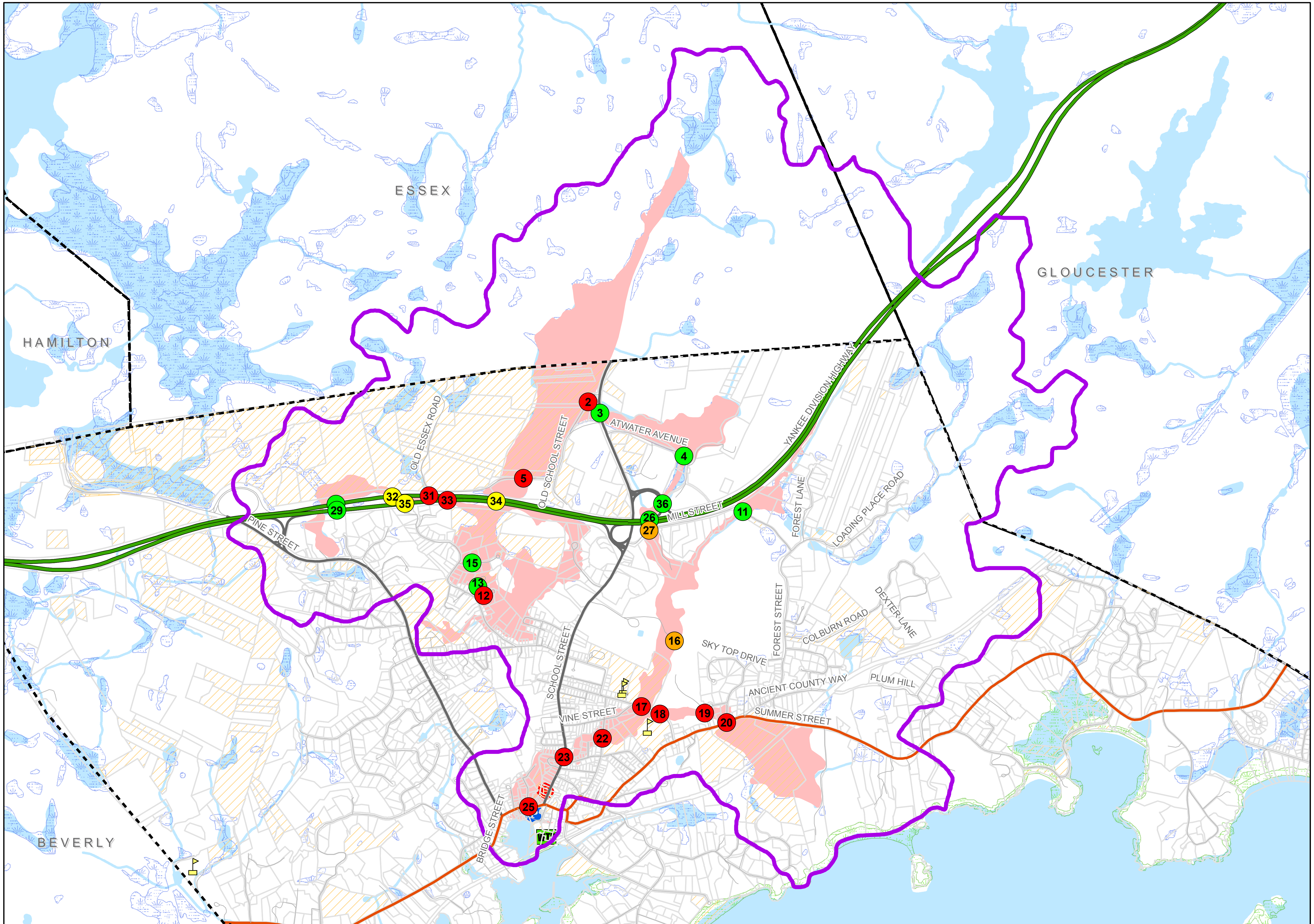
Figure 8A

Sawmill Brook Culvert & Green Infrastructure Analysis
Manchester-by-the-Sea, Massachusetts
November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\SeaLevelRise_BalancedEnergy2025.mxd

M-1476



2050 STORM FREQUENCY CAUSING OVERTOPPING
Balanced Energy Use,
Storm Surge or Sea Level Rise

LEGEND

Storm Frequency Causing Overtopping
- 25 Year Storm
- 50 Year Storm
- 100 Year Storm
- >100 Year Storm
- Sawmill Brook Watershed
- Town Owned Property
- Sea Level Rise Balanced
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 8B

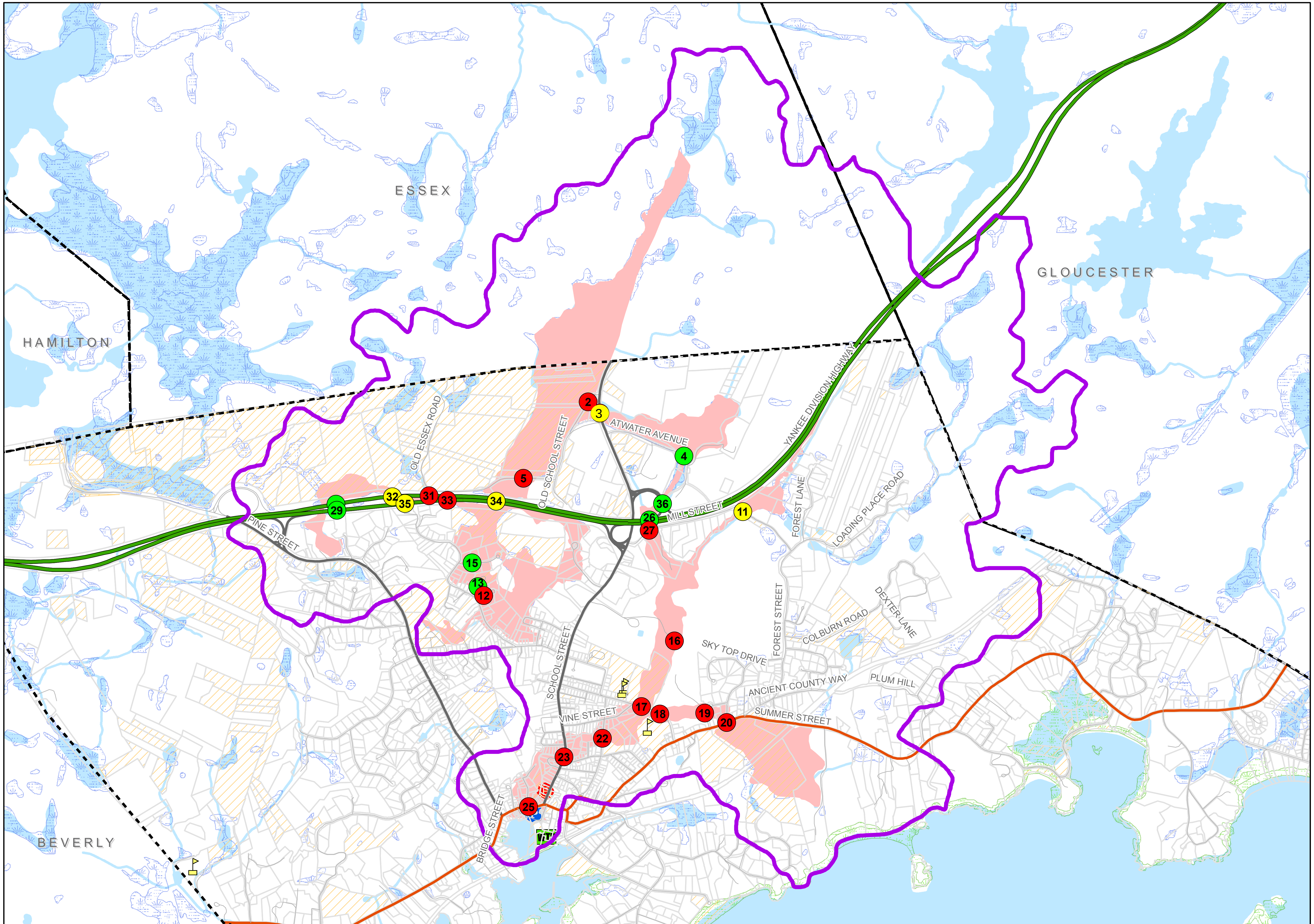
Sawmill Brook Culvert & Green Infrastructure Analysis
Manchester-by-the-Sea, Massachusetts
November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\SeaLevelRise_BalancedEnergy2050.mxd

M-1476

2100 STORM FREQUENCY CAUSING OVERTOPPING
Balanced Energy Use,
Storm Surge and Sea Level Rise



LEGEND

Storm Frequency Causes Overtopping

- 25 Year Storm
- 50 Year Storm
- 100 Year Storm
- >100 Year Storm
- Sawmill Brook Watershed
- Town Owned Property
- Sea Level Rise Balanced
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

N

0 875 1,750

Feet

1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 8C

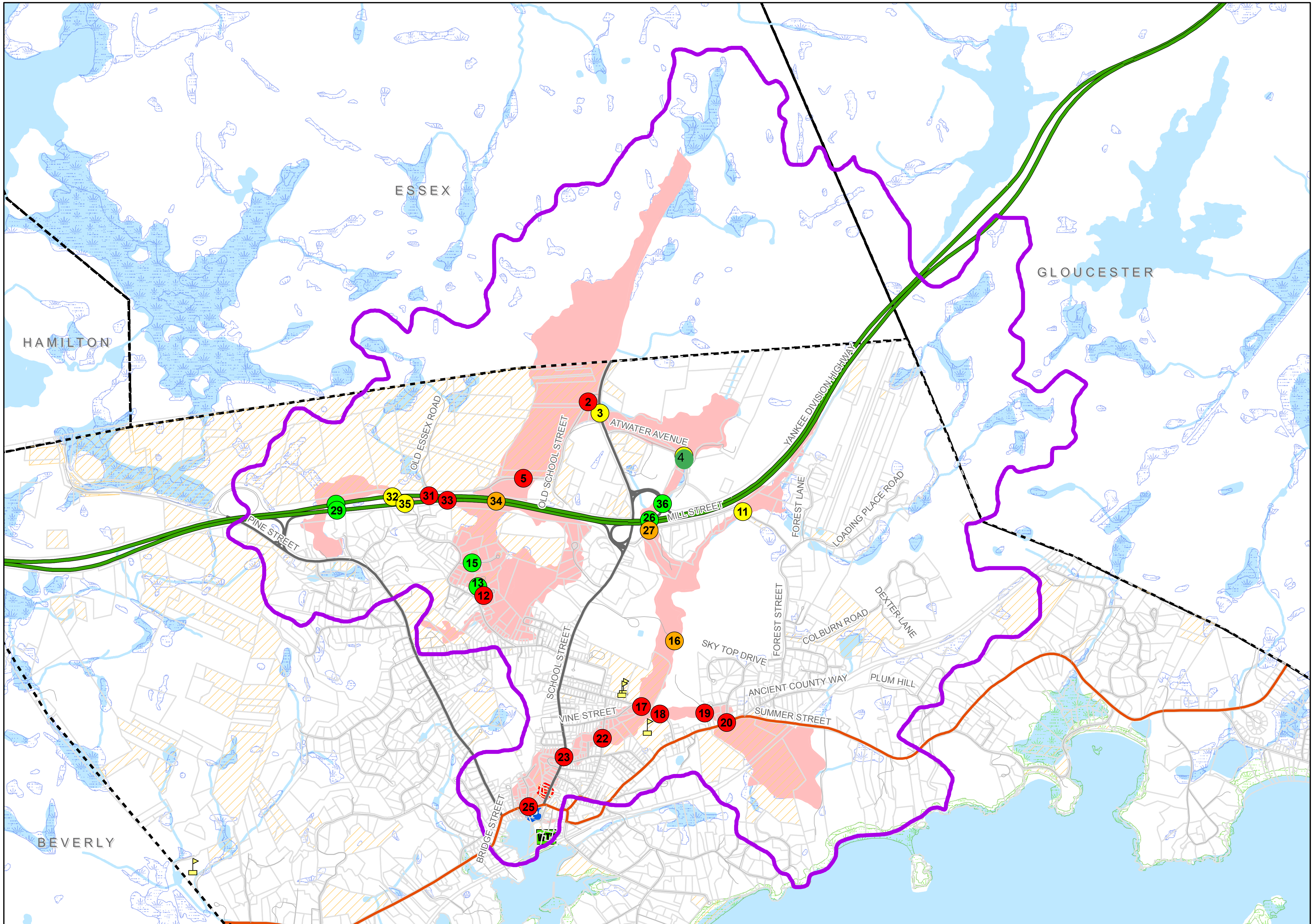
Sawmill Brook Culvert & Green Infrastructure Analysis Manchester-by-the-Sea, Massachusetts

November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\SeaLevelRise_BalancedEnergy2100.mxd

M-1476



2025 STORM FREQUENCY CAUSING OVERTOPPING
Fossil Intensive Energy Use
Storm Surge or Sea Level Rise

LEGEND

Storm Frequency Causing Overtopping

- 25 Year storm
- 50 Year Storm
- 100 Year Storm
- >100 Year Storm
- Sawmill Brook Watershed
- Town Owned Property
- Model Output
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

N

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

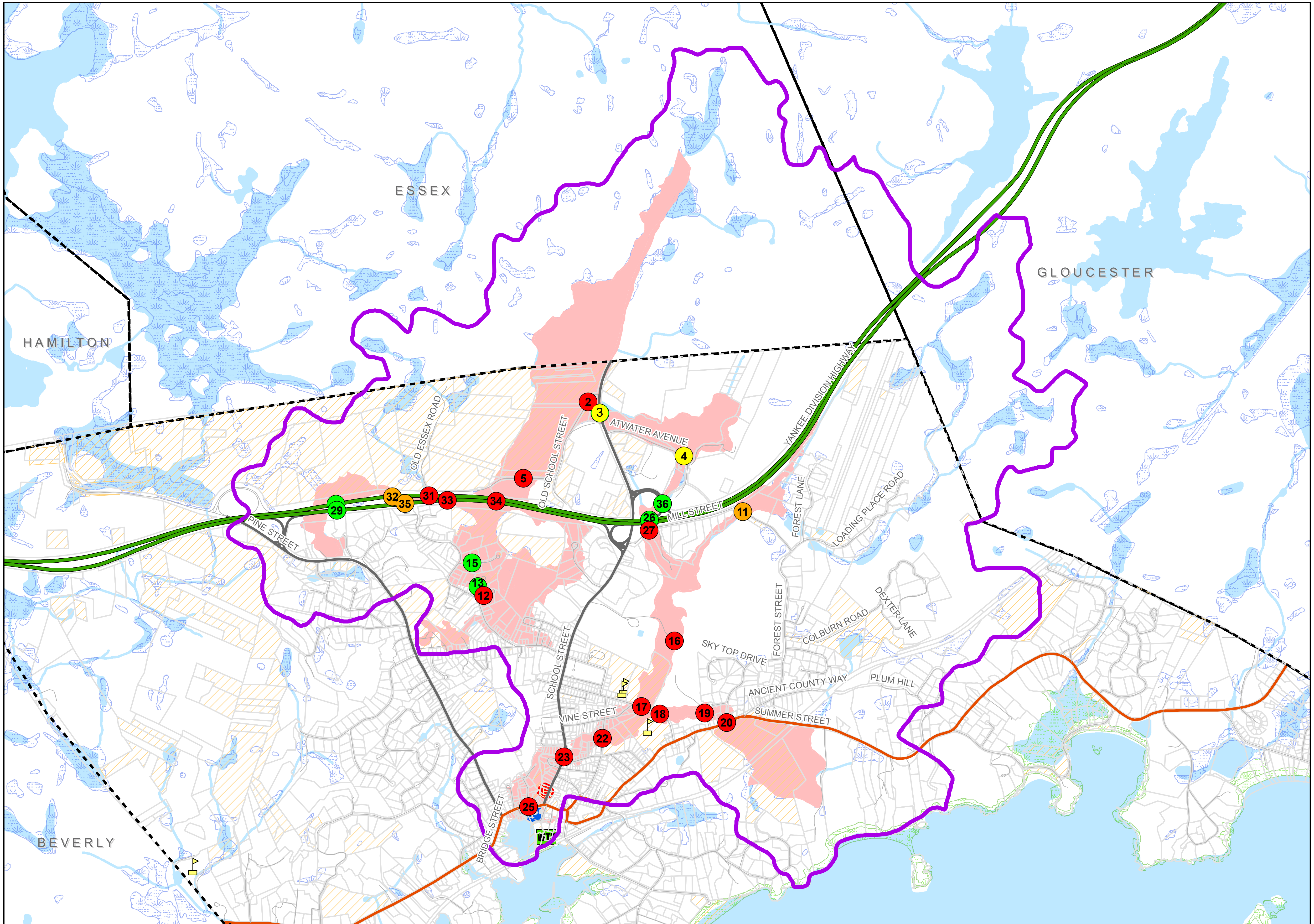
Figure 9A

Sawmill Brook Culvert & Green Infrastructure Analysis
Manchester-by-the-Sea, Massachusetts
November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\StormSurge_FossilIntensive_2025.mxd

M-1476



2050 STORM FREQUENCY CAUSING OVERTOPPING
Fossil Intensive Energy Use
Storm Surge or Sea Level Rise

LEGEND

Storm Frequency Causing Overtopping

- 25 Year Storm
- 50 Year Storm
- 100 Year Storm
- >100 Year Storm
- Sawmill Brook Watershed
- Town Owned Property
- Model Output
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

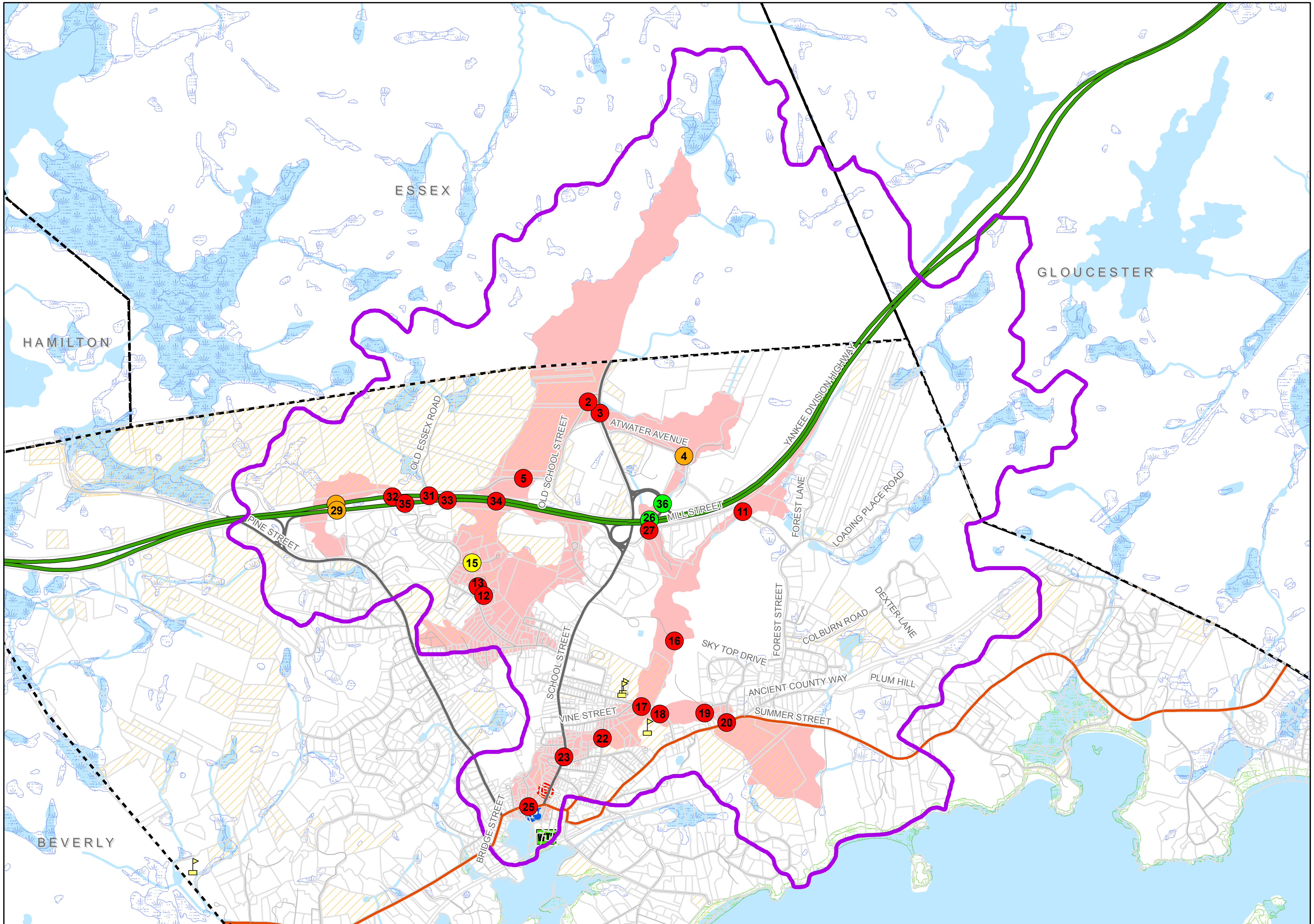
Figure 9B

Sawmill Brook Culvert & Green Infrastructure Analysis
Manchester-by-the-Sea, Massachusetts
November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\StormSurge_FossilIntensive_2050.mxd

M-1476



2100 STORM FREQUENCY CAUSING OVERTOPPING
Fossil Intensive Energy Use
Storm Surge or Sea Level Rise

LEGEND

Storm Frequency Causing Overtopping

- 25 Year Storm
- 50 Year Storm
- 100 Year Storm
- >100 Year Storm
- Sawmill Brook Watershed
- Town Owned Property
- Sea Level Rise Fossil Intensive
- Inland Wetlands
- Coastal Wetlands
- Waterbodies

LOCUS MAP

0 875 1,750
Feet
1:21,000

NOTES

Data sources: Town of Manchester-by-the-Sea, Office of Geographic and EnvironmentalInformation (MassGIS), Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Figure 9C

Sawmill Brook Culvert & Green Infrastructure Analysis
Manchester-by-the-Sea, Massachusetts
November 2015

Tighe&Bond
Consulting Engineers
Environmental Specialists

Path: G:\GIS\MA\ManchesterMA\avproj\SeaLevelRise_FossilIntensive2100.mxd

M-1476