Hydraulic Modeling and Culvert Size Analysis, West Falmouth Harbor, West Falmouth, MA

Prepared For:
Cape Cod Conservation District
270 Communications Way, Unit 1-H
Hyannis, MA 02601

Prepared By:
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August 2015

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List of Acronyms

CCCD	Cape Cod Conservation District
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
Ft	Feet
LiDAR	Light Detection and Ranging
LNB	Little Neck Bay
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MR	Mean Tide Range
MTL	Mean Tide Level
NAVD88	North American Vertical Datum of 1988
NOAA	National Ocean and Atmospheric Administration
NRCS	Natural Resource Conservation Service
OP	Oyster Pond
QAPP	Quality Assurance Project Plan
RFP	Request for Proposals
RMSE	Root Mean Squared Error
RTK	Real Time Kinematic
SB	Shrub Bog
SMS	Surface Water Modeling System
USGS	United States Geological Survey
WFH	West Falmouth Harbor
WSE	Water Surface Elevation

1.0 INTRODUCTION

The Cape Cod Conservation District (CCCD) is currently conducting a study to determine the feasibility of restoring tidal exchange (tidal prism) to two tidally-restricted embayments in the West Falmouth Harbor watershed. Information is required to inform culvert replacement designs necessary for restoring estuarine ecosystems, including salt marsh and tidal flat. Woods Hole Group, Inc. was contracted by the CCCD to conduct a culvert sizing analysis using a hydrodynamic analytical model. The work was completed in accordance with the CCCD *Request for Proposals Hydraulic/Hydrodynamic Modeling and Culvert Sizing Analysis*, the CCCD Quality Assurance Project Plan for West Falmouth Harbor Restoration Feasibility Assessment (May 2014), and the Woods Hole Group, Inc. *Quality Assurance Project Plan Addendum for Hydraulic/Hydrodynamic Modeling and Culvert Size Analysis* (May 2015). This effort is being funded through the Massachusetts Department of Environmental Protection Water Quality Planning Grant 604(b) Program.

West Falmouth Harbor (WFH) is an approximately 180 acre sheltered embayment connected to Buzzard's Bay in West Falmouth, MA. In the WFH area, there are two distinct embayments, Oyster Pond and Little Neck Bay, connected to the harbor via culverts. Oyster Pond is hydraulically connected to Harbor Head by a 3.8 foot diameter culvert under the Shining Sea Bikeway. Little Neck Bay is hydraulically connected to WFH by a 1 foot diameter culvert under Chapoquoit Road. The upper area of Little Neck Bay is separated into an additional unnamed embayment, referred to as Shrub Bog, connected to Little Neck Bay by a 0.5 foot culvert under Little Neck Bars Road (Figure 1-1). The presence of undersized culverts combined with shoaling restricts tidal exchange between each embayment and West Falmouth Harbor, resulting in degraded habitat for shellfish and finfish, and reduced food web support to West Falmouth Harbor.

The modeling and analysis was conducted to determine the optimal size culverts for improving tidal flushing to enhance water quality and habitat for the Oyster Pond and Little Neck Bay systems. For the Little Neck Bay/Shrub Bog system, the amount of desired tidal flushing restoration is balanced by the increased potential flooding risk during storm events to the surrounding properties as specified in the CCCD *Request for Proposals (RFP) Hydraulic/Hydrodynamic Modeling and Culvert Size Analysis, West Falmouth Harbor, West Falmouth, MA (2015)*. Furthermore, Shrub Bog has a diverse freshwater ericaceous community that could be adversely affected by increased tidal (saltwater) influences. As specified in the RFP (CCCD, 2015), tidal restoration at Oyster Pond is not confined by any low-lying structures or properties.

Storm response through the culvert in each embayment is limited by the crest elevation of the roadways/pathways separating them from West Falmouth Harbor (Table 1-1). Storms producing surge levels greater than the respective roadway elevations (Chapoquoit Road for Little Neck Bay and Shrub Bog, Little Neck Bars Road for Shrub Bog, and Shining Sea Bikeway for Oyster Pond) will overtop the roads and inundate the upstream embayments. For instance, FEMA defines the 100-year storm surge elevation in West Falmouth Harbor as 13.1 ft NAVD88, which is well above the elevation of the roadway over the culverts and renders flow through the culverts inconsequential during severe storms; however, the culverts will provide drainage following the storm. Any modification in culvert sizing, especially at Little Neck Bay, should be conscious of flood protection and drainage capacity following storms.

Table 1-1. Roadway elevations at each embayment.

Roadway	Embayment	Road Elevation (ft-NAVD88)
Chapoquoit Road	Little Neck Bay	5.92
Little Neck Bars Road	Shrub Bog	3.11
Shining Sea Bikeway	Oyster Pond	6.21

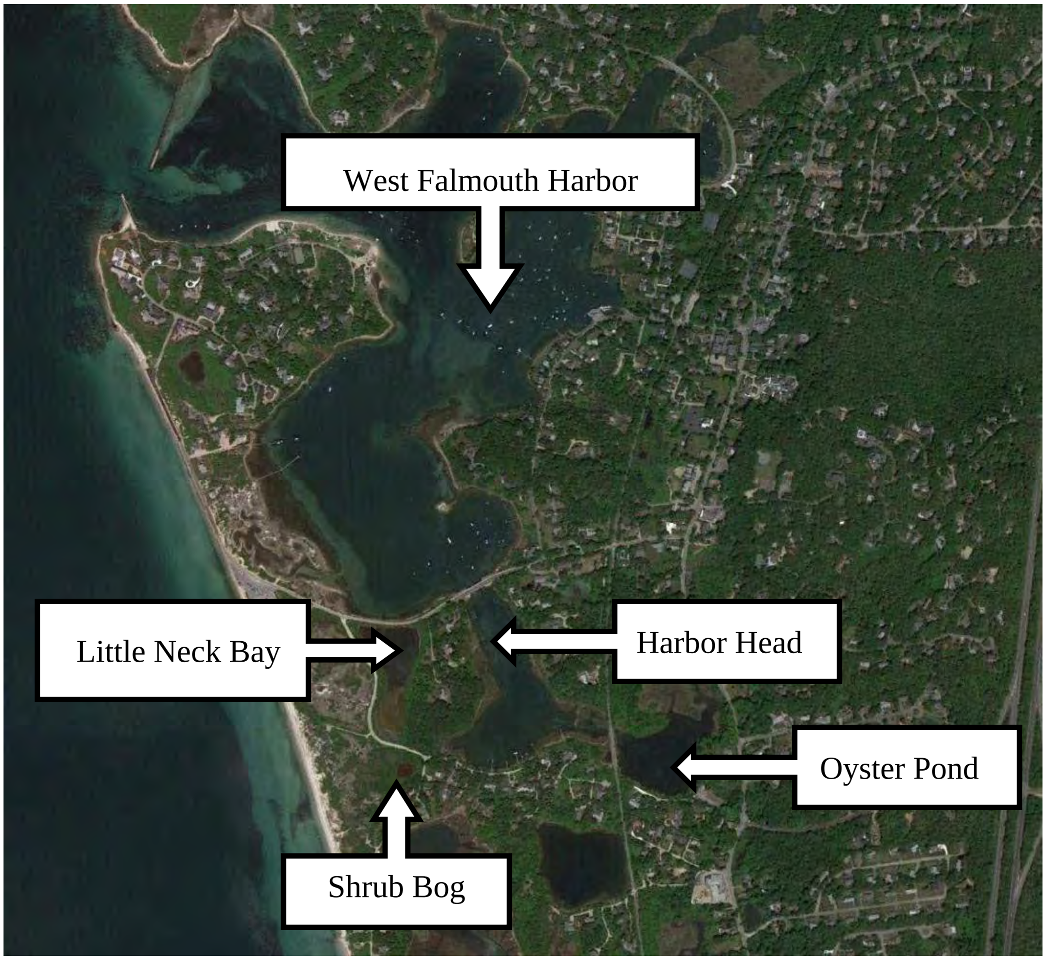

Figure 1-1. Location map of the study area.

This report is divided into the following sections:

1. Introduction
2. Model description and calibration. This section describes the model theory and design variables for each system.
3. Existing conditions in Little Neck Bay and Oyster Pond. This section describes application of the calibrated model for both normal and storm tides at each embayment under existing conditions to provide a baseline for alternatives analysis.
4. Design alternatives in each embayment. In this section, increased culvert sizes and variations in invert elevations are analyzed for Little Neck Bay/Shrub Bog. Effects of increasing the culvert size, with and without the shoals upstream and downstream of the culvert in Oyster Pond, also are investigated.
5. Summary of results and recommendations. This section summarizes results of the alternatives analysis with recommendations.

2.0 MODEL DEVELOPMENT

This section describes the technical approach, model configuration, calibration, and validation for the analytical models used to assess the existing Oyster Pond and Little Neck Bay systems.

2.1 TECHNICAL APPROACH

The technical approach utilized for both the Little Neck Bay/Shrub Bog and Oyster Pond subsystems involves a numerical procedure for calculating the tidal response in a marsh connected to a tidally influenced estuary (West Falmouth Harbor) by a full or partially full flowing culvert. A brief summary of the model background, theory, and assumptions are provided herein, but for a complete background and details on the model the reader is referred to the Woods Hole Group, Inc. May 12, 2015 Quality Assurance Project Plan (QAPP) Addendum. The assumptions are that the sea level in the marsh is independent of position, and that the flow through the culvert is described by a standard head-loss relationship, which depends on the culvert geometry, material roughness, and depth of flow. For Little Neck Bay, the flow control structure is either a partially closed culvert due to sediment aggradation at the Little Neck Bay invert representing existing conditions, or a new concrete pipe culvert (alternative conditions). For Oyster Pond, the flow control structure is either a culvert and tidal shoals, both upstream and downstream of the culvert, that act as weirs representing existing conditions, or a culvert with the shoals removed (alternative conditions). The head-loss vs. discharge relationship is assumed to be quadratic for a circular pipe.

Given the assumption of a horizontal sea surface within the marsh, the conservation-of-mass equation for the water in the marsh is

$$A(h_{marsh})\frac{dh_{marsh}}{dt} = Q_{culvert} + Q_{rain} \tag{1}$$

$$Q_{culvert} = -au \tag{2}$$

where t is time; $h_{marsh}(t)$ is the elevation of the water level in the marsh (NAVD 88 feet); A is the surface area of the marsh, which is prescribed as a function of h_{marsh} through the measured hypsometric relationship; $a(t)$ is the cross-sectional area of flow in the culvert; and $u(t)$ is the average flow velocity in the culvert. Velocity is defined as positive when flowing from the marsh toward the harbor (i.e. downstream). Q_{rain} is the volumetric flow rate into the marsh resulting from rainfall.

For circular pipe culverts, it is straightforward to calculate the relevant geometric parameters required to determine the velocity (cross-sectional area, A, the wetted perimeter, P, and hydraulic radius $(R_c = A/P)$.

Using Manning's equation to determine the flow rate as a function of the hydraulic radius and the slope of the energy grade line (S)

$$Q_{culvert} = \frac{1.45}{n} A{R_c}^{2/3} S^{1/2}, \tag{4}$$

where S is calculated as $$S = \frac{h_2 - h_1}{L_{culvert}}, \tag{5}$$

L_{culvert}

$L_{culvert}$ is the length of the culvert, h_1 and h_2 are the upstream and downstream head, and n is the Manning's friction factor determined empirically and based upon the culvert material.

The solution of (4) for the velocity (V) is the volumetric flow rate Q divided by the cross sectional area (A).

In addition to culvert flow, Oyster Pond, especially during ebb tides, is subject to weir flow over the tidal shoals. Weir flow is calculated as:

$$Q_{weir} = k_t C L_{weir} H^{2/3} \tag{5}$$

Where k_t is coefficient to account for fully submerged flow, if applicable, L_{weir} is the width of the weir, H is the depth of flow relative to the weir height, and C is the weir discharge coefficient based on the gravitational acceleration constant *(g)* calculated as:

$$C = \frac{2}{3}^{3/2} g^{1/2} \tag{6}$$

2.2 MODEL CONFIGURATION

This section presents site specific data for the basins in the study area and describes how these data are used to configure the analytical culvert models. Specifically, the model requires topographic/bathymetric data to define the model geometry, and tidal data to provide model boundary conditions and calibration data.

2.2.1 Model geometry

The technical approach for the analytical model requires a prescribed relationship between the inundated surface area of the pond and the water surface elevation. This relationship can be determined from the detailed topographic/bathymetric data and described by a hypsometric curve. The hypsometric curve describes the relationship between surface area and elevation. Site specific topographic and bathymetric data for the embayments was collected by the Cape Cod Conservation District (CCCD) and Natural Resource Conservation Service (NRCS). The surrounding topography and shallow bathymetry were also supplemented with LIDAR data collected by the United States Geological Survey (USGS) in 2011. Figures 2-1 and 2-2 show the color contour data of the combined topographic and bathymetric data for Oyster Pond and Little Neck Bay systems. Although the data do not provide complete coverage of the bathymetric elevations for either embayment, the data available are detailed enough to provide a reasonable estimate of the system.

Figure 2-1. RTK survey data provided by Cape Cod Conservation District and Natural Resource Conservation Service.

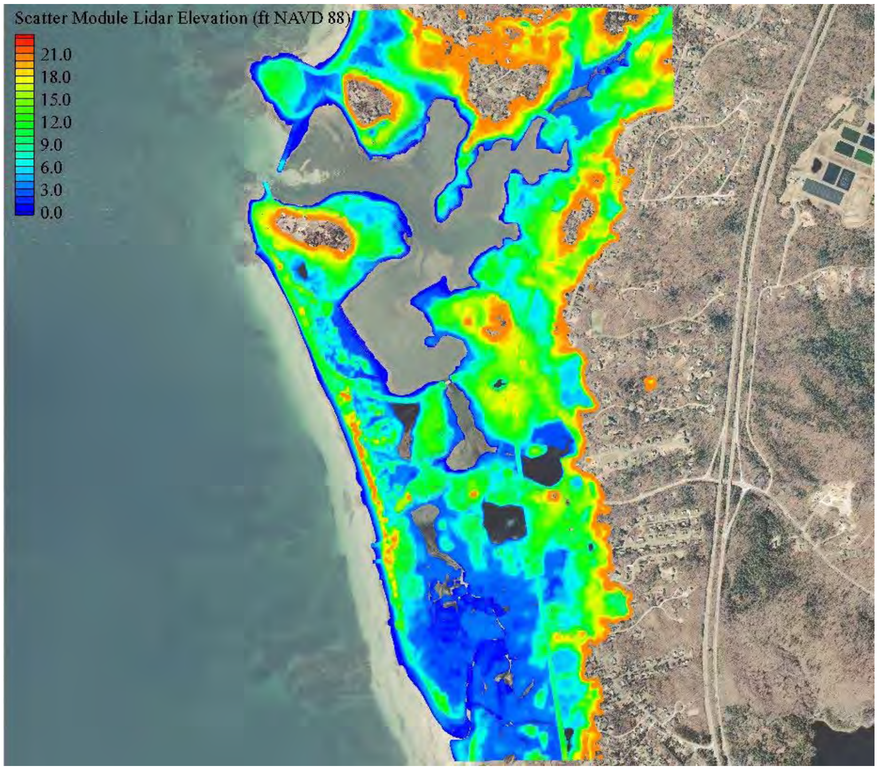

Figure 2-2. LiDAR data coverage of West Falmouth Harbor.

Little Neck Bay and Shrub Bog

The bathymetric and LIDAR data were combined to generate distinct hypsometric curves for Little Neck Bay and Shrub Bog. The hypsometric curve allows for the area of the basin inundation to be determined for a given water surface elevation in the model. Basin hypsometry for Little Neck Bay was used to develop a mesh grid for the system (Figure 2-3). Chapoquoit Road was used to define the northernmost extent of the grid, while Little Neck Bars Road was used as the dividing boundary between Little Neck Bay and Shrub Bog. The mesh grid was then converted into a hypsometric curve (Figure 2-4) defining the relationship between the elevation in the basin and the surface area of the basin. Culvert inverts and dimensions were provided by CCCD and are listed in Table 2-1.

Table 2-1. Culvert specifications For West Falmouth Harbor to Little Neck Bay.

Culvert Dimensions Connecting West Falmouth Harbor to Little Neck Bay	
Invert in WFH	-1.07 ft NAVD88
Invert in LNB	0.51 ft NAVD88
Diameter	1 ft
Length	38 ft

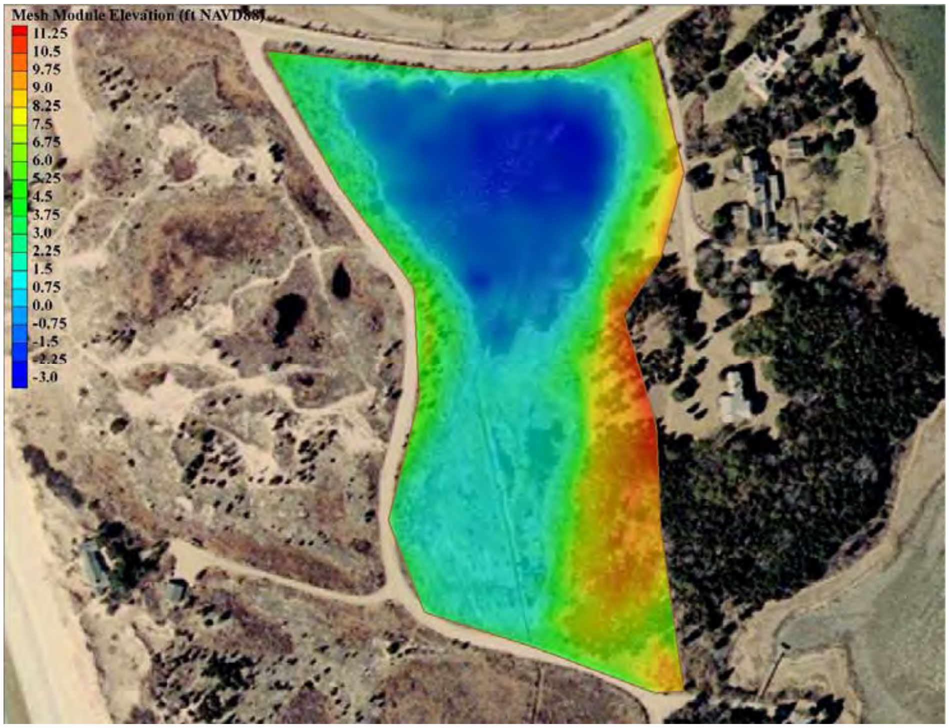

Figure 2-3. Grid coverage used to define the hypsometry for Little Neck Bay.

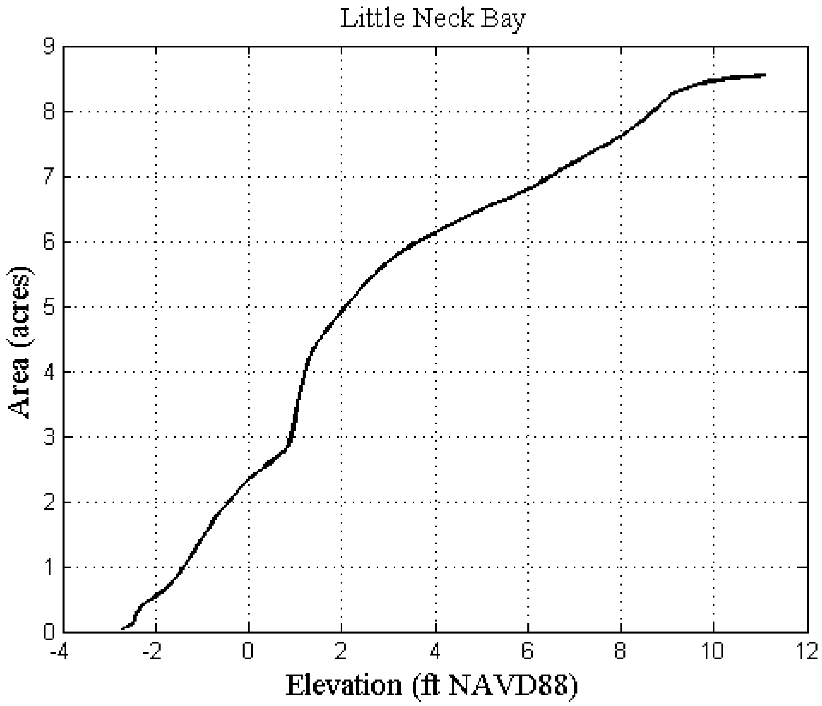

Figure 2-4. Hypsometric curve of Little Neck Bay.

Using the same techniques, a grid (Figure 2-5) and hypsometric curve (Figure 2-6) were generated for Shrub Bog. Although the tidal exchange in Shrub Bog was not expected to be impacted significantly for the design alternatives, the water surface elevation (WSE) in Shrub Bog is a key input to the model for drainage and, due to the low elevation of Little Neck Bars Road, Shrub Bog provides storage during storm events. Culvert specifications connecting Shrub Bog to Little Neck Bay are shown in Table 2-2.

Table 2-2. Culvert specifications for Little Neck Bay to Shrub Bog.

Culvert Dimensions Connecting Little Neck Bay to Shrub Bog		
Invert in LNB	0.48	ft NAVD88
Invert in SB	0.72	ft NAVD88
Diameter	0.5	ft
Length	40	ft

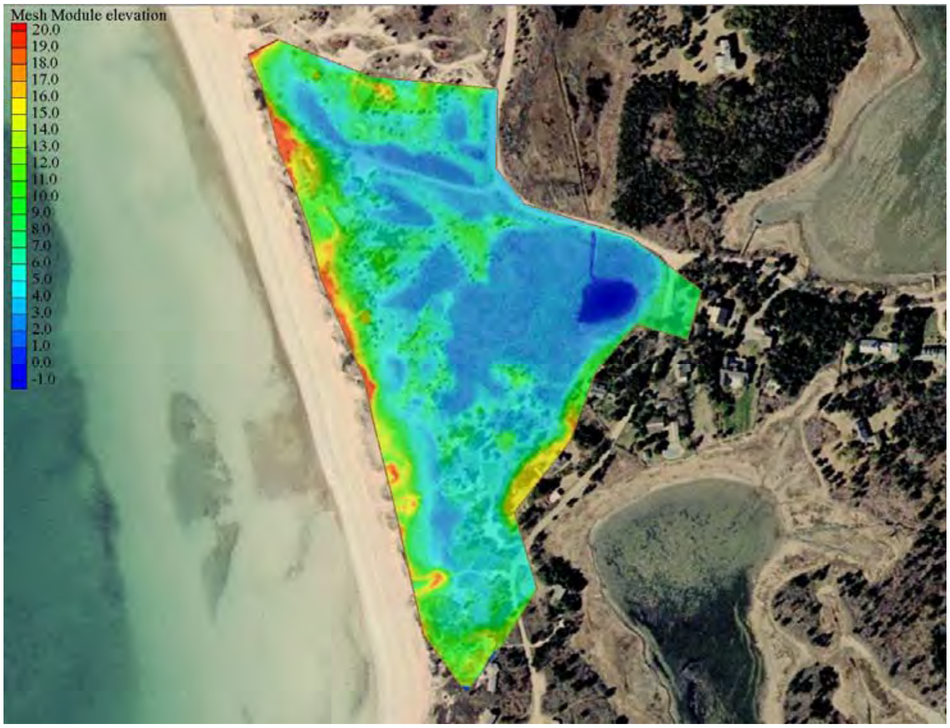

Figure 2-5. **Grid coverage used to define the hypsometry for Shrub Bog.**

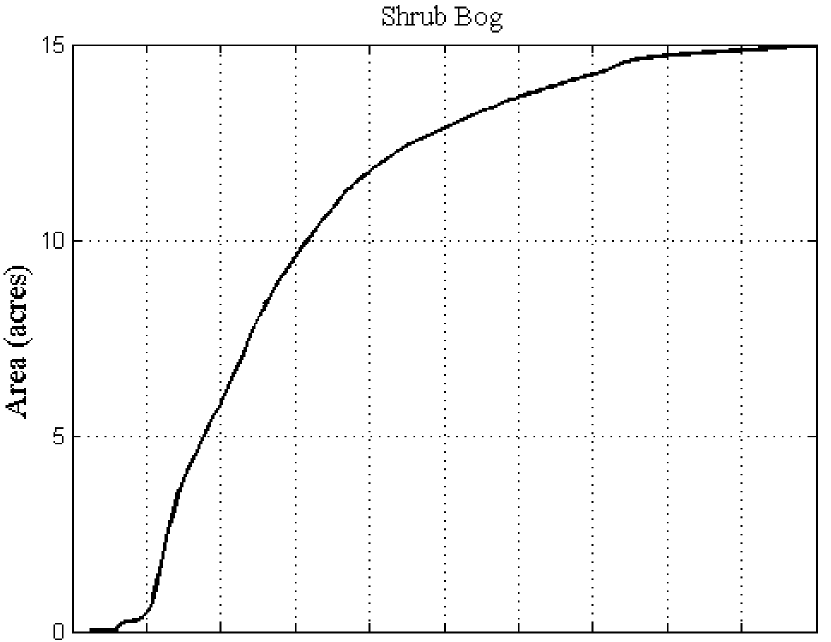

Figure 2-6. **Hypsometric curve of Shrub Bog.**

Oyster Pond and Vicinity

The bathymetric and LIDAR data were combined to generate distinct hypsometric curves for Oyster Pond and approach channels. Analysis of the tidal data provided by CCCD indicated the channel between Harbor Head and the Oyster Pond culvert outlet significantly damped the tidal response during ebb events. A detailed discussion of the tidal data is provided in the following section. To accurately model the tidal response in the Oyster Pond, two separate basins were developed for the hypsometric model. The lower basin, referred to as Tidal Creek, used a small grid (Figure 2-7) reflected in smaller total area in the hypsometric curve (Figure 2-8). The second basin, Oyster Pond, used a larger grid (Figure 2-9) and is reflected in the larger area in the hypsometric curve (Figure 2-10). Culvert specifications connecting Oyster Pond to the tidal creek under the Shining Sea Bikeway are listed in Table 2-3.

Table 2-3. Culvert specifications for Oyster Pond to the tidal creek section of Harbor Head.

Culvert Dimensions Connecting Harbor Head to Oyster Pond		
Invert in tidal creek	-1.78	ft NAVD88
Invert in oyster Pond	-1.71	ft NAVD88
Diameter	3.8	ft
Length	30	ft

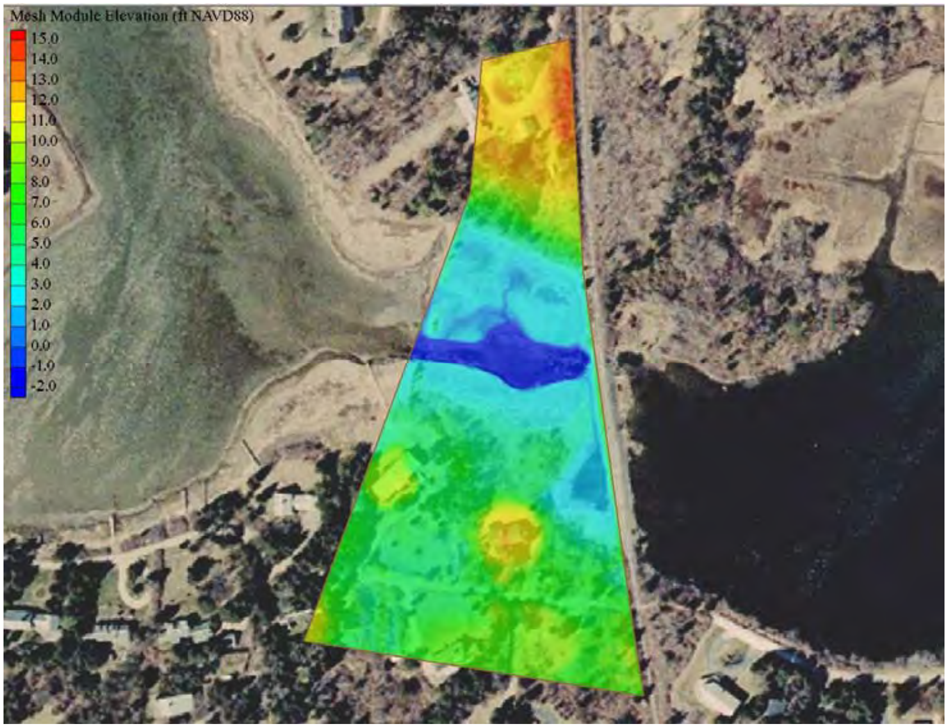

Figure 2-7. Grid coverage used to define the hypsometry of the tidal creek between the Oyster Pond culvert and Harbor Head.

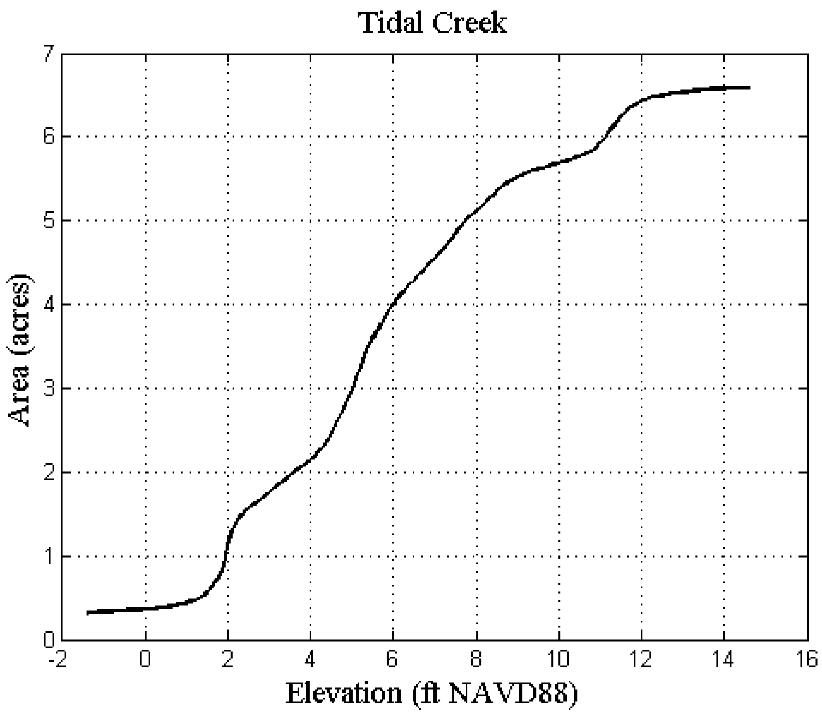

Figure 2-8. Hypsometric curve of the tidal creek area.

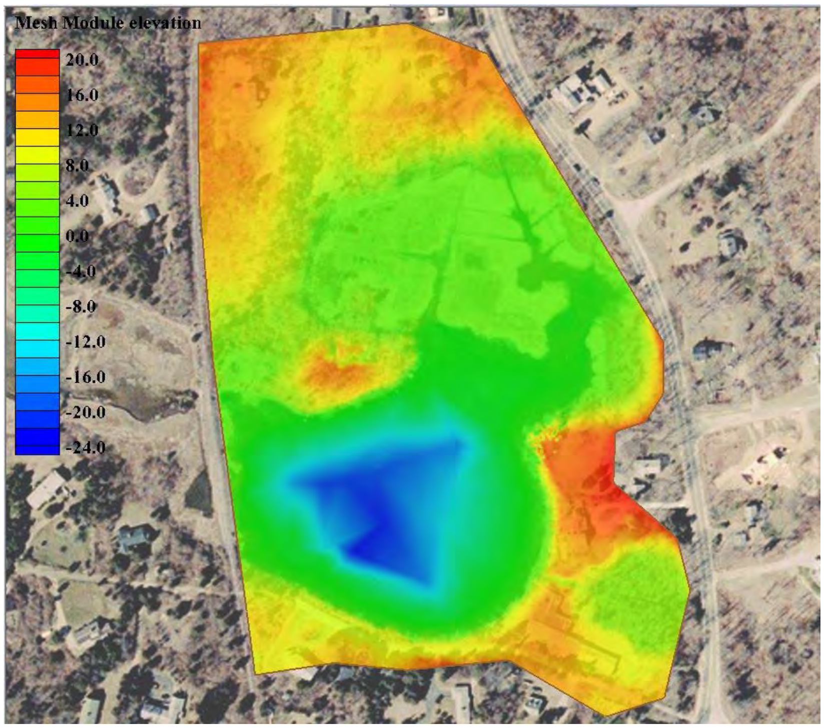

Figure 2-9. Grid coverage used to define the hypsometry of Oyster Pond.

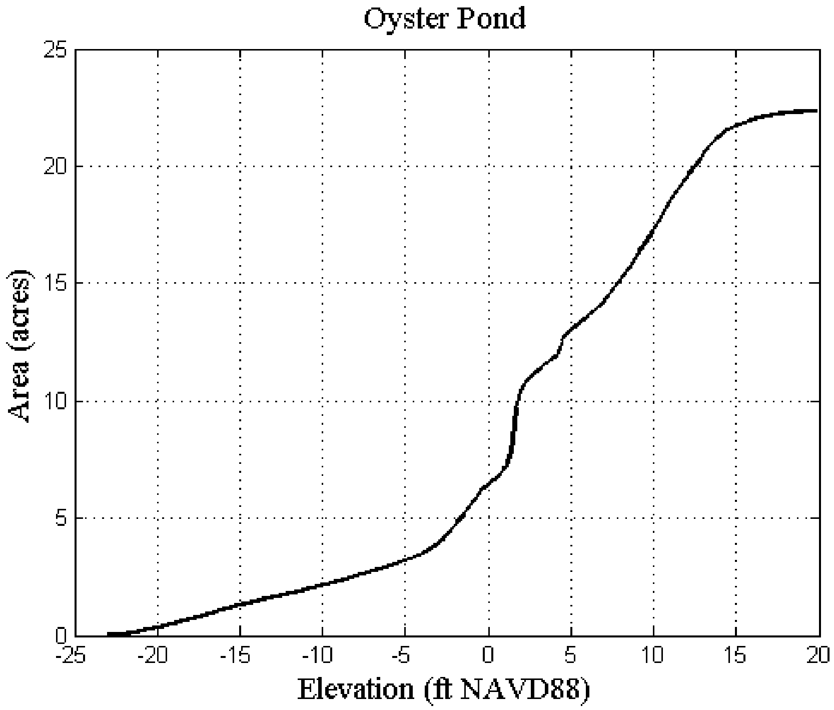

Figure 2-10. Hypsometric curve of Oyster Pond.

2.2.2 Boundary Conditions

The analytical model computes a unique solution for the water surface elevation within each basin based on the conditions specified on the model domain boundary. The primary boundary condition is the water surface elevation (WSE) at West Falmouth Harbor, the seaward boundary of the model. The boundary conditions were specified using WSE data collected by the CCCD project partners from June 4, 2014 to July 22, 2014 (47 day deployment) within West Falmouth Harbor, Little Neck Bay, Shrub Bog, and Oyster Pond and its downstream channel. The complete time series of water surface elevation (WSE) for the Little Neck Bay and Oyster Pond systems are shown in Figure 2-11, where the vertical axis represents the WSE in feet NAVD88 and the horizontal axis represents time in 2014. The scale of Figure 2-11 is not intended to reveal short-term details; rather, it reveals the relative tidal attenuation and relative WSE within each system. Typical for the region, there is a diurnal inequality within West Falmouth Harbor, resulting in a higher high tide and a lower high tide each day. There also is the expected two-week modulation of the tide within West Falmouth Harbor, producing spring and neap tides.

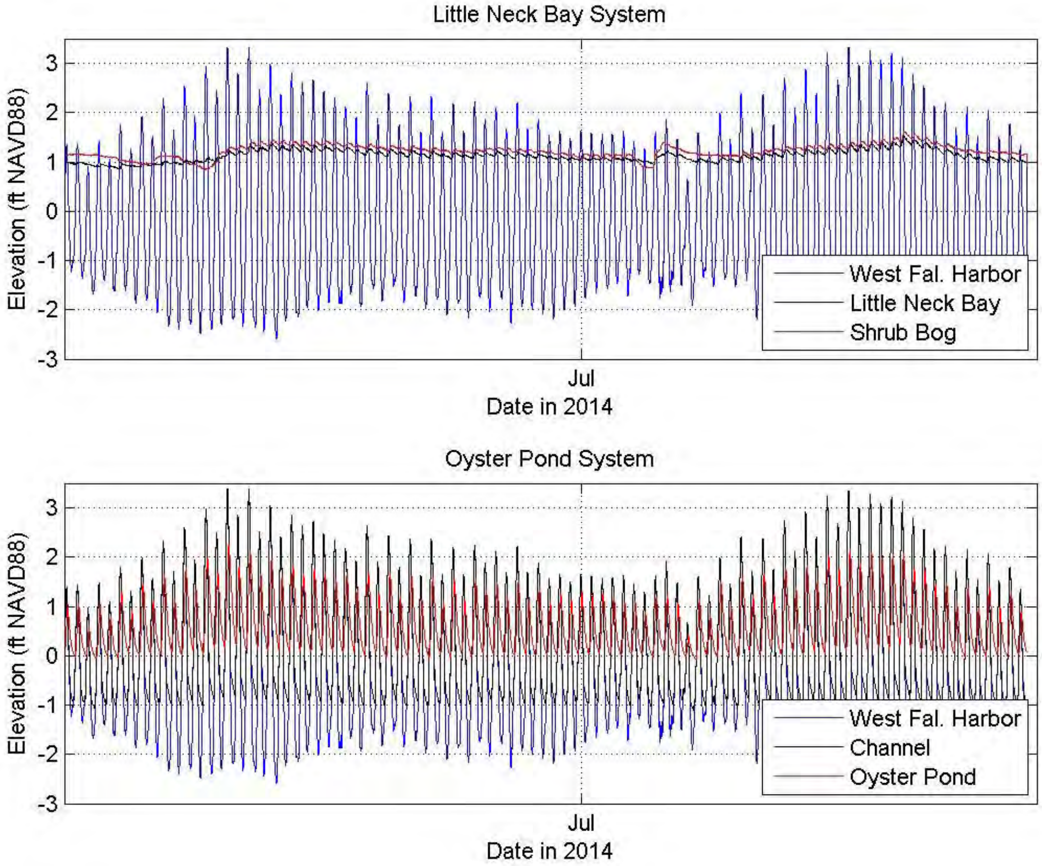

Figure 2-11. Time series of water surface elevation in West Falmouth Harbor.

Table 2-4 shows the tide metrics including mean high water (MHW), mean low water (MLW), mean tide level (MTL), the mean tidal range (MR), etc. for the collected tide data. These tidal metrics are based only on the observed water levels for the data collected in 2014, and are not directly comparable to the long-term tidal benchmarks (e.g., MHW, MLW, etc.) established by NOAA over a 19 year tidal epoch. Due to the short time frame of the observations, the tidal metrics are more easily influenced by non-tidal (residual) processes (winds, pressures, rainfall, etc.). However, the observed data indicates that West Falmouth Harbor experiences a full semidiurnal tidal range of 3.85 feet with a MTL of 0 ft NAVD88, which is essentially mean sea level. The tide range for Chapoquoit Point in Buzzards Bay is 3.82 ft according to NOAA Station 8447685, which means that there is insignificant attenuation of the tide between Buzzards Bay and the location of the CCCD tide gauge deployed in West Falmouth Harbor. The WSE data collected in West Falmouth Harbor by the CCCD project partners provides the tidal forcing at the seaward boundary for both model(s), and drives the tidal exchange in each of the smaller basins.

Table 2-4. Tide metrics (ft, NAVD88) and statistics for the Little Neck Bay and Shrub Bog embayments based on observed water levels.

Tidal Metrics	West Falmouth Harbor (ft, NAVD88)	Little Neck Bay System		Oyster Pond System	
		Little Neck Bay (ft, NAVD88)	Shrub Bog (ft, NAVD88)	Tidal Creek (ft, NAVD88)	Oyster Pond (ft, NAVD88)
Mean Higher-High Water	2.17	N/A	N/A	2.35	1.60
Mean High Water	1.93	N/A	N/A	2.09	1.42
Mean Tide Level	0.00	1.12	1.22	0.57	0.74
Mean Low Water	-1.92	N/A	N/A	-0.94	0.06
Mean Lower-Low Water	-2.03	N/A	N/A	-0.98	0.04
Tidal Maximum	3.33	1.53	1.63	3.39	2.27
Tidal Minimum	-2.75	0.86	0.85	-1.10	-0.07
Mean Range	3.85	1.13[1]	1.18[1]	3.03	1.36

1. Mean water surface elevation including large non-tidal effects.

Figure 2-11 (bottom panel) indicates there is tidal attenuation occurring within the Oyster Pond system. Table 2-4 also indicates that there is significant attenuation of the tide within the Oyster Pond system as there is a 65% reduction in the mean tide range from West Falmouth Harbor. Additionally, the tidal creek accounts for 44% of this tidal attenuation while Harbor Head accounts for 21% of the attenuation; therefore, the tidal creek is an important tidal dampener within this system. Of importance, mean high water and mean low water are 0.67 feet greater and 1 foot lower, respectively, in the tidal creek than in Oyster Pond. This indicates that the culvert is restrictive both to ebb and flood tidal flow since more tidal range could be restored to the pond on the flood tide, and the pond is not fully draining on the ebb tide.

Figure 2-11 (top panel) indicates the tide is drastically attenuated between West Falmouth Harbor and Little Neck Bay, and subsequently Shrub Bog. The maximum tidal range within the Little Neck Bay system was less than a foot according Table 2-4, and the tide range from West Falmouth Harbor was attenuated by over 87%. Therefore, the culvert is extremely restrictive to point that Little Neck and Bay Shrub Bog exhibit water level patterns that are not consistent with a primarily tidally forced system. As a result, tidal metrics were not calculated for the Little Neck Bay and Shrub Bog system since they are not based on tidally driven processes. Instead, only the minimum, maximum and mean water levels are provided. Rainfall, percolation into the surrounding flats, and evapotranspiration are likely causes of these water surface fluctuations for the Little Neck Bay system. The bottom panel in Figure 2-12 below presents the rainfall record at Hyannis Airport over the tide gauge deployment period for the Oyster Pond (top panel) and Little Neck Bay (middle panel) systems. From this figure it is evident that rainfall causes significant spikes in the mean tide level within both Little Neck Bay and Shrub Bog, indicating that rainfall has a large influence on the Little Neck Bay system. The dashed window shown in Figure 2-12 indicates a large rainfall event, over 1.8-in and illustrates the impact on the Little Neck Bay system. The mean water surface elevation in Little Neck Bay increased rapidly from 0.9 to 1.4 ft NAVD88 during this event. This same large rainfall event is not evident in the tide record at Oyster Pond indicating the Oyster Pond system has less freshwater input and/or much better drainage characteristics than Little Neck Bay System, which needed 4.5 days for water levels to return to normal. These data sets were not used as boundary conditions in the model, but were instead used to provide insight into the system response to tidal and precipitation forcing, calibration window selection, and as a comparison with modeled water levels.

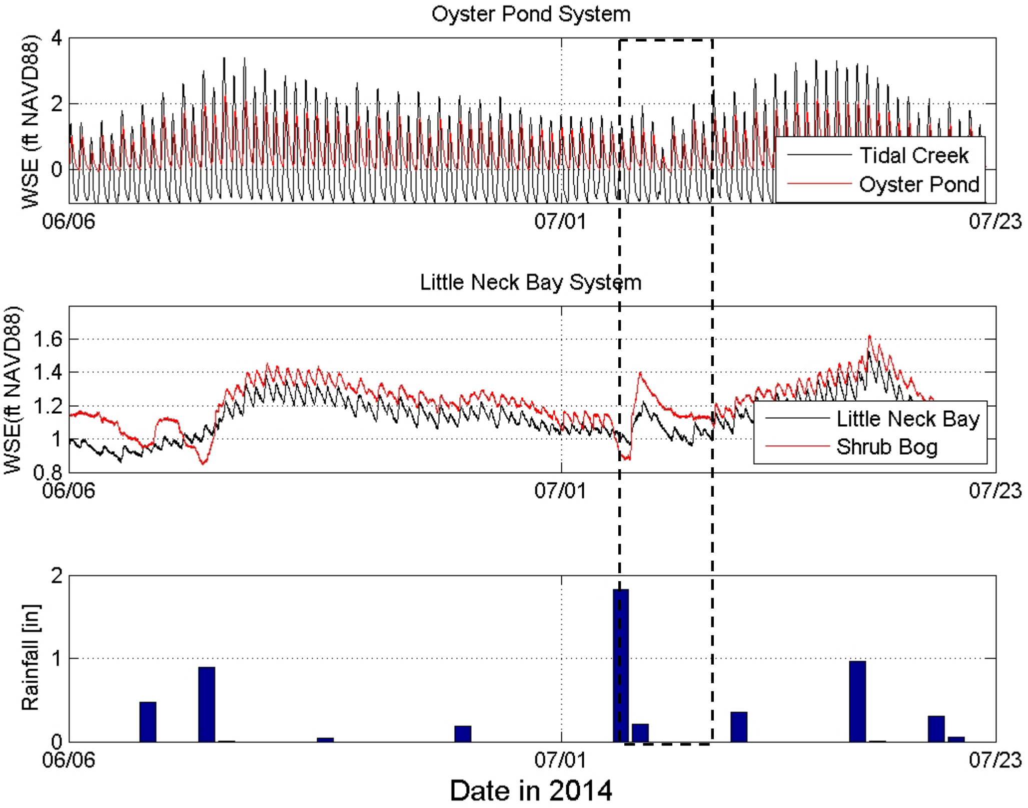

Figure 2-12. Time series of water surface elevation in Little Neck Bay and Shrub Bog.

2.3 MODEL CALIBRATION

Model calibration is a process by which unknown input model parameters (e.g., frictional coefficients) are adjusted within a reasonable range of values until model results match observations with an acceptable level of error. Calibration parameters include Manning's *n* roughness coefficients, effective culvert length, and seepage from the system for the culvert under model existing conditions. The May 2015 Woods Hole Group, Inc. QAPP Addendum specifies the methods for evaluating model performance. Initially, model performance is qualitatively assessed by visually comparing time series plots of observed and modeled water levels to ensure that the results pass the eye test. Model error is then quantified by computing standard error statistics including the model bias and Root Mean

Square Error (RMSE). Model performance is evaluated on the basis of error statistics, and the U.S. EPA recommends that hydrodynamic variables (i.e. water surface elevation) have relative error less than 30%; however Woods Hole Group internally requires the water surface elevation variable on these projects to be within at least 10% error.

As discussed in the previous section, the tidal forcing from West Falmouth Harbor to the Little Neck Bay system was significantly attenuated, which allowed for rainfall and other non-tidal factors to be detected along with the effects of the tidal response within the Little Neck Bay/Shrub Bog system. Tidal forcing is the primary boundary condition for the model and will have the most influence over the culvert sizing analysis. Therefore, a portion of the water surface elevation time series that showed the least non-tidal factors was chosen for the modeling input. After analyzing Figure 2-12, the time period of 06/20/2014 through 06/27/2014 was selected as the model calibration period since it exhibited the fewest non-tidal residual variations such as rainfall. The same time period was used for both the Little Neck Bay/Shrub Bog model (Figure 2-13) and the Tidal Creek/Oyster Pond Model (Figure 2-14). The horizontal axis presents time (in days) of the model simulation, while the vertical axis presents the water surface elevation (WSE) in the pond relative to NAVD88, feet.

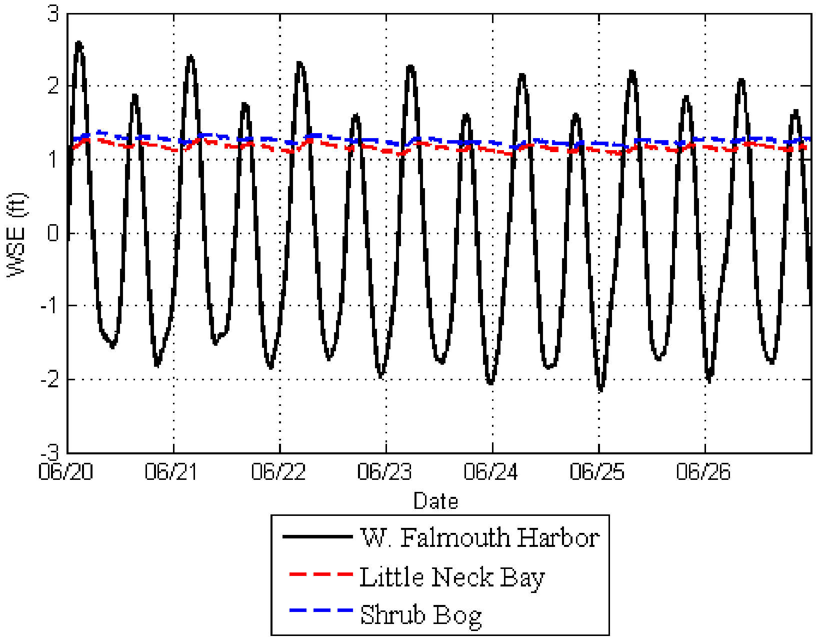

Figure 2-13. Time series of water surface elevations used for model calibration in Little Neck Bay and Shrub Bog.

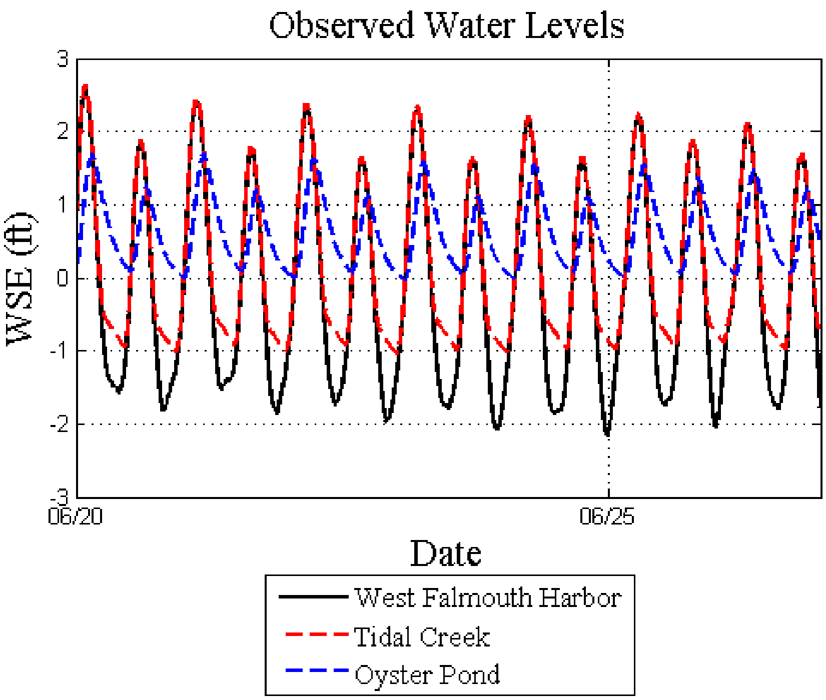

Figure 2-14. Time series of water surface elevations used for model calibration in Tidal Creek and Oyster Pond.

2.3.1 Little Neck Bay and Shrub Bog

For the Little Neck Bay/Shrub Bog culvert model, three unknown input model parameters were varied within reasonable ranges to calibrate the model for each culvert; the Manning's roughness coefficient *(n)* of the existing culvert, effective length, and losses due to seepage into the surrounding flats and evaporation (Q_{leak}). For both culverts and basins, a large number of simulations were conducted with systematically varied values for the model parameters. In Little Neck Bay, a single effective length and variable seepage rate provided a consistent and accurate representation of the tidal response. In Shrub Bog, however, the presence of the channel/mosquito control ditch and large proportion of dry area necessitated a stepped variation in roughness length and seepage rates based on water surface elevation in the basin. The value(s) for the input parameters for Little Neck Bay and Shrub Bog are tabulated in Table 2-5.

Table 2-5. Values of the unknown model input parameters used for the Little Neck Bay and Shrub Bog Culverts.

Input Parameter	Little Neck Bay	Shrub Bog
Effective diameter (ft)	0.69	0.5
Effective Length (ft)	40	40 – 140
Manning's Roughness	0.026	0.019
Seepage Rate (ft^3/sec)	0-0.073	0 – 0.11

The model results and measured observations in Little Neck Bay and Shrub Bog are shown in Figure 2-15 and 2-16. The horizontal axis presents time (in days) of the model simulation, while the vertical axis presents the water surface elevation (WSE) in the pond relative to NAVD88, feet. Standard measures of error were used to quantify the model error, specifically the bias, which indicates whether a model tends to over or under predict values when compared with observations, and root mean squared error (RMSE), which gives insight into how well the model replicates the observations. In Little Neck Bay, during the week long calibration period, the bias was calculated to be 0.001 feet and the RMSE was calculated as 0.02 feet, while in shrub bog the bias was 0.01 feet and the RMSE was 0.02 feet. The calculated percent error for the tidal time series were within the 10% acceptance criteria for both systems. Error statistics for Little Neck Bay and Shrub Bog are found in Table 2-6. Both the Little Neck Bay and Shrub Bog embayments are not tidally driven, with observed mean water level ranges of less than 1/10th of a foot in each embayment. Average highs, lows, water levels and ranges for Little Neck Bay and Shrub Bog are listed in Table 2-7.

$$Bias = \sum \frac{modeled - observed}{number\ of\ observations}$$

$$RMSE = \sqrt{\sum \frac{(modeled - observed)^2}{number\ of\ observations}}$$

$$\%\ error = \frac{tidal\ metric}{MHW_{observed} - MLW_{observed}} x100\%$$

Table 2-6. Error statistics for existing conditions model calibration.

Basin	Bias	RMSE
Little Neck Bay	-0.001	0.02
Shrub Bog	0.01	0.02

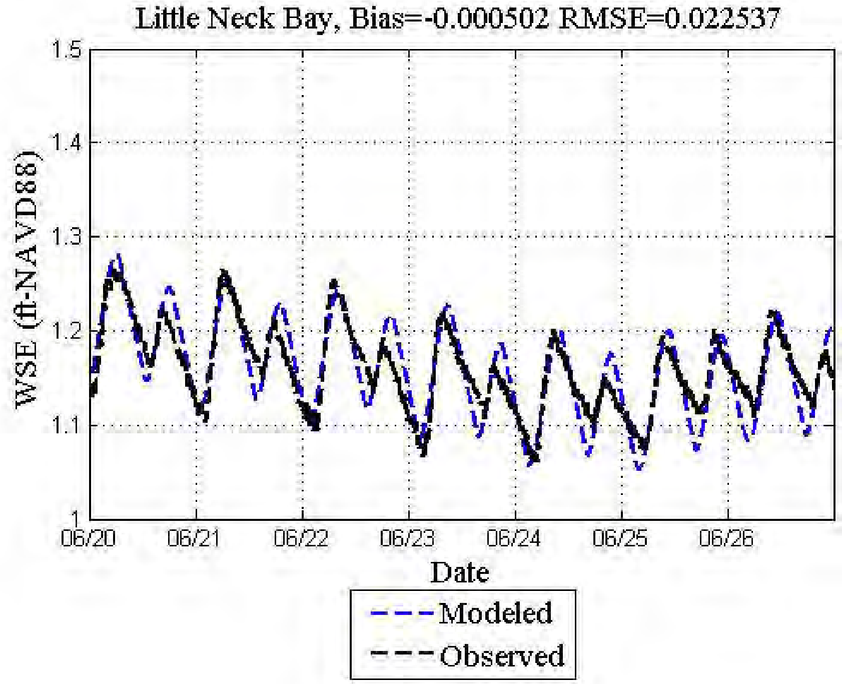

Figure 2-15. **Time series of observed and modeled water levels in Little Neck Bay during calibration.**

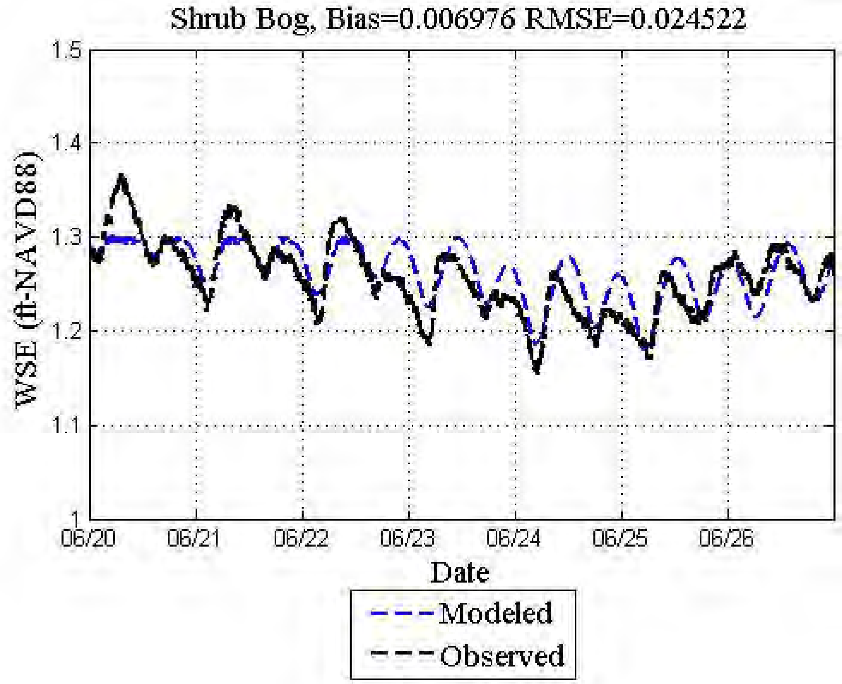

Figure 2-16. **Time series of observed and modeled water levels in Shrub Bog during calibration.**

Table 2-7. Modeled and observed mean high water levels, mean low water levels, mean water levels and mean ranges (ft) in Little Neck Bay and Shrub Bog during the calibration period.

	Little Neck Bay			Shrub Bog		
Metric	**Observed**	**Modeled**	**Difference**	**Observed**	**Modeled**	**Difference**
Unit	ft	ft	ft	ft	ft	ft
MHW	1.19	1.22	0.03	1.27	1.29	0.02
MLW	1.13	1.09	-0.04	1.24	1.22	-0.02
MTL	1.16	1.16	0	1.25	1.25	0
Mean Range	0.06	0.13	0.07	0.03	0.07	0.04

2.3.2 Tidal Creek and Oyster Pond

For the Tidal Creek and Oyster Pond culvert model, in addition to the culvert connecting Tidal creek to Oyster Pond, the presence of the shoals in both bays behave similar to weirs during ebb flows. Due to the weir-like behavior during ebb tides, and behavior as an open channel (Tidal Creek) and round pipe culvert (Oyster Pond) during flood tides, additional parameters included the weir height (z_{weir}) and width (L_{weir}). In Tidal Creek during flood, the unknown model input parameters varied within reasonable ranges to calibrate the model were the Manning's roughness coefficient (n) of the creek and Harbor Head, effective length of the channel, the channel width, while losses due to seepage into the surrounding flats and evaporation (Q_{leak}) were assumed to be negligible. During ebb events, as the water level lowers in the channel, the weir-like behavior begins to dominate, and two parameters were adjusted - the weir height and weir length. In Oyster Pond, during flood, parameters varied were the Manning's roughness coefficient, the culvert width, and culvert effective length, which also included the shoaled section of Oyster pond at the culvert mouth, while during ebb, the weir height and weir width were adjusted within reasonable values. The value(s) of the unknown input parameters for the Tidal creek and Oyster Pond are tabulated in Table 2-8.

Table 2-8. Values of the unknown model input parameters used for the Oyster Pond culvert and Tidal Creek channel.

Input Parameter	Tidal Creek channel	Oyster Pond culvert
Effective channel length (including Harbor Head) (ft)	1,500	150
Effective channel width (ft)	35	3
Manning's Roughness	0.013	0.023
Seepage Rate (ft^3/sec)	0	0
Weir height (ft NAVD88)	-1.0	-0.05
Weir width (ft)	35	20

The model results and measured observations in Tidal Creek and Oyster Pond are shown in Figure 2-17 and 2-18, respectively. The horizontal axis presents time (in days) of the model simulation, while the vertical axis presents the water surface elevation (WSE) in the pond relative to NAVD88, feet. During ebb events, the magnitude of flow rates were compared between the channel and weir in Tidal Creek and the culvert and weir in Oyster Pond, and the limiting flow rate was applied to the model. Standard measures of error were used to quantify the model error, specifically the bias, which indicates whether a model tends to over or under predict values when compared with observations, and root mean squared error (RMSE), lending insight into how well the model replicates the observations. In Tidal Creek, during the week long calibration period, the bias was calculated to be -0.05 feet and the RMSE was calculated as 0.07 feet, while in shrub bog the bias was -0.09 feet and the RMSE was 0.13 feet (Table 2-9). The calculation of the percent error for the mean tide range were within the 10% acceptance criteria from the May 2015 QAPP Addendum as shown in Table 2-10, and well within the 30% acceptance criteria of the EPA guidance. The magnitude of the differences is small, on the order of 0.1 foot (1.2 in).

Table 2-9. Error statistics for existing conditions model calibration.

Basin	Bias	RMSE
Tidal Creek	-0.05	0.07
Oyster Pond	-0.09	0.13

Table 2-10. Modeled and observed mean high water levels, mean low water levels, mean water levels and mean ranges (ft) in Oyster Pond and the Tidal Creek during the calibration period.

	Tidal Creek			Oyster Pond		
Metric	Observed	Modeled	Difference	Observed	Modeled	Difference
	feet	feet	feet	feet	feet	feet
MHW	2.02	1.99	-0.03	1.41	1.33	-0.09
MLW	-0.97	-0.97	0.00	0.03	0.03	-0.01
MTL	0.52	0.51	-0.02	0.72	0.68	-0.05
Mean Range	2.99	2.96	-0.03	1.38	1.30	-0.08

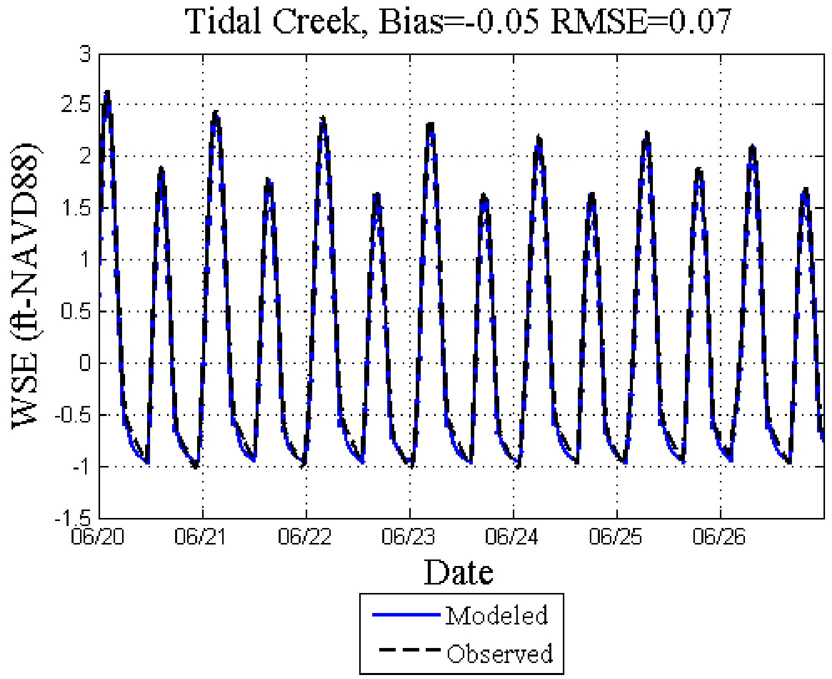

Figure 2-17. **Time series of observed and modeled water levels in Tidal Creek during calibration.**

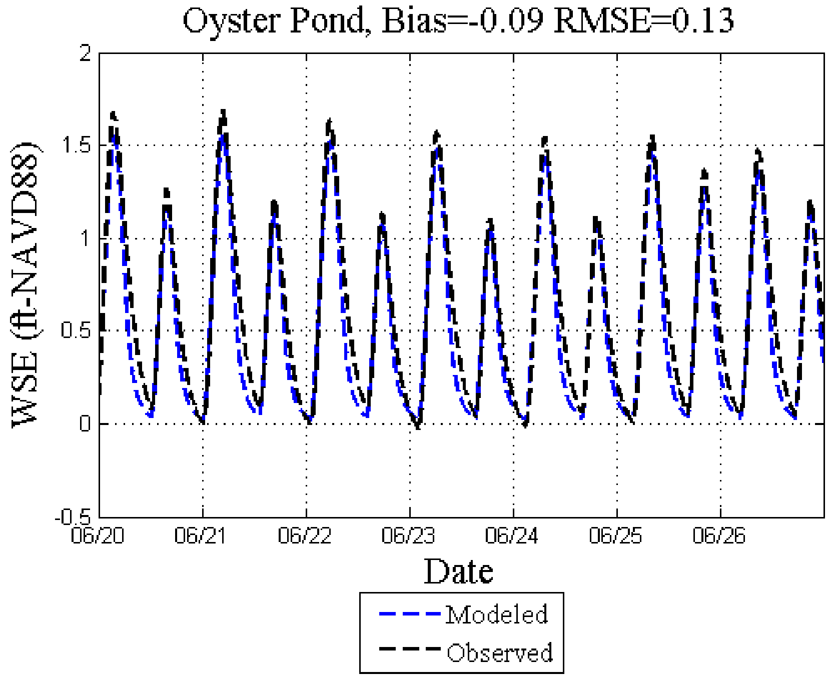

Figure 2-18. **Time series of observed and modeled water levels in Oyster Pond during calibration.**

3.0 HYDRAULIC COMPARISON FOR EXISTING CONDITIONS

The calibrated model was then applied to simulate both normal tides and storm surge scenarios under existing conditions for Oyster Pond and Little Neck Bay Systems. The simulations utilize the calibrated and validated model without making changes to model parameters; only the model boundary conditions are modified to represent storm event (e.g., coastal storm surge) scenarios. Two indicators of the flushing ability for tidal systems include the tidal prism, the volume of water between mean low water and mean high water, and residence time (i.e., the amount of time it takes for a system to fully exchange the tidal prism). Storm simulations were designed to simulate the potential influence on increased water surface elevation (and thus increased flooding potential or duration) during storm surge events in West Falmouth Harbor.

3.1 NORMAL TIDAL CONDITIONS

The 47-day time series of water surface elevations in West Falmouth Harbor collected by CCCD was applied to the calibrated models to simulate for normal tides for the Little Neck Bay and Oyster Pond systems.

3.1.1 Little Neck Bay and Shrub Bog

As discussed in section 2.3, the water levels in both Little Neck Bay and Shrub Bog exhibit minimal tidal forcing, and are sensitive to environmental processes including rainfall, seepage, and evaporation. These factors affect the water levels in both basins at a similar magnitude as the tides. The modeled and observed tidal statistics in both basins are shown in Table 3-1. These statistics include the effects of both tidal and atmospheric forcing and serve to provide a baseline for comparison. Modeled tidal metrics were used to provide a baseline for comparing alternatives, while the observed data are for informational purposes only. Because of the minimal effect of tidal forcing in both embayments, the tidal metrics traditionally analyzed (MHW, MLW, etc.) are not applicable, and instead the maximum, minimum, and mean water surface elevation in each basin were compared. Figure 3-1 shows the extent of inundation for the Little Neck Bay system and surrounding properties for minimum and maximum water surface elevations, respectively, under normal tides and existing conditions.

Table 3-1. Measured versus modeled tidal metrics in Little Neck Bay.

Tidal Metric		Little Neck Bay	
	Units	**Observed**	**Modeled**
Maximum Water Elevation	ft	1.53	1.36
Minimum Water Elevation	ft	0.86	0.95
Mean Water Surface Elevation	ft	1.13	1.18
Maximum Range (max -min)	ft	0.67	0.41

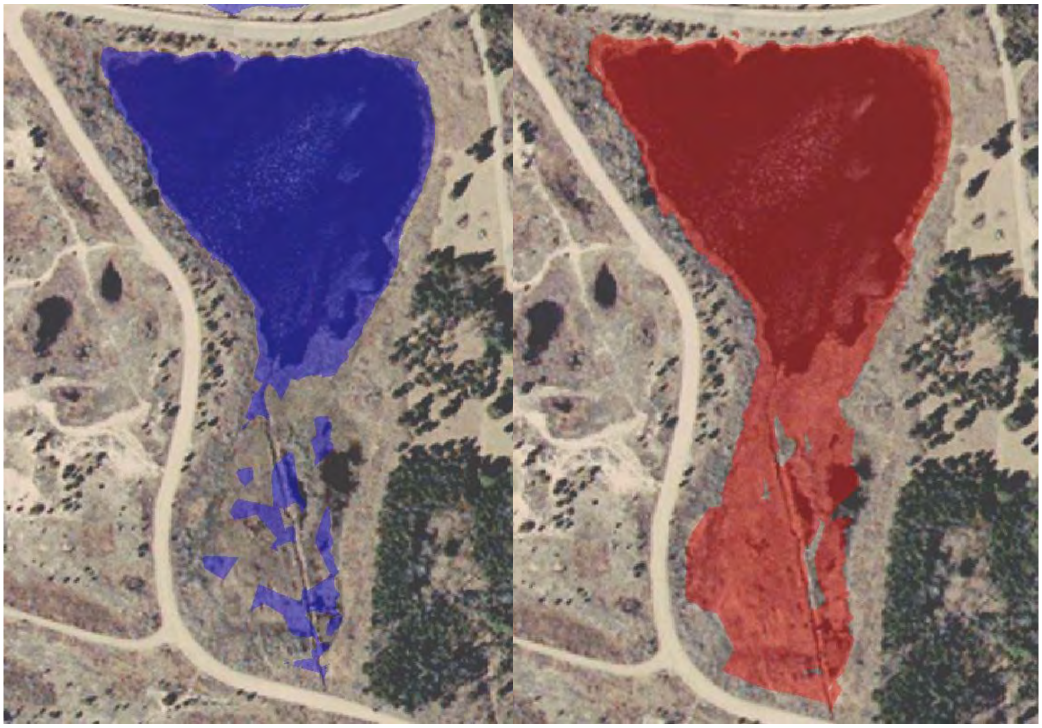

Figure 3-1. Extent of inundation at Little Neck Bay for the minimum (blue, left) and maximum (red, right) modeled WSE from Table 3.1.3.1.2 Tidal Creek and Oyster Pond

3.1.2 Oyster Pond and Tidal Creek

Tidal Creek and Oyster Pond are both strongly influenced by the tidal signal in West Falmouth Harbor and not appreciably influenced by atmospheric conditions. The presence of both the culvert and shoals are the main cause of damping in the system and provide a reliable metric for comparison between existing conditions and any proposed alternatives. Table 3-2 shows the observed and modeled tidal metrics in Oyster Pond with the modeled metrics to be used for alternatives analysis. Figure 3-2 shows the extent of inundation for the Oyster Pond system and surrounding properties for MLW and MHW, respectively, under normal tides and existing conditions.

Table 3-2. Measured versus modeled tidal metrics within Oyster Pond.

Tidal Metric		WFH	Oyster Pond	
	Units	Observed	Observed	Modeled
MHW	ft	1.93	1.44	1.31
MLW	ft	-1.92	0.06	0.03
MTL	ft	0.00	0.75	0.67
MHHW	ft	2.17	1.60	1.45
MLLW	ft	-2.03	0.04	0.01
Mean Range	ft	3.85	1.38	1.28

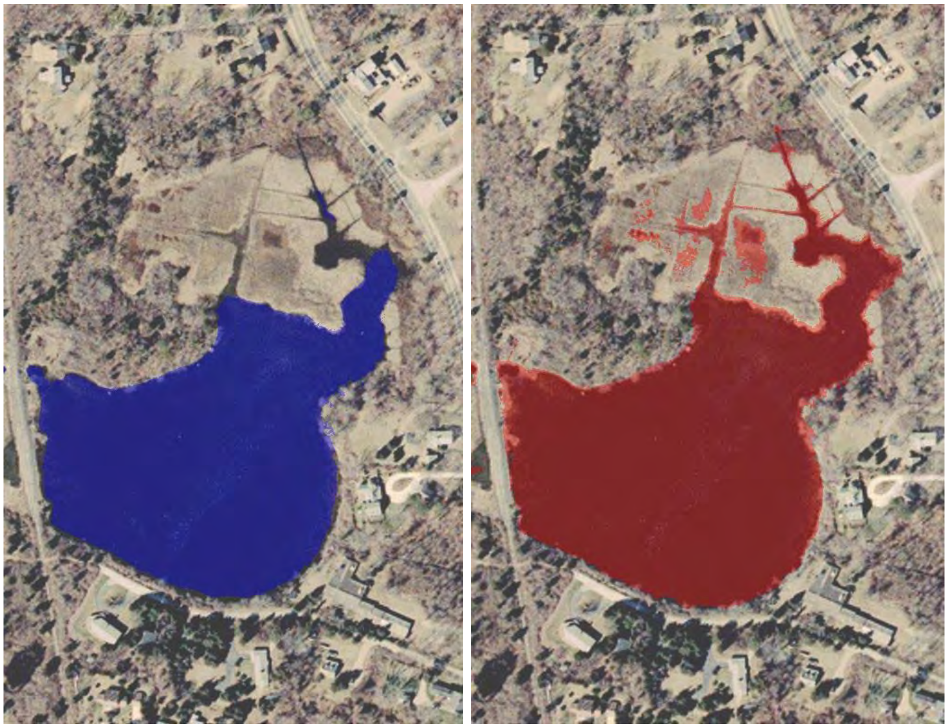

Figure 3-2. Extent of inundation in Oyster Pond at MLW (blue, left) and MHW (red, right) modeled WSE from Table 3.2.

3.2 STORM EVENTS

3.2.1 Development of Return Period Storm Scenarios

West Falmouth Harbor provides the boundary condition that drives the response in both the LNB/SB model and the TC/OP model. The 47-day time series in West Falmouth Harbor provided by CCCD was analyzed to determine MHW, MLW, and MTL to develop a synthetic semidiurnal tidal signal for use in conjunction with storm surges developed using a logarithmic regression line from the most recent FEMA 10-, 50-, 100-, and 500-year return frequency storm surges (Figure 3-3). The most recent FEMA surge elevations are higher than the previous storm surge elevations developed by the United States Army Corps of Engineers (USACE) tidal flood profiles; however, below the 10 year level, the elevation differences for the regressed water surface elevations are not appreciably different. The tidal metrics were determined using a 30-day time window from the beginning of the deployment period. The tidal amplitude was half of the range (MHW-MLW), and used a sinusoidal function with a period of 12.4 hours. In Buzzards Bay, the storm surges are expected to be a result of shorter duration tropical storms (e.g. a hurricane) as opposed to a longer duration Nor'easter. The storm surge was superimposed over the tide signal to generate a synthetic storm surge with a duration of 24 hours followed by approximately eleven days of normal tidal cycle to provide an indication of the culverts ability to drain after inundation (Figure 3-3). The storm scenarios simulated included the 1-, 3-, 4-, 10-, and 100-year return period storm surge events for each system as shown in Table 3-3.

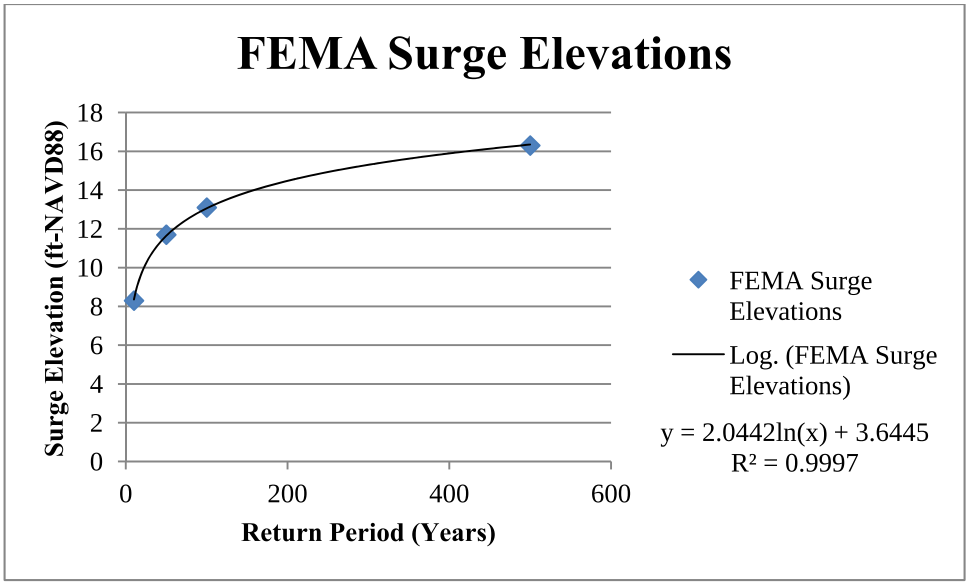

Figure 3-3. **FEMA surge elevations and logarithmic regression line.**

Table 3-3. **Return Period Storm Events used for modeling.**

Return Period Storm Event [Years]	Water Surface Elevation in West Falmouth Harbor [NAVD88 ft]
1-Year	3.6
3-Year	5.9
4-Year	6.5
10-Year	8.4
100-Year	13.1

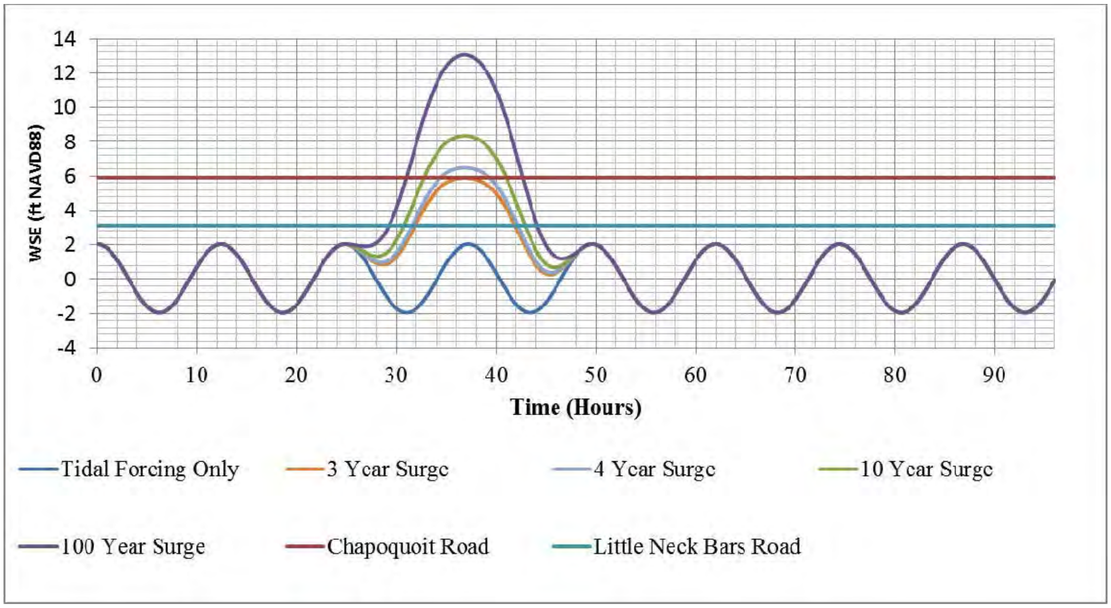

Figure 3-4. **Time series of synthetic tide, 3-year, 4-year, 10-year, and 100-year storm surge events.**

3.2.2 Little Neck Bay and Shrub Bog

Volumetric flow of storm surge through the culverts connecting Little Neck Bay and Shrub Bog is limited by the low elevation of Chapoquoit Road (5.9 ft-NAVD88) and Little Neck Bars Road (3.11 ft-NAVD88) as highlighted in Figure 3-5. During a 3-year return period event (Figure 3-6), an event that is not predicted to overtop the roadway, the restrictive nature of this culvert minimizes the water levels in the system. Chapoquoit Road is at a low enough elevation that even a higher frequency 4-year return period event is predicted to overtop the road and flood the system. During these conditions the road acts as a weir with a modeled weir width of 200 feet. Figure 3-7 illustrates storm response and flooding potential under existing conditions during the four-year event with weir flow dominating over culvert flow in both basins. The volumetric flow over the roadway quickly fills Little Neck Bay to a water level that overtops Little Neck Bars Road, which has an elevation of only 3.11 feet. The culvert is essentially inconsequential for storm scenarios larger than the 3-year return event since the volume of sheet flow overtopping the roadway is much greater than the flow through the culvert. These storm modeling results indicate that the restrictive nature of the culvert under Chapoquoit Road limits storm surge from West Falmouth Harbor from overtopping Little Neck Bars Road where the storm surge elevation is below the elevation of Chapoquoit Road; however, this does not account for stormwater runoff and drainage.

Figure 3-5. **Locus map showing low-lying roadways in the vicinity of Little Neck Bay.**

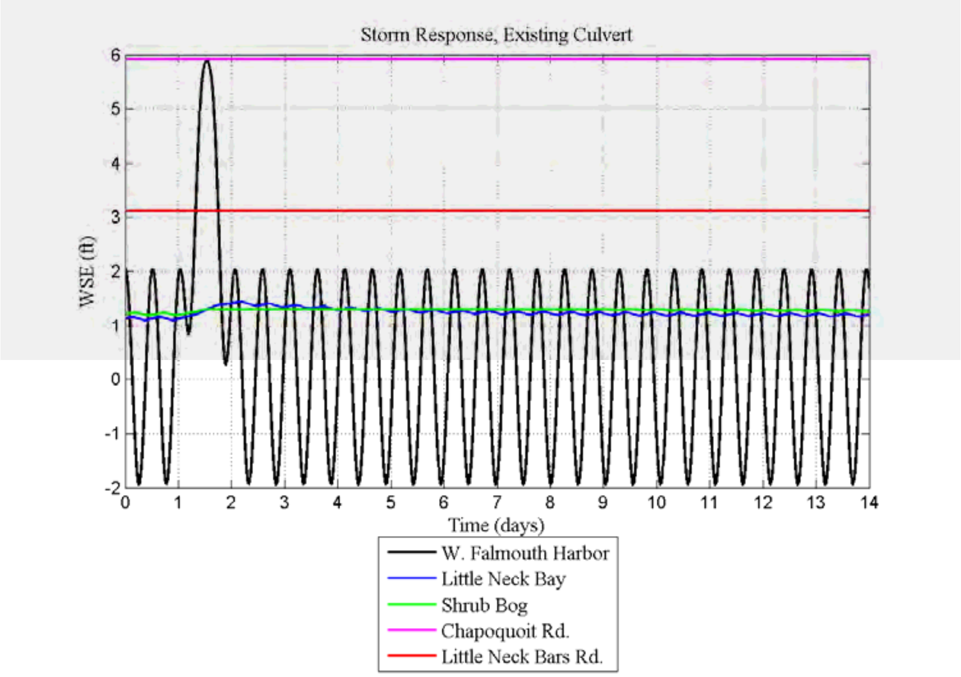

Figure 3-6. **Little Neck Bay and Shrub Bog water levels during the 3-year return period storm event.**

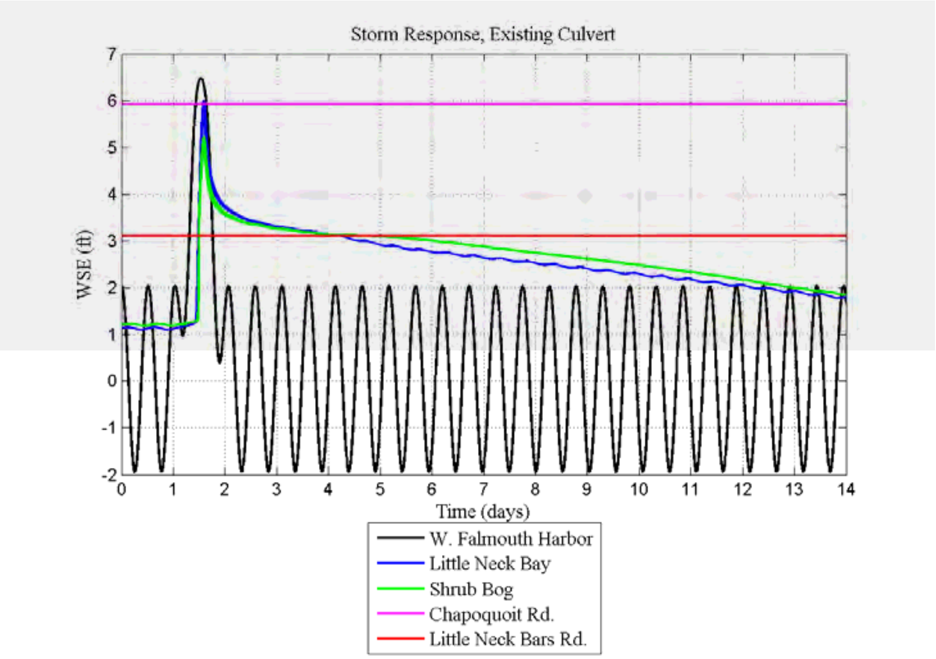

Figure 3-7. Little Neck Bay and Shrub Bog water levels during the 4-year return period storm event.

Figure 3-8 shows the contours of the limiting elevations indicating the potential flooding for the Little Neck Bay system and surrounding properties based on the simulated storm surge elevations in the pond. The roadways provide no protection from surges above the 3-year level (cyan) with extensive flooding due to the 10-year (orange) and 100-year (red) surge events. Flooding into Little Neck Bay and Shrub Bog at the 4-year level is not expected to adversely impact residences adjacent to the embayment; however, this flood event defines the threshold any design alternatives as flow over the Little Neck Bars roadway creates a hazardous condition likely to impede egress along the roadway and can damage or destroy it. Drainage through the existing culverts is restricted such that the system requires approximately eleven (11) days to return to pre-inundation water levels.

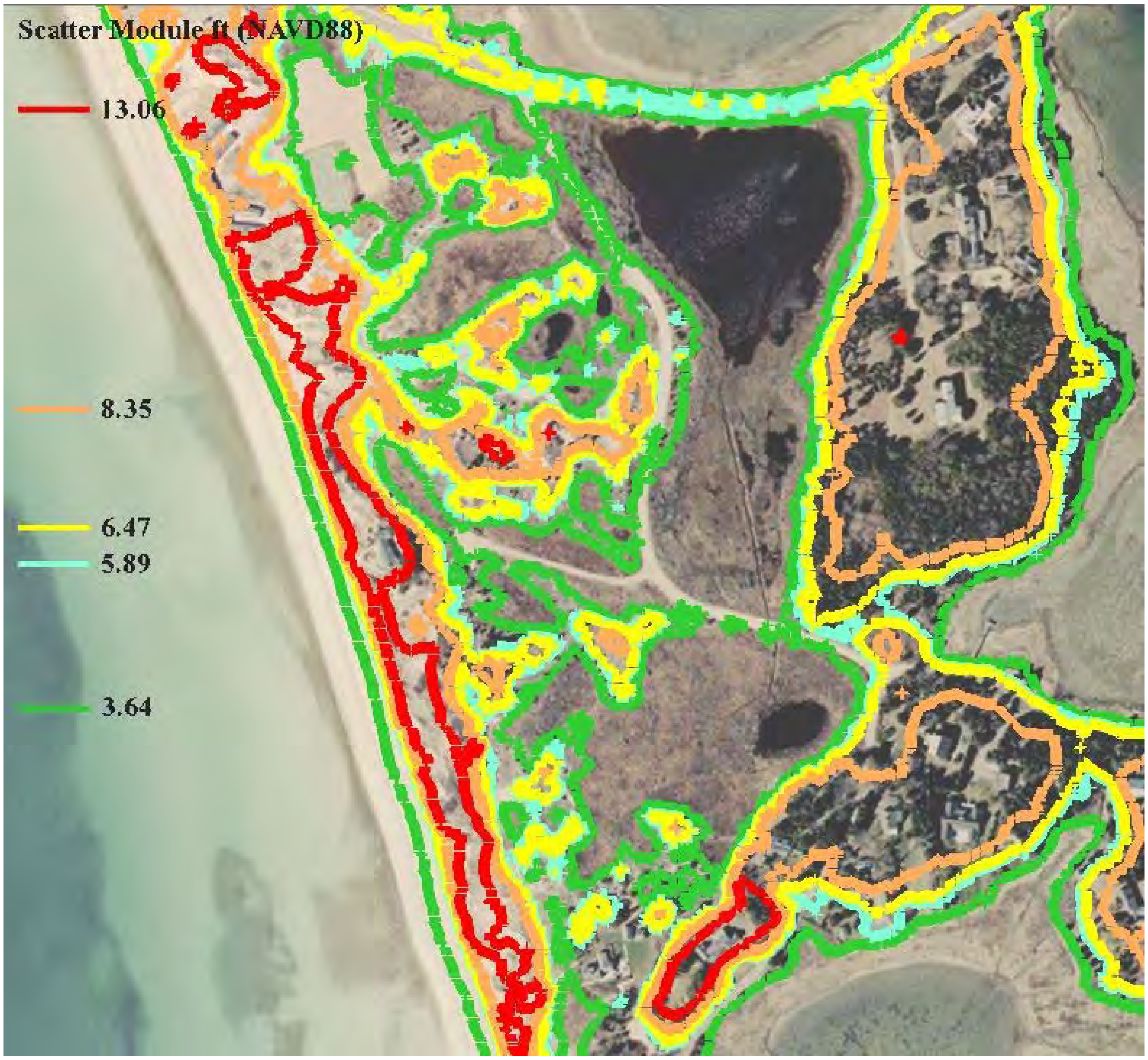

Figure 3-8. Contours showing the limiting elevations in the Little Neck Bay/Shrub Bog system for the 1-year (green), 3-year (cyan), 4-year (yellow), 10-year(orange), and 100-year (red) storm surge events.

3.2.3 Oyster Pond and Tidal Creek

Storm surge response in the Oyster Pond is limited by the elevation of the Shining Sea Bikeway at (6.209 ft-NAVD88) as highlighted in Figure 3-9. While the elevation of the Shining Sea Bikeway is higher than that of Chapoquoit Road at Little Neck Bay, the bikeway is briefly overtopped during the same storm event. Figure 3-10 is a time series of storm response at Oyster Pond during the 3-year return event, while Figure 3-11 is the time series of water surface elevation during the 4-year return event showing overtopping of the bikeway during peak surge. During the 4-year return event, the bikeway acts as a weir with a modeled weir width of 200 feet. The storm surge elevation in Oyster Pond increases 38% from the 3-year to the 4-year return period storm event. During the 4 year storm event, water levels in Oyster Pond return to pre-inundation levels in approximately one day.

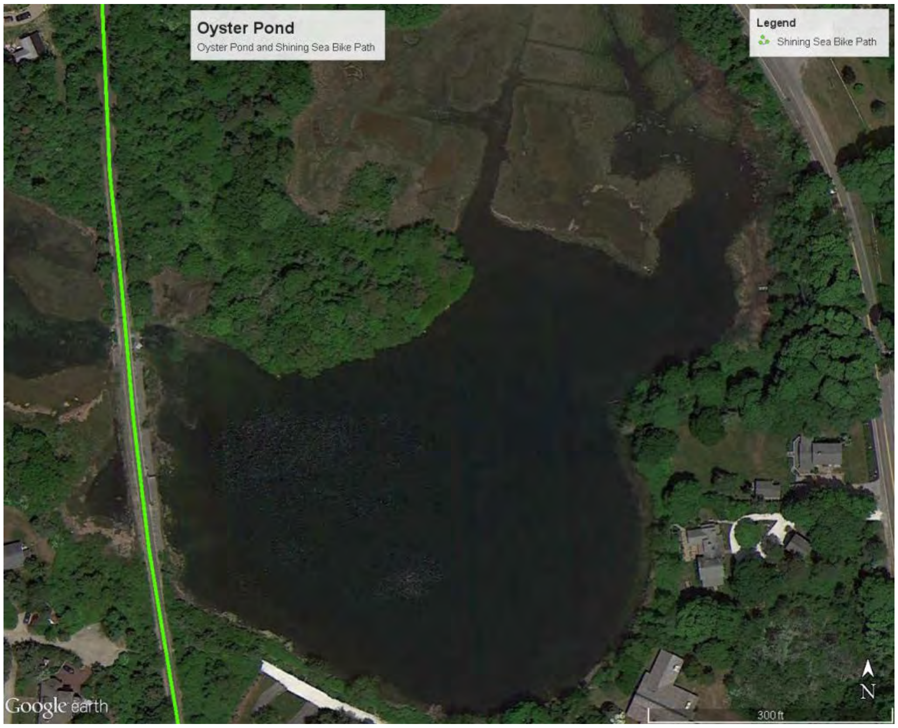

Figure 3-9. Locus map of Oyster Pond and Shining Sea Bike Path

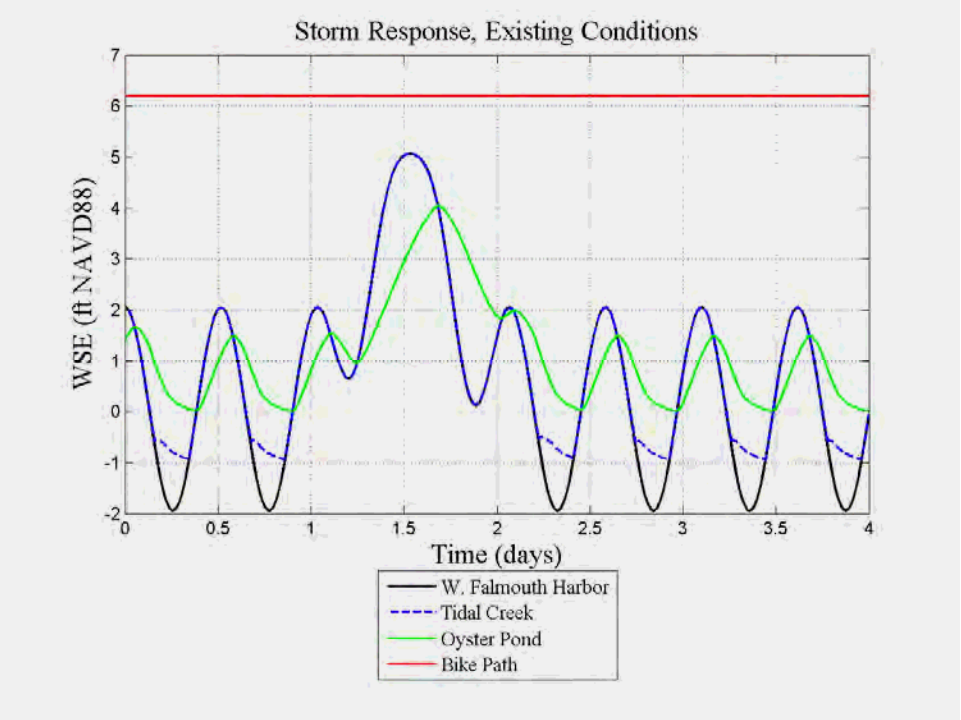

Figure 3-10. Surge response in Oyster Pond during the 3-year return frequency event.

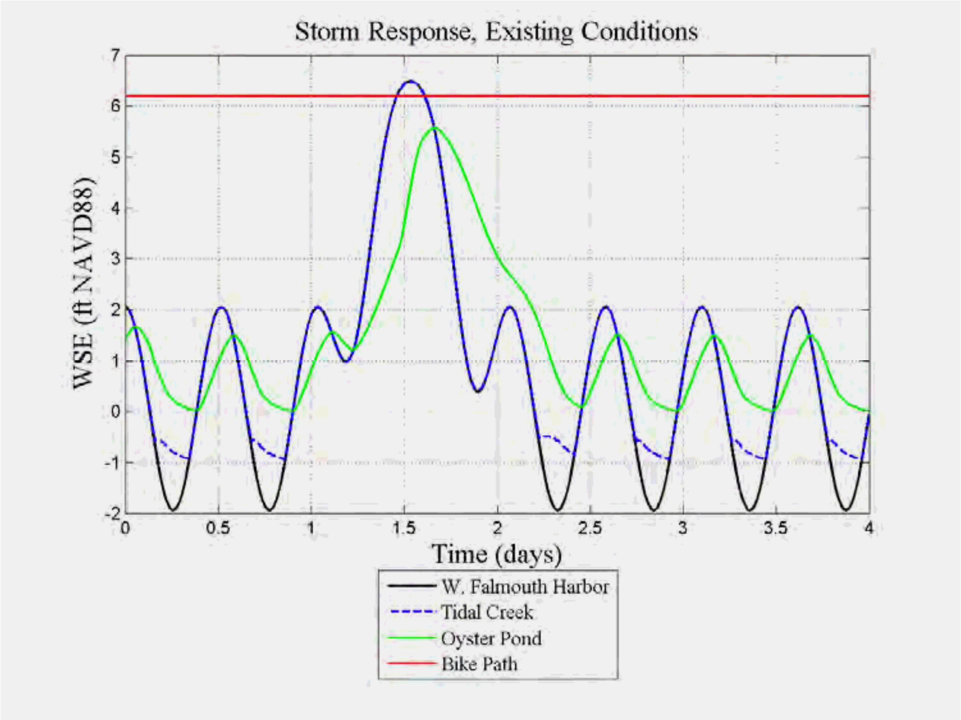

Figure 3-11. **Surge response in Oyster Pond during the 4-year return frequency event.**

Figure 3-12 shows the contours of the limiting elevations indicating the potential flooding for the Oyster Pond system and surrounding properties based up on the simulated storm surge elevations in the pond. The bikeway provides no protection from surges above the 3-year level (cyan) with extensive flooding of upland areas due to the 10-year (orange) and 100-year (red) surge events. Flooding into Oyster Pond at the 4 year level is not expected to adversely impact the residences adjacent to the embayment, however this flood event defines the threshold any design alternatives as flow over the bikeway creates a hazardous condition likely to impede egress along the roadway and can damage or destroy it, but the embayment design alternatives are not restricted by inundation of the bike path.

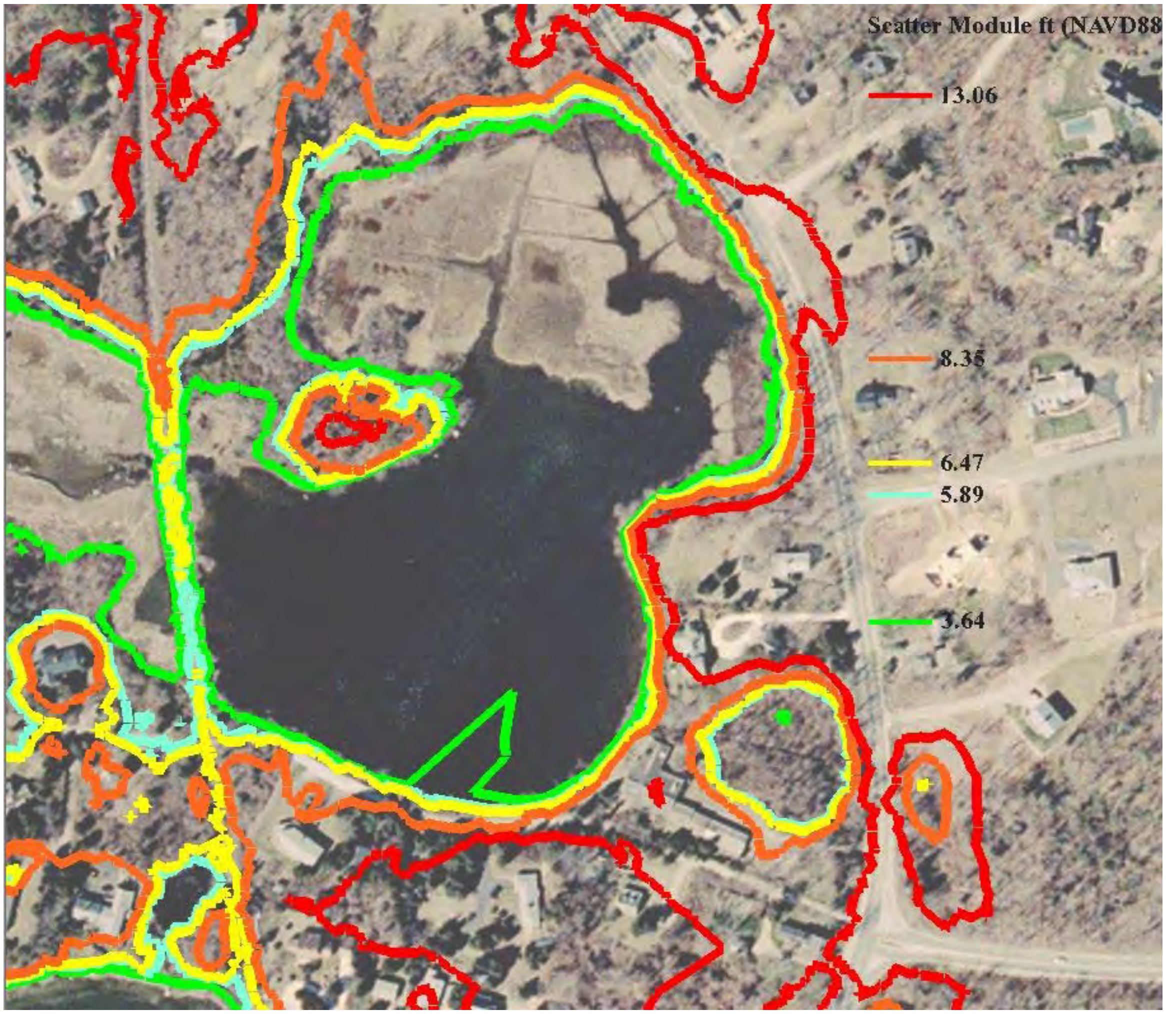

Figure 3-12 **Contours showing the limiting elevations in the Little Neck Bay/Shrub Bog system for the 1-year (green), 3-year level (cyan), 4-year (yellow), 10-year (orange), and 100-year (red) storm surge events.**

3.3 SEA LEVEL RISE

Future sea level rise (SLR) projections were estimated to assess the impacts to the Oyster Pond and Little Neck Bay systems. The sea level rise predictions were compared to the model results for the Oyster Pond and Little Neck Bay systems under existing conditions, but not explicitly simulated as this was not a part of the scope of work. Scientific research indicates that global (eustatic) sea level has risen approximately 6 to 8 inches over the last century (EPA, 2000). This eustatic rise in sea level has occurred in part due to glacial isostasy, warming of the world oceans, and melting of continental glaciers. Along most of the US coast, tide gage data show that local sea levels have been rising 2.5 to 3.0 mm/yr, or 10 to 12 inches over the past century. Locally, long-term tide gage data collected at the NOS (National Ocean Service) station in Woods Hole, MA provides the closest measurements to West Falmouth Harbor (NOAA, 2014). Tide gage data from the Woods Hole station for the period 1932 to 2014 indicate a rise in sea level of 2.83 mm/yr, or 11.1 inches over the past century (Figure 3-13).

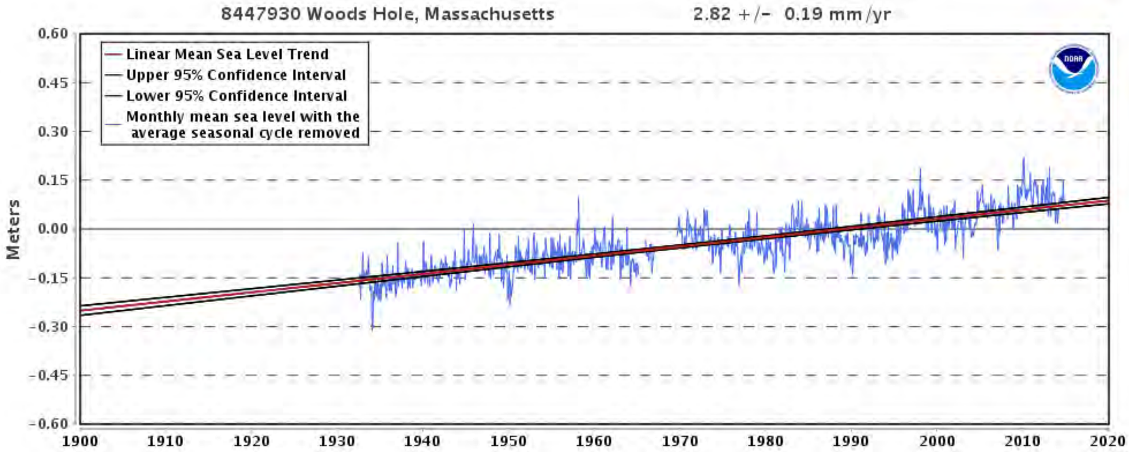

Figure 3-13. Long-term tide data from NOS gages at Woods Hole showing relative rise in sea level (NOAA, 2014).

The topic of sea level rise and accelerated sea level rise in the 21st century and beyond has been the subject of much debate. Because the tide gage stations measure sea level relative to the land, which includes changes in the elevations of both water levels and the land, tide gages measure relative sea level rise, and not the absolute change in sea level. Therefore, the rates of relative sea level rise have greater relevance to the evaluation of coastal hazards from sea level rise, than do changes in eustatic sea level. The Intergovernmental Panel on Climate Change (IPCC) has spent considerable time and energy reviewing and analyzing the current state of knowledge of past and future changes in sea level in relation to climate change. Recently, a consortium of government agencies has completed a National Climate Assessment (Parris et al., 2012) that provides guidance on appropriate selection of Sea Level Rise (SLR) scenarios. Under this guidance, four (4) projected rates of sea level rise (highest, intermediate-high, intermediate-low, and low) are presented. For this study, the SLR was used and projected over 50 years (to 2065) corresponding roughly to the expected service life of a new culvert system if constructed. This method derives locally specific estimates for sea level rise that span a broader range of scenarios than the IPCC estimates alone. These values also include the local changes in land elevation (e.g., subsidence, rebound).

The four (4) projected rates of sea level rise for West Falmouth Harbor including highest, intermediate-high, intermediate-low, and low are presented in Table 3-4. The intermediate and high sea level rise rates are considerable increases that could have significant impacts on the entire West Falmouth Harbor system. For instance, the intermediate low rate would increase the MTL in West Falmouth Harbor to 0.86 ft NAVD88, which is slightly above the current MTL in Oyster Pond (0.74 ft NAVD88) and would likely increase the MTL in Oyster Pond. For the Little Neck Bay system, Little Neck Bars Road (Elevation 3.11 ft NAVD88) will be overtopped daily during high tide in 2065 for the intermediate-high and high sea level rise rates if the full tidal prism is restored uninhibited to Little Neck Bay.

Table 3-4. Projected sea level rise for the West Falmouth Harbor over a 50 year time horizon between 2015 and 2065.

Sea Level Rise Rate	Sea Level Increase (ft)	MHW (ft) in 2065 at WFH
None	0.00	1.93
Low	0.62	2.55
Intermediate Low	0.86	2.79
Intermediate High	1.81	3.74
Highest	2.90	4.83

4.0 ALTERNATIVES ANALYSIS

Multiple design alternatives were investigated using both the Little Neck Bay/Shrub Bog culvert model and the Tidal Creek/Oyster Pond culvert model. The overall goal of the modeling was to determine the optimal culvert size to maximize tidal flushing restoration while managing flooding risk for developed upland properties.

4.1 LITTLE NECK BAY AND SHRUB BOG

In Little Neck Bay and Shrub Bog, the level of desired tidal exchange also is limited by the constraints imposed by the low elevation of Little Neck Bars Road and surrounding properties, and the desire to minimize additional tidal exchange in Shrub Bog. For instance, optimizing tidal exchange between Little Neck Bay and West Falmouth Harbor would benefit habitat in Little Neck Bay; however, there would be increased risk of overtopping the lower Little Neck Bars Road and flooding the freshwater ecosystem in Shrub Bog with salt water. As an area with freshwater plant communities and surrounding low-lying properties, Shrub Bog therefore affects potential solutions for the combined Little Neck Bay/Shrub Bog system. With those constraints in mind during the simulation of design alternatives, three alternatives were investigated:

- Replacing the existing culvert with a larger culvert (Section 4.1.1);
- Lowering the invert elevation during pipe replacement (Section 4.1.1); and
- For perspective, a third alternative was investigated to identify the culvert configuration that maximized tidal exchange within Little Neck Bay neglecting the upland flooding constraints (Section 4.1.2). This alternative helped understand the maximum restoration potential and associated incremental flooding risk.

4.1.1 Optimizing Culvert Size with Consideration for Upland Constraints

In this section, the preferred alternative should not increase the upland flood risk to infrastructure, property, or ecosystems, the culvert sizing analysis is controlled by the storms events rather than normal tides. The 3-year return period storm event is the largest storm event to not cause significant overtopping of Little Neck Bars Road for existing conditions and is used as the benchmark for culvert sizing with regards to additional flood risk. The 3-year event was selected based on the analysis in Section 3 showing sheet flow over Little Neck Bars Road exceeds culvert flow for storms of 4-year and greater magnitude. Simulations were conducted using replacement of the existing culvert with circular concrete pipes with diameters ranging from 1- to 2-feet in 0.25 foot increments for two different upstream invert elevation scenarios including the existing invert elevation of 0.51 ft NAVD88 (Alternative 1) and lowering the invert to 0 ft NAVD88 (Alternative 2). Tables 4-1 and 4-2 show the storm surge elevation response in Little Neck Bay for the existing and lowered inverts, respectively, for various culvert sizes. The red highlighting in the tables indicates an elevation greater than that of Little Neck Bars Road (3.11 ft-NAVD88). The culvert sizing analysis indicated the largest culvert diameter not increasing overtopping risk to Little Neck Bars road is 1.25-ft for either the existing or lowered invert elevation scenarios. Figures 4-1 and 4-2 show the storm surge response in Little Neck Bay and Shrub bog for a 1.25-ft diameter pipe at the existing and lowered inverts, respectively, during a 3-year storm event. The results from Tables 4-1 and 4-2 and Figures 4-1 and 4-2 indicate that the lowered invert produces slightly lower storm surge elevations in Little Neck Bay than the existing invert for the same culvert diameter. This is due to a lower starting MTL in Little Neck Bay for the lowered invert elevation and the restrictive nature of the culvert limiting storm surge inflow.

Table 4-1. Storm Surge Elevation (ft-NAVD88) in Little Neck Bay with the invert elevation at 0.51 ft-NAVD88. Red highlighting indicates an elevation greater than 3.11 ft-NAVD88.

Little Neck Bay (Existing Invert)						
Recurrence/Culvert Diameter	0.69 ft	1.0 ft	1.25 ft	1.5 ft	1.75 ft	2.0 ft
Normal tides	1.2	1.8	2.0	2.2	2.4	2.7
1-year event	1.4	2.4	3.0	3.2	3.6	4.0
2-year event	1.4	2.6	3.2	3.6	4.1	4.6
3-year event	1.4	2.7	3.2	3.8	4.3	4.9
4-year event	6.3	6.4	6.4	6.4	6.4	6.4
5-year event	6.7	6.7	6.7	6.7	6.7	6.7
6-year event	7.0	7.0	7.0	7.0	7.0	7.0
7-year event	7.3	7.3	7.3	7.3	7.3	7.3
8-year event	7.5	7.5	7.5	7.5	7.5	7.5
9-year event	7.7	7.7	7.7	7.7	7.7	7.7
10-year event	7.8	7.83	6.7	6.7	6.7	6.7
15-year event	8.5	8.5	8.5	8.5	8.5	8.5
20-year event	8.9	8.9	8.9	8.9	8.9	8.9
25-year event	9.3	9.3	9.3	9.3	9.3	9.3
50-year event	10.4	10.4	10.4	10.4	10.4	10.4
100-year event	13.1	13.1	13.1	13.1	13.1	13.1

Table 4-2. Storm Surge Elevation (ft-NAVD88) in Little Neck Bay with the invert elevation at 0.0 ft-NAVD88. Red highlighting indicates an elevation greater than 3.11 ft-NAVD88.

Little Neck Bay (Lowered Invert)						
Recurrence\Culvert Diameter	0.69 ft	1.0 ft	1.25 ft	1.5 ft	1.75 ft	2.0 ft
Normal tides	1.2	1.4	1.5	1.7	2.0	2.2
1-year event	1.4	2.1	2.6	3.1	3.2	3.6
2-year event	1.4	2.3	3.0	3.3	3.8	4.2
3-year event	1.4	2.4	3.1	3.5	4.0	4.5
4-year event	6.3	6.3	6.4	6.4	6.4	6.4
5-year event	6.7	6.7	6.7	6.7	6.7	6.7
6-year event	7.0	7.0	7.0	7.0	7.0	7.0
7-year event	7.3	7.3	7.3	7.3	7.3	7.3
8-year event	7.5	7.5	7.5	7.5	7.5	7.5
9-year event	7.7	7.7	7.7	7.7	7.7	7.7
10-year event	7.8	7.8	7.8	7.8	7.8	7.8
15-year event	8.5	8.5	8.5	8.5	8.5	8.5
20-year event	8.9	8.9	8.9	8.9	8.9	8.9
25-year event	9.3	9.3	9.3	9.3	9.3	9.3
50-year event	10.4	10.4	10.4	10.4	10.4	10.4
100-year event	13.1	13.1	13.1	13.1	13.1	13.1

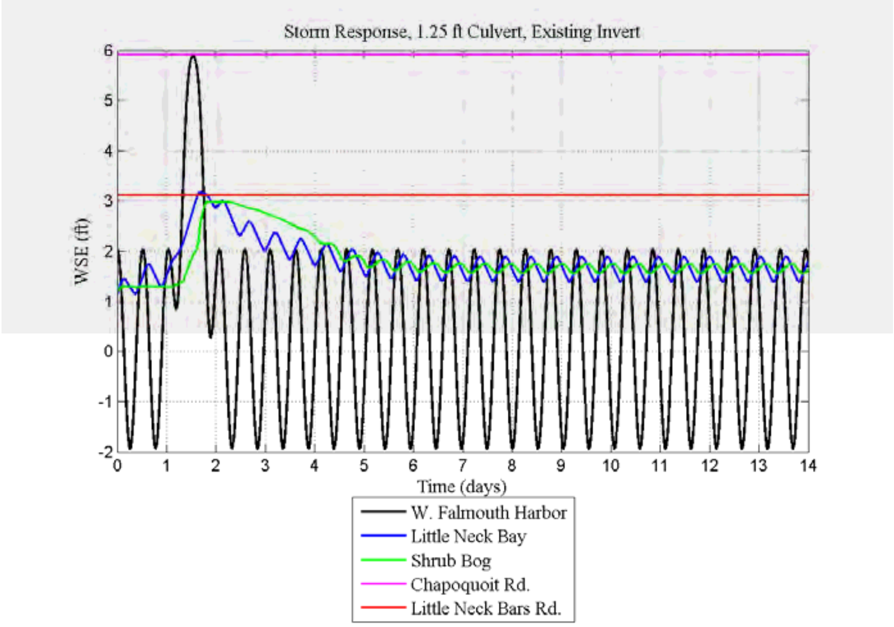

Figure 4-1. **Time series of storm surge response for a culvert diameter of 1.25 feet at Chapoquoit Road for the existing invert elevation (0.51 ft NAVD88) during the 3-year storm event.**

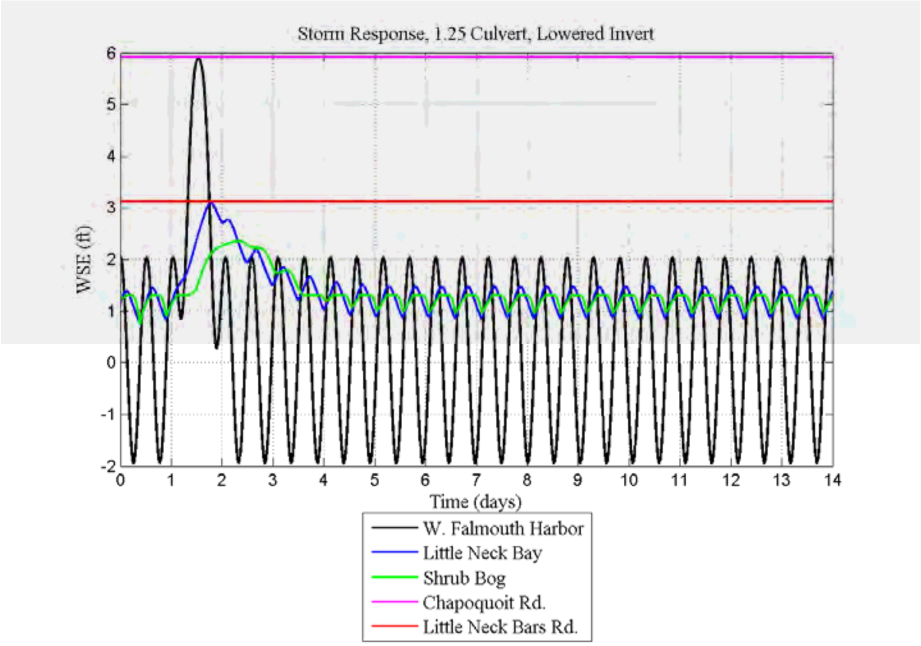

Figure 4-2. **Time series of storm surge response for a culvert diameter of 1.25 feet with the invert lowered to 0.0 ft-NAVD88 (bottom) during the 3-year storm event.**

The 1.25-ft diameter culvert for both inverts was then simulated for the 47-day water surface elevation time series provided by CCCD to assess the effect on tidal exchange in both basins for normal tides (Figures 4-3 and 4-4). Tidal metrics for the proposed alternative are compared with the existing conditions in Table 4-3. As mentioned in previous sections, the existing tidal metrics are for comparison because tidal exchange is restricted to such a degree that atmospheric and environmental forcings have a large impact on the water levels in relation to the tides in West Falmouth Harbor. The increase in MHW and lowering of MLW result in an increase in the mean range of 0.88 feet and 1.09 feet for the existing and lowered invert elevation scenarios, respectively. As a result, the existing tidal prism of 24,000 ft^3 increased to approximately 201,000 ft^3 for the 1.25 ft diameter culvert at the existing invert and 198,000 ft^3 for the 1.25 ft culvert with the lowered invert elevation. There was also a corresponding decrease in the residence time from 6 days for the existing conditions to about a half day for either Alternative, which is approximate to a tidal cycle. The reason for such a drastic increase with a small increase in pipe diameter is the significantly large low-lying area further inundated with small increases in the water surface elevation of Little Neck Bay as indicated by the hypsometry in Figure 2-10. The results also indicate that the lowered invert produces slightly smaller tidal prism in Little Neck Bay than the existing invert due to a lower starting MTL in Little Neck Bay for the lowered invert case and the restrictive nature of the culvert limiting storm surge inflow. Following the 3-year storm event, Figures 4-1 and 4-2 show the system returns to pre-inundation levels in approximately 2 to 3 days with the larger culvert, which is a reduction from 11 days for existing conditions. The velocities through the culvert increased, which should reduce shoaling potential within the culvert itself. Figures 4-5, 4-6, 4-7, and 4-8 show the extent of inundation under normal tides for the Little Neck Bay system and surrounding properties for MLW and MHW. Note that disconnected areas are not expected to be inundated and are an artifact of the elevation data. Figures 4-9 and 4-10 show the extent of inundation for the 3-year storm.

Table 4-3. Modeled tidal metrics and flushing characteristics in Little Neck Bay for Alternative 1, a 1.25-ft diameter pipe culvert (with invert 0.51 NAVD88), and Alternative 2, a 1.25 diameter pipe culvert at a lowered invert elevation (0.0 NAVD88).

	Little Neck Bay			
	Unit	**Existing**	**Alt. 1**	**Alt. 2**
Culvert Diameter	ft	0.7	1.25	1.25
Invert Elevation	ft	0.51	0.51	0.0
MHW	ft	1.26	2.09	1.72
MLW	ft	1.12	1.07	0.49
MTL	ft	1.19	1.58	1.10
MHHW	ft	1.28	2.20	1.82
MLLW	ft	1.11	1.04	0.46
Mean Range	ft	0.14	1.02	1.23
Intertidal Area	ft^2	16,800	63,010	89,723
Tidal Prism	ft^3	23,667	201,150	197,640
Residence Time	days	6.2	0.9	0.7
Mean Velocity (Flood)	ft/s	3.3	8.9	8.6
Mean Velocity (Ebb)	ft/s	2.3	7.9	7.6
Post Storm Recovery Time	days	12+	3	1.5

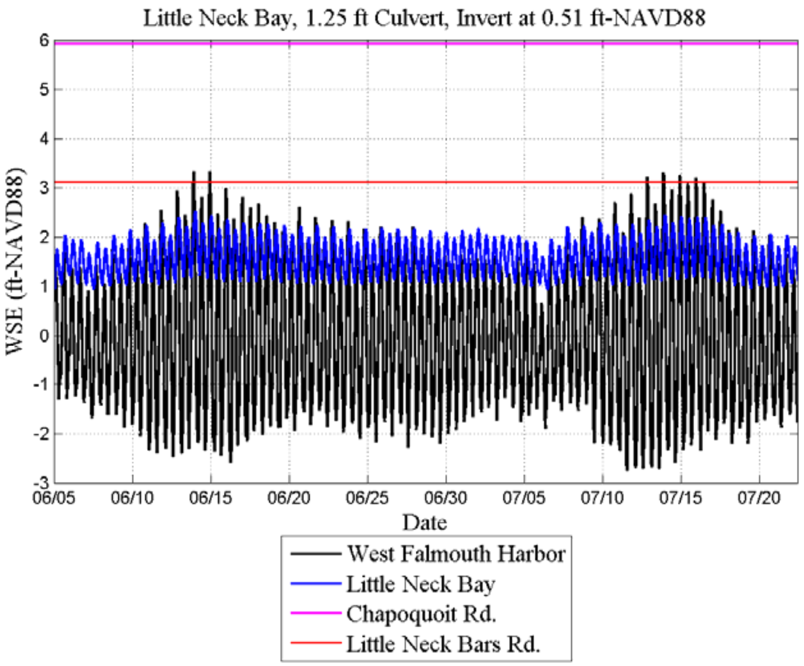

Figure 4-3. Time series tidal response for a culvert diameter of 1.25 feet at the existing invert elevation (0.51 ft NAVD88) through Chapoquoit Road using the CCCD data.

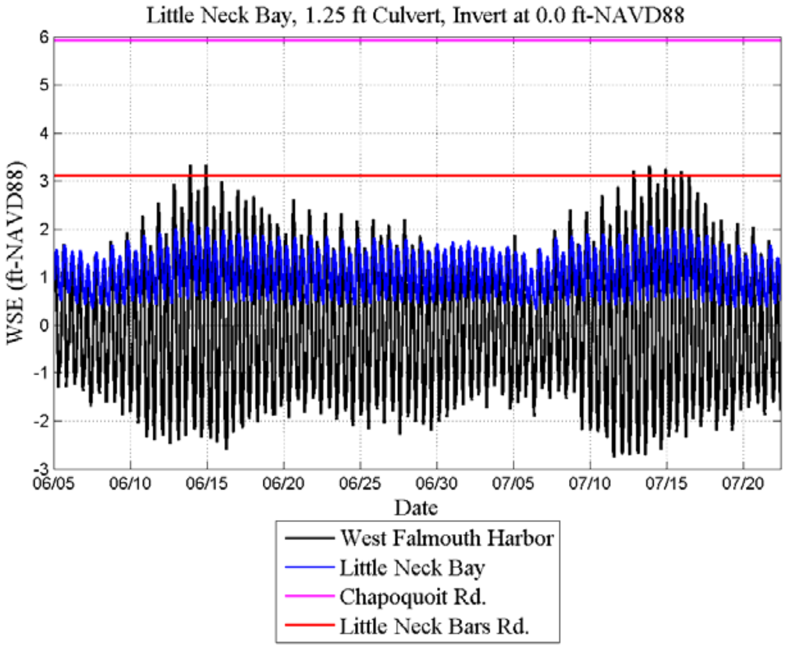

Figure 4-4. **Time series tidal response for a culvert diameter of 1.25 feet (top) and a culvert diameter of 1.25 feet with an invert at 0 ft-NAVD88 at Chapoquoit Road using the CCCD data.**

Figure 4-5. **Extent of inundation at MLW for Little Neck Bay (left) and Shrub Bog (right) for the culvert replacement at the existing invert elevation.**

Figure 4-6. **Extent of inundation at MHW at Little Neck Bay (left) and Shrub Bog (right) for the culvert replacement at the existing invert elevation.**

Figure 4-7. **Extent of inundation at MLW at Little Neck Bay (left) and Shrub Bog (right) for the culvert replacement and lowered invert elevation.**

Figure 4-8. Extent of inundation at MHW at Little Neck Bay (left) and Shrub Bog (right) for the culvert replacement and lowered invert elevation.

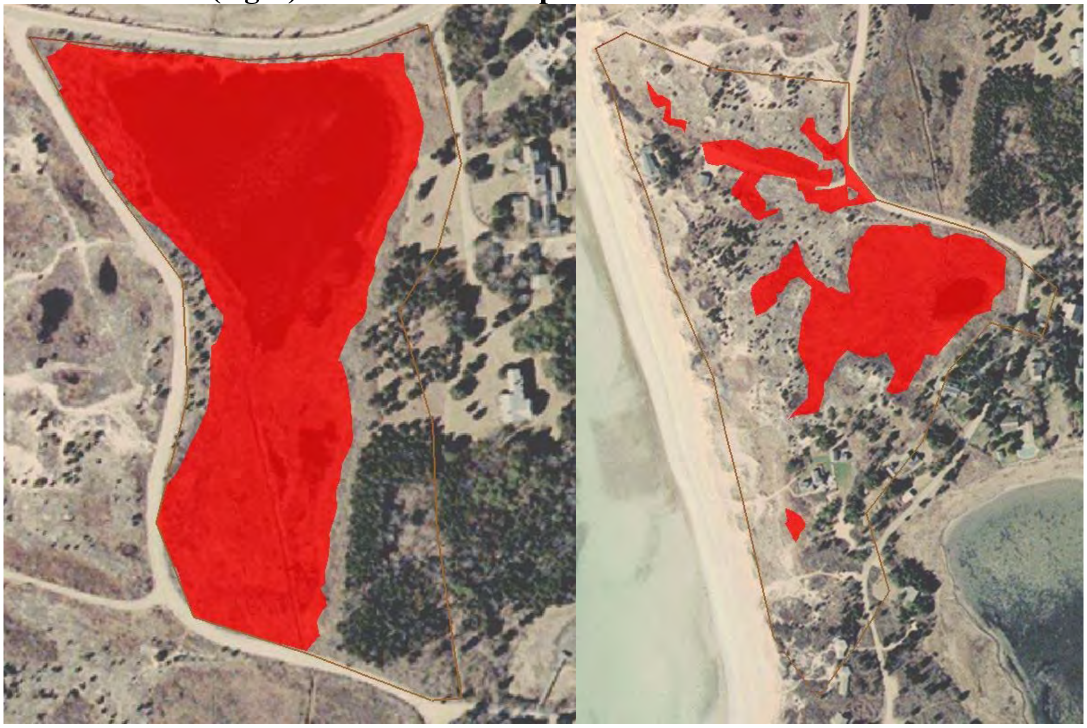

Figure 4-9. Extent of inundation during 3-year storm event at Little Neck Bay (left) and Shrub Bog (right) for the culvert replacement elevation.

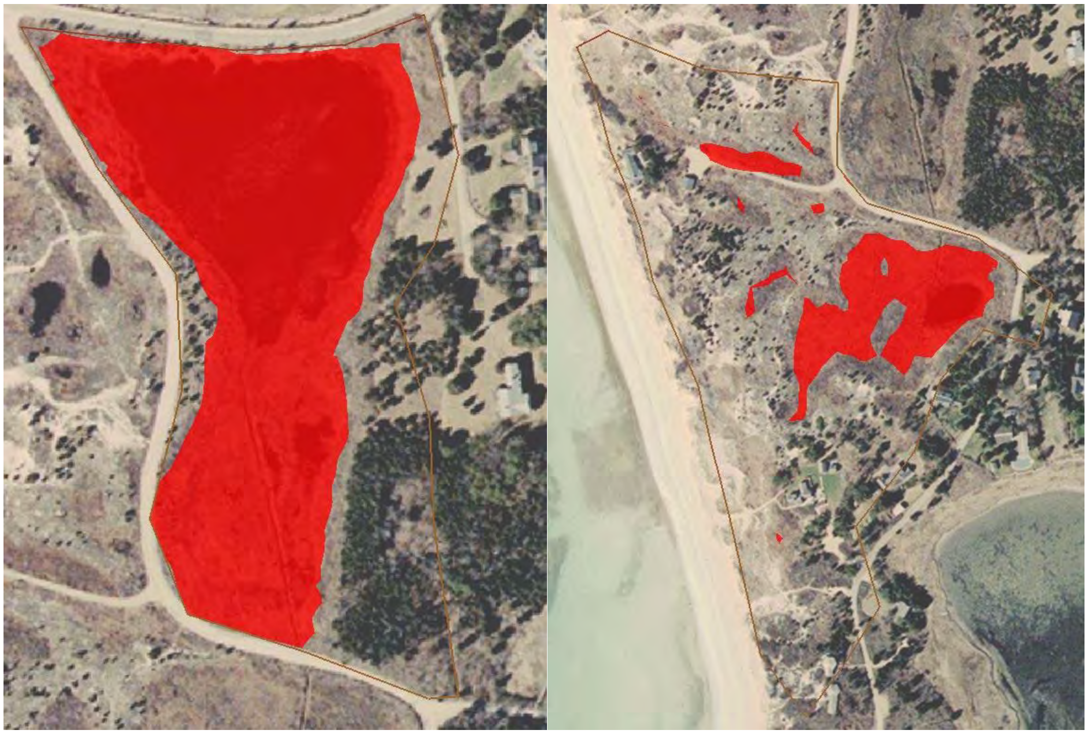

Figure 4-10. Extent of inundation for 3-year storm at Little Neck Bay (left) and Shrub Bog (right) for the culvert replacement and lowered invert elevation. (Note disconnected areas are not expected to be inundated and are an artifact of the elevation data).

4.1.2 Alternative to Maximize Tidal Exchange in Little Neck Bay

In this section, a culvert sizing analysis was conducted to evaluate the culvert size that would restore maximum tidal prism to Little Neck Bay. This alternative was evaluated independent of constraints considering additional upland flooding risk associated with Little Neck Bars Road and Shrub Bog. The increase in tidal prism is likely to maximize the ecological benefits within the Little Neck Bay embayment. Simulation of this alternative, then, provides perspective on the maximum potential for restoration. Simulations were conducted using replacement of the existing culvert with circular concrete pipes with diameters of 2-, 3-, and 4-feet in addition to the prior alternative. The upstream invert of the Little Neck Bay culvert was reduced to -1.0 feet NAVD88 which is slightly higher than the invert elevation of -1.07 feet NAV88 at West Falmouth Harbor to maintain flow out of the culvert during lower water levels in Little Neck Bay.

Tidal metrics for each culvert size are shown in Table 4-4. The results indicate that increasing the culvert diameter from 1.25 ft to 2.0 ft increases the tidal prism an additional 21% and reduces the residence time to less than 1 day. Increasing the diameter from 2.0 ft to 3.0 ft increases the tidal prism by an additional 48%, while increasing the diameter from 3.0 ft to 4.0 ft provides less than a 9% additional increase in the tidal prism. The 3-ft diameter culverts allows for the MHW and MHHW in West Falmouth Harbor to be attained within Little Neck Bay. For 2-, 3-, and 4-ft diameter culverts, MLW and MLLW are reduced by approximately the same amount, -1.6 ft, which is higher than West Falmouth Harbor due the invert elevation (i.e., Little Neck Bay will not drain below the culvert invert elevation). Based on the modeling results, the 3-ft diameter culvert provides the most significant increase in tidal prism restoration and residence time reduction, while the 4-ft diameter culvert only provides small additional benefit.

A larger 3 to 4-ft culvert may raise some safety concerns for small children and small pets. As a result, the 3-ft diameter culvert set to an invert elevation of -1 ft NAVD88 will not provide headspace at high tide for a small child to breath; however, a 4-ft diameter culvert will provide almost a foot of headspace and increase the tidal prism. Therefore, a 4-ft diameter culvert would be the preferred alternative to both maximize tidal prism and safety within the Little Neck Bay system if upland constraints are not considered. Grates may also be considered for both ends, but this will require regular maintenance to prevent clogging with detritus and other debris. Due to the increased likelihood of overtopping Little Neck Bars Road, however, the installation of a tidal control such as a flapgate, or increasing the roadway elevation could also be considered in conjunction with a larger culvert replacement; however, this would add cost and require periodic maintenance.

Table 4-4. Modeled tidal metrics and flushing characteristics in Little Neck Bay for case of maximum tidal restoration.

		WFH	Little Neck Bay				
Metric	**Unit**	**Existing**	**Existing**	**Maximum Flow Alternatives**			
Culvert Diameter	ft	N/A	0.69	1.25	2	3	4
Invert Elevation	ft	N/A	0.50	0	-1.0	-1.0	-1.0
MHW	ft	1.93	1.26	2.09	1.40	1.94	2.06
MLW	ft	-1.92	1.12	1.07	-0.57	-0.66	-0.71
MTL	ft	0.00	1.19	1.58	0.42	0.64	0.68
MHHW	ft	2.17	1.28	2.20	1.55	2.15	2.28
MLLW	ft	-2.03	1.11	1.04	-0.58	-0.68	-0.72
Mean Range	ft	3.85	0.12	1.02	1.97	2.6	2.77
Intertidal Area	ft^2	N/A	16,800	63,010	107,300	133,670	140,300
Tidal Prism	ft^3	N/A	23,667	197,640	240,580	357,580	387,610
Residence Time	days	N/A	6.2	0.7	0.4	0.3	0.3

4.2 OYSTER POND AND TIDAL CREEK

Oyster Pond does not have the same constraints as Little Neck Bay with regard to storm flooding as the surrounding properties are elevated and there is no known presence of sensitive freshwater habitat as indicated by the RFP (CCCD, 2015). Therefore, the culvert sizing analysis was conducted to maximize the tidal prism restoration. The alternative analysis was conducted in two stages. A culvert sizing analysis was conducted to determine the optimal size culvert to replace the existing the culvert. Second, the effects removing the shoals from the upstream side (Oyster Pond) to a modeled elevation of -1.7 ft-NAVD88 and on the downstream side (Tidal Creek) to an elevation of -3.5 ft-NAVD88 were evaluated using the model for both the existing culvert and the alternative. The supplemental analysis of upstream and downstream shoals was evaluated since the existing shoals in the approach channels to the Oyster Pond culvert go dry at low tides, thereby limiting tidal circulation.

4.2.1 Box Culvert Sizing

This alternative included a culvert sizing analysis to assess the improvements that could be made to the Oyster Pond system by only changing the culvert geometry (i.e., no modifications to the adjacent shoals). Simulations for the culvert sizing analysis were conducted using a concrete box culvert with a height of 4 feet and widths ranging from 4 feet up to 8 feet in 2 foot increments at the existing upstream and downstream inverts. The model was then used to evaluate the 47-day time series provided by CCCD to assess the effect on tidal exchange in Oyster Pond for normal tides. The modeling results determined that the 4x4 box culvert increases the tidal prism by 280,000 ft^3 (72%) and that increasing the width beyond 4 feet provides little additional exchange between Oyster Pond and the Tidal Creek. Table 4-5 lists the tidal metrics for the existing condition and the proposed design alternatives. The increase in MHW and lowering of MLW increase the mean tidal range from 1.3 feet for existing to 2.0 feet for the different sizes, with a corresponding reduction in residence time compared to the existing culvert. Figure 4-11 is the time series of storm response for the Tidal Creek/Oyster Pond subsystem during the 3-year event with a 4x4 box culvert, Figure 4-12 shows storm response with a 4x6 culvert, and Figure 4-13 shows storm response with a 4x8 foot culvert. The figures indicate the system would drain the storm water and return to pre-inundation levels with almost no delay for each alternative, which is a reduction from the 1 day currently required to drain storm water for existing conditions.

Overall, a larger culvert size should reduce the shoaling potential within the culvert since the larger opening will allow more tidal exchange, as shown in Table 4-5. The mean velocity increases from the existing culvert to the 4x4 box culvert, but then decreases for each larger size culvert. The 4x8 box culvert produces lower mean flood and ebb velocities than the existing culvert, which increases the potential for shoaling within the culvert. Keeping the culvert to a smaller 4x4 box culvert will maximize tidal exchange while maintaining the velocity through the culvert to reduce shoaling potential within the culvert. The final design should include scour protection on either side of the culvert. Lastly, installing a larger culvert will potentially raise safety concerns for small children and pets in an area nearby the well-traveled bike path. A 4-ft tall box culvert with an invert set to -1.7 ft NAVD88 will not produce enough headspace for a small child to breath within the culvert during MHW. The height of the culvert should be increased to 5-ft in order to provide at least 1-ft of headspace in the culvert at high tide, which will not change the tidal metrics since the full tidal prism has been restored. Grates on either end of the culvert may also be feasible, but they also require maintenance and may inhibit finfish passage.

Table 4-5. Modeled tidal metrics and flushing characteristics comparison of existing 3.8-ft- diameter culvert at Oyster Pond with shoals, and box culverts.

Tidal Metrics and Elevation (ft-NAVD88)					
Tidal Metric	**Unit**	**Existing culvert**	**4x4 box culvert**	**4x6 box culvert**	**4x8 box culvert**
MHW	ft	1.31	1.98	1.99	1.99
MLW	ft	0.03	0.004	-0.005	-0.01
MTL	ft	0.67	0.99	0.99	0.99
MHHW	ft	1.45	2.21	2.22	2.22
MLLW	ft	0.01	0.00	-0.01	-0.02
Mean Range	ft	1.28	1.98	2.00	2.00
Intertidal Area	ft^2	54,553	172,825	174,100	174,225
Tidal Prism	ft^3	387,620	668,470	675,870	677,270
Residence Time	days	3.1	1.9	1.9	1.9
Mean Velocity (Flood)	ft/s	4.1	6.6	4.8	3.8
Mean Velocity (Ebb)	ft/s	2.2	2.3	1.8	1.5
Post Storm Recovery Time	days	1	≈ 0	≈ 0	≈ 0

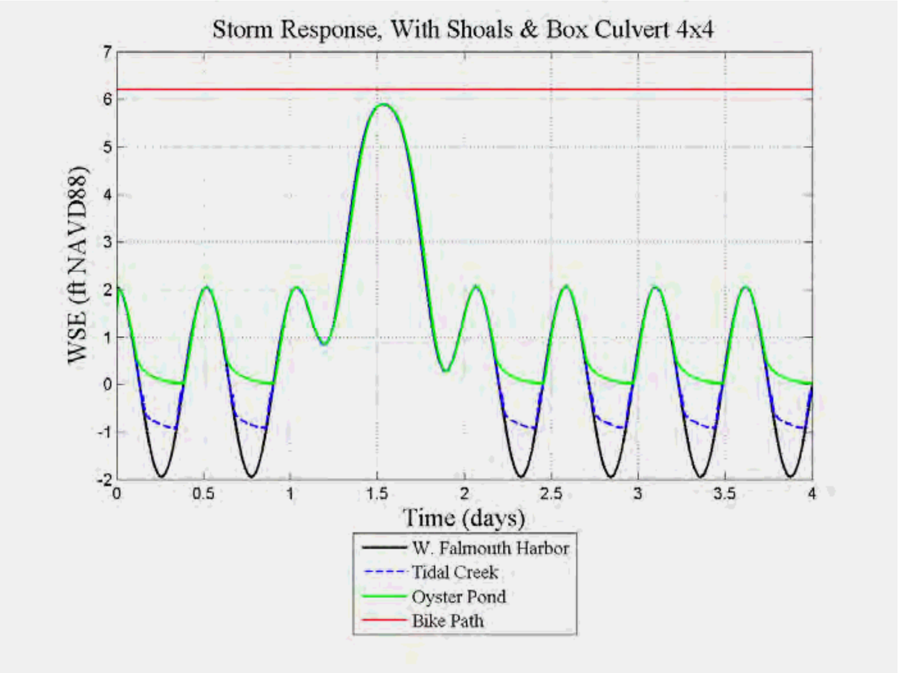

Figure 4-11. Modeled surge response to the 3-year storm a 4-by-4 ft box culvert connecting Oyster Pond to Tidal Creek.

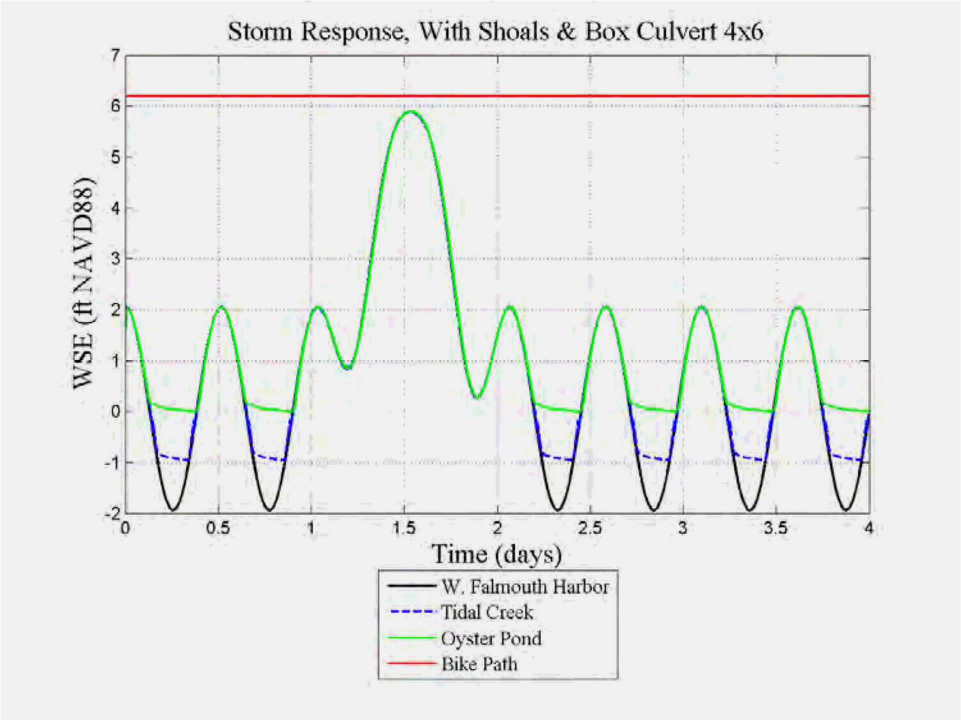

Figure 4-12. Modeled surge response to the 3-year storm a 4-by-6 ft box culvert connecting Oyster Pond to Tidal Creek.

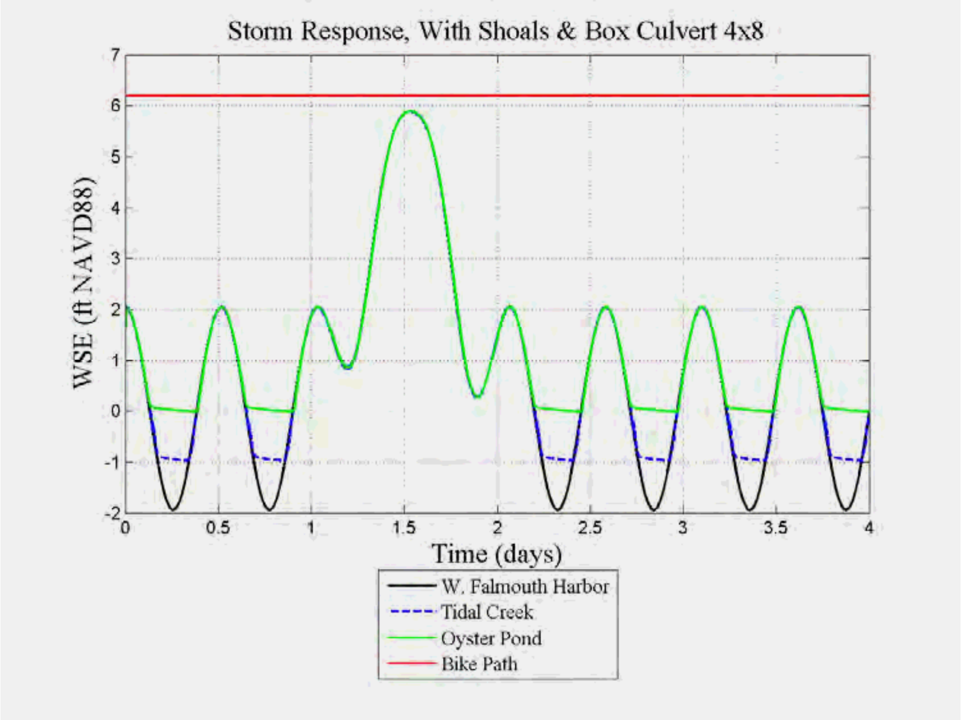

Figure 4-13. Modeled surge response to the 3-year storm a 4-by-8 ft box culvert connecting Oyster Pond to Tidal Creek with existing shoals in place.

4.2.2 Shoal Removal

This alternative evaluates the additional benefits of removing the adjacent shoals to an elevation of -1.7 ft-NAVD88 on the upstream side (Oyster Pond) and -3.5 ft-NAVD88 on the downstream side (Tidal Creek) for both 1) the existing culvert and 2) the proposed culvert. The first scenario includes the removal of the existing ebb and flood tide shoals while maintaining the existing culvert configuration. The model was used to evaluate the influence of the shoals on tidal exchange in Oyster Pond for normal tides (Figure 4-14). The results in Table 4-6 show that significant tidal prism is restored to the pond with a corresponding decrease in residence time indicating that simply removing the shoals removes much of the attenuation in the system. Simulations were then conducted for the 3-year storm event as shown in Figure 4-15, which is the largest storm event to not cause overtopping of the Shining Sea Bikeway for existing conditions. Following the 3-year storm event, the system returns to pre-inundation levels in approximately 0.25 days (one ebb cycle) for the existing culvert, which is an improvement from 1 day for existing conditions. Figure 4-16 shows the extent of inundation under normal tides for the Oyster Pond and surrounding properties for MLW (left) and MHW (right) and Figure 4-17 shows the extent of inundation for the 3-year storm.

This second scenario evaluated removal of the shoals in conjunction with replacing the existing culvert with a 4x4 box culvert to evaluate the 47-day time series provided by CCCD to assess the effect on tidal exchange in Oyster Pond for normal tides as shown in Figure 4-18. Only the 4x4 box culvert was evaluated since the culvert sizing analysis in Section 4.2.1 determined that increasing the width beyond 4 feet provides little additional tidal prism. Table 4-6 lists the tidal statistics for the existing condition and the proposed design alternatives. The increase in MHW and lowering of MLW increase the mean tidal range from 1.98 ft for the 4x4 box culvert scenario to 3.36 feet for the 4x4 box culvert with shoal removal. There is also corresponding significant increase in intertidal area and reduction in residence time. Figure 4-19 is the time series of storm response for the Tidal Creek/Oyster Pond subsystem during the 3-year event. The figure indicates the system returns to pre-inundation levels with almost no delay. Figure 4-20 shows the extent of inundation under normal tides for the Oyster Pond system and surrounding properties for MLW (left) and MHW (right) and Figure 4-21 shows the extent of inundation for the 3-year storm.

Overall, the results indicate the shoals are a major contributor to tidal attenuation within the Oyster Pond system for both normal tides and storm events. Shoaling is likely to return without maintenance. Shoal removal may not be feasible from an environmental permitting standpoint.

Table 4-6. Modeled tidal metrics and flushing characteristics comparison of existing 3.8-ft- diameter culvert at Oyster Pond and the 4x4 box culvert both with and without shoals.

Modeled Oyster Pond Tide Metrics (ft-NAVD88)					
		Existing Culvert		4x4 Box Culvert	
Tidal Metric	**Unit**	**Shoaled**	**Shoals removed**	**Shoaled**	**Shoals removed**
MHW	ft	1.31	1.79	1.98	1.98
MLW	ft	0.03	-1.03	0.00	-1.38
MTL	ft	0.67	0.38	0.99	0.30
MHHW	ft	1.45	2.03	2.21	2.21
MLLW	ft	0.01	-1.05	0.00	-1.39
Mean Range	ft	1.28	2.82	1.98	3.36
Intertidal Area	ft^2	69,830	189,430	172,825	225,530
Tidal Prism	ft^3	387,620	857,270	668,470	1,025,000
Residence Time	day	3.1	1.4	1.9	1.1
Mean Velocity (Flood)	ft/s	4.1	7.6	6.6	8.0
Mean Velocity (Ebb)	ft/s	2.2	7.0	2.3	7.0
Post Storm Recovery Time	days	1	0.25	≈ 0	≈ 0

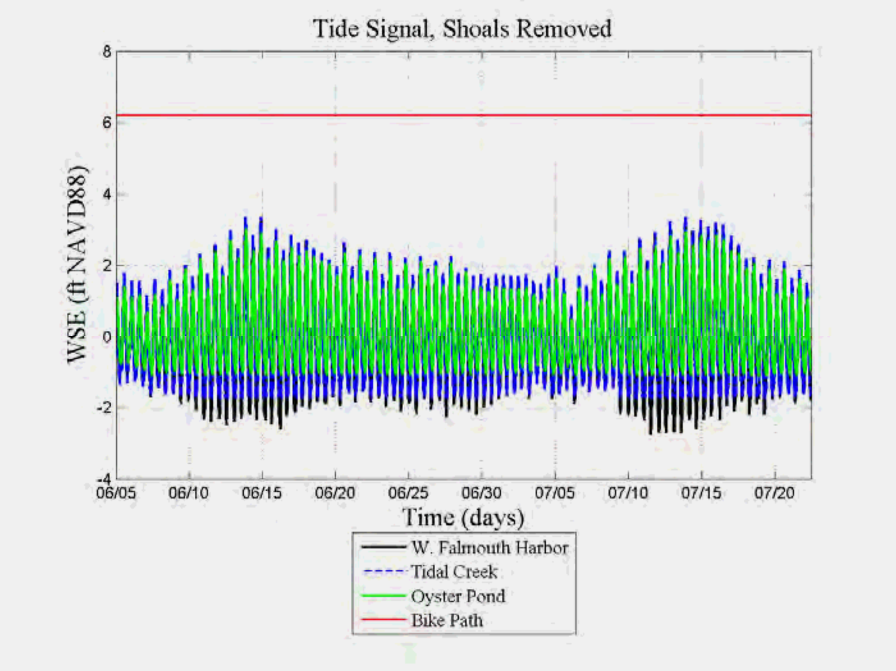

Figure 4-14. Modeled WSE for the 47-day tidal forcing signal for the existing culvert with shoals removed upstream and downstream of the Oyster Pond culvert.

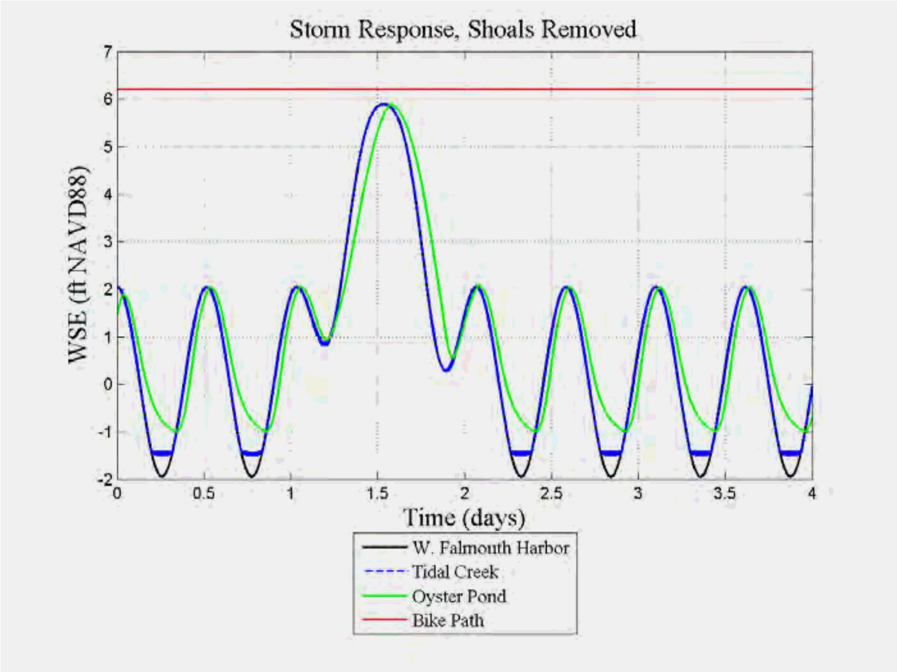

Figure 4-15. Surge response to the 3-year storm with shoals removed upstream and downstream of the Oyster Pond culvert.

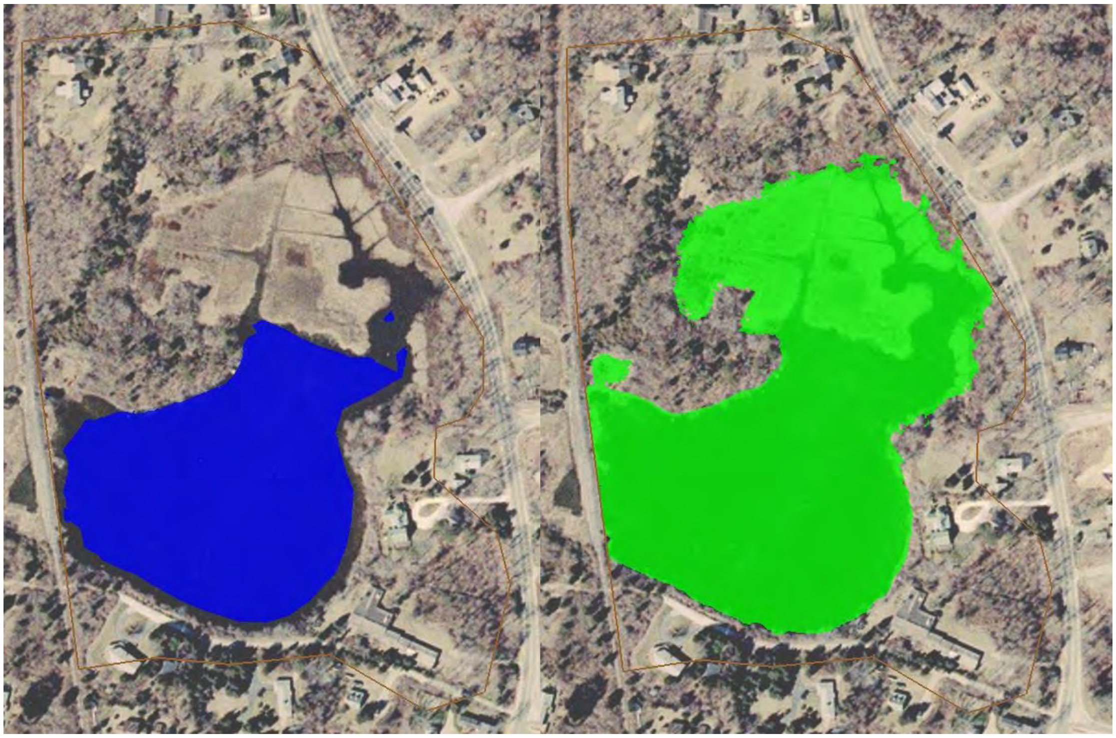

Figure 4-16. Extent of inundation at MLW (left) and MHW (right) at Oyster Pond for the existing culvert with the shoals removed. with 4.3 acres of intertidal area.

Figure 4-17. **Extent of inundation for 3-year storm at Oyster Pond for the existing culvert with the shoals removed.**

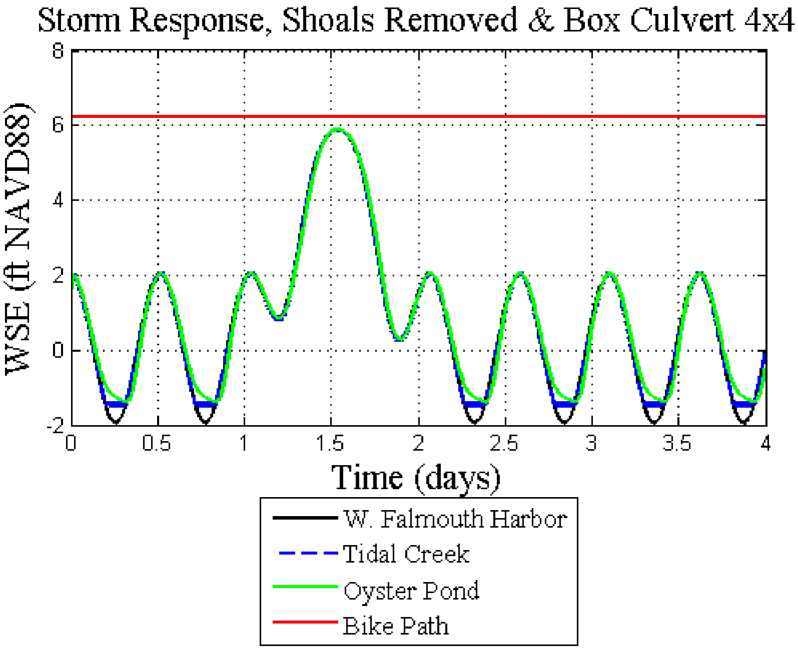

Figure 4-18. **Modeled surge response to the 3-year storm for current culvert and a 4-by-4 ft box culvert connecting Oyster Pond to Tidal Creek. In both scenarios shoals have been removed.**

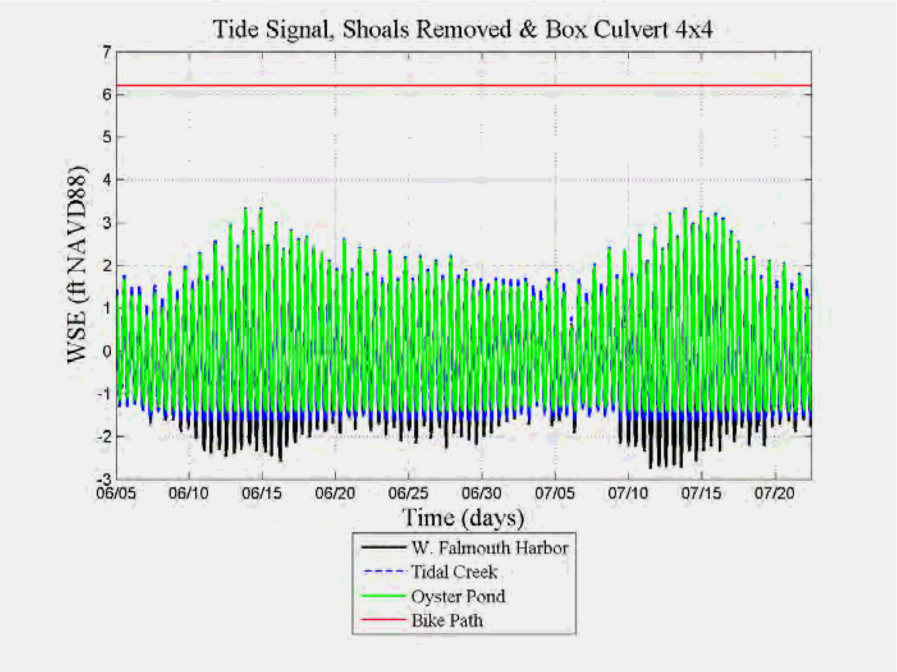

Figure 4-19. **Modeled response to the 47-day tidal forcing signal for current culvert and for a 4 ft by 4 ft box culvert connecting Oyster Pond to Tidal Creek. In both scenarios shoals have been removed.**

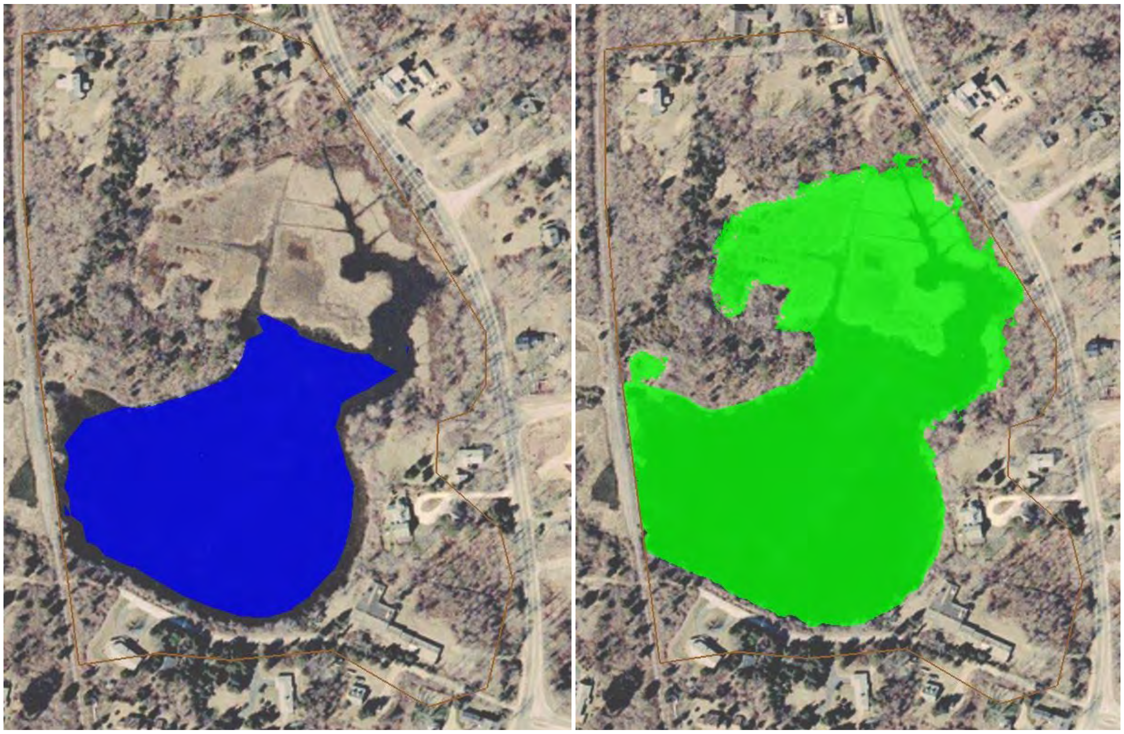

Figure 4-20. **Extent of inundation at MLW (left) and MHW (right) at Oyster Pond for the proposed box culvert with the shoals removed with 5.2 acres of intertidal area.**

Figure 4-21. Extent of inundation for 3-year storm at Oyster Pond for the proposed box culvert with the shoals removed.

5.0 SUMMARY OF RESULTS AND RECOMMENDATIONS

This report describes the development, calibration and application of an analytical hydrodynamic model for a culvert sizing analysis of two embayments within West Falmouth Harbor, Oyster Pond and Little Neck Bay, in the Town of Falmouth. The objective of the culvert sizing analysis was to determine the optimal size culvert for each system to restore maximum tidal flushing to the marsh, while managing the risk of flooding to low lying infrastructure and residential homes.

The models were setup using topographic, bathymetric, and survey data, and calibrated using tide data. The calibrated models were able to satisfy the acceptance criteria of the May 2015 QAPP Addendum for the data statistics of measured versus modeled water surface elevations for the calibration period. During storm events in both subsystems, the elevations of the roadways are lower than the 4-year storm event, with flooding of each system for storms more intense than a 3-year return period likely to be dominated by flow over the roadways rather than flow through the culverts.

The culvert sizing analysis for Oyster Pond determined that replacing the existing 3.8 ft diameter pipe with a 5’x4’ box culvert restores significant tidal prism, improves storm drainage capacity, maintains tidal velocities within the culvert to reduce shoaling potential, and addresses safety considerations with respect to head room during normal tides. Increasing the culvert width to 6-ft is a feasible option, but will provide only limited additional tidal prism while increasing construction costs. There did not appear to be increased flooding risk for the properties surrounding Oyster Pond during normal tides or the 3-year storm event (selected for analysis since storms of greater intensity are expected to overtop the Shining Sea Bikeway). The existing flood and ebb shoals were shown to cause significant attenuation of the tidal flushing for Oyster Pond, and they can be considered for removal; however, this may be difficult from an environmental permitting standpoint. Additionally, the final design should include scour protection for each end of the culvert.

The culvert sizing analysis for Little Neck Bay determined that a 4-ft diameter pipe culvert between West Falmouth Harbor and Little Neck Bay maximized the tidal prism restoration, improved the drainage capacity during large rainfall events, and addressed safety considerations. The tidal current velocities through the replacement culvert will be greater than through the existing culvert, which should reduce shoaling potential within the culvert. While Little Neck Bars Road was not overtopped during normal tides for a 4-ft diameter pipe culvert, there would be an increased risk to overtopping of Little Neck Bars Road into Shrub Bog during relatively small and more frequent storm surge events from West Falmouth Harbor. If no significant incremental risk of overtopping Little Neck Bars Road is determine to be a limiting criteria for the restoration project, then the maximum culvert size connecting West Falmouth Harbor and Little Neck Bay would be limited to 1.25-ft, which is only 0.25-ft greater than the existing culvert diameter. This would minimize incremental flooding risk for storms up to a 3-year return period; more severe storms with return periods of 4-years and greater would overtop Chapoquoit Road, presenting risk of flooding in Shrub Bog regardless of the culvert connecting Little Neck Bay and West Falmouth Harbor. Considering that the water surface elevations of limiting storm events and that Chapoquoit Road will be inundated below the FEMA 10-year surge level (i.e., 4-year and greater), Little Neck Bars Road is likely to be overtopped whether the culvert is replaced or not. If the larger 4-ft diameter culvert is selected, then the installation of a flap gate at the culvert entrance at Chapoquoit Road and/or Shrub Bog should be considered to protect the upland infrastructure and ecosystems.

6.0 REFERENCES

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