# Mill Pond Restoration
# Conceptual Design Report
# Truro, Massachusetts

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**Prepared for: Cristina Kennedy**
Division of Ecological Restoration
Massachusetts Department of Fish & Game
251 Causeway Street, Suite 400
Boston, MA 02114
(617) 626-1246

**Prepared by: Mitchell Buck, P.E. & Anneliese Schmidt**
Woods Hole Group
A CLS Company
107 Waterhouse Road
Bourne, MA 02532 USA
(508) 540-8080 x210

**With Project Partners: Nils Wiberg, P.E. & Sean Arruda, P.E.**
Fuss & O'Neill, Inc.
317 Iron Horse Way #204
Providence, RI 02908 USA
(401) 861.3070 x4559

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# 1. INTRODUCTION AND BACKGROUND

The work in this report was completed by The Woods Hole Group, Inc. and project partners Fuss & O'Neill for the Division for Ecological Restoration (DER) and Town of Truro under agreement RFR DER 2019-01. The goal of this study was to develop several conceptual restoration alternatives for the undersized culvert under Mill Pond Road, and then select a preferred alternative with the clients and stakeholders to pursue for eventual construction.

## 1.1. Background

The purpose of this project is to investigate restoring tides and improving storm drainage for Mill Pond by replacing an undersized culvert under Mill Pond Road. This current study will expand on previous work by Woods Hole Group and the Louis Berger Group by developing and evaluating four (4) restoration alternatives using hydrodynamic models based on collected field data. An alternatives analysis will then be conducted to evaluate the improvements to tides and storm drainage while also assessing their impacts to habitat, private property, and the general public. Recommendations on selecting a preferred alternative will be made, and the eventual alternative selected for construction will need to be decided by the client and stakeholders.

Mill Pond is a shallow coastal embayment in Truro, Massachusetts, that is connected to the Pamet River Basin through a culvert underneath Mill Pond Road, and a breach in an abandoned railway berm (Figure 1). The Pamet River Basin includes the Pamet River, Little Pamet River, and Eagle Neck Creek, which are in various phases of restoration by the Town of Truro (Truro) and The Woods Hole Group, Inc. The area of interest for this Scope of Work (SOW) as shown in Figure 1 includes Mill Pond upstream of the Mill Pond Road culvert (yellow outline), the shallow embayment downstream between Mill Pond Road and an abandoned railroad berm (red outline, referred to as "middle basin"), and the breach through the berm that connects the system with Pamet Harbor (purple outline). The Town and the Truro Conservation Trust own the land surrounding the Mill Pond culvert. The downstream side of the former railroad bed is owned by the Pamet Harbor Yacht Club and the upstream side is owned by several private property owners.

The project encompasses two potential tidal restrictions, one at the Mill Pond Road crossing and the second at the former railroad bed breach. Mill Pond Road crossing consists of a 36-inch diameter pipe underneath Mill Pond Road, which is undersized and has led to degradation of the salt marsh habitat upstream in Mill Pond. A second potential tidal restriction occurs at the breach through the former railroad berm that was shown to be a tidal restriction for Eagle Neck Creek restoration project to the south. This has resulted in Mill Pond being recognized as TR-2 in the Cape Cod Atlas of Tidally Restricted Salt Marshes, identified as TR-SM-2 on the Cape Cod Water Resources Restoration Project, and was approved as a DER Priority Project in 2011 (RFR DER 2011-01). Subsequently, the Mill Pond culvert structure was heavily flooded and damaged during the winter 2018 storm season and the Town of Truro is concerned that this culvert structure is at risk to future storm damage and even failure. The Town, with assistance from DER, now seeks to conduct a field investigation as a first step towards assessing potential culvert replacement or flow control alternatives to reduce storm flooding and drainage damage while also providing ecological restoration of salt marsh habitat.


**Figure 1.** **Overview of the Pamet River Basin showing Mill Pond (yellow outline), the downstream middle basin (red), and Pamet Harbor junction (purple). Also shown are Pamet River, Little Pamet River, and Eagle Neck Creek to the south.**

## 1.2. History of Mill Pond

A review of historical records revealed that Mill Pond has been tidally restricted since the late 1700s, when a “grist mill” was built just North of the current culvert location (Figure 2). This grist mill was operational until 1859 (Richards, 2021; video link https://youtu.be/ukBAVDtK4W4).

The railroad berm, which runs between the middle basin and Pamet harbor, was built in 1869 and was in operation until the 1960s (MassMoments). The berm blocked flow into the middle basin and Mill Pond, until it was breached during a storm in 1978. The berm was further eroded during a storm of 1991. The culvert under Mill Pond Road was also damaged during the 1991 storm and was replaced with a temporary 3-foot diameter pipe, which is still in place today (Louis Berger Group, 2013). Further damage was reported in 2018, which has led to the current study.

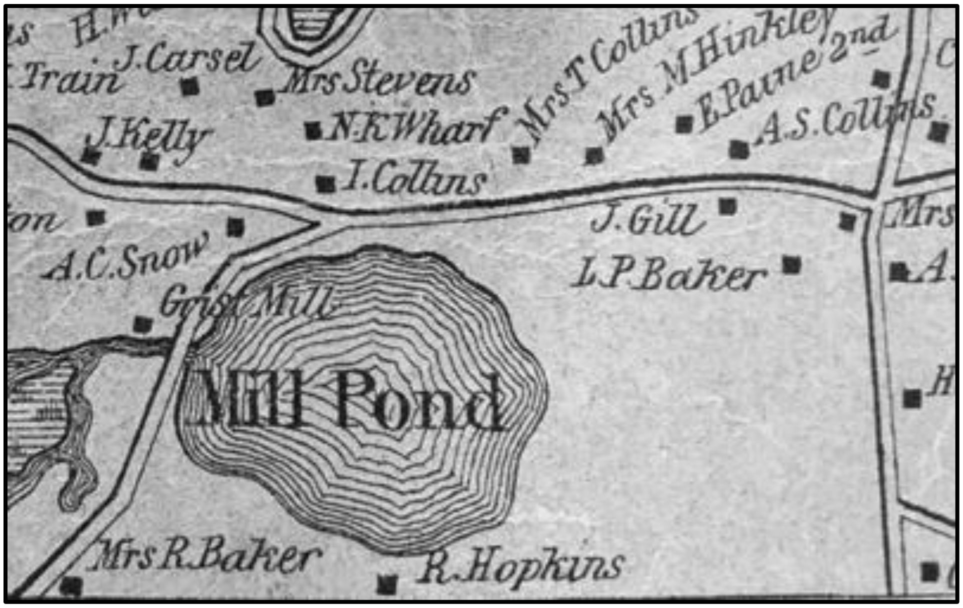


**Figure 2. Historic 1858 Map of Mill Pond (Richards, 2021).**

## 1.3. Priors Studies

The Louis Berger Group previously investigated the Mill Pond system with the intentions of replacing the culvert to restore tidal flow. The available documents which are the result of that work are:

- *Mill Pond Tidal Assessment Truro, Massachusetts* prepared by Geosyntec Consultants (June 2011)
- *Mill Pond Mill Pond Road Partial Topographic Survey* prepared by Bryant Associates and the Louis Berger Group (June 27, 2012).
- *Mill Pond Restoration Project Cover Type Map and Report* prepared by the Louis Berger Group for the Department of Fish and Game Division of Ecological Restoration (June 2012).
- *Hydraulic Modeling Report for Mill Pond Restoration Project* prepared by the Louis Berger Group for the Cape Cod Conservation District (January 2013).
- *Mill Pond Restoration Hydraulic Modeling: 15-foot by 7-foot Concrete Culvert Analysis* prepared by the Louis Berger Group (June 19, 2013).

These field investigations included the collection of topographic, tide, and vegetation coverage, and the results were used within a hydraulic model, HEC-RAS 1D, to develop restoration alternatives.

Louis Berger Group modeled several culvert replacement alternatives using HEC-RAS 1D including a 7-foot high box culvert with varying widths of 6, 9, 10, and 15 feet. The model was run in unsteady state mode for tides and was calibrated and verified using the collected tide data. Results showed significant improvements to tidal hydraulics with the smallest alternative (6’Wx7’H) as summarized in Table 1, with the larger culverts eliminating tidal dampening and phase delay. Sea level rise was evaluated based on values determined by the Army Corp in 2011 and therefore needed to be updated to reflect the currently accepted projections.

**Table 1. Louis Berger Group 2013 model results for culvert replacement alternatives.**

| Model Scenario | Tidal Dampening (feet) | Phase Delay (minutes) |
|---|---|---|
| Existing Conditions | 1.90 | 102 |
| 6’W x 7’H culvert | 0.46 | 24 |
| 9’W x 7’H culvert | 0.02 | 0 |
| 10’W x 7’H culvert | 0 | 0 |
| 15’W x 7’H culvert | 0 | 0 |

### 1.4. Purpose of Study

The purpose of this project is to investigate restoring tides and improving storm drainage for Mill Pond by replacing an undersized culvert under Mill Pond Road. This current study will expand on previous work by Woods Hole Group and the Louis Berger Group by developing and evaluating four (4) restoration alternatives using hydrodynamic models based on collected field data. An alternatives analysis will then be conducted to evaluate the improvements to tides and storm drainage while also assessing their impacts to habitat, private property, and the general public. Recommendations on selecting a preferred alternative will be made, and the eventual alternative selected for construction will need to be decided by the client and stakeholders.

## 2. FIELD INVESTIGATIONS

Field investigations were collected previously by the Louis Berger Group, however, the Woods Hole Group determined that updated and supplemental field data were needed to fulfill anticipated future engineering design and permitting needs. Additionally, much of the older field data was not available in an electronic format. Therefore, a preliminary field investigation was conducted by the Woods Hole Group in 2021, which collected supplemental and updated data needed for evaluating replacement alternatives. Refer to Preliminary Field Investigation for Mill Pond Restoration Project Memo (dated June 30, 2021) for more detailed information, and summary of the data used within this report are described herein. For the tide study consisted of three (3) conductivity, temperature, and pressure (CTD) instruments that were deployed in Pamet Harbor (MP3), the middle basin (MP2), and Mill Pond (MP1), which recorded salinity, water temperature and water surface elevations over a lunar cycle (~30 days). Time series of the tidal study show closely matching water levels in the harbor and middle basin, and a damped signal in Mill Pond (Figure 3). The tides in the Pamet Harbor are semi-diurnal, with a spring-neap cycle. The middle basin is connected to Pamet Harbor through the breach in the railroad berm. Mill Pond is connected to the middle basin by a 3-foot diameter circular culvert, which is 53 feet long, running under Mill Pond Road. The invert elevations are 1.61 (downstream) and 2.03 (upstream) feet NAVD88. There are large scour holes on either side of the culvert between Mill Pond and the middle basin, which are caused by water exiting the culvert at high speeds. Due to these scour holes, the invert elevations of the culvert are lower than the pond bed in Mill Pond. There are tidal flats and salt marsh in the middle basin, and salt marsh in Mill Pond around the culvert outlet and the perimeter of the Pond. The collected tide data (Figure 33) shows that the middle basin has full tidal range, indicating the breach in the railroad berm is large enough to allow full tidal flow in the middle basin. The tidal signal in Mill Pond is attenuated by the undersized culvert as shown by the tidal datums developed from the 2021 field investigation for Mean Higher High Water (MHHW), Mean Higher Water (MHW), Mean Tide Level (MTL), Mean Low Water (MLW), Mean Lower Low Water (MLLW), and Mean Tide Range (MR) in Table 2.

Table 2. Tidal datums calculated for the CTD instruments deployed at Pamet Harbor, Mill Pond, and the Middle basin in 2021.

| Location | Station | MHHW | MHW | MTL | MLW | MLLW | Mean Tide Range |
|---|---|---|---|---|---|---|---|
| | | Feet-NAVD88 | | | | | Feet |
| Harbor | MP-1 | 4.97 | 4.47 | -0.11 | -4.70 | -5.13 | 9.17 |
| Middle Basin | MP-2 | 5.12 | 4.64 | 0.68 | -3.27 | -3.30 | 7.91 |
| Mill Pond | MP-3 | 2.90 | 2.76 | 2.03 | 1.30 | 1.27 | 1.46 |

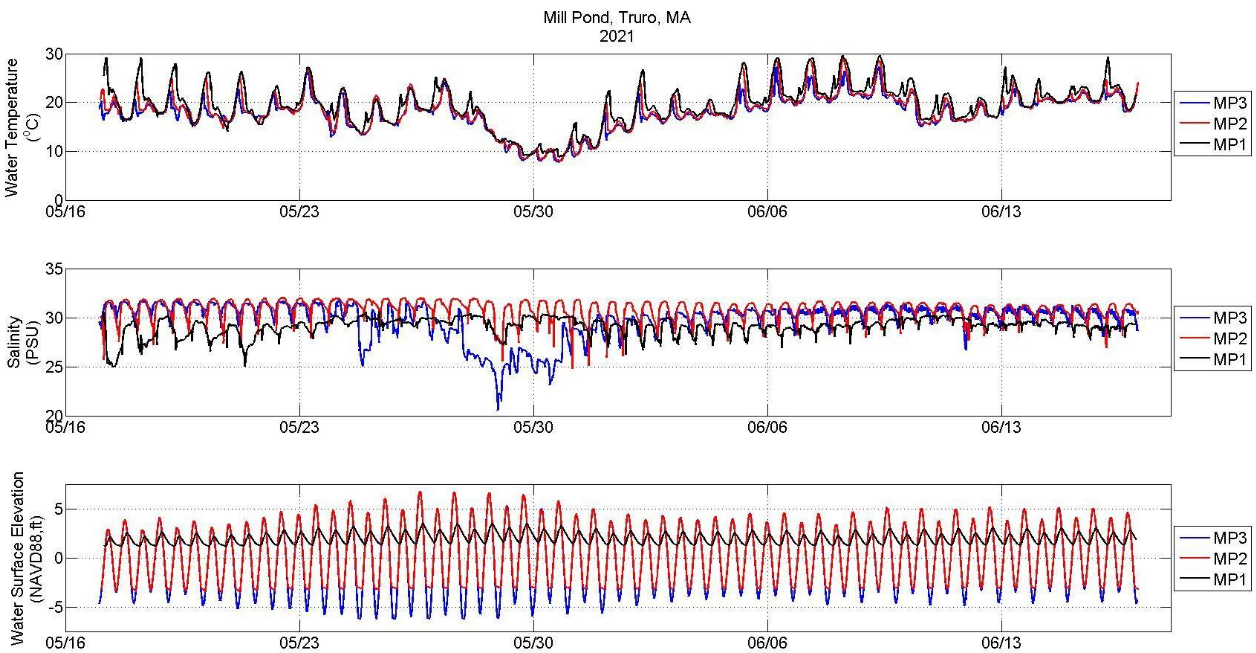


Figure 3. Time series of the data collected by the CTD instruments. From top to bottom: Water temperature, Salinity, and water surface elevation. MP1 is in Mill Pond, MP2 in the middle basin, and MP3 in the harbor. Note that a rainstorm at the end of May decreased salinity for several days.

Topographic and bathymetric surveys of the Mill Pond, middle basin, and Pamet Harbor were also conducted to collect elevation data needed for engineering design. These collected data sets were processed in CAD and ArcGIS to create a topobathymetric map of Mill Pond system (Figure 4). A coastal resources delineation was also conducted in 2021 by a Woods Hole Group Professional Wetland Scientist (PWS) who delineated coastal beach, salt marsh, and bordering vegetated wetland (BVW), and the approximate location toe of the coastal bank (Figure 5). Approximately 3 acres of saltmarsh resource area was delineated within Mill Pond. Additionally, Mill Pond is located within the FEMA regulatory floodway, specifically an AE12 flood zone, which means that it is also located with Land Subject to Coastal Storm Flowage (LSCSF). Additionally, geotechnical soil borings were collected at Mill Pond in and analyzed by a laboratory in 2021, and the results were utilized within a geotechnical analysis in this study by Fuss & O'Neill.

As part of the 2022 scope of work, a survey was conducted by a Woods Hole Group Professional Land Surveyor (PLS) to locate drinking water wells and septic systems on abutting properties for which information was available and that could be located in the field. Locating these systems will allow for the determination of impacts, if any, associated with restored tides or storm flooding from the alternatives. A plan titled *Existing Septic and Well Locations of Properties in Vicinity of Mill Pond Road* was created that shows the location of drinking water wells and septic systems and is included in Attachment A.

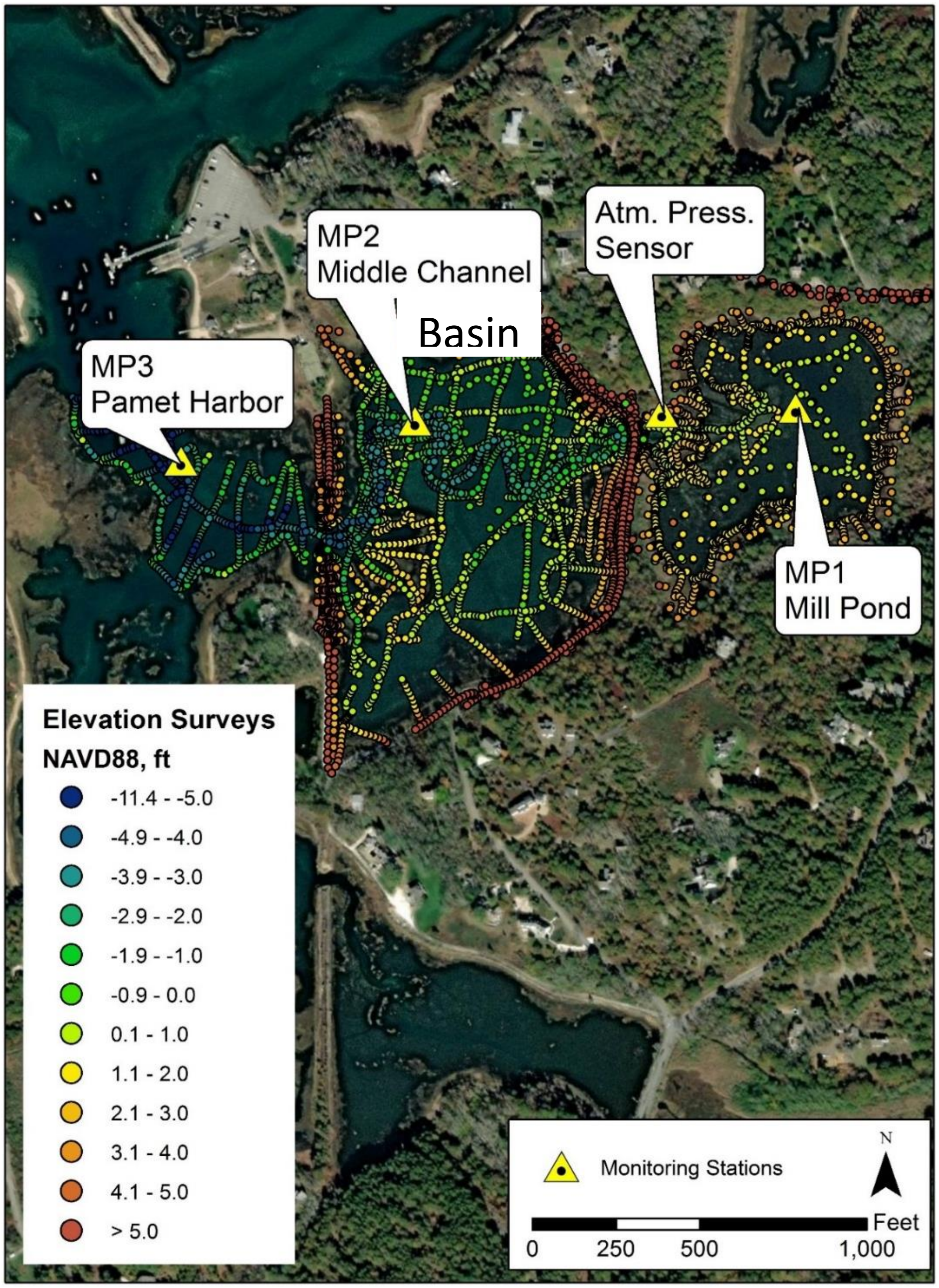


**Figure 4.** **Map showing the locations of the CTD instruments deployed for the tide study and coverage of the topographic and bathymetric surveys in 2021.**

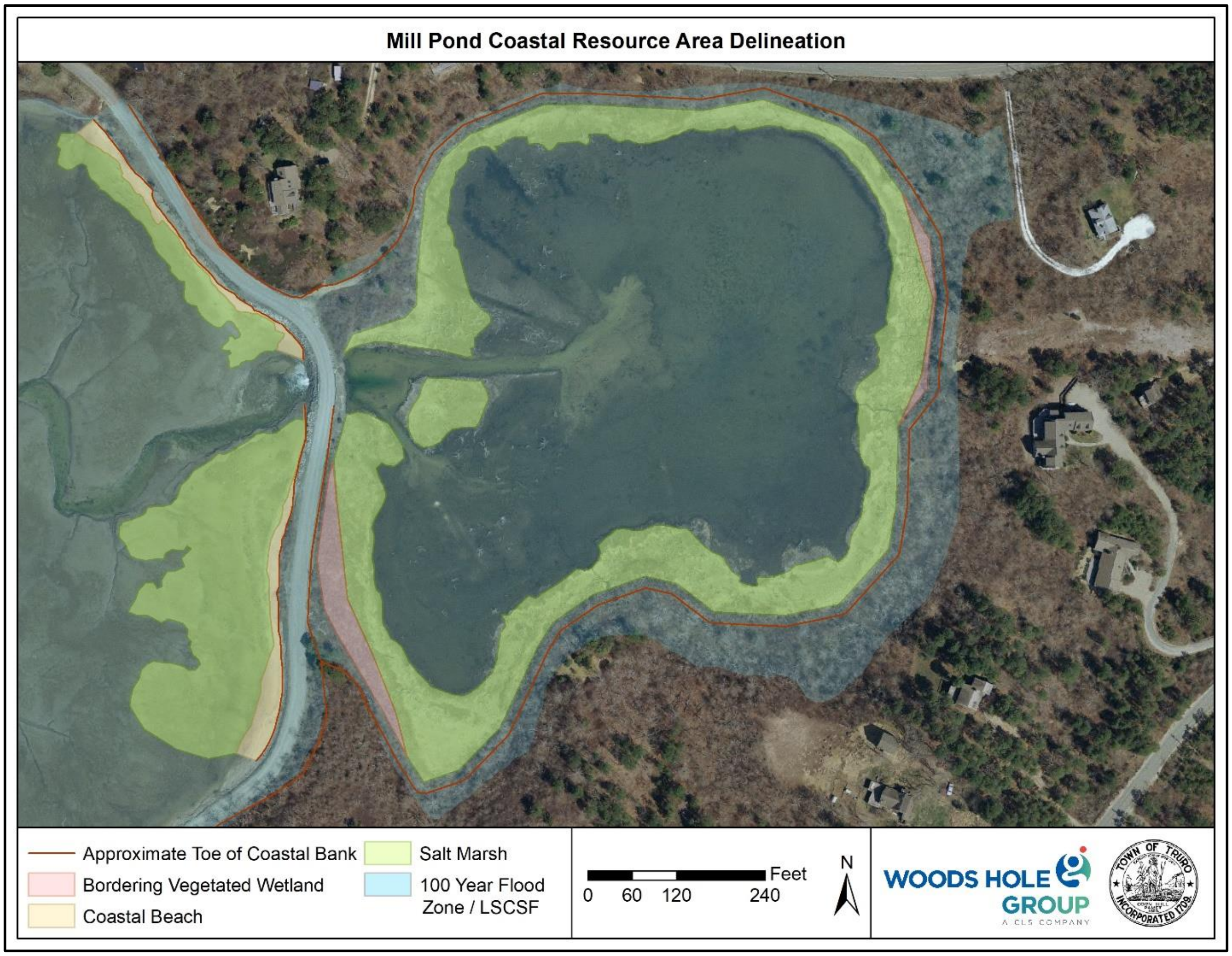


**Figure 5. Coastal resource areas delineated in 2021 along Mill Pond Road and Mill Pond basin.**

## 3. HYDRODYNAMIC MODEL

A stepped one-dimensional (1D) and two-dimensional (2D) hydrodynamic model approach was employed to understand the system. First, a hypsometric model was utilized for the 1D approach, which uses water levels, culvert dimensions, and basin geometry to determine the water level response in the basin. This model was calibrated and used to determine the size of the opening(s) needed to restore tidal flow and drainage to Mill Pond. These results were then used to refine the development of alternatives for the 2D model that can more accurately capture the geometry and hydrodynamics of the complicated Mill Pond system.

### 3.1. Hypsometric Model for Culvert Replacement Sizing

The 1D hypsometric model is an in-house developed model implemented through MATLAB. The model is based on hypsometric curve for a given basin, which is a cumulative distribution function of elevation (topography and bathymetry) used to determine basin volume relative to water levels. Hypsometric curves were previously developed for both the Mill Pond and Middle basin basins based on the topography and bathymetry collected in 2021, which is reproduced below in Figure 6.

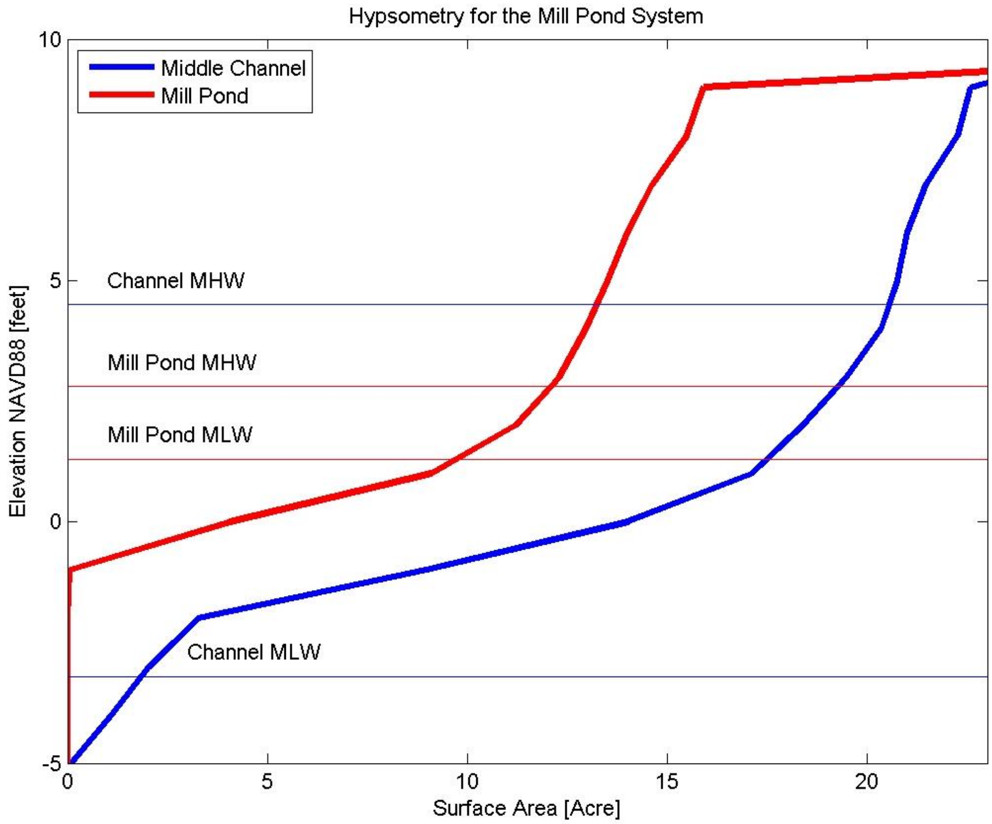


**Figure 6. Hypsometric curves for Mill Pond and the downstream Middle Basin plotted with their respective MLW and MHW tidal datums.**

The technical approach utilized by the hypsometric model involves a simple procedure for calculating the tidal response in a marsh or pond connected to the ocean by a full or partial opening. The assumptions are that the sea level in the marsh is independent of position, i.e. is constant throughout the marsh, and that the flow through the culvert is described by a standard hydraulic head-loss relationship, depending on the type of flow control structure and depth of flow. Possible flow control structures include a bridge structures, circular pipe culverts, box culverts, weirs, arches, and open channels that are either rectangular or triangular in cross-section. The hydraulic computations for the marsh system are based on the volume conservation equation for the water in each marsh basin:

$$A_{marsh} \frac{dh_{marsh}(t)}{dt} \; Q_{culvert} \qquad \text{Eq. 1}$$

where $t$ is time

$A_{marsh}$ is the surface area of the marsh basin

$h_{marsh}(t)$ is the time-varying water surface elevation in the basin

$Q_{culvert}(t)$ is the volume flow rate

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

$$A(h_{marsh})\frac{dh_{marsh}}{dt} = Q_{culvert} \quad \text{Eq. 2}$$

$$Q_{culvert} = -au \quad \text{Eq. 3}$$

The surface area of the marsh $A$ is prescribed as a function of marsh $h$ 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 ocean (i.e., downstream). For circular or rectangular pipe culverts, it is straightforward to calculate the relevant geometric parameters required to determine the velocity (cross-sectional area $a(t)$, the wetted perimeter P, and hydraulic radius r).

Using the measured water surface elevation in the middle basin as a boundary condition, and the above equations, we can obtain the flow volumes and velocities through a culvert and water surface elevations in Mill Pond. In calibration of this model, it was found that the invert elevation of the culvert inlet is lower than the bottom elevation of Mill Pond bed, which means that there is the potential for the pond bed to go dry at low tide. However, it was also found that that there is a island at the pond outlet that acts as a weir and drains water through a narrow channel downstream to the Mill Pond culvert inlet (Figure 7). When the water level in the pond is low and the tide going out, the flow through the culvert is controlled by the flow around the island that acts a weir (Figures 8). The equations governing weir flow using Bernoulli are as follows:

$$\boldsymbol{K = 0.4 + 0.5\frac{h}{b}} \quad \text{Eq. 4}$$

$$\boldsymbol{Q = \sqrt{32.2 * 2} * b * h^{\frac{3}{2}}} \quad \text{Eq. 5}$$

$$\boldsymbol{A = b * h} \quad \text{Eq. 6}$$

$$\boldsymbol{V = \frac{Q}{A}} \quad \text{Eq. 7}$$

Tidal flow through the culvert utilized the Manning's flow equations as follows:

$$\boldsymbol{K = 1.49} \quad \text{Eq. 8}$$

$$\boldsymbol{V = \frac{k}{n} * r^{\frac{2}{3}} * (\frac{h}{l})^{\frac{1}{2}}} \quad \text{Eq. 9}$$

$$\boldsymbol{Q = V * A} \quad \text{Eq. 10}$$

Where K is a constant, h is the head difference between the culvert entrance and exit, b the width of the weir, n manning's n, a friction coefficient, r the hydraulic radius, l the length of the culvert, and A the area of flow. The equations solve for either the flow, Q, or the flow velocity, V, and use continuity (equations 7 and 10) to solve for the other.

This 1-D model is computationally efficient and can be run for a variety of culvert sizes to optimize the geometry of the connection to return tidal flow to Mill Pond.

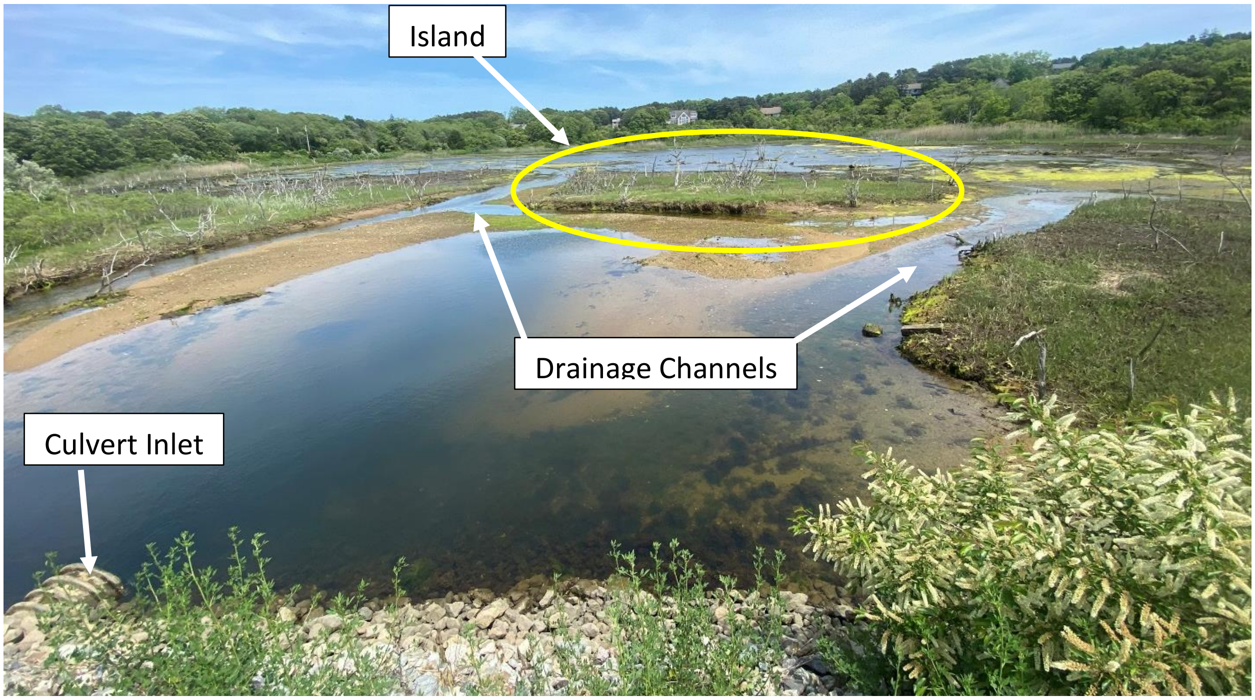


**Figure 7. Photo of the Mill Pond culvert inlet (bottom left), the island (yellow circle) that acts as a weir, and the drainage channels around it.**

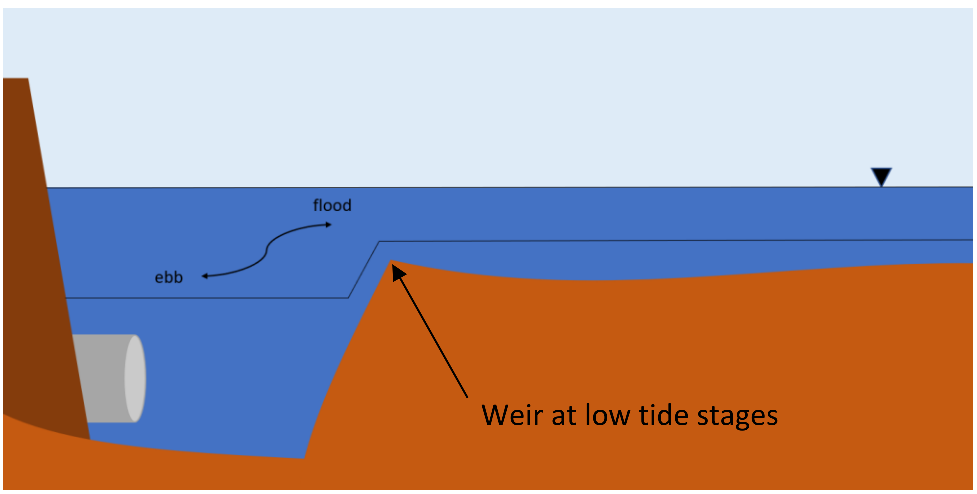


**Figure 8. Sketch of the culvert through the embankment and into Mill Pond, the invert is at a lower elevation than the bed of the pond, which causes a weir effect over the island and into the scour pit that impedes full drainage. Note the graphic is not to scale.**

### *3.1.1. Calibration*

Calibration of the hypsometric model involved varying the geometry, height, and width, of the weir, the threshold at which the outgoing flow switches from pipe flow to weir flow, and the Manning's *n* value for friction for pipe flow and for the mixed weir and pipe flow. Final values and goodness of fit parameters are provided in Table 3.

**Table 3. Input parameters and output model statistics for the 1-D hypsometric model**

| Parameter | Value | Units |
|---|---|---|
| **Input Parameters** | | |
| Manning's n | 0.065 | -- |
| Manning's n (mixed flow) | 0.1 | -- |
| Length culvert | 53 | feet |
| Diameter culvert | 3 | feet |
| Culvert invert elevation | -1.6 | feet NAVD |
| Weir height | 0.8 | feet |
| Weir width | 6 | feet |
| % weir, % pipe flow | 90, 10 | % |
| **Output Parameters** | | |
| Threshold | 1.4 | feet |
| RMSE | 0.092 | feet |
| bias | -0.0046 | feet |

Goodness of fit parameters are the root mean square deviation (RMSE) and bias.

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum(\boldsymbol{P_{mod}} - \boldsymbol{P_{obs}})^2}{\boldsymbol{n}}} \quad \text{Eq. 11}$$

$$\boldsymbol{Bias} = \frac{\sum \boldsymbol{P_{mod}} - \boldsymbol{P_{obs}}}{\boldsymbol{n}} \quad \text{Eq. 12}$$

Where $P_{mod}$ are the modeled points, $P_{obs}$ the observed points, and $n$ the number of sample points. With these parameters, the modeled water levels are representative of the observed water levels (Figure 9). The model slightly underestimates the water levels during larger tides, as seen in the figure and by the negative bias value. The RMSE indicates that our modeled values lie on average within 0.09 feet, or 1.1 inches, of the observed values, which is considered a very good fit.

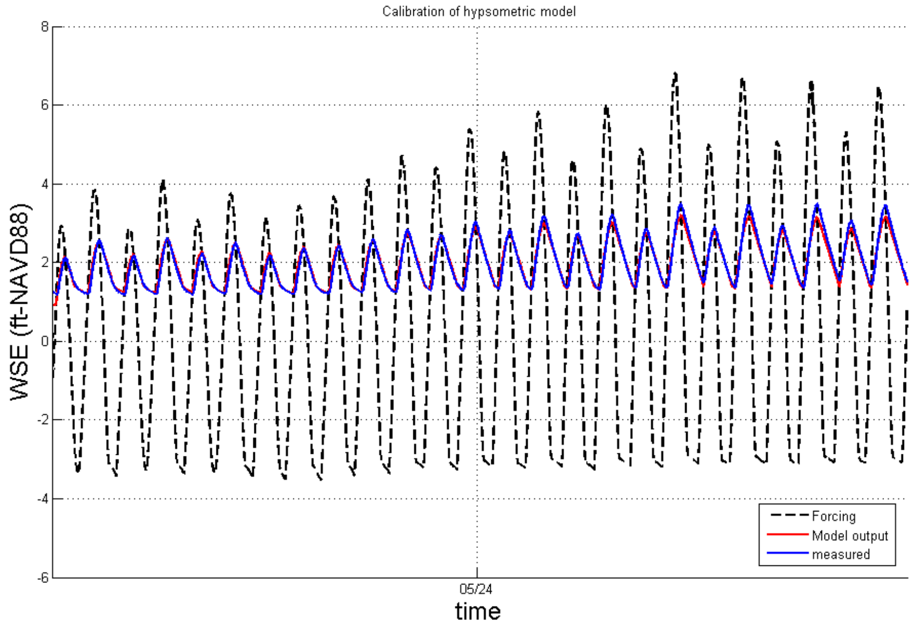


**Figure 9. Boundary conditions at Pamet Harbor compared to measured and modeled water levels in Mill Pond based on the hypsometric model.**

### *3.1.2. Results*

The hypsometric model was run for a suite of culvert widths ranging from the existing diameter, three feet, and up to 14 feet where the restoration results plateaued. Tidal flow was considered to be restored when the tidal datums in Mill Pond match the water level downstream and there is little to no phase lag between the tidal signals. A 7 ft culvert height was selected initially based on the results of the prior modeling study by Louis Berger Group. Then the hypsometric model was used to evaluate a range of culvert heights, which determined that a taller culvert did not provide any additional tidal restoration upstream in Mill Pond. The results of the hypsometric modeling for the 7-foot high culvert are shown in Figure 10 that plots culvert widths relative to the restored tidal datum elevations in Mill Pond. The hypsometric model results generally indicated the following:

- The high tide elevations for MHW and MHHW increase dramatically as the culvert size increases from the existing 3 foot width to about an 8 foot width and then plateau at the 10-ft culvert width. For a 10-ft wide culvert, the MHW and MHHW datums generally match upstream and downstream of the culvert, and, therefore, culvert widths greater than 10-feet are not likely to provide any further tidal restoration.
- These results corroborate the results of the HEC-RAS 1D modeling conducted by Louis Berger Group, which indicated that a 10-ft wide culvert effectively eliminates tidal dampening.
- An 8-foot wide culvert restores tidal datums to within a few tenths of a foot as compared to the 10-ft wide culvert.
- While there are significant gains for the high tide elevations (MHW & MHHW) in Mill Pond, the low tides do not see similar improvements as the MLW elevation only decreases by a few tenths of a foot. This appears to be related to the weir effect that the island has on limiting drainage from the pond to the culvert inlet.

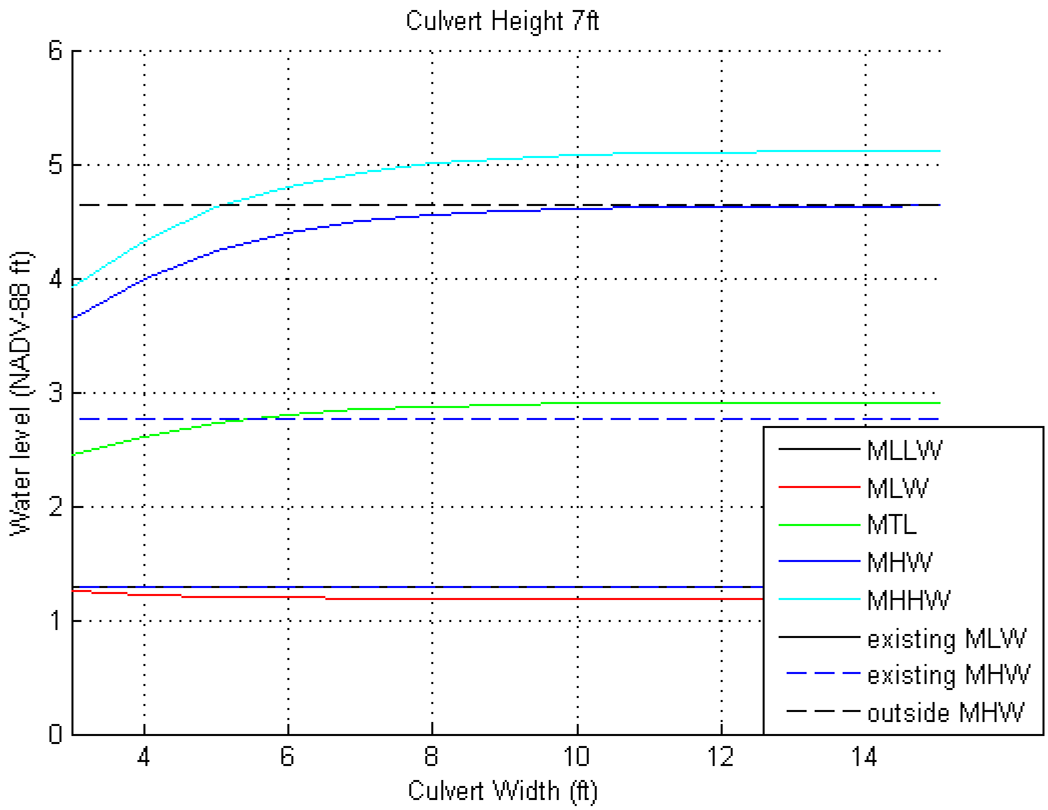


**Figure 10. Hypsometric model results for tidal datums in Mill Pond corresponding to various alternative culvert widths.**

### 3.2. HEC-RAS 2D Model Development, Calibration, and Validation

Woods Hole Group utilized the US Army Corps of Engineers model HEC-RAS (Brunner, 1995) to simulate two-dimensional (2D) unsteady flow that accounts for tides within the Mill Pond system. The 2D version of HEC-RAS uses a finite-volume solution scheme based on a computational grid mesh instead of the interconnected riverine channel cross-section approach utilized by the one-dimensional (1D) version HEC-RAS employed by Louis Berger Group. While HEC-RAS 1D can still be applicable to Mill Pond system, HEC-RAS 2D is a newer version that tends to perform better in tidal systems where the interconnected grid mesh can capture complex multidirectional flows in channels and marshes due to tidal forcing.

HEC-RAS 2D solves the conservation of mass and the shallow water equations (SWEs) with simplifying assumptions (Equations 10, 11 and 12, respectively). The equations are discretized on a non-uniform cartesian grid using a finite-volume formulation. HEC-RAS is widely used for 2D unsteady flow simulations to aid in engineering projects of roadway crossings with hydraulic openings.

$$\frac{\delta H}{\delta t} + \frac{\delta(hu)}{\delta x} + \frac{\delta(hv)}{\delta y} + q = 0 \qquad \text{Eq 13}$$

Where u and v are velocities in the northward and eastward directions, t is time, x and y are cartesian coordinates, H (h) is the depth, and q is the source/sink flux.

$$\frac{\delta v}{\delta t} + u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} = -g\frac{\delta H}{\delta y} + v_t\left(\frac{\delta^2 v}{\delta x^2} + \frac{\delta^2 v}{\delta y^2}\right) - c_f v + fu \qquad \text{Eq 14}$$

$$\frac{\delta u}{\delta t} + u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} = -g\frac{\delta H}{\delta x} + v_t\left(\frac{\delta^2 u}{\delta u^2} + \frac{\delta^2 v}{\delta y^2}\right) - c_f u + fv \qquad \text{Eq 15}$$

Where u and v are velocities in the northward and eastward directions, t is time, x and y are cartesian coordinates, $c_f$ is the bottom friction coefficient, and f is the Coriolis parameter.

In the configuration for this modeling effort, the Diffusion-Wave form of the SWEs was used in place of the full-momentum equations, forming a one-equation model (Eq. 4). This form can be used under the assumption that velocity is a function of the balance between the pressure gradient (from tidal forcing at the boundary) and the bottom friction (represented using Manning's n).

$$V = \frac{-\left(R(H)\right)^{2/3}}{n}\frac{\nabla H}{|\nabla H|^{1/2}} \qquad \text{Eq 16}$$

Where V is the velocity vector, R is the hydraulic radius, H is the surface elevation gradient, and the Manning's *n*.

The grid used for this modeling effort has a resolution of 25 meters (Figure 11, top) with a refinement region to a 10-meter resolution around the culvert (Figure 11, inset). The grid cell elevations were extracted from the collected topographic and bathymetric survey data in 2021, which was supplemented with the 2016 Massachusetts Digital Elevation Model (DEM) that is a compilation of the latest publicly available LiDAR and bathymetric data sets. The culvert location, diameter, and invert elevations were established in the model. A weir was placed along the road since it acts as a weir when overtopped. Two additional weirs were placed across the two channels that drain Mill Pond to the culvert inlet (Figure 7), which captures the behavior of the flow of water to the scour hole (Figure 11). The scour holes themselves had to be inserted by manually lowering the bottom elevation, since these were not captured in the elevation data.

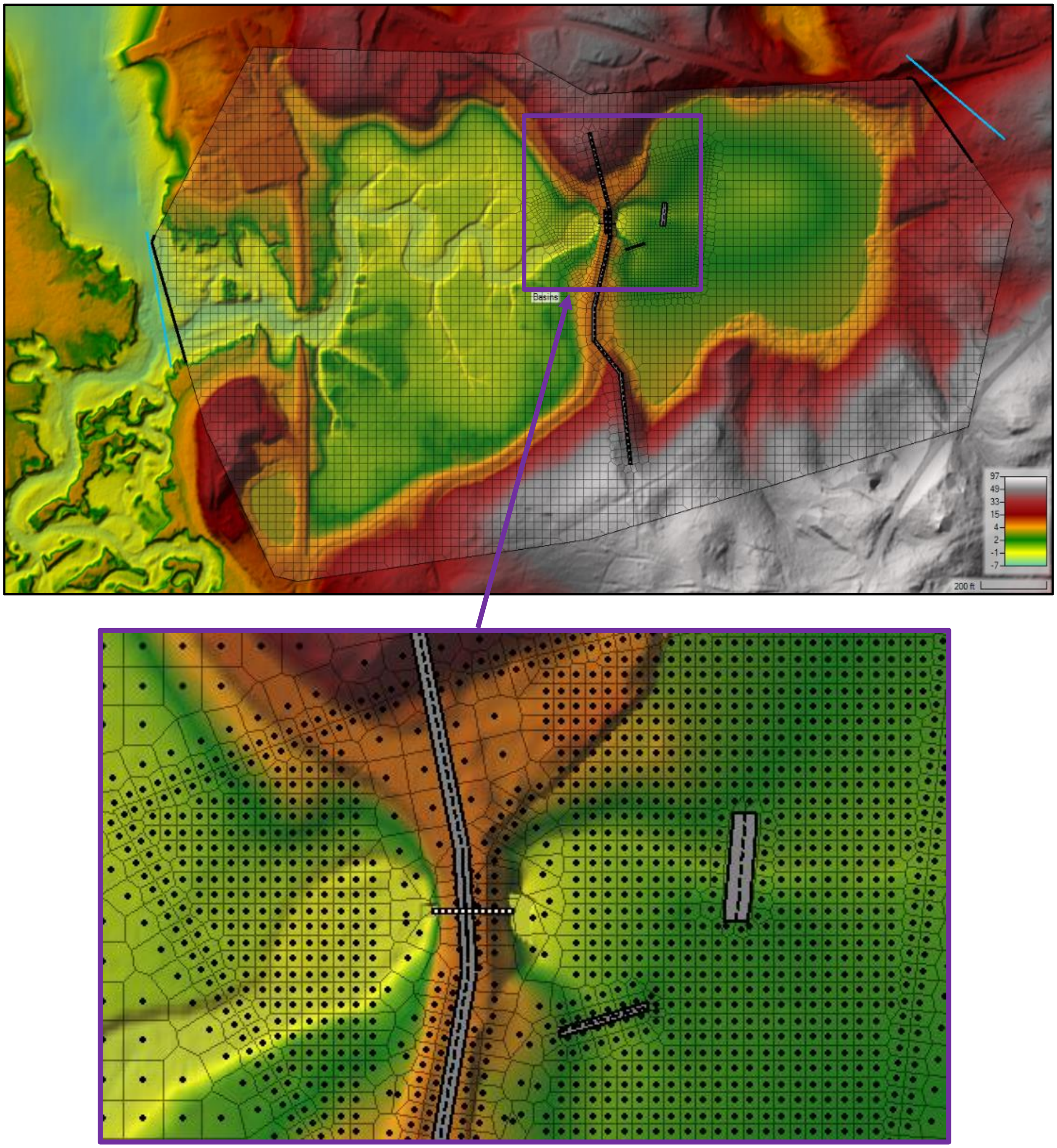


**Figure 11. HEC-RAS 2D model grid domain (top) for the Mill Pond system and the refinement region in the 2D model around the road, culvert and the weirs symbolized as grey rectangles with dashed lines (bottom).**

### *3.2.1. Boundary Conditions*

HEC-RAS 2D was setup and run for existing conditions under normal (daily) tides first to allow for model calibration and verification. Then the model was then run for storm conditions to evaluate the current risks of storm flooding in and around Mill Pond. Finally, both normal tides and storm conditions were simulated with sea level rise to understand how the tides and storms will change for existing conditions in the future. This modeling provides a baseline to understand existing conditions that will allow for the comparison with alternatives later in this report.

### *3.2.2. Normal Tides*

The 2021 tide gauge data collected in Pamet Harbor (Station MP3 in Figure 4) was used to establish the boundary conditions with which to force the 2D model. The water level observations with the middle basin and Mill Pond, MP2 and MP1, respectively, were used for model calibration and verification. Comparison between these observed water levels show that while the railroad berm does not cause any tidal restriction, the culvert under Mill Pond does causes significant tidal damping and lag as shown in Figure 12.

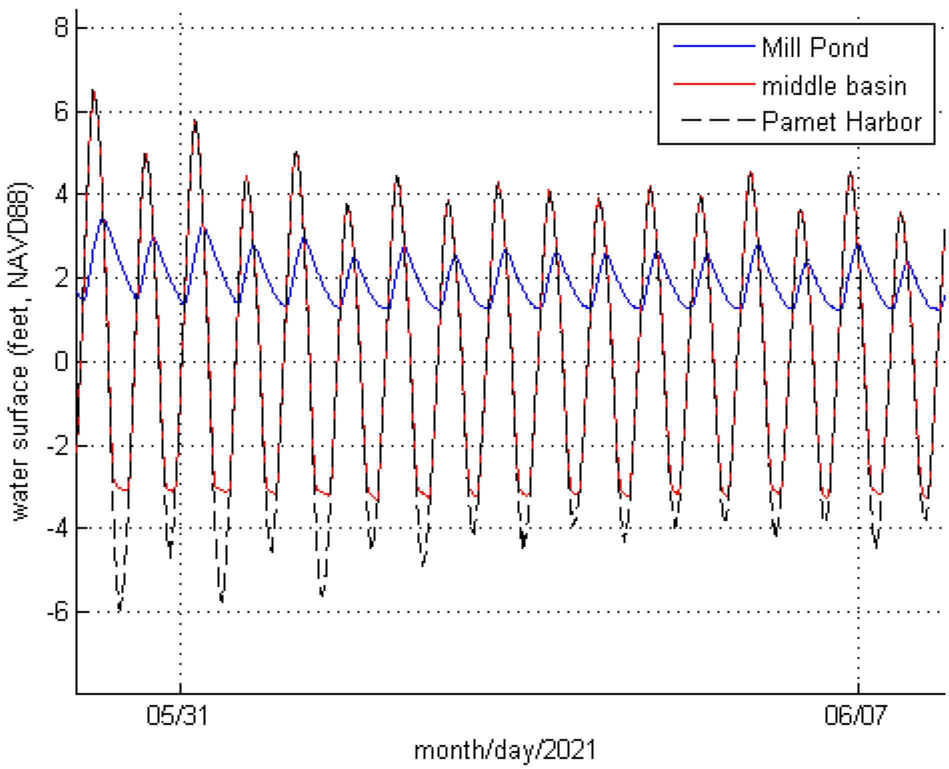


**Figure 12. Time series of the observed water levels measured at three CTD instrument locations.**

### *3.2.3. Calibration*

HEC-RAS 2D was calibrated for existing conditions and normal tides using the same parameters specified in Table 3 for the hypsometric model. The middle basin was first calibrated, and once that was achieved Mill Pond was calibrated. Manning's n was set to 0.03 for the whole domain, with override values in Mill Pond of 0.065. The parameters for the weir structures were kept as the default. Both basins were calibrated to within two inches of the observed data (Table 4). The difference in Mill Pond is that the water level decreases at a slightly faster rate than observed (Figure 13), which leads to the higher bias value. However, this value is still well within the acceptable range of error.

**Table 4. Goodness of fit parameters for the HEC-RAS model of the Mill Pond system.**

| Basin | RMSE (ft) | Bias (ft) |
|---|---|---|
| Middle basin | -0.042 | 0.088 |
| Mill Pond | 0.002 | 0.130 |

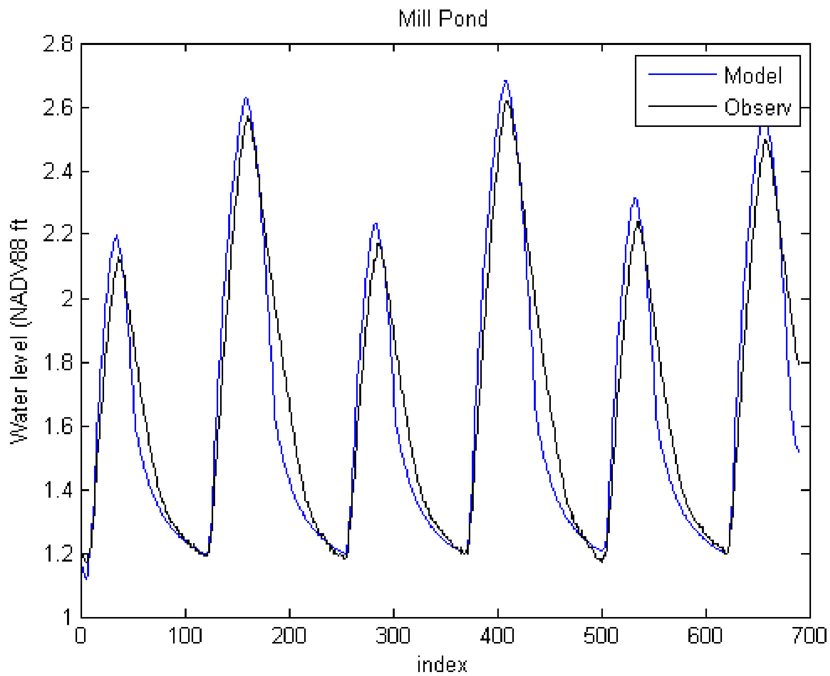


**Figure 13. Comparison of the 2D modeled vs observed water surface elevations in Mill Pond.**

### *3.2.4. Sea Level Rise*

Sea level rise the increase of the mean sea level over time due to the effects of climate change such ocean expansion and glacial melting. Sea level rise was chosen based on the NOAA sea level projections shown in Figure 14 (*Sea-Level Curve Calculator (army.mil)*). For Mill Pond, a 2070 time horizon was chosen because this is consistent with the typical design lifetime of a flow control structure, which is roughly 50 years. An intermediate-high projection was chosen as a conservative estimate, which resulted in 2 feet of sea level rise for the future year 2070. This is consistent with the year and risk level used for the Eagle Neck Creek culvert replacement project, another MA-DER culvert restoration project located in the Pamet Harbor basin. A sea level rise of 2 feet in 2070 would possibly put the existing Mill Pond Roadway at risk from flooding during monthly spring high tides as shown in Table 5. Additionally, an additional 86,194 square feet (1.97 acres) of Mill Pond would be inundated in 2070 with 2-feet of sea level rise.

**Table 5. Tidal datums for Pamet Harbor and Mill Pond simulated for existing conditions in both present day and 2070 with 2 feet of sea level rise.**

| Location | Year | Tidal Datums (feet-NAVD88) | | | | | Tidal Range (feet) | Area Inundated (feet$^2$) |
|---|---|---|---|---|---|---|---|---|
| | | MHHW | MHW | MTL | MLW | MLLW | | |
| Harbor | Present | 4.97 | 4.47 | -0.11 | -4.70 | -5.13 | 9.17 | -- |
| | 2070 | 6.97 | 6.47 | 1.89 | -2.70 | -3.13 | 9.17 | -- |
| Mill Pond | Present | 2.96 | 2.82 | 2.03 | 1.25 | 1.25 | 1.71 | 430,706 |
| | 2070 | 3.68 | 3.55 | 2.54 | 1.53 | 1.50 | 2.18 | 516,900 |

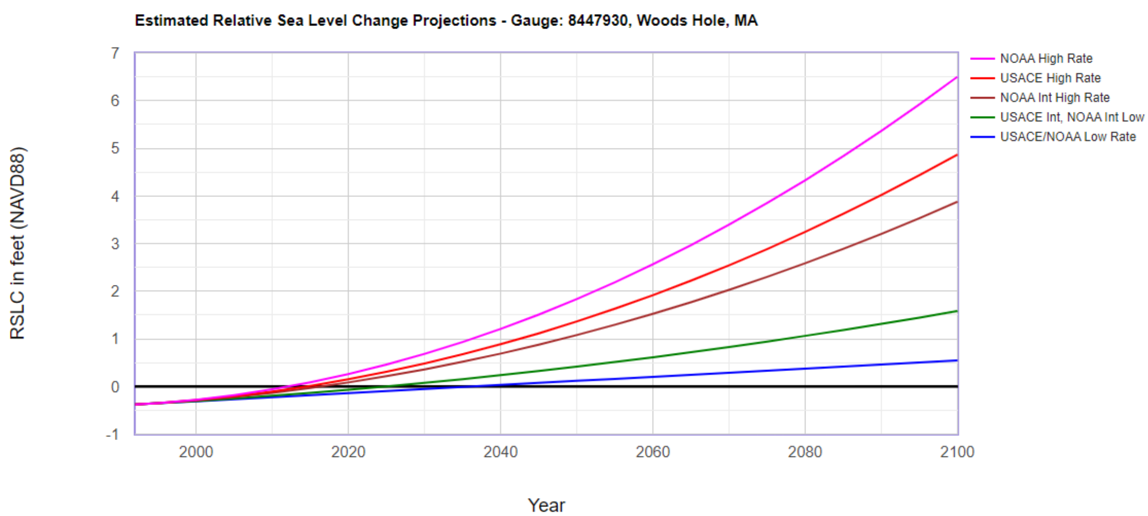


**Figure 14. USACE/NOAA sea level rise projection curves. *(Sea-Level Curve Calculator (army.mil))*.**

### *3.2.5. Return Period Storms*

Synthetic storm events were created for return period storm including the 2-year, 5-year, 10-year, 20-year, 50-year, and 100-year storm levels, which have an annual percent chance occurrence of 50%, 20%, 10%, 5%, 2%, and 1%, respectively. Water surface elevations associated with return period storm events were taken from the North Atlantic Coastal Comprehensive Study (NACCS) from a point offshore of the Pamet Harbor entrance (USACE, 2015). The observed tidal signal was transformed to match the maximum water elevation during the highest tidal cycle (Figure 15). Wave action was not considered since the upper reaches of Pamet Harbor and Mill Pond are sheltered from offshore waves and have very restricted-fetch basins.

Storm events were simulated in both present day and in 2070 with 2-feet of sea level rise and the resulting maximum water surface levels in Mill Pond associated with return period storm events are shown in Table 6. However, only the 2-year and 5-year return period storms were simulated with sea level rise since larger storms will overtop the roadway (approximately 7.5 feet NAVD88) negating the function and contributions of the culvert to storm flooding. Note that Mill Pond Road is endanger of overtopping from a 10-year return period storm event in present day but this flooding risks increases to a 2-year storm in 2070.

**Table 6. Water levels at the boundary condition, Pamet Harbor, for the return period storms in present day and 2070.**

| Projection | Return Period Storm Interval | | | | | |
|---|---|---|---|---|---|---|
| | 2-year | 5-year | 10-year | 20-year | 50-year | 100-year |
| Present Day | 6.69 | 7.18 | 7.54 | 7.87 | 8.26 | 8.63 |
| 2070 (with 2-feet of SLR) | 8.69 | 9.18 | 9.54 | 9.87 | 10.26 | 10.63 |

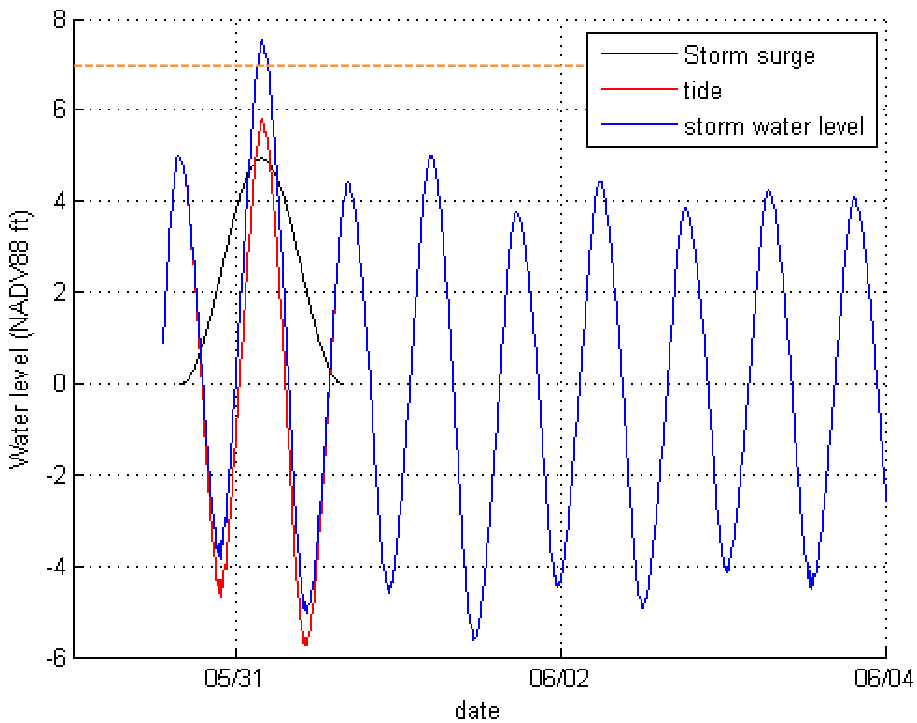


**Figure 15. Storm boundary condition (in Pamet Harbor) for the 20-year storm. Mill Pond Roadway elevation shown approximately by the orange dashed line.**

Overtopping was determined by looking at the cross section of the lowest point in Mill Pond Road, which lies just south of the existing culvert location (Figure 16). Under existing conditions, overtopping occurs from the middle basin side over the road starting south of the culvert where the roadway elevation is lower. Overtopping with the existing conditions occurs starting with a 10-year storm in present day, and increases to a 2-year storm with an intermediate-high projection of sea level rise (2-feet) in 2070 (

Table 7).

**Table 7.** **Storm induced maximum water level (feet-NAVD88) in Mill Pond, and whether the road overtops the existing culvert configuration.**

| Existing culvert | Maximum water level in Pamet Harbor | Maximum water level in Mill Pond | Road overtopped |
|---|---|---|---|
| 2-year | 6.69 | 3.40 | No |
| 5-year | 7.18 | 3.51 | No |
| 10-year | 7.54 | 3.75 | Yes |
| 20-year | 7.87 | 3.77 | Yes |
| 50-year | 8.26 | 5.48 | Yes |
| 2-year with sea level rise | 8.69 | 8.29 | Yes |

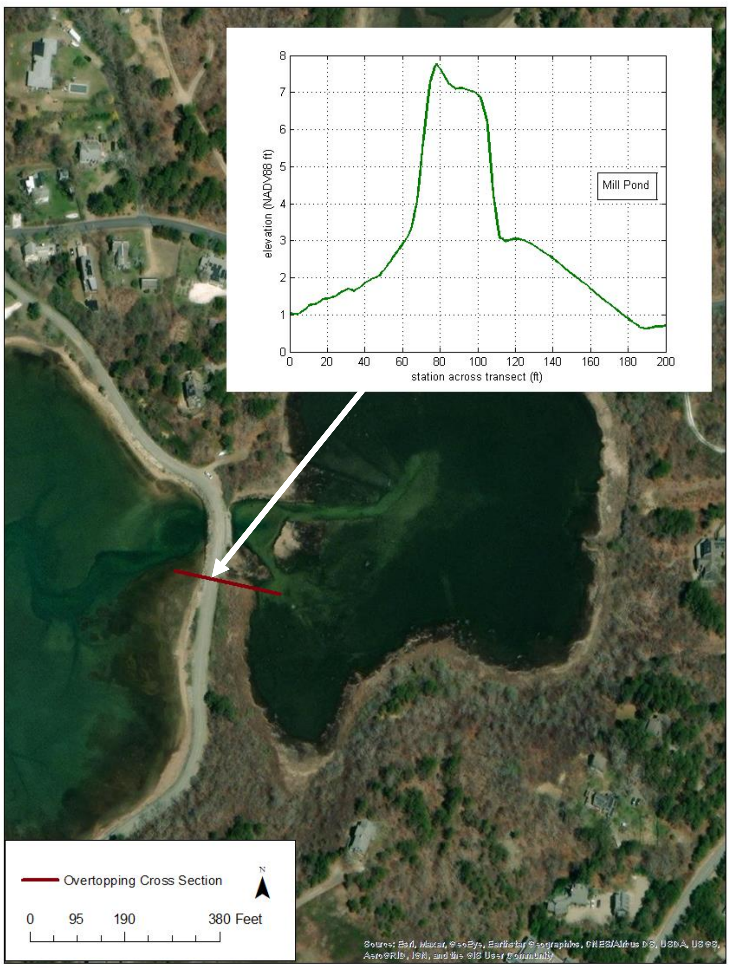


**Figure 16** **Cross section of the lowest point of Mill Pond Road used to determine overtopping or wetting of the road. Note that the Mill Pond (upstream) side of the culvert is at a lower elevation than the downstream side.**

## 3.3. Alternatives Development and Modeling

Culvert replacement alternatives were developed and then evaluated using the hydrodynamic models to determine the potential for improved tidal restoration and drainage as well as potential adverse impacts from flooding to abutters. Replacement alternatives consisted of both culverts and open channel "breach" alternatives. The prior study completed by Louis Berger Group was also consulted as a reference point for development of alternatives. After consideration of a number of alternatives undergoing a preliminary evaluation, a suite of four (4) main alternatives were chosen for further evaluation using the calibrated and verified HEC-RAS 2D model as described in this section.

### *3.3.1. Alternatives Development*

Initially, a suite of preliminary culvert replacement alternatives was considered including different culvert and channel configurations both with and without the roadway. These early alternatives were evaluated using the models, and then screened with the DER and stakeholders to select four (4) alternatives for further evaluation. The 1-D hypsometric model demonstrated that tidal restoration in Mill Pond was directly proportional to increasing culvert width from the existing 3-feet width up to a 10-ft width, where wider culverts did not result in additional restoration. Louis Berger Group had previously determined that a 10-foot-wide by 7-foot-high box culvert would restore the full tidal range to Mill Pond and eliminate any phase lag between peak high and low tides, which was selected as their preferred alternative. This conclusion also aligned with the hypsometric modeling results, which also indicated that there was no additional tide restoration for culverts greater than 7-feet-high. Based on consultations with the project team who wanted to address safety concerns and accommodate recreation use such as paddlers, an 8.5 foot-high-culvert was selected with a width of 10-feet as Alternative 1 as shown in Figure 17. The culvert configuration was chosen as three-sided open bottom box culvert filled with stone in order to provide a natural bottom that also serves as a scour countermeasure. While Alternative 1 consists of a three-sided open bottom culvert, it was simulated as a box culvert in HEC-RAS 2D since they perform the same from a hydrodynamic standpoint.

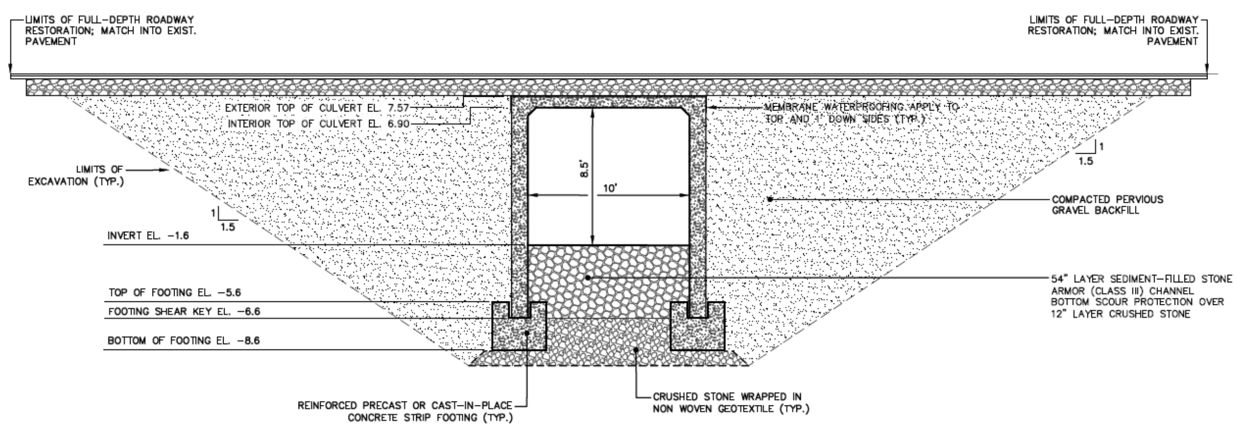


**Figure 17. Alternative 1: 10 foot width by 8.5 foot high open bottom culvert.**

While a 10-ft wide culvert fully restores tides to Mill Pond according to the hypsometric model, this large opening may be more prone to shoaling due to reduced flow velocities through the culvert relative to the small tidal prism and storage volume in the pond. Additionally, culverts that are 10-feet in width or greater have additional permitting requirements with MassDOT as discussed in Section 5. The hypsometric model determined that the 8 ft wide culvert restored tidal datums in Mill Pond to within a few tenths of a foot of the 10-ft wide culvert, which is still an acceptable level of restoration. The narrower culvert width would likely increase flow velocity to reduce shoaling while not require additional permitting. Therefore, an 8-ft wide three-sided open bottom culvert was chosen as the second alternative, which was also set to a height of 8.5 ft (Figure 18).

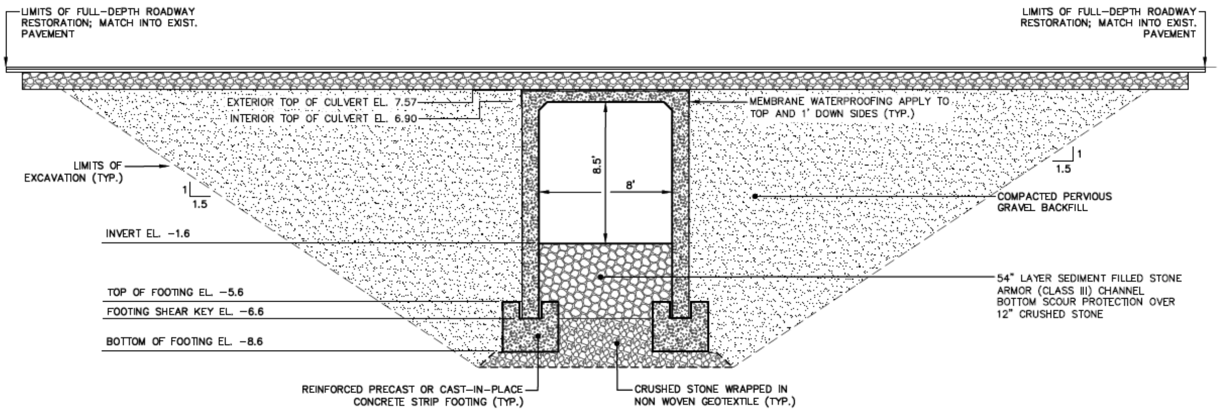


**Figure 18. Alternative 2: 8 foot wide by 8.5 foot high open bottom culvert.**

During the on-going project discussions with the DER, stakeholders, and project team, a more forward-thinking approach was developed where an open channel "breach" would be constructed in place of the culvert and the roadway would be abandoned. The thinking behind this approach was to plan for future climate change where sea level rise will threaten the roadway requiring increasing its coastal resiliency through more regular maintenance and repairs or by raising the roadway elevation itself. Both of those options come with significant long-term costs, and, therefore, roadway abandonment represents a "retreat" option so that the infrastructure would not have to be maintained or improved by the Town. The "breach" would simply be modeled as open channel without any bridge or roadway overtop.

The Louis Berger Group had previously evaluated a 15-foot-wide culvert that could have a clear span bridge overtop, however, their HEC-RAS modeling determined that there would be no additional hydrodynamic benefits to a culvert wider than 10 feet. This finding was also corroborated by the Woods Hole Group hypsometric modeling as discussed in Section 3.1, and two (2) open channel "breach" alternatives were developed. Alternative 3 is a simple 15-foot-wide breach in place of the existing culvert with no roadway or bridge overtop as shown in Figure 19. While the additional width will not provide any additional tidal restoration, it will provide a larger hydraulic cross section to accommodate storm runoff and drainage.  The invert elevation would largely be maintained as compared to the culvert alternatives, and the height of the breach would simply be to the top of the embankment, approximately 10-feet.

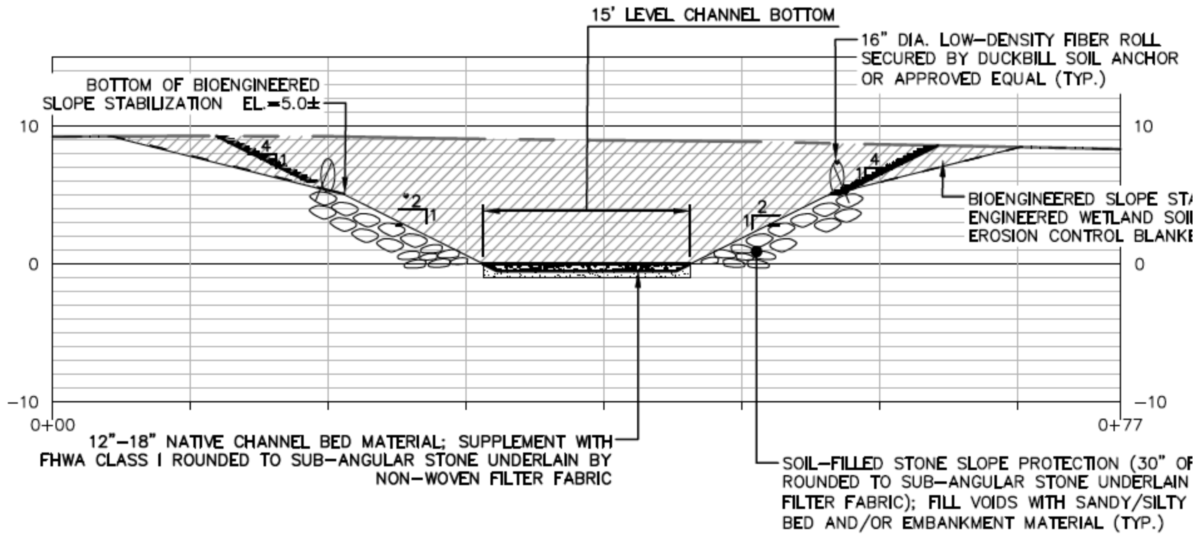


**Figure 19. Alternative 3: 15-foot width open channel breach with no roadway overtop.**

The fourth and final alternative was selected based on further input from stakeholders who desired to understand how the Mill Pond system may respond to very large opening where additional road surface and embankment would be removed. The intent for Alternative 4 was to try to return the roadway surface and embankment back to its natural state matching the coastal resources present. An initial evaluation determined that this breach could be well over 100-foot in width, which would see the roadway and embankment returned back to the native coastal resources either side. However, the stability of an inlet decreases as its width increases making more prone to sedimentation and shoaling, which could potentially close off the pond if flows are too low. Therefore, the channel width was chosen based on empirical stable inlet equations. These equations give the cross-sectional area of an inlet which will not shoal given the tidal prism, which is related to the velocity through the opening. If velocities are low, the channel will shoal and potentially close off. If velocities are high, the channel will erode and become larger. When the velocity is equal to the equilibrium velocity, the inlet is stable and neither grows nor closes. To determine the stability of the inlet opening, the equilibrium opening size was calculated based on the tidal prism in Mill Pond.

The tidal prism is the product of the average tidal range and the average surface area. Using the restored tidal datums are area for Mill Pond, the maximum restored tidal prism is:

$$(MHW - MLW) * A_{MTL} = 3.12ft * 225{,}080ft^2 = 702{,}250ft^3$$

The equilibrium inlet area, $A_{eq}$, is defined as:

$$A_{eq} = CP^q$$

Where C and q are empirical constants, and P is the tidal prism in metric units. C is on the order of magnitude $10^{-4} - 10^{-5}$, and q is on the order of 1. Using the larger value of C, 1.08E-4, we get an equilibrium area of 22.8 $ft^2$. A channel width of 10 feet and depth of 2 feet will approximately achieve the equilibrium area, which is much less than the desired width approaching 100-feet.

With the desire to construct a large breach option that would also be a stable inlet, a hybrid approach was taken for the fourth alternative where an 95-foot-wide breach would be constructed with a 10-foot-wide low flow channel in the middle and 14-foot-wide saltmarsh benches on either side (Figure 20). The saltmarsh benches would be set to the elevation of the existing saltmarsh platform, and then planted with saltmarsh vegetation. This would allow for higher stages of the tide to flood the salt marsh benches while concentrating low tide flows in the 10-foot-wide channel to prevent sedimentation and shoaling.

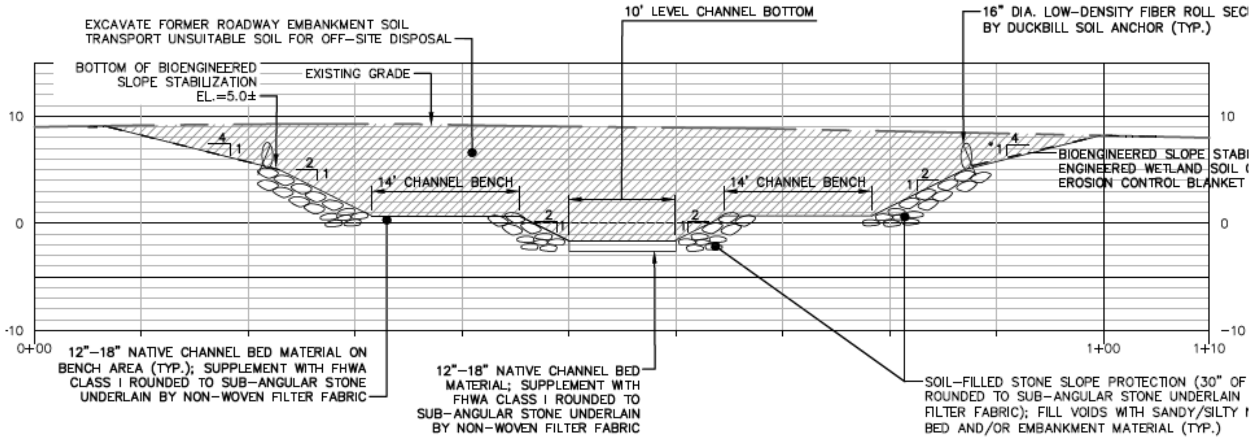


**Figure 20.** **Alternative 4: The ~95-foot-wide breach with a 10-foot-wide inner channel and 14-foto wide saltmarsh benches. No roadway remains overtop.**

A summer of the four alternatives developed in this section are presented in Table 8 below.

**Table 8. Four alternatives simulated in HEC-RAS 2D.**

| Alt. # | Alternative Description | Total Width (feet) | Inner Channel width (feet) | Height (feet) | Structure Invert (ft-NAVD88) |
|---|---|---|---|---|---|
| 1 | Culvert 10'Wx8.5'H | 10 | N/A | 8 | -1.6 |
| 2 | Culvert 8'Wx8.5'H | 8 | N/A | 8 | -1.6 |
| 3 | Open Channel 15'W | 15 | N/A | 10 | -1.7 |
| 4 | Open Channel 95'W | 95 | 10 | 10 | -1.7 |

### *3.3.2. Alternatives Modeling Results*

Each of the four (4) alternatives in Table 8 were modeled with HEC-RAS 2D and the resulting tidal datums and intertidal areas in Mill Pond are presented in Table 9. Overall, the model results are very similar, within a tenth of a foot, between each of the four alternatives where MHW/MHHW increases significantly but MLW/MLLW does not. This result matches the hypsometric modeling results which indicated that the island in Mill Pond acts as a weir that limits drainage as described in Section 3.1. The increase in MHW/MHHW results in an increased intertidal area of approximately 3.5 acres, which is significant. This is also the region typically inhabited by salt marsh vegetation, which is an indicator for potential restoration.

**Table 9. Tidal datums, range, and intertidal area for the existing conditions and alternatives.**

| Alt. # | Alternative Description | MHHW (ft) | MHW (ft) | MTL (ft) | MLW (ft) | MLLW (ft) | Mean Tidal range (ft) | Intertidal (Acres) | Intertidal Area Change (Acres) |
|---|---|---|---|---|---|---|---|---|---|
| -- | Existing | 2.96 | 2.81 | 2.04 | 1.25 | 1.25 | 1.56 | 7.1 | -- |
| 1 | Culv. 10x8.5 | 4.74 | 4.33 | 2.77 | 1.21 | 1.21 | 3.12 | 10.6 | +3.5 |
| 2 | Culv. 8x8.5 | 4.66 | 4.26 | 2.74 | 1.22 | 1.21 | 3.04 | 10.5 | +3.4 |
| 3 | 15-ft Breach | 4.78 | 4.37 | 2.80 | 1.21 | 1.21 | 3.16 | 10.6 | +3.5 |
| 4 | 95-ft Breach | 4.78 | 4.37 | 2.79 | 1.21 | 1.21 | 3.16 | 10.6 | +3.5 |

To determine the change in flooding impacts of the four (4) alternatives, return period storms from Table 10 were simulated as described in Section 3.2.5. All four (4) alternatives show similar results for the storm simulations, where maximum flood elevations are within a few tenths of a foot across all alternatives for a given storm. This is due in part to the openings for all four (4) alternatives being so large that they behave similarly hydraulically. Overtopping of Mill Pond Road also occurs for the values highlighted in grey and bolded, which reduces the contributions to flooding from the culvert. Note that the alternatives increase the water surface (i.e. flooding) elevations in Mill Pond during storms over existing conditions, which is expected with such large openings. However, these elevations do not appear to significantly impact properties or structures since the top of the coastal bank, where the structures are, are at a much higher elevation.

**Table 10. Maximum water surface elevation in Mill Pond for each storm and alternative. Bolding and shading indicates storms that overtop of the low point of Mill Pond Road (approximately 7.5' NAVD).**

| Alternative | 2-year | 5-year | 10-year | 20-year | 50-year | 100-year | 2-year (SLR 2070) |
|---|---|---|---|---|---|---|---|
| Existing | 3.40 | 3.51 | 3.75 | **3.77** | **5.48** | **6.09** | **8.29** |
| 8x7 culvert | 6.42 | 6.89 | 7.23 | **7.56** | **8.07** | **8.63** | **8.69** |
| 10x7 culvert | 6.63 | 7.11 | **7.46** | **7.79** | **8.24** | **8.63** | **8.69** |
| 15-foot breach | 6.69 | 7.18 | **7.54** | **7.87** | **8.26** | **8.63** | **8.69** |
| 90-foot breach | 6.69 | 7.18 | **7.54** | **7.87** | **8.26** | **8.63** | **8.69** |

## 3.4. Sediment Mobility and Scour Countermeasures

Sediment mobility within the basin and inlet was evaluated using an analytical sediment transport model for a first level assessment. The sediment mobility model is based on the established concept that sediments begin to move when sufficient stress is applied to the estuary bottom (bed). Typically, a mild, steady flow over a bed of cohesionless grains will not result in sediment transport (Fredsoe & Deigaard, 1992). However, when subjected to a large enough flow, the driving forces impacting sediment grains exceed the stabilizing forces, and sediment will begin to move resulting in scour and accretion.

Replacing the existing 3 ft diameter culvert with a substantially larger culvert will allow for considerably more flow during normal daily tides and especially during significant coastal storms as discussed in the prior section. Therefore, it is necessary to conduct a scour analysis that will aid in the design of scour countermeasures at both ends of the culvert for the proposed replacement culvert. Woods Hole Group computed scour and designed countermeasures based on the output from the HEC-RAS 2D model and using the Federal Highway Administration (FHWA) Hydraulic Engineering Circular Number 14 (HEC14) *Hydraulic Design of Energy Dissipators for Culverts and Channels*.

The scour calculations were completed for the each alternative based on Equation 5.1 for culverts shown below, and the flow rates through the culvert that were extracted from the HEC-RAS 2D modeling conducted above.

$$\left[\frac{h_s}{R_c}\right] = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta} \qquad \text{HEC14 Eqn. 5.1}$$

where,

$h_s$ = scour depth (ft)
$R_c$ = hydraulic radius (ft) = wetted perimeter.
Q = flow discharge ($ft^3$/sec)
g = acceleration due to gravity (32.2 ft/$s^2$)
t = time (minutes) = 30 minutes
σ = material standard deviation = $(D_{84}/D_{16})^{0.5}$ = 1.87 for sand
$C_{s}$ = slope correction coefficient = 1
$C_h$ = drop height adjustment coefficient = 1

The calculations assumed that the culvert was flowing full during storm conditions. Additionally, since the sediment is primarily cohesionless sandy material, σ was set to 1.87 and a recommended duration of 30 minutes were utilized based on HEC14. The resulting total scour depth for the proposed conditions are shown in Table 11 below.

HEC23 was then used to design the scour countermeasures using equation 18.1 and the results are shown in Table 11 below. The results indicated that the minimum median diameter (D50) riprap size is just under a foot, and for design the riprap should be upsized to the next size, class 4, that has a D50 of 14 inches. The minimum layer thickness should be double the D50 of around 28 inches (2.4 feet) at the culvert inlet, outlet, and within the culvert. This scour apron would extend 10 into Mill Pond from the inlet and 20 ft downstream from the outlet based on HEC23 guidance.

$$D_{50\,riprap} = \frac{K_r\,y_0}{(S_g-1)}\left(\frac{V_{ac}^2}{g y_0}\right)^{0.33} \qquad \text{HEC23 Eqn. 18.1}$$

where,

$D_{50}$ = riprap size (ft)
$K_r$ = sizing coefficient = 0.68 for design
$V_{ac}$ = average culvert velocity ($ft^3$/sec)
$y_0$ = average flow depth
$S_g$ = riprip specific gravity = 2.65

**Table 11. Modeled velocities and flow rates and calculated scour and countermeasure design.**

| Alt. # | Alternative | Base Max Velocity (ft/s) | Base Max Flow (cfs) | 10yr Max Velocity (ft/s) | 10yr Max Flow (cfs) | Scour Depth (feet) | Riprap $D_{50}$ (ft) | Design $D_{50}$ (in) |
|---|---|---|---|---|---|---|---|---|
| 1 | 10Wx8.5H | 1.8 | 280.7 | 2.0 | 325.0 | 7.9 | 0.71 | Class 4 14 inches |
| 2 | 8Wx8.5H | 2.9 | 251.6 | 2.9 | 306.6 | 7.7 | 0.97 | |
| 3 | 15-foot breach | 2.1 | 346.2 | 3.2 | 400.5 | 8.6 | 0.78 | |
| 4 | 95-foot breach | 1.5 | 370.0 | 1.8 | 415.8 | 8.7 | 0.63 | |

The scour analysis determined that there is the potential for sediments to be scoured and mobilized during high flow events especially during storms. While scour countermeasures will be in place, it is possible that material could be mobilized outside of the armored areas especially in the pond itself.

Through dimensional analysis, Shields (1936) derived an expression that identifies the point where bed stress equals bed resistance. The Shields parameter (ψ) results from equating the driving and stabilizing forces for a flat bed. Once the Shields parameter has been calculated at points of interest, the resulting values can be compared to a critical Shields parameter ($\Psi_{cr}$) to determine if sediment initiation occurs at each point of interest. The critical value of $\psi$ for the initiation of sediment motion is found by using a methodology to determine the threshold Shields' Criterion, $\psi_{cr}$ (Soulsby, 1997):

$$\psi_{cr} = \frac{0.30}{1+1.2D_*} + 0.055\left[1 - e^{-0.020D_*}\right]$$

where $D_*$ is the dimensionless grain size given by:

$$D_* = \left[\frac{g(s-1)}{\nu^2}\right]^{1/3} d_{50}$$

where $v$ is the kinematic viscosity of water.

The Shields' criterion is applicable to cohesionless sediments consistent with sediments found in the Mill Pond culvert vicinity based on the subsurface investigation, however, much finer material was noted in the pond upstream so this analysis may not be as applicable there. However, no sediment data was collected there.

Settling velocity, or fall velocity, is the lower velocity threshold at which a suspended particle settles out of a fluid that would lead to shoaling (accretion). Settling velocity for the 0.54 mm $d_{50}$ sediments was calculated using Stoke's Law (Equation 4)

$$\omega_s = \frac{1}{18}\frac{{d_{50}}^2 g(SG-1)}{\upsilon}$$

where

$\omega_s$ is the settling velocity
$d_{50}$ is the median grain size of the sediment (0.54 mm)
g is the acceleration due to gravity (32.2 ft/s$^2$)

SG is the specific gravity of the particle assumed to be quartz (2.65)
$\upsilon$ is the kinematic viscosity of water (1x10$^{-5}$ ft$^2$/s).

The settling velocity was calculated to be 0.86 ft/s for a median $d_{50}$ of 0.54 mm, which is less than the modeled peak velocities in Table 12 indicating that accretion is not likely to be significant for peak flows conditions within the culvert or open channels for the alternatives.

**Table 12. Sediment Mobility Analysis.**

| Alternative | Bed shear stress (5% of $u_{max}$) | Shields Parameter | Mobility status? | Settling Velocity ft/s | Channel/culvert Shoaling? |
|---|---|---|---|---|---|
| 8x8 | 0.120 | 0.021 | No | 0.86 | No |
| 10x8 | 0.085 | 0.015 | No | | No |
| 15ft | 0.150 | 0.026 | No | | No |
| 90ft | 0.075 | 0.013 | No | | No |

## 4. ALTERNATIVES EVALUATION

An alternatives analyses was conducted that compared each of the four (4) alternatives against each other and to existing conditions based on the model results. This includes evaluating the impacts, both positive and negative, that the alternatives would have on Mill Pond, habitat, infrastructure, and surrounding properties. Overall, each of the four alternatives produce a similar amount of tidal restoration and increased storm drainage, which represents a marketable improvement over existing conditions. A comparison of the four (4) Alternatives and assessment of impacts is provided below:

- **Tidal Restoration:** The HEC-RAS 2D model results indicated that the each of the four (4) alternatives restore a similar level of tides (within a tenth of a foot) to Mill Pond effectively doubling the current mean tide range from approximately 1.5 to 3.1 feet (Table 9). The tidal restoration gains are largely for high tides with minimal gains on the low tides due to the weir effect that the island has on pond drainage as shown in Figure 21 where MLW for the existing and alternatives modeling constitutes the same red line. However, the model cannot predict if this island will remain or not following culvert replacement when full tidal flow is restored, and it is possible that the pond could drain completely during low tides creating a tidal flat in the pond.
- **Storm Flooding Impacts:** The HEC-RAS 2D model results indicated that each of the alternatives produce a similar amount of storm flooding, or storm surge elevations, in Mill Pond since they all are large openings that function similarly hydraulically. Higher flood (storm surge) elevations will occur in Mill Pond over existing conditions due to the larger openings allowing for easier passage of storm flows, however, the larger opening will also allow for better storm drainage, thereby reducing the duration of flooding. While the storm flood elevations in Mill Pond are higher by approximately 2.5 feet for the alternatives (Figure 22) as compared to existing conditions (Figure 23), the flooding does not significantly impact properties since the dwellings/structures are built on higher ground. There is a steep, elevated coastal bank around Mill pond that effectively contains the storms flows.
- **Drainage:** The phase lag time in peak tides was about 102 minutes for the existing culvert, which is effectively reduced to zero for each of the alternatives. This will benefit both

flushing during normal tides to provide greater intertidal area and facilitate storm drainage to reduce the duration of flooding during storms.

- **Railroad Berm Influence:** The 2021 field investigation concluded that the channel through the former railroad berm downstream of Mill Pond, which separates the middle basin from Pamet harbor, does not appear to attenuate the tides. This study utilized the HEC-RAS 2D model to confirm this finding and also determine whether there any additional hindrances for storm flooding or drainage. The HEC-RAS 2D model results were checked and it was confirmed that the former railroad berm has little effect on attenuation of the tides or storm flooding and drainage. Therefore, the existing channel or breach through the railroad is sufficiently already sufficiently sized from a hydrodynamic standpoint.
- **Impacts to Wells and Septics:** Figure 21 demonstrates that there do not appear to be any properties or dwellings that are significantly impacted by the alternatives as compared to existing conditions. The additional flooded areas tend to be low lying areas along the face of the coastal bank. According to the Septic and Well Plan in Attachment A, these systems are located a far enough distance away and elevation above these restored tides meaning that saltwater flooding or intrusion through the groundwater should not impact these systems.
- **Sedimentation Impacts:** It is likely that the channel carves out a more coherent channel and remains sandy. Unclear whether fine sediment in marsh will mobilize….possibly in areas where a drainage pathway/channel could form. However, similar to Stewarts creek just draining the flat may not remove sediment.
- **Habitat Impacts:** Figure 21 demonstrates the additional intertidal area gained for the alternatives, which have very similar results. In total, the gain in intertidal area is about 3.5 acres, which has the potential to create additional saltmarsh and shellfish habitat. The increased tidal range will also certainly benefit these resources by reducing the amount of time during the tidal cycle that they flooded and increasing water quality through improved flushing. Alternative 4 will also create additional saltmarsh by converting roadway embankment directly to saltmarsh.

  Improved tidal flushing and storm drainage will reduce freshwater ponding and increase salinity. Oysters and mussels were observed in abundance downstream of Mill Pond Rd, but not upstream. By restoring habitat connectivity through a larger culvert or opening, it is expected that this may create the potential shellfish habitat.
- **Public Benefit:** The culvert alternatives, #1 and 2, have been designed for sufficient headspace within the culvert to minimize safety hazards and also allow for recreational paddlesport passage. The open channel “breach” alternatives, #3 and 4, have open tops so there is also minimal safety risks and no limits for paddlesports. Additionally, Alternatives 3 and 4 abandon the roadway and could potentially allow for a public access pathway in its pace. However, the impact of abandoning the road on motor vehicles/traffic versus creating additional recreational opportunities and reducing Town maintenance costs will have to be evaluated further.

The alternative analysis is discussed further in the Fuss & O’Neill Conceptual Design Report found in Attachment B, which also includes the Alternatives Analysis comparison table.

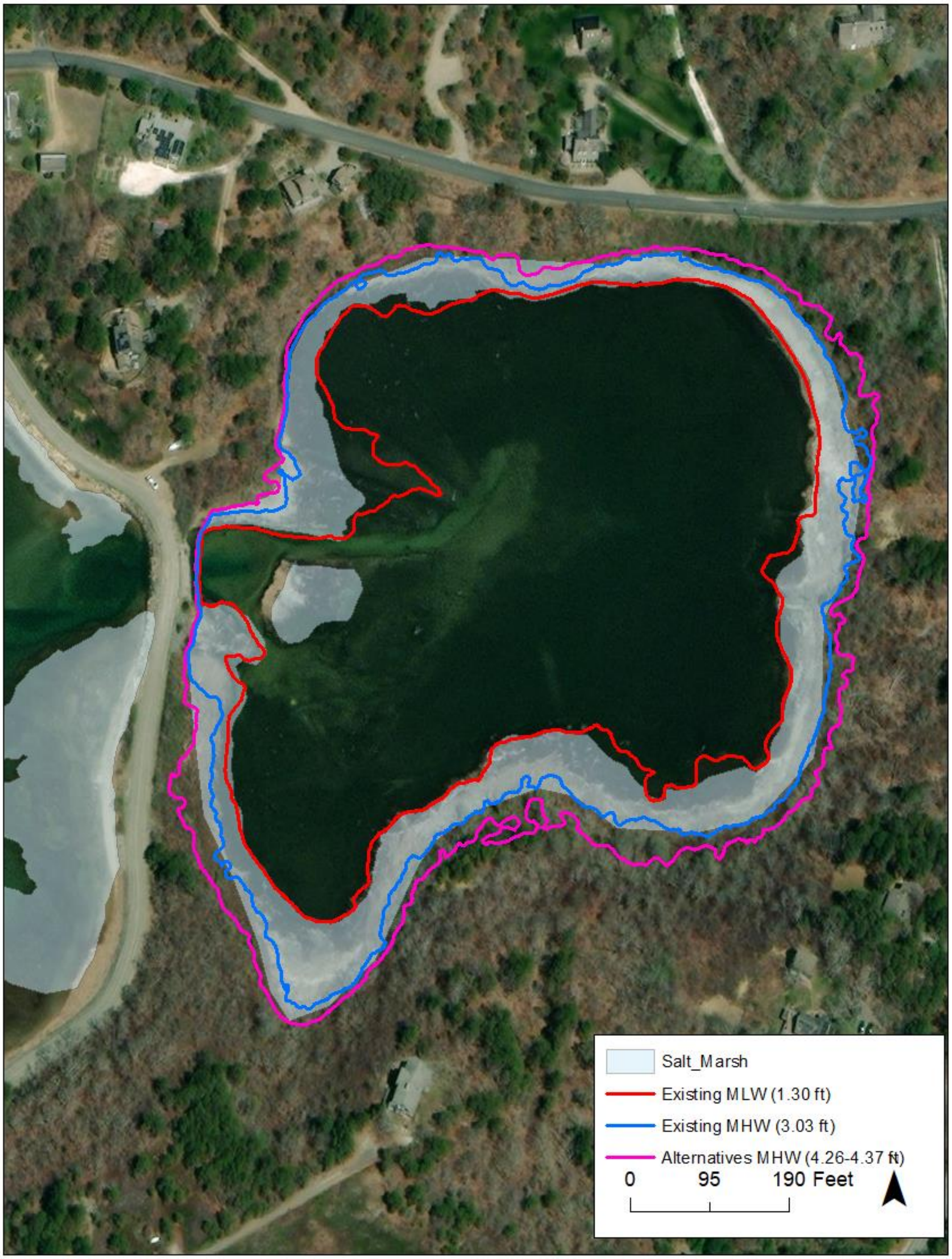


**Figure 21. Comparison of the extent of existing salt marsh relative to MLW and MHW levels for existing conditions (red/blue) and the alternatives (pink).**

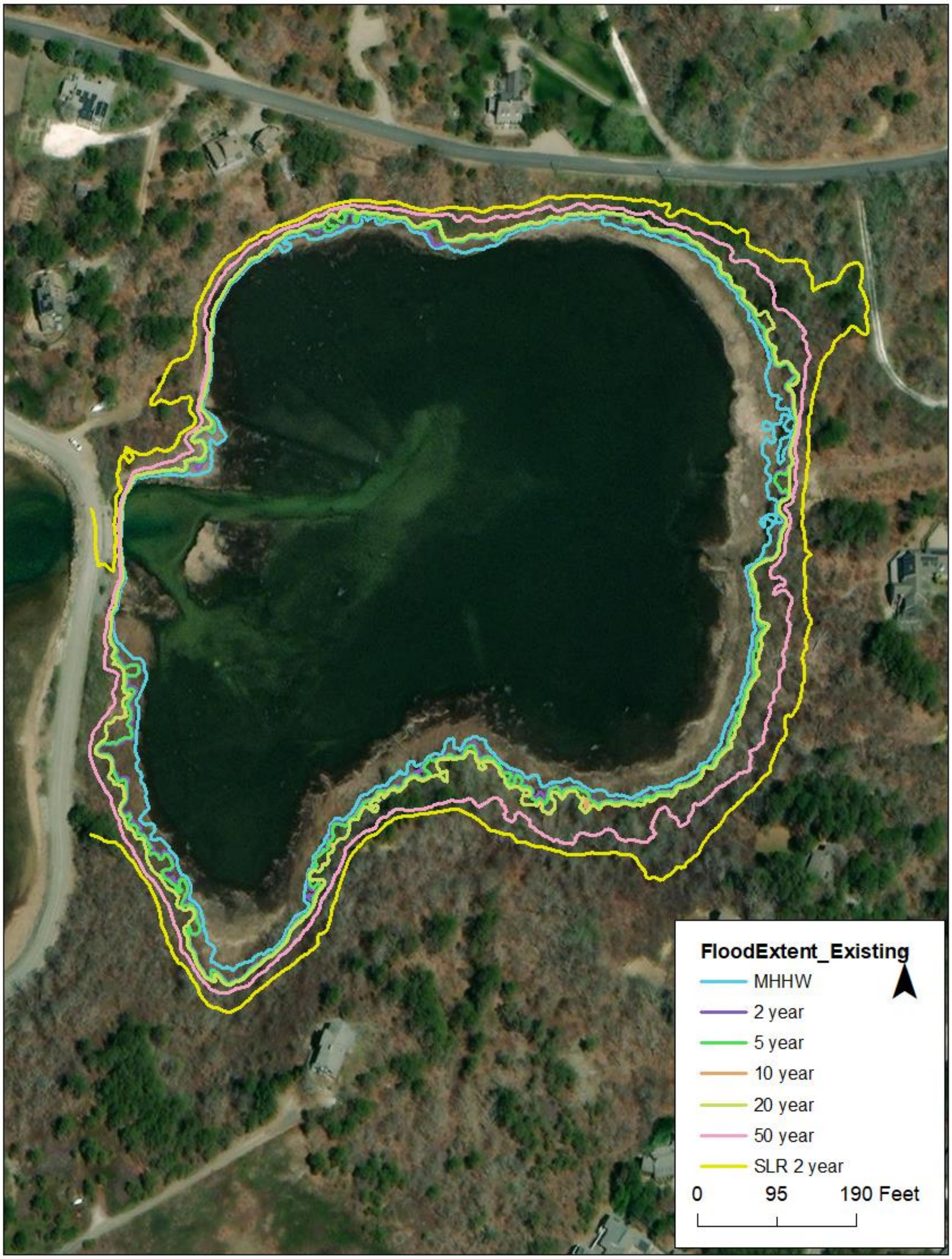


**Figure 22. Comparison of the extent of existing salt marsh relative to return period storms with and without sea level rise (SLR) for existing conditions modeling.**

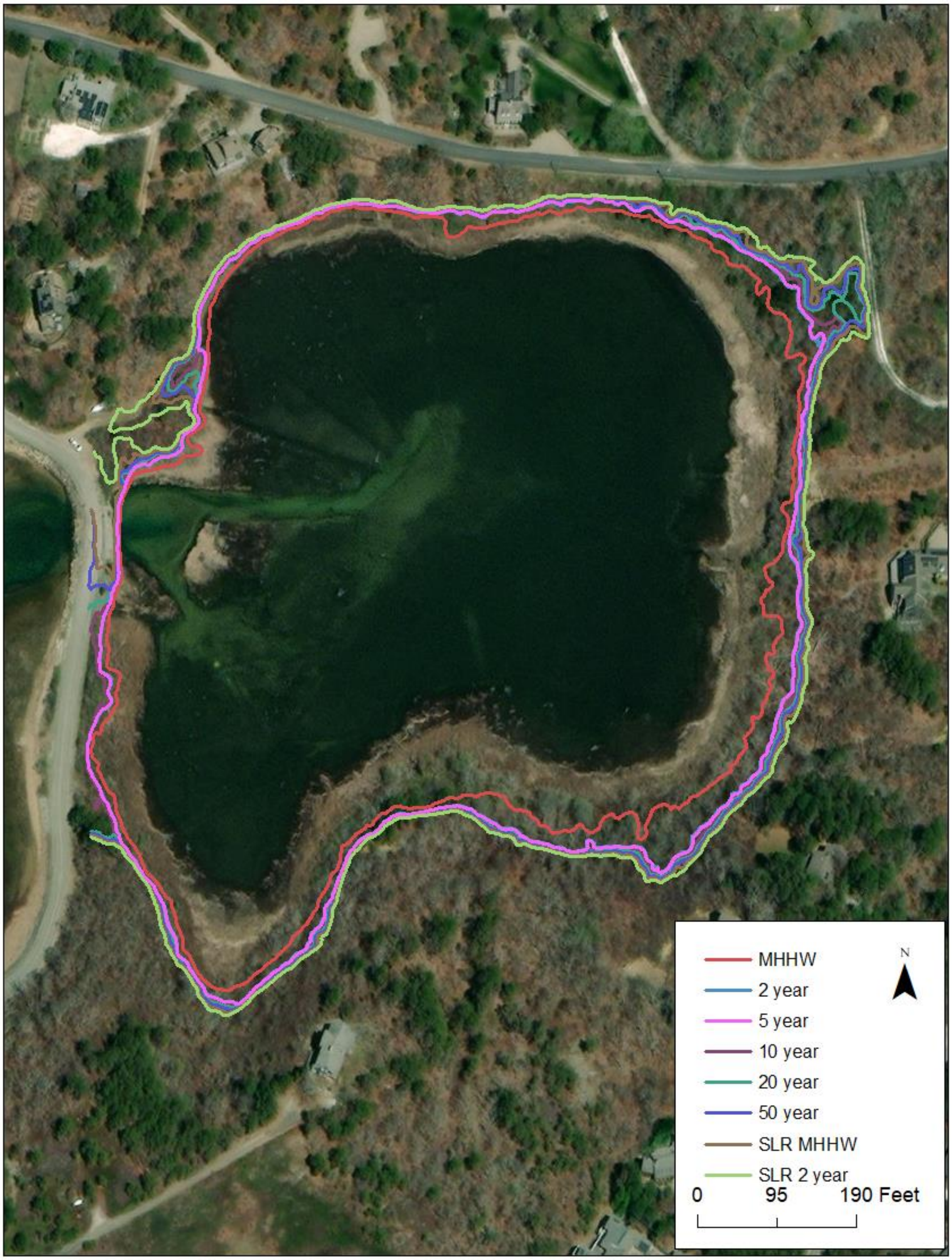


**Figure 23. Comparison of the extent of existing salt marsh relative to MHHW and return period storms with and without sea level rise (SLR) for the alternatives modeling.**

- **Mill Pond Road Coastal Resiliency** – Currently, Mill Pond Rd is vulnerable to overtopping during the relatively small 10-year storm event, but will potentially be at risk from spring high tide flooding with 2-ft of sea level rise in the future (year 2070). This will result in more regular maintenance and repairs and also result in more road closures during flooding and repairs. Therefore, the roadway will have to be made more resilient if it is to be maintained into the future especially if a culvert alternative is chosen as the preferred alternative. One way to increase the coastal resiliency is to redesign and reconstruct the roadway to a higher elevation. Figure 24 shows the peak water surface (surge) elevation associated with return period storms events in present day and 2070 with 2-feet of sea level rise. The figure demonstrates that the lowest portion of the roadway, just south of the culvert, is approximately 7.5 feet NAVD88, which is prone to flooding during the 10-year return period storm in present day. In 2070, the roadway is being overtopped by high spring tides and small-scale storm events. At minimum, the roadway would have to be raised by 2-feet to 9.5 feet NAVD88 to keep up with sea level rise and prevent flooding during the 10-year storm in 2070. This would require raising approximately 1,200 feet of roadway length between 31 Mill Pond Rd just north of the culvert and 15 Mill Pond Rd to south at the intersection with Post Drive. Therefore, roadway raising is not as simple as just addressing the roadway over the culvert, which creates a substantially larger project over a simple culvert replacement.

  Another option is to not to increase the coastal resiliency of the road, but, rather, to abandon and remove the road so that it does not have to be maintained or rebuilt in the future. Road abandonment goes hand in hand with the open channel breach alternatives, since the open channel requires minimal maintenance while also ensuring that there is no aging thoroughfare infrastructure above. There is also potential for further enhancements with this alternative such as removing additional roadway surface beyond the breach area to restore with native habitats and possibly establish a recreational trail and access. Roadway abandonment does need to be fully explored before it can selected as a viable alternative. For instance, Mill Pond Road represents one of two egresses along with Depot Road for vehicles and especially emergency response vehicles to and from Pamet Harbor. Although Depot Road is the main thoroughfare between Pamet Harbor and Route 6, while Mill Pond Road is the smaller, less direct, and less traveled of the two roads.

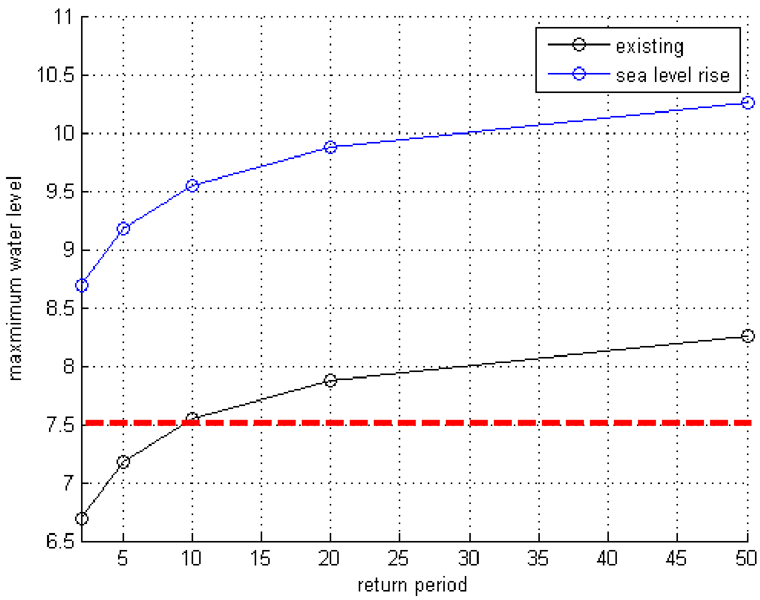


**Figure 24** **Maximum water levels at the middle basin side of Mill Pond Road (feet-NAVD) for each return period up to 50-years. Current lowest roadway point is 7.5 feet NAVD as shown by the red line.**

## 5. PERMITTING PATH

The proposed culvert restoration project proposed herein will have significant impacts to both environmental resources and regulatory areas that will trigger the need for environmental permits from local, state, and federal agencies. The coastal wetland resources that would potentially be impacted would include saltmarsh, land subject to coastal storm flowage, tidal flat, BVW, coastal beach, and land under ocean. However, it is anticipated that regulatory agencies would potentially look favorably on an alternative that would have both ecological habitat restoration and storm drainage benefits. Prior to preparing or filing any permit applications, the Woods Hole Group recommends the following pre-permitting consultations and meetings in order obtain input and/or guidance from the public, stakeholders, and regulators.

- **Public Outreach Meeting:** It is recommended that the Town host a Public Outreach meeting that is intended to engage the public and other stakeholders about the project. The Town will receive that they can incorporate, as necessary, prior to pursuing permits.
- **Pre-Application Meeting with Regulators:** Prior to filing any permit applications, Woods Hole Group recommends to consult with regulatory agencies in a pre-application meeting with the Massachusetts Environmental Policy Act Office (MEPA), Massachusetts Coastal Zone Management (CZM), Massachusetts Department of Environmental Protection (MassDEP), USACE, and others as necessary. The goal would be to gain feedback about the proposed design, resource and property impacts, and permitting path for the project.
- **Massachusetts Division of Marine Fisheries Consultation:** The Massachusetts Division of Marine Fisheries (DMF) should be contacted for information regarding essential fish habitat and time of year restrictions for resources occurring in the Mill Pond project area. The

purpose of this will be to obtain written determinations from DMF indicating whether the project will be subject to time of year restrictions for in-water work.

The project is not located within Natural Heritage's Estimated or Priority Habitat for rare species so they will not need to be consulted. Mill Pond is also not located within an Area of Critical Environmental Concern (ACEC) and does not appear to have any Environmental Justice (EJ) populations within several miles of the site.

Following the pre-permitting consultations and meetings with stakeholders and regulatory agencies, Woods Hole Group anticipates that at least six (6) environmental permits and/or licenses will need to be filed for any of the four (4) alternatives:

1. **Massachusetts Environmental Policy Act Environmental Notification Form:** Since the project will be submitted as a Notice of Intent (NOI) for an Ecological Restoration Project to the Town of Falmouth Conservation Commission, therefore, a Division of Marine Fisheries (DMF) review and a DEP Section 401 Water Quality Certification must be obtained before the Town of Falmouth Order of Conditions can be issued. It is expected that the Mill Pond project will trigger (at a minimum) the Massachusetts Environmental Policy Act (MEPA) Wetlands, Waterways and Tidelands threshold 301 CMR 11.03(3)(a)1.a. for alteration of one or more acres of salt marsh or bordering vegetated wetlands based on a review of the modeling results. This threshold carries the requirement for a mandatory Environmental Impact Report (EIR), and the total area of impact to wetland resources will be required for permitting.

   However, according to 301 CMR 11.11 of the MEPA regulations it is possible to request a waiver from the requirement of an EIR in cases where preparation of the EIR would result in an undue hardship for the proponent, and the EIR would not serve to avoid or minimize damage to the environment. Given the environmental benefits associated with the project and the extensive analyses conducted in support of the project, it is likely that a waiver request would be viewed favorably. As such, the project team proposes the preparation of an Expanded Environmental Notification Form (EENF) that allows for the request for a waiver of the mandatory EIR. The EENF will demonstrate the project meets the standards for a waiver per 301 CMR 11.11(1)(b) and 11.11(3)(a) and (b). The EENF will be prepared following the form and content of an EIR as described in 301 CMR 11.07(6). The document will contain detailed information describing and analyzing the project and its alternatives and will assess the potential environmental impacts and mitigation measures. The stormwater regulations will be reviewed relative to the selected alternative, and, if necessary, a Stormwater Management Plan may need to be developed. Key members of the project team will prepare for and attend the required on-site meeting to present the project to MEPA officials.

2. **MassDEP Section 401 Water Quality Certificate:** Per 314 CMR 9.04(12), an application for a Section 401 Water Quality Certification (WQC) will be required to be filed with the Massachusetts Department of Environmental Protection (MassDEP) Wetlands and Waterways Program if the project will involve dredging of 100 cubic yards or greater material in the area of the culvert and culvert headwall and/or the upstream flood tide shoal to help restore flow. A WQC would require that sediment samples to be collected and tested to show the physical characteristics of the dredge material and compared with regulatory thresholds listed in 314 CMR 9.00 for the proposed placement or disposal

options. Plans for disposal and/or placement of sediment excavated would be described, including procedures and locations for temporary storage and containment, dewatering, points of discharge, construction sequencing, and expected duration of work.

3. **Conservation Commission Ecological Restoration Notice of Intent:** An application for an Ecological Restoration Notice of Intent (NOI) to the Truro Conservation Commission will be prepared and submitted following the receipt of the MEPA and Water Quality certificates for the project. Documentation will be provided showing that the Mill Pond project meets the definition of Ecological Restoration per 310 CMR 10.04, and that the project meets the eligibility criteria for a Tidal Restoration Order of Conditions per 310 CMR 10.13(5). An Operation and Management Plan (O&MP) will be prepared and consist of a general document (i.e., not an adaptive monitoring and management plan) prescribing basic requirements for operations, inspection and maintenance of the site. Following the filing of the Ecological Restoration NOI, the application will be heard by the Truro Conservation Commission at a public hearing to obtain a Restoration Order of Conditions (ROOC) for the project (as long as does not trigger a Limited Project).

4. **U.S. Army Corps of Engineers Permit:** An application for a US Army Corps of Engineers (USACE) Permit will be prepared and submitted to the New England District office. Prior to preparation of the permit application the USACE will be consulted regarding the relevant permitting process and whether a Section 404 General Permit or Individual Permit is required. It is likely that due to the resource impacts that a more extensive Individual Permit could be required. Alternatively, this project could potentially be eligible for an aquatic ecosystem restoration project under Section 206 of the USACE's Continuing Authorities Program if it could be demonstrated that historic marsh habitat was lost by the Bikeway embankments/culverts and that restoration of tidal flow and flushing will reintroduce salinity that would eliminate Phragmites restoring native marsh. Documentation will be developed in consultation with the MA Historical Commission (MHC) during the Section 106 compliance process, as well as results of an archaeological survey and consultations with the local tribal organizations.

5. **MassDEP Chapter 91 License:** Per 310 CMR 9.05(2), an application for a Chapter 91 License will be required to be filed with the MassDEP Wetlands and Waterways Program because the project will involve work that includes excavation and dredging in navigable waterways of the Commonwealth (i.e., below the MHW line). The filing will include a narrative with site maps and engineering plans. This application will be filed after a ROOC for the project has been obtained from the Truro Conservation Commission.

6. **Massachusetts Coastal Zone Management Federal Consistency Review:** An application to MA Coastal Zone Management (CZM) for Federal Consistency Review will be prepared and submitted due to the trigger for a WQC and USACE permits. The application will address consistency of the project will all applicable CZM policies.

7. **MassDOT Chapter 85 Permitting:** Additionally, culverts with a width equal to or greater than 10-ft in will require Chapter 85 Permitting with MassDOT. Therefore, if Alternative 1, the 10-foot-wide by 8.5-foot-wide culvert is selected as the preferred alternative then it would require Chapter 85 permitting with MassDOT. This would add significant time and costs to the permitting scope. The 8-ft wide culvert and breach alternatives would be exempt.

## 6. FUSS & O'NEILL CONCEPUTAL DESIGN REPORT

Project partner Fuss & O'Neill conducted a separate engineering design analysis for the four (4) alternatives presented herein and then drafted conceptual design drawings. The details of the work are found in Attachment B and included the following items:

- Conceptual layout and cross-section drawings for each of the four (4) alternatives.
- A preliminary geotechnical analysis based on the soil borings collected in 2021.
- Scour countermeasures will be developed based on Woods Hole Group scour calculations.
- Opinion of construction and long-term maintenance costs
- Alternatives analysis table

## 7. DISCUSSION AND RECOMMENDATIONS

The goal of this study was to develop conceptual restoration alternatives for the existing, undersized culvert underneath Mill Pond Road that would restore tidal flow, enhance habitat, and improve storm drainage in Mill Pond while minimizing impacts to abutters. Woods Hole Group developed a hydrodynamic model, HEC-RAS 2D, for the Mill Pond system based on collected field data and available data sets to evaluate existing conditions. This study confirmed that the existing 3-foot-diameter culvert under Mill Pond Road attenuates the tidal flow into Mill Pond and causes high flow velocities that have resulted in scour holes on either side of the culvert. However, the model results also determined that the former railroad berm did not have a significant influence on tides or storm flooding and drainage, indicating that there is likely no action needed there to improve the hydrodynamics of the Mill Pond system.

Woods Hole Group then developed four (4) alternatives based on prior studies that were then evaluated using the HEC-RAS 2D hydrodynamic model including:

- Alternative 1 – 10 foot wide by 8.5 foot high open bottom culvert.
- Alternative 2 – 8 foot wide by 8.5 foot high open bottom culvert.
- Alternative 3 – 15 foot wide open channel "breach" with 2H:1V sideslopes
- Alternative 4 – 95 foot wide breach with a 10-foot-wide inner channel, 14-foot-wide saltmarsh benches, and 2H:1V and 4H:1V sideslopes.

A 1D hypsometric model was used to help determine the optimal hydraulic opening sizes, which corroborated the Louis Berger Group studies that indicated a 10-foot-wide culvert would restore full tidal flow and minimize lag time in drainage. The model results determined that the each of the four (4) alternatives provided similar levels of tidal restoration and storm drainage improvements, and which were all improvements over existing conditions. Increasing the tidal range will potentially increase the habitat available for salt marsh and shellfish species by upwards of 3.5 acres. Each of the alternatives will also open the provide more passage for recreational use such as paddlers while reducing safety hazards by providing plenty of headspace.

The maximum storm surge water levels in Mill Pond are similar for all 4 alternatives as well and are increased over existing conditions; however, there do not appear to be any additional significant impacts to private property, dwellings, structure, wells, or septic systems at this time. The roadway overtops during storms larger than the 10-year storm event, which reduces the contributions of storm flooding through the culvert for larger storms anyways.

Since each of the four alternatives produces similar model results, selecting a preferred alternative to pursue final design, permitting, and construction becomes more of a decision based whether there is a preference by the community to maintain the road and install a culvert using Alternatives 1 or 2, or abandon the road and create in an open channel using Alternative 3 or 4. If the road is kept, it is likely to be at risk from flooding during high spring tides in 2070, which is on the order of the design lifetime of a culvert. Therefore, the coastal resiliency of the road will have to be improved through armoring of the embankment and raising the roadway surface at least 2-feet to keep pace with sea level rise. A road raising of 2-feet would require over 1,200 feet of roadway to be raised, which is a significant effort that is likely much more costly than the culvert replacement itself. These issues will be raised during subsequent presentations to the Truro Board of Selectmen in an effort to receive support for an alternative to pursue final engineering design, permitting, and construction. It will take the community coming together to make some hard decisions about what direction that the Town should take for Mill Pond Road and its culvert.

Future considerations that should be considered for the next phase of work include the following:

- Research the history of the historic Grist Mill location to avoid possible disturbance to ruins during construction. It may be necessary for the Town to consult with an archelogy team to determine whether a dig needs to be conducted.
- The 15-ft and 90-ft wide breach options have the potential to allow for wave transmission that is currently attenuated by the roadway and culvert. While these would most likely be small, locally generated wind-waves within Pamet Harbor, it is possible that they could still cause adverse impacts to the shoreline and coastal bank that have not been exposed to any wave energy in recent time. Therefore, it is recommended that a wind-wave generation and transmission analysis be conducted if one of the breach alternatives, #3 or 4, are chosen.
- Both the hypsometric 1D model and HEC-RAS 2D model determined that the island located approximately 100-feet upstream of the Mill Pond inlet causes a weir effect that impedes drainage of Mill Pond. This results in the low tide elevation (i.e. MLW) not to change appreciably from existing to proposed (alternatives) conditions. It is not clear whether increased tidal flow from implementing one of these alternatives will erode this feature and negate this weir effect or whether it will remain since it is located over 100-feet from the culvert.
- No sediment data is available from within the pond so it is unclear whether any of the fine sediment will be mobilized once tidal flow is fully restored. The fine material tends to be cohesive in nature meaning that it can resist mobilization by flows as compared to fine sand. Collection of shallow push cores in the pond may help determine the depth of this fine layer, and whether there is any native marsh peat or sand underneath. This may provide some insight with regards to whether there is the potential for a large release of fine material from Mill Pond.
- Dredging of the island and even Mill Pond bed could be explored to remove the weir effect and fine material on the surface, however, that would constitute a significant additional effort in terms of analyses, engineering design, and permitting. It may be advantageous to implement an alternative prior to going through a significant additional effort to permit new dredging within a wetland resource area for possibly minimal gains since Mill Pond has such as small surface area.
- If one of the breach alternatives are selected, the Town should further explore enhancing public benefit of the project by creating public access with a trail over the former roadway.

- Town should continue its public outreach especially if a breach alternative is chosen since road abandonment is likely to be a highly debated topic.

## 8. REFERENCES


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## Attachment A – Existing Septic and Well Locations of Properties in Vicinity of Mill Pond Road


WOODS HOLE GROUP
A CLS COMPANY
107 WATERHOUSE ROAD, BOURNE, MA 02532
TELEPHONE: (508) 540-8080 FAX: (508) 540-1001

Date

Revisions

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Surveyed By:
Woods Hole Group
107 Waterhouse Road
Bourne, MA 02532
508-540-8080

Title:

Existing Septic and Well Locations of Properties in the Vicinity of Mill Pond Road
Prepared For:
Town of Truro, MA

Project Number: 18-0189-02
Dwg File: 18-0189_SEPTICS5.dwg
Scale: 1" = 100'
Date: 04/29/2022
Approved: Joel Kubick
Drawn: Lindsay Pisapio

## Attachment B – Fuss & O'Neill Conceptual Design Report