TOWN OF TRURO

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Memorandum

To: Members of the Pamet Harbor Commission
From: Jarrod J. Cabral, Department of Public Works Director
Date: January 19, 2023
Subject: DPW Update

The following items will be reviewed/discussed at the January 19th Harbor Commission Meeting.

Floats
Harbor Parking lot
Harbor Cameras
CC Reader
Drainage
Corn Hill overflow parking lot
Jetty
Mill Pond culvert design alternatives

Sincerely,
Jarrod J. Cabral
Director
Department of Public Works
Truro Ma 02666

Mill Pond Salt Marsh Restoration Alternatives Assessment Technical Memorandum

Town of Truro

Truro, MA

June 2022

317 Iron Horse Way, Suite 204
Providence, RI 02908

Project No. 20181290.A10

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Town of Truro

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Executive Summary

Currently, the Mill Pond Road culvert restricts tidal flow into Mill Pond from Pamet Harbor and, ultimately, Cape Cod Bay. The purpose of this project is to replace the damaged and undersized culvert at the Mill Pond Road dike with a larger structure or alternative breach design.

Structural, geotechnical analyses, and this technical memorandum were developed by Fuss & O'Neill, Inc. (F&O) in conjunction hydrologic/hydraulic analyses performed by Woods Hole Group (WHG). These analyses were completed to assess conditions and support development of 30% conceptual design drawings for the proposed alternatives to replace the of the existing 36-inch corrugated polyethylene pipe culvert on Mill Pond Road. A total of four alternatives were considered in the development of this report including two larger open bottom precast culverts and two embankment breach formations.

To assess the severity of the restriction and the potential for ecological restoration, the anticipated effects of replacing the undersized culvert with a larger culvert structure or open channel entailing abandonment of the road were evaluated. Woods Hole Group, Inc. (WHG) assessed the current and proposed alternative culvert and breach scenarios and provided recommendations for channel bed scour [protection measures for respective alternatives.

- Culvert Alternative No. 1: Single 8'-0"W x 8'-6"H Three-Sided Precast Concrete Box Culvert
- Culvert Alternative No. 2: Single 10'-0"W x 8'-6"H Three-Sided Precast Concrete Box Culvert
- Breach Alternative No. 1: 15' Bottom Width with Uniform Channel Banks
- Breach Alternative No. 2: 10' Bottom Width with Adjacent 15' Elevated Benches

An assessment of the above alternatives was completed, entailing consideration of construction costs, operation and maintenance costs and consideration of other evaluation criteria. Upon completing this assessment, it was determined that a breach channel with a 65-foot top width is the preferred alternative for subsequent design and implementation, subject to review and discussion with the Truro Selectboard and receipt of public input from ongoing outreach efforts

1 Project Description and Purpose

1.1 General Site Description and Project Purpose

The Project Site (Site) is located on Mill Pond Road (MPR) where the roadway crosses over a tidal creek referred to as the Mill Pond Channel stemming from Pamet Harbor to Mill Pond in Truro, Massachusetts. The Mill Pond Channel conjoins with the Pamet River and subsequently forms Pamet Harbor.

The earthen causeway supporting Mill Pond Road (MPR) effectively functions as a dike restricting tidal flows to, and drainage flows from, the Mill Pond impoundment. A 36-inch corrugated polyethylene pipe (CPP) conveys drainage from Mill Pond to the Pamet River (Figure 1).

Mill Pond has an extensive usage history dating back to the Revolutionary War Period. During the mid-19th century, Truro and other Cape Cod towns enjoyed economic success as major producers of salt from its shoreline waters. Mill Pond was regularly used as one of the largest salt works in New England. In 1869, a railroad bed was constructed across Pamet Harbor, which restricted Tidal Flows to Mill Pond, converting the impoundment to a freshwater marsh.

Figure 1 — Mill Pond Road Culvert Location

The freshwater condition remained until large storm events in 1978 and 1991 completely breached the former railroad embankment. The existing 36-inch CPP pipe was installed after the 1991 storm as a temporary measure, with the intent to subsequently install a larger timber bridge as a permanent structure. The bridge was never constructed and the 36-inch CPP remains today.

The roadway embankment covering over the culvert is subject to wave and roadway runoff erosion, resulting in a narrowing of the roadway shoulders over the culvert, and requiring regular repair and replenishment of stone armor scour protection.

The purpose of this project is to replace the undersized culvert that tidally restricts Mill Pond with a larger structure or channel breach alternative that will allow increased tidal flushing to restore degraded salt march resources, provide water quality improvements, and improve drainage runoff flows from the impounded system under both normal and storm flow conditions.

Woods Hole Group (WHG) is currently completing refined hydraulic modeling of alternative culvert sizes and configurations, in conjunction and collaboration with the structural and civil layout assessments described in this technical memorandum. The results of WHG's analyses and recommendations are contained in a separate technical memorandum to be provided to the Town of Truro in support of this project.

1.2 Existing Conditions

Conditions observed at the project site in May and June 2021 are described in the following sections. An existing conditions survey with current tidal elevations is provided as Attachment A.

1.2.1 Culvert and Downstream Channel/ Riverbank

The existing 36-inch diameter CPP below MPR has a total length of approximately 54 feet and is sloped from east to west at approximately 0.7 percent, having invert elevations of -2.03 and -1.6 (NAVD88) at its downstream (west) and upstream (east) ends, respectively. The downstream end of the culvert emerges from the causeway into a stone armored channel that discharges to the downgradient connecting to Pamet River.

Figure 2 — Downstream Culvert Outlet and Stone Armor Slope Protection (Facing North)

The areas surrounding the Mill Pond Channel are dominated by tidal conditions and supports a saltwater environment exhibited by the channel being surrounding by salt marsh vegetation and marsh flats farther downstream. The downstream channel is bounded by the Pamet Harbor Yacht Club to the north and Mill Pond Road/Post Drive to the south.

Approximately 1,600 feet downstream of the CPP, a breached former railroad embankment conveys tidal flow from Mill Pond to Pamet Harbor. The former railroad embankment appears to consist of sand with former railroad abutments of cut stone exposed in places at the breach..

The downstream face of the embankment is currently in poor condition as exhibited by displaced slope protection and debris build up around the culvert discharge point. The Town of Truro completes maintenance on the embankment annually to restore displaced riprap and repair areas of erosion. In addition, a scour hole is positioned at the discharge area at the beginning of the Mill Pond Channel.

Figure 3 — Upstream Culvert Outlet, Scour hole and Shoaled Sediment (facing east)

Figure 4 — Downstream Tidal Channel and Abutting Salt Marsh (facing west)

1.2.2 Upstream Channel and Impoundment

The Mill Pond tidal impoundment upstream of the culvert receives water from upland areas via groundwater and overland runoff. The impoundment is bounded by salt marsh and other intertidal habitat around its perimeter, with forested residential properties bording the wetlands to the south, east and north, with a portion of the impoundment northern bank formed by the embankment slope supporting Depot Road.

Figure 5 — Upstream Culvert Outlet and Stone Armor Slope Protection (facing south)

The upstream end of the CPP projects from the earthen causeway supporting MPR, which is partially covered by stone armor protection over and adjacent to the culvert. Indications of a tidal restriction near the culvert's end include a scour hole with an intertidal island formed by shoaled sediment, a significant tidal lag and muting, poor drainage during inland precipitation events, and bank erosion adjacent to the culvert.

1.2.3 Roadway Approaches

The existing paved surface of MPR consists of two travel lanes (one lane in each direction) with a total width of approximately 18 feet. Metal beam guardrails are located on both sides of the roadway at its crossing over the culvert, with approximately 12-inches of clearance from the guardrail face to the edge of pavement (little to no shoulder).

Embankment slopes behind the guardrails exhibit signs of erosion and steepening, providing inadequate lateral support to the guardrail system, as indicated by leaning posts supporting the horizontal rail on the roadway's southbound (western) travel lane. Concrete posts are positioned beyond the ends of the metal beam guardrails in both directions at an approximate 8 foot spacing.

Figure 6 — Mill Pond Roadway Approach to Culvert (facing north)

Survey measurements along the roadway's centerline profile on both sides of the culvert indicate low points approximately 80 feet north and 115 feet south of the culvert (0.1 feet and 0.65 feet lower, respectively, than the roadway elevation at the culvert). The roadway is pitched to the upstream (east) slope in proximity to the culvert, with a small section south of the culvert nearly flat.

1.2.4 Roadway Stormwater Drainage

Stormwater runoff north of the culvert generally flows along the roadway's curb at the edge of pavement, with a leaching catch basin on the southbound (west) lane approximately 420 feet north of the culvert providing partial drainage. Runoff continuing past this drainage structure generally is generally conveyed as sheet flow to the shoulder and adjacent land along the northbound (east) lane, with the majority of runoff discharging from the road at the low point immediately north of the culvert and adjacent to a secondary residential driveway and sandy pull-out area.

Runoff arriving at the culvert from the north continues to the low point south of the culvert, where it generally is conveyed as sheet flow to Mill Pond as along the northbound shoulder and slope. A leaching catch basin is located on the northbound shoulder approximately 160 feet south of the culvert.

1.2.5 Flood Zones

Federal Emergency Management Agency (FEMA) Flood Map No. 25001C0227J for Barnstable County (with an effective date of July 16, 2014) depicts the project site as being located within a 'Zone AE' special flood hazard area with a 1% annual chance base flood elevation of 12 feet (NAVD88). The downstream tidal channel west of MPR is designated as a 'Zone AE' special flood hazard area with a 1% annual chance base flood elevation of El 13 feet (NAVD88). FEMA Flood Zone boundaries are depicted on the Existing Conditions Plan provided as Attachment A.

1.2.6 Contaminated/Hazardous Materials

There are no known or expected hazardous materials or contaminants located within the roadway and in off-roadway areas within the Project Site that would need to be managed during construction associated with the replacement of the existing culvert or excavation of an open channel alternative. Supplemental investigations of the environmental quality of soils comprising the causeway embankment are recommended in the subsequent project phase to confirm the above understanding.

1.3 Scope of Report

The primary scope of this report is to present findings of preliminary geotechnical and structural analyses completed to date and provide conceptual layouts for replacement culvert and open channel alternatives following removal of the Mill Pond Road culvert to improve tidal flows to Mill Pond and restore deteriorated salt marsh areas.

2 Geotechnical Investigation and Design Evaluation

The following sections summarize findings from a geotechnical investigation and preliminary design analysis completed in support of the replacement of the existing culvert. The contents of this section are subject to the limitations provided as Attachment B.

2.1 Program Objective

The objectives of the subsurface investigation was to assess subsurface conditions at the Mill Pond Road culvert (Site). To achieve these objectives, Fuss & O'Neill completed the following field investigation:

- Conduct two (2) geotechnical boreholes (B-1 and B-2) at the Site and collect soil samples
- Visually classify soil samples
- Complete three (3) gradation analyses on selected representative soil samples

Prior to conducting this investigation, the Natural Resources Conservation Service (NRCS) soil report for the Site, provided as Attachment C, was reviewed. The results of the subsurface investigation and laboratory testing, and preliminary design assessments, are presented below.

2.2 Subsurface Exploration Program

The subsurface exploration program consisted of two (2) boreholes (B-1 and B-2) completed by Soil X, Corp of Leominster, Massachusetts under subcontract to Fuss & O'Neill, Inc. Boreholes were completed on June 1 and 2, 2021 utilizing a truck-mounted drill rig. Hollow-stem augers were used to set the casing at each borehole. Boreholes were advanced using 4-inch inner-diameter flush wall casing and tricone roller bit. The approximate locations of the borings are depicted in Figure 7. All borings were observed and logged by a Fuss & O'Neill engineer. Boring logs are provided as Attachment D.

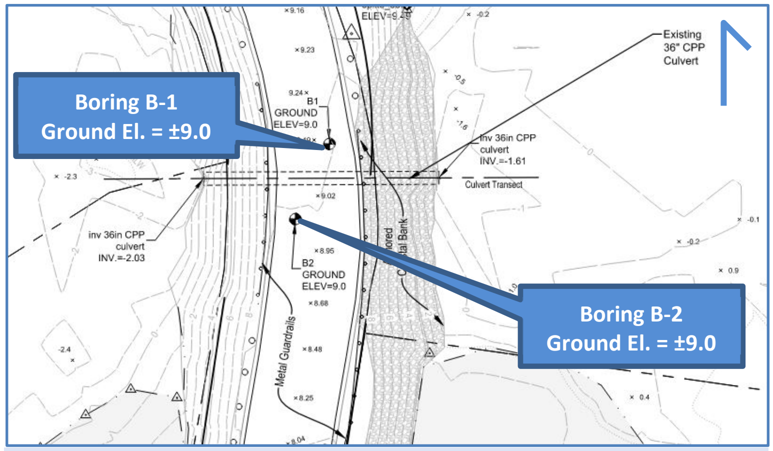

Figure 7 — Subsurface Boring Locations

Borings were advanced to depths ranging from 51 feet to 80 feet below the existing ground surface. Split spoon soil samples were obtained continuously to about 21 feet and then at intervals of 5 feet thereafter using the Standard Penetration Test (SPT) per ASTM D-1586 at each borehole location. The SPT consists of driving a 2-inch outside-diameter split spoon sampler 24 inches with a 140-pound hammer free-falling 30 inches. The number of blows required to drive the sampler from 6 to 18 inches is the Standard Penetration Resistance, also known as the SPT N-value, which is a relative indicator of the *in-situ* soil relative density or consistency. Boreholes were backfilled with tamped soil cuttings upon completion covered with cold patch asphalt prior to leaving the site.

During explorations, subsurface soils were visually classified utilizing the Burmister Classification System. This system describes soil composition based upon the percentage of soil particle size present in the sample with the major soil particle size listed first following other soil components described as "and" (indicating 35-50% by weight), "some" (indicating 20-35% by weight), "little" (indicating 10-20% by weight), or "trace" (indicating 0-10% by weight). Descriptions of each soil strata encountered during the investigations are provided in the Subsurface Profile section below.

Borehole B-1 was terminated without refusal at a depth of approximately 80 feet below the ground surface. The casing was driven to a depth of 74 feet below the ground surface and the split spoon sampler was advanced to the termination depth. Borehole B-2 was terminated without refusal at a depth of approximately 51 feet below the ground surface. The casing was driven to a depth of 49 feet below the ground surface and the split spoon sampler was advanced to the termination depth.

2.3 Subsurface Profile

Generalized subsurface conditions at the Site are described below, based on the results of the explorations and observations at the time of drilling.

- **General Description:** Brown sandy fill over brown to reddish brown native sand.

- **Fill:** Very loose to medium dense, brown, fine to medium sand with varying amounts of fine gravel and trace amounts of silt. One sample within the fill material contained trace amounts of woody fibrous material. Approximately seven (7) feet of sandy fill material was encountered in borings B-1 and B-2.

- **Native Sand:** Loose to medium dense, brown to reddish brown, fine to coarse sand with varying amounts of fine to coarse gravel and trace amounts of silt. At the transition point between the fill material and the native sand two samples had a main constituent of fine gravel with some fine to coarse sand and trace silt. The native sand layer was encountered beneath the fill in both borings and extended to the termination of each boring.

2.4 Laboratory Testing

Laboratory testing consisted of three (3) grain size analyses (per ASTM D6913) performed by Thielsch Engineering of Cranston, Rhode Island. Testing was performed to confirm visual classification of soils in the field. The results of the sieve analyses are included as Attachment E and are summarized below in Table 1.

Table 1
Summary of Laboratory Test Results

Sample No.	Identification Test		
	Sieve Analysis (ASTM D6913)		
	% Gravel	% Sand	% Silt
B-1 / S-2	0.0	97.7	2.3
B-2 / S-5	5.9	93.1	1.0
B-2 / S-12	6.8	92.0	1.2

2.5 Groundwater Conditions

Surveyed ground surface elevations at borings B-1 and B-2 are reported by Woods Hole Group at EL. 9.03 and 8.97 (NAVD88), respectively. Due to the tidal influence present at Mill Pond and the Pamet Harbor, groundwater elevations may fluctuate due to the tidal cycle, in additional to seasonally and due to storm- or drought-related events.

Groundwater was observed at the time of the subsurface investigation in each boring at depth of 7 feet below the ground surface. Since the borings were advanced utilizing cased borehole techniques involving water being poured into the boreholes during the driving process, natural groundwater levels are expected to vary from the measured values. Groundwater observation wells were not installed at the site.

A summary of groundwater elevations measured within the boreholes is provided in Table 2.

Table 2
Summary of Boring Groundwater Elevations

Boring No.	Date	Groundwater	
		Depth Below Ground (ft)	Approx. Elev. (ft, NAVD88)
1	6/1/2021	7	2.03
2	6/2/2021	7	1.97

2.6 Geotechnical Design Evaluations and Recommendations

Geotechnical design evaluations and recommendations presented below were developed by RMA GeoEnvironmental (RMA) under subcontract to Fuss & O'Neill. RMA was provided the geotechnical data report developed as part of the initial subsurface investigation as well as preliminary conceptual drawings for the culvert alternatives under consideration, in support of their preliminary design evaluations and foundation recommendations.

2.6.1 Seismic Design Parameters and Liquefaction Potential

Lower zones within the subsurface profile appear to have the potential for liquefaction under potential future seismic events and should be evaluated further under future design analyses. Depending on the results of those future analyses, alternative ground improvement methods should be considered and identified for potential implementation during the project's construction phase, as described in Section 2.6.2 below.

2.6.2 Recommended Foundation

A preliminary bearing capacity analysis was completed by RMA utilizing the subsurface investigation information and conceptual design drawings provided by Fuss & O'Neill. The analysis was completed using three independent bearing capacity equations (Bowles, Terzaghi, and Vesic) in accordance with established engineer practice and accepted principles of soil mechanics. These methodologies rely on weighted average of the N-values obtained during the subsurface investigation for footing influence depths that are corrected for field conditions, overburden, and groundwater table condition along with strength parameters (unit weight, friction angle, etc.) correlated from boring information.

Based on the results of the analysis, allowing for one-inch of total long-term settlement, the wingwalls and strip footings depicted on the conceptual drawings will provide adequate support for the proposed culvert structure, provided that the footings bear on a minimum of 12 inches of compacted crushed stone wrapped in non-woven geotextile fabric, as shown. This evaluation assumes a bearing pressure of 3,500 pounds per square foot (psf) for the culvert structures under consideration; as shown on the conceptual drawings, recommended footings should be designed with a width of 4 feet and be embedded below the scour depth determined from WHG's scour analyses.

Due to the loose lower zones observed within the boring's soil profile, a ground improvement method such as rammed aggregate piers should be considered to reduce the potential for settlement under a potential future seismic event. The scope of future investigations should consider the identified preferred alternative from the current evaluation; ground improvement methods would only be warranted for an alternative to construct a replacement culvert, and would not be required under either breach scenario.

Rammed aggregate piers (RAPs) consists of vertical columns of aggregate installed on a grid within the footprint of the construction. Piers are installed by placing and mechanically tamping lifts of aggregate through a bottom-fed pipe. The pipe is driven to the bottom of the pier depth and subsequently withdrawn and tamped downward during installation of the aggregate, forming bulbs along the length of the pier. Aggregate piers improve conditions at the site by displacing, and thereby, densifying the surrounding soil at each column and transferring loads from the spread footings to the underlying suitable soil.

Spread footings at the wingwalls and along the length of the alternative culvert walls and wingwalls will be constructed over the improved area following implementation of the rammed aggregate piers. As there is no dewatering required and the installation process does not generate any spoils during construction, this soil improvement approach is typically used to reduce the potential for long-term settlement where liquifiable conditions are identified under potential future seismic events.

2.6.3 Embankment Considerations

Within the limits of proposed excavation, sections of the embankment that are disturbed as part of activities to construct the replacement structure will be reconstructed to provide vertical and lateral support for both the new structures and the overlying roadway. This will be achieved by placement of an appropriate structural backfill (e.g., gravel borrow) and ensuring placement of this material under controlled conditions to achieve the required compaction and in-place density stated in the project's technical specifications.

For any construction during freezing weather, soil bearing surfaces in exposed culvert footing excavations should be protected from frost by use of insulated blankets, ground heaters or other acceptable methods. Specifications for protection and placement of materials would be developed under future phases of design entailing a replacement culvert structure, and would not apply for either alternative open channel configuration.

It is understood that potential increases of the embankment's crest (roadway) elevation may be evaluated as potential variants of the culvert alternatives assessment presented in the sections below. Considerations relative to either raising or not raising the embankment crest include the following:

- Not raising the embankment crest will result in more frequent and severe future inundation/overtopping conditions under sea level rise projections outlined by Woods Hole Group's June 2022 Hydraulic Analysis Report. These overtopping events will impact usability of MPR for normal and emergency response uses. In addition, overtopping events will result in increased maintenance and repair of the road and slopes due to scour erosion.
- Raising the embankment crest will reduce, and possibly avoid depending on the magnitude of the increase, the impacts noted above however will require supplemental field investigations and analyses to evaluate horizontal layout and structural considerations in designing a higher embankment configuration that would be structurally adequate to support a public road.
    - Horizontal considerations include potential impacts to adjacent wetland resources by the increased base with of the embankment's cross-section that would be entailed with slopes remaining at their current configuration (i.e., not increasing the proposed slopes, which would increase stability concerns).
        - Such impacts to adjacent wetlands may be prohibitive considering the length of road that would need to be raised (approximately 1,600 feet). In addition, soils adjacent to the existing embankment may not be structurally suitable to support the weight of soils placed as to laterally expand the embankment, and thus would need to be excavated and replaced with suitable soil or augmented by geosynthetics or other ground improvement methods.
    - Structural considerations include potentially incorporating retaining walls along the top and/or bottom of the embankment to provide lateral support for soils placed to increase the embankment crest in order to avoid or minimize the extent of encroachment into adjacent wetlands (that would otherwise result from a widening of the embankment's base, as described above).
        - A number of wall structure types and configurations could be evaluated. Supplemental subsurface investigations would be required to evaluate soil properties along the length of the embankment in support of subsequent design analyses. If unsuitable soil conditions are identified, improvement methods and/or deeper wall configurations would likely be required.

2.7 Geotechnical Construction Considerations

2.7.1 Surface and Groundwater Management

As noted above, water elevations within the boreholes were measured at El. 1.91 – 2.03 feet (NAVD88) during subsurface exploration. These observed elevations are in the vicinity to the Mean High-Water elevation (El. 2.75 feet, NAVD88) immediately upstream of MPR. Water levels are expected to fluctuate moderately with the varying tidal elevations and seasonal conditions during construction.

Based on the proposed culvert invert elevation (El. -1.6, NAVD88) and conceptual culvert/foundation system developed from preliminary foundation design evaluations to date, it is expected that excavations may be required to El. -9.6 or lower, which is approximately 12-feet below observed groundwater levels within the causeway. Temporary seepage cutoff (e.g., steel sheeting) and groundwater dewatering systems will need to be designed and implemented by the contractor to maintain adequately dewatered conditions for construction of the foundation elements.

As part of these measures, surface water flowing within the channel will need to be maintained throughout the period of construction. It is expected that flow will be maintained through the existing culvert during the period of construction of the proposed culvert or open channel. Upon completion of construction of the replacement culvert, or partial construction of the alternative breach channel, the existing culvert will be abandoned in place or removed and replaced with compacted backfill.

2.7.2 Excavations

It is expected that approximately 19 vertical feet of embankment fill material will need to be excavated below the roadway surface to remove embankment (fill) soil supporting MPR and underlying native soil to allow placement of proposed foundation elements and culvert/wall structures on a suitable subgrade surface.

Temporary excavation slopes will range between a maximum of 1.5H:1V to 2H:1V for culvert alternatives, unless otherwise reinforced or shored, to allow construction equipment to safely reach the deepest/interior work areas. Consideration of the type of equipment expected for construction will affect the configuration of shoring systems and platforms for position of equipment required to construct culvert structures, if selected. It is expected that embankment breach alternatives can be constructed without any temporary shoring systems.

While other cutoff and shoring systems may also provide suitable conditions for mobilization of materials and equipment in support of construction operations, it is expected that steel sheeting would be most cost effective given the limited area and depth of excavation required below expected groundwater elevations, as well as this type of system being most widely used by contractors in the region.

2.7.3 Obstructions

Based on our observations at the site and review of available reports and records, it does not appear that structures or other objects that would obstruct excavation work associated with the alternative culvert structure or channel configurations under consideration. If such structures or objects are encountered and are determined to be abandoned or remnant structures, it is expected that they will be partially or completely removed as required to allow placement of proposed materials and structures in accordance with the developed drawings and specifications.

2.7.4 Protection of Adjacent Structures

Adjacent structures include the paved roadway beyond the proposed work limits depicted on the conceptual alternative drawings and the leaching catch basin to the south of the MPR culvert. It is expected that proposed construction activities will be conducted in a manner avoiding interruption to, or temporary relocation of, this structure. Temporary steel sheeting is expected to be installed if a culvert alternative is selected, to limit the extent of impacts resulting from excavation to the depths required for construction of the proposed structure.

It is also noted that existing steel guardrails in the immediate vicinity of the culvert will be removed and replaced with steel-backed timber guardrails if either replacement culvert alternative is selected.

2.7.5 Additional Earthwork Considerations

The following controls or methods should be employed during construction of either culvert alternative to ensure that the structures are not compromised by inadequate structural fill or improper construction techniques.

- Fill used as gravel borrow for bridge/footing foundations or for embankment fill should meet the gradation requirements of MassDOT Item No. M1.03.0 Type b and should be free of organic material, construction debris, ice, snow, and other deleterious material. The on-site fill may be selectively reused as bedding and backfill materials adjacent to the culvert structure, subject to inspection and testing to verify gradation requirements are met in other excavation areas. The existing native soils are not suitable for reuse for these applications.
- Crushed Stone may be used for wet subgrades, as a replacement for fill used below foundation level. This material is to be a crusher-run stone quarry product, should meet the gradation requirements of MassDOT Item M2.01.4 (minus ¾-inch crushed stone), and should be wrapped in a geotextile separation fabric.
- Fill placed above footings should be placed in loose lifts not to exceed 12 inches in thickness and should be compacted to 95 percent of maximum dry density as determined by ASTM 1557, Method C.

Excavation, fill placement, and footing construction for cul;vert alternatives should be conducted under dry conditions. Excavation shoring and side slopes, where used, should be in accordance with Occupational Safety and Health Administration (OSHA) standards. This will require that methods be developed and implemented to bypass tidal and storm flows at the site through temporary structures while the replacement structure is being constructed. It will also require the cutoff and drawdown of groundwater within the excavated areas until constructed features are backfilled to a high enough elevation that structures and materials are not potentially compromised by natural high surface water and/or groundwater conditions (e.g., floods, seasonal high tides, storm surges, etc.).

Dewatering within excavated areas would likely be most effectively completed by installing and operating appropriately sized and spaced conventional groundwater dewatering sumps. These sumps should be employed in concert with positive cutoff methods provided by driven cofferdam/shoring sheets in order to maintain water levels sufficiently below the ground surface to allow placement of soil materials and structures under controlled conditions. The contractor will be responsible for design of these provisions, which will subsequently be reviewed for acceptance by the design engineer.

3 Culvert Structure Alternatives Assessment

The following sections summarize the results of assessments of alternative culvert structure configurations at the Project Site.

3.1 Culvert Structure Design Criteria

Alternative culvert structures evaluated would meet applicable requirements of the American Association of State Highway and Transportation Officials (AASHTO) Load Resistance and Factor Design (LRFD) Specifications and MassDOT's Bridge Manual and Highway Specifications. Primary conceptual design parameters are listed below.

Vehicle Loading:	HL-93
Vehicle Speed:	25 MPH
Overhead Clearance:	18" over MHW

There is no current or proposed marine traffic that affects the structure's layout. There is potential that this channel is, or will be, used by recreational paddlers and fish passage. Therefore, the height of the structure was set strictly based on hydraulic modeling recommendations, recreational access and fish passage as outlined by Woods Hole Group.

3.2 Alternative Culvert Structure Configurations

Two precast concrete open bottom culvert configurations were evaluated, both of which would meet the project's restoration objectives by increasing tidal volumes and elevations to/from Mill Pond while also improving drainage from Mill Pond following large storm events (dimensions indicated are hydraulic opening sizes):

- **Culvert Alternative No. 1:** Single 8'-0"W x 8'-6"H Three-Sided Precast Concrete Box Culvert
- **Culvert Alternative No. 2:** Single 10'-0"W x 8'-6"H Three-Sided Precast Concrete Box Culvert

Plan, profile and section views of these alternatives are provided on drawings Culvert Alt-1 and Culvert Alt-2 included in Attachment F. The following general considerations are noted for both culvert alternatives.

- The structure's configuration is compatible (i.e., construction- and cost-effective) with the geotechnical foundation recommendations outlined above.
- The structure's configuration supports placement of sediment within voids of stone armor scour protection to provide a natural channel substrate through the culvert.
- The alternative culvert opening sizes provide improved tidal volumes and ranges to support restoration of salt marsh areas within Mill Pond, and improve post-storm drainage conditions (i.e., allowing impounded water to drain out more quickly vs. existing conditions).

- A replacement culvert would maintain MPR as a local roadway for normal use and emergency response. The elevation of MPR could potentially be increased in the future in response to sea level rise conditions.
- Maintaining the culvert and embankment reduces energy within Mill Pond during coastal storm events, in comparison to breach channel alternatives being considered.

These and other considerations are further evaluated in relation to the two culvert configurations and breach alternatives in Section 6 below.

3.3 Culvert Structure Span and Foundation

The subsurface investigation observed unsuitable (non-structural) soil forming the embankment, with traces of organic material (timber) observed in one of the borings. This fill material would be excavated and removed/replaced with compacted structural backfill adjacent to/over the culvert structures.

As noted above, based on the findings of the subsurface investigation and preliminary geotechnical design analyses, the culverts and wingwalls can be placed on concrete spread footings with the potential need for supplemental ground improvement within the footprint of the footings depending on the results of future design analyses. Both culvert structure alternatives would have a span of approximately 32 feet based on conceptual layout analyses conducted to date. Other relevant design considerations include the following:

- The conceptual wingwall configuration will minimize impacts to adjacent wetlands by reducing the amount of fill that would otherwise be required to provide stable embankment slopes, and by reducing discharge velocities emerging from the culvert structure.
- Stone armor channel and slope protection will be placed along the beyond the limits of the culvert for additional scour protection and to protect embankment slopes during higher energy storm conditions.

Future design evaluations in the project's next phase will further assess scour countermeasures that would be required within and beyond the limits of the culvert and on embankment slopes (i.e., based on wave generation analyses, and stormwater drainage analyses for the roadway).

3.4 Culvert and Tidal Channel Alignment

The conceptual culverts alignments included in Attachment F position the proposed precast concrete culverts immediately south of the existing CPP and channel. Offsetting the proposed culverts would allow tidal and drainage flows to be maintained through the existing CPP during construction of the new culvert, at which point flow would be diverted through the new culvert to allow removal of the existing CPP (or removal/burial of the CPP ends and infilling the remaining central section with flowable fill).

Shifting the culverts south maintains general alignment with the existing tidal channel to Pamet Harbor and would direct flow within Mill Pond toward the shoaled area shown on Figure 5. Future layout analyses may entail adjusting the alignment further to discharge flows into Mill Pond north of the shoaled area, however that may result in a conflict with the existing culvert and/or reduce alignment with the tidal channel to Pamet Harbor. Future supplemental field investigations of sediment properties on both sides of MPR would also be considered in potential dredging and/or grading sediment to create continuous channels from the culvert's ends to existing channels in Mill Pond and leading to Pamet Harbor.

3.5 Channel and Bank Protection

The channel bottom within the culvert and immediately adjacent to the ends of the culvert (to the limits of the splayed wingwalls) will be stabilized with sediment-filled stone armor as scour protection upstream and downstream of the culverts. The dimensions of the scour aprons beyond ends of the culvert would be evaluated and updated in future design analyses. Embankment slopes immediately adjacent to the culvert openings (to the extent of excavation required for placement of the culver) would be protected by vegetated soil-filled stone armor and toe protection. Based on preliminary scour assessments by Woods Hole Group, it is expected that stone armor would be required to meet Federal Highway Administration (FHWA) Class IV sizing (D_{50} of 14 inches) and be placed in layer with a minimum thickness of 36" over a crushed stone bedding layer underlain by geotextile filter fabric. Embankment slopes would be seeded and covered with a biodegradable erosion control blanket to establish coastal grass vegetation for additional surface stabilization.

As shown on the drawings included in Attachment F, the open-bottom culvert would be configured with sediment-filled stone armor placed to provide a natural channel substrate. A concrete cutoff wall has been included in the conceptual layout drawings to provide additional protection against movement of armor stones within the culvert due to excessive scour velocities, however would be evaluated in future design phases to determine if it is required or other measures could be incorporated to provide improved protection against potential movement (e.g., increasing stone size, or grouting lower ¼ of stones before placing infilled sediment). It is expected that future design evaluations would also consider the cross-sectional configuration of the channel bottom within the culvert to improve channel conditions (e.g., water depths) for aquatic animals and/or paddlecraft passing through the structure.

3.6 Roadway Layout and Drainage

Mill Pond Road's cross-section over the embankment and culvert currently consists of two approximately 9-foot wide travel lanes (no outer stripes) with approximate 12-inch wide grassed shoulders inside the face of metal beam guardrails bordering the embankment over the tidal channel, as shown on Figure 8. The conceptual roadway section depicted on drawings included in Attachment F maintains existing travel lane widths within the limits of excavation required to construct the culvert, which conforms to the Town's requirements for a 'Type B' roadway (defined as a road serving 5-10 residential properties).

Figure 8 — Mill Pond Road Layout (facing south)

Steel-backed timber guardrails are conceptually proposed to replace the existing metal beam guardrails. Standard MassDOT guardrail section requirements including a minimum of 24-inches of compacted soil behind guardrails to provide lateral support for driven posts, as shown on Figure 9. Guardrails are conceptually depicted along both lanes within the limits of excavation associated with the culvert, and would be evaluated in future design phases to adjacent the extent required along both lanes to provide adequate protection to prevent errant vehicles from striking the bridge's wingwalls or entering the steeply sloped banks and open water.

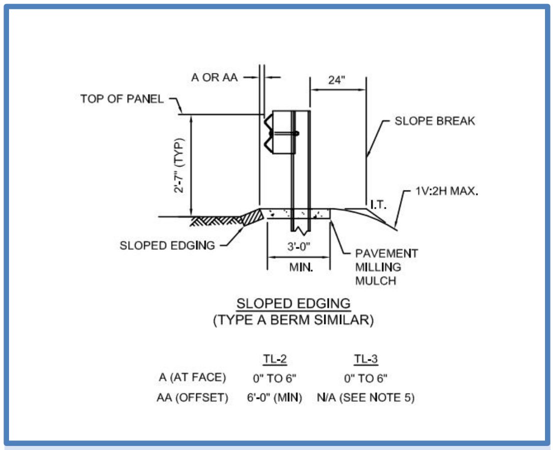

Figure 9 — Typical MassDOT Guardrail Section

The conceptual embankment/roadway section depict the faces of guardrails a minimum offset of 3-feet from the edges of pavement, providing an standard shoulder along both travel lanes and the 24-inch minimum width of level soil being the both guardrails. Future design phases would determine how respective segments of the roadway approaching the culvert and over the culvert would be crowned or pitched uniformly to provide positive drainage from the road to existing or additional drainage structures conveying runoff to adjacent wetlands and open water areas.

3.7 Operation and Maintenance

Operation and maintenance guidelines for respective elements associated with the culvert alternatives are outlined below. Specific and more detailed requirements, including inspection and recordkeeping frequencies, would be developed as part of an Operation and Maintenance Plan in support of future permitting activities.

- Concrete Culvert and Headwall/Wingwall Structures
  - Inspection and maintenance/repair of concrete surfaces for damage and deterioration (e.g., cracks, delamination, exposed reinforcing steel).
- Stone Armor Scour and Slope Protection
  - Inspection and maintenance/repair of stone armor if displaced or damaged from storm events, runoff or anthropogenic factors.
- Vegetative Stabilization
  - Inspection and maintenance to assure that embankment slopes and other areas subject to runoff erosion are stable.

4 Causeway Breach Alternatives Assessment

The following sections summarize the results of conceptual design evaluations of the proposed breach alternatives to remove the existing culvert and create an open channel through the causeway supporting MPR. These alternatives would result in elimination of Mill Pond Road as a pedestrian and vehicle travelway between Depot Road and Post Drive.

4.1 Breach Channel Design Criteria

Breach channel alternatives considered would provide increased tidal and drainage conveyance to/from Mill Pond in comparison to either culvert alternatives. Hydraulic modeling analyses by Woods Hole Group have evaluated upstream water levels and conditions affecting bordering properties and the embankment supporting Depot Road on Mill Pond's northern bank. Sizing of the channel alternatives have been developed to achieve restoration objectives without causing impacts to bordering upland properties.

Channel banks on both sides of alternative breach channels would incorporate stone armor slope protection on lower elevations and bioengineered bank stabilization on upper intertidal portions to protect the adjacent embankment soils from scour, wave and runoff erosion.

As noted above, any breach alternative would result the loss of pedestrian/vehicular traffic between Depot Road and Post Drive. Pavement would be maintained to the residential property south of the intersection with Depot Road through Mill Pond Road to maintain access to that residence. Remaining segments of the embankment would have pavement removed and be restored to a natural (soil or vegetated) surface. Considerations for emergency vehicle access and maneuvering on the resulting cul-de-sac roadway segments would need to be identified (if any) and evaluated to determine if additional layout modifications (e.g., to accommodate the turning radius of an emergency response vehicle) would need to be incorporated in a future design phase.

While it is not anticipated that the channel would be navigated by powered watercraft, it is likely that the channel would provide adequate widths and water depths for small boats to access Mill Pond.

4.2 Alternative Breach Channel Configurations

Two alternative breach configurations were evaluated and are described in the following sections, as depicted on drawings Breach Alt-1 and Breach Alt-2 included in Attachment F

- **Breach Alternative No. 1:** 15' Bottom Width with Uniform Channel Banks
- **Breach Alternative No. 2:** 10' Bottom Width with Adjacent 15' Elevated Benches

The following general considerations are noted for both breach alternatives.

- As noted above, both alternatives would allow increased inundation into Mill Pond during coastal storm events. Potential impacts to the Depot Road embankment and other adjacent properties, and potential protection/mitigation measures, would need to be evaluated in a future design phase.
- Public access accommodations including vehicle parking, pedestrian access and provisions for potential emergency response would need to be evaluated in a future design phase.

- Both breach configurations would significantly improve passage conditions for aquatic life and recreational paddlers.
- Embankment slopes bordering the breach channel would incorporate vegetated stabilization practices to provide wetland habitat bordering the waterway.

4.3 Channel Improvements

Both breach alternatives would improve tidal exchange and drainage from Mill Pond, and improve resiliency of the system to withstand future climate changes (both anticipated increased precipitation and sea level rise), in comparison to both existing conditions and both culvert alternatives.

The channel bed for both alternatives would be stabilized with native channel substrate incorporating natural cobbles sized to remain stable potential future storm events that would be evaluated in a future design phase. Similarly, armor protection for channel banks would be sized baased on future supplemental hydraulic and wave generation analyses by Woods Hole Group.

The increased width of both breach alternatives would provide improved connectivity for aquatic organisms and enhance natural processes including sediment transport and elevated salinity levels and lower low tides supportive of degrading salt marsh resources bordering Mill Pond.

As noted above, the channel opening would increase water levels and wave energy within the Mill Pond impoundment, both of which could potentially affecting the stability of the embankment slope supporting Depot Road. This potential concern would need to be investigated/evaluated in a future design phase.

4.4 Pavement Removal and Embankment Restoration

Figure 10 — Limit of Pavement Removal South of Mill Pond Road / Depot Road Intersection (facing south)

Both breach alternatives involve abandonment of Mill Pond Roadway due to the breach through the causeway, with the asphalt pavement to be removed and conceptually replaced with a gravel walking path bordered by grassed shoulders. As shown in Figure 10, pavement would be removed from the northern segment of Mill Pond approximately 150 feet south of the intersection of Mill Pond Road and Depot Road and continue to a location immediately north of the culvert, as shown in Figure 11. The limit of pavement removal will maintain access to a residential driveway at 40 Mill Pond Road, which is north of the limit of pavement removal shown in Figure 10.

Pavement removal on Mill Pond Road's southern segment would begin approximately 150 feet east of the Post Drive/Mill Pond Road intersection and continue to the southern limit of the conceptual breach channel, as shown in Figures 12 and 13, respectively.

Boulders (or a lockable reflectorized swing gate) would be placed at the ends of pavement removal north and south of the breach channel to prevent vehicular access while still providing access for maintenance and emergency vehicles. Consultation would likely be required to determine access requirements to the secondary informal access to a residential property at 31 Mill Pond Road (shown in the background in Figure 10), which has its primary driveway at 62 Depot Road.

At each of limits of pavement removal, it is anticipated that a crushed stone apron would be constructed, and/or a stormwater biowswale or other infiltration practice constructed, to prevent erosion from precipitation runoff draining from upgradient paved areas.

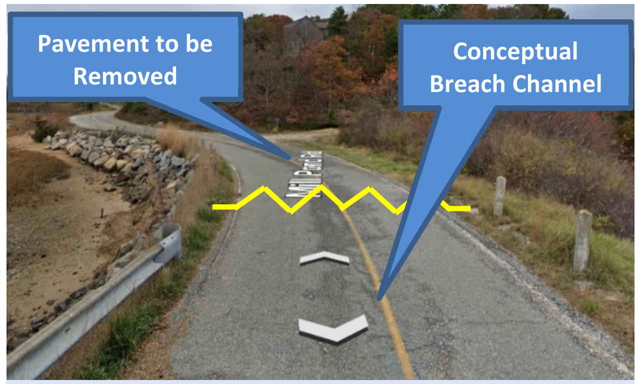

Figure 11— Approximate Limit of Pavement Removal and Channel Breach North of Mill Pond Culvert (facing north)

Figure 12 — Limit of Pavement Removal South of Mill Pond Road / Post Drive Intersection (facing north)

Figure 13 — Approximate Limit of Pavement Removal and Channel Breach South of Mill Pond Culvert (facing south)

4.5 Operation and Maintenance

Operation and maintenance guidelines for respective elements associated with the breach alternatives are outlined below. It is not anticipated that a formal Operation and Maintenance Plan would be required for a breach channel as it is expected to be resilient to current and future environmental conditions at the site.

- Stone Armor and Bioengineered Channel Bank and Embankment Slope Stabilization
  - Inspection and maintenance/repair to assure that channel banks subject to channel, runoff and/or wave erosion remain stable.
- Channel Bed Scour Protection
  - Inspection and maintenance/repair of channel bed if scour erosion undermines, or could potentially undermine, adjacent channel banks.
- Gravel Pathway and Vegetated Shoulders
  - Inspection and maintenance/repair of the gravel pathway and vegetated shoulders for signs of erosion from stormwater runoff from paved areas.

5 Construction Phase Issues Assessment

The following sections outline evaluations completed to address construction phase issues associated with construction of respective culvert and breach alternatives.

5.1 Sequence of Construction

5.1.1 Culvert Alternatives

The anticipated sequence of construction for both culvert alternatives is described below. It is noted that the contractor would be responsible for establishing and implementing its own construction sequence and phasing based on its selected means and methods of construction, which must be developed in compliance with future permit authorizations and performance requirements established in the (future) contract specifications.

<u>Phase 1</u>

1. Establish survey control, traffic controls, and staging areas.
2. Install erosion & sedimentation controls and perform any necessary clearing required to construct modifications and improvements.
3. Remove and dispose the existing pavement on Mill Pond Road within the limits of excavation necessary to construct the new culvert structure.
4. Install "Phase 1" temporary cofferdamming to enable excavation and installation of temporary shoring around the footprint of the proposed culvert structure. The existing 36-inch CPP culvert would remain in place to maintain tidal/drainage flows between Mill Pond and Pamet

Harbor until the new culvert is in place.

5. Dewater area as required within limits of the "Phase 1" cofferdam. Discharge from dewatering pumps shall be discharged into a dewatering basin prior to being released to the environment. Contractor's proposed methods shall be described in a water control plan submittal, submitted for engineer's review and acceptance.
6. Construct culvert, wingwalls and associated structures. Construct proposed in-river improvements including channel realignment, channel scour and slope protection practices and establish vegetation in disturbed areas.

Phase 2

1. Remove the "Phase 1" cofferdam around the new culvert to allow tidal/drainage flows through this structure.
2. Install "Phase 2" cofferdamming (if/as required) around the existing culvert to allow is removal (or abandonment in place by placement of flowable fill into the culvert and removal/burial of exposed ends).
3. Construct remaining embankment slope and toe protection.
4. Construct roadway and stormwater improvements including, curbing/berm, guardrails, the pavement surface course and roadway striping.
5. Place seed and install plantings along the roadway shoulders and restore all disturbed areas.
6. Remove perimeter erosion and sedimentation controls upon establishing stable vegetation.

5.1.2 Breach Alternatives

The anticipated sequence of construction activities for both breach alternatives is described below. As for the culvert alternatives, the contractor would be responsible for establishing and implementing its own construction sequence and phasing in compliance with permitting and contract specification requirements.

1. Establish survey control, traffic controls, and staging areas.
2. Install erosion & sedimentation controls and perform any necessary clearing that will be required to construct modifications and improvements.
3. Remove and dispose the existing pavement on Mill Pond Road from the upper limits of pavement removal to the limit of the excavation necessary to complete the desired breach formation.
4. Install "Phase 1" temporary cofferdamming around the portion of the breach section that does not obstruct flow through the existing culvert.
5. Complete channel bed grading, grade breach side slopes and construct stone armor bank protection and bioengineered bank stabilization in the "Phase 1" work area.
6. Remove temporary "Phase 1" cofferdamming and divert flows through the partially-constructed breach channel.
7. Install temporary "Phase 2" cofferdamming around the existing culvert and proposed breach

channel and banks.

8. Remove the existing culvert and embankment soils.
9. Complete channel bed grading, grade breach side slopes and construct stone armor bank protection and bioengineered bank stabilization in the "Phase 2" work area.
10. Remove temporary "Phase 2" cofferdamming and restore tidal flow through the complete breach channel.
11. Construct gravel pathway and install boulders/gates at pavement limits north and south of the breach channel.
12. Place seed and install plantings within the "Phase 2" work area, along the pathway shoulders and restore all disturbed areas.
13. Remove perimeter erosion and sedimentation controls upon establishing stable vegetation.

5.2 Temporary Traffic Detour and Management

Traffic would be detoured during construction of both culvert and breach alternatives as closure of MPR would be required. The closure would enable continued access to residential properties near Depot Road and at Post Drive. It is estimated the construction associated with both culvert alternatives would require approximately 4-5 months to complete.

The temporary detour, which would entail use of Depot Road and Old County Road, would need to be reviewed and approved by Truro Public Safety officials prior to construction.

5.3 Temporary Cofferdamming and Control of Water

Surface water control will be required for both culvert and breach channel alternatives, and groundwater control will be required for construction of both culvert alternatives due to the need for deeper excavations associated with construction of the culvert foundations and channel bed scour countermeasures. Surface water bypass flow diversion measures will be required to maintain tidal and drainage flows to/from Mill Pond during the entire period of construction for all alternatives.

While specific practices employed to bypass surface water around active construction areas will be determined by the contractor based upon its preferred means/methods and construction sequence, as noted above all measures would be required to comply with permit and contract specification performance requirements, and be reviewed and accepted by the engineer prior to implementation. Primary elements for control of water at the site for respective alternatives are outlined below.

- The existing culvert will be used to maintain tidal/drainage flows to/from Mill Pond during initial phases of construction.

- Large bulk sandbag cofferdams or steel sheeting will likely be used to temporarily prevent surface water and tidal flows from entering active work areas upstream and downstream of MPR.
- It is anticipated that a steel sheeting cofferdam would be utilized for culvert alternatives to provide groundwater cutoff for the lowered excavations association with construction of the culvert foundation. Groundwater dewatering would be employed to dewater the work area and allow culvert construction to occur in a controlled environment. Specific measures employed for groundwater dewatering will be determined by the contractor based on its proposed means and methods, where such practices would need to comply with permitting and contract specification performance requirements, respectively.

5.4 Preliminary Opinion of Probable Construction Cost

The budgetary opinion of construction cost associated with respective culvert and breach channel alternatives are summarized in Table 3 below. All conceptual alternative costs include a 20 percent contingency and are typically expected to be accurate within -30% to +50% (depending on market conditions and other factors at the time of construction), resulting in a stated construction cost range.

These costs do not include future costs for supplemental field investigations, engineering analyses, design development, permitting, and construction oversight. It should also be noted that the costs only include fees associated with the construction cost and do not include long-term operation and maintenance costs. Detailed opinions of cost are provided in Attachment G, based on assessments of material quantities corresponding to conceptual drawings included in Attachment F.

Table 3
Order-of-Magnitude Opinions of Probable Construction Cost for Conceptual Alternatives

Conceptual Alternative	Order of Magnitude Opinion of Cost	-30%	+50%
Culvert Alternative No. 1	$1.56M	$1.17M	$2.20M
Culvert Alternative No. 2	$1.71M	$1.49M	$2.42M
Breach Alternative No. 1	$795K	$596K	$1.13M
Breach Alternative No. 2	$1.05M	$785K	$1.48M

6 Salt Marsh Restoration Alternatives Assessment

An assessment of each alternative was performed under consideration of identified criteria including site compatibility/natural resources criteria, construction phase criteria and long-term operation and maintenance criteria.

The following sections provide brief descriptions of respective criteria considered for this assessment, followed by a review of assessment matrices developed to evaluate each alternative. A preliminary recommendation for the preferred alternative, subject to receipt and incorporation of input from project partners, property owners and other project stakeholders, is provided at the end of this section.

6.1 Evaluation Criteria

Respective criteria identified to assess relative advantages/disadvantages for each alternative are described in following sections.

6.1.1 Site Compatibility/Natural Resources Criteria

The following site compatibility and natural resources criteria were considered in assessing each alternative.

Environmental Impacts

- Minimize environmental impacts, requirements, regulatory barriers
- Minimize number of permit applications under consideration of the following programs:
    - Massachusetts Environmental Protection Agency Environmental Notification Form
    - Notice of Intent
    - MADEP Chapter 91 License
    - Army Corps of Engineers Section 404 Permit
    - MADEP Section 401 Water Quality Certification
    - MA Coastal Zone Management

Wave Action and Vulnerability

- Minimize the potential for wave action during coastal storm events to destabilize the slope supporting Depot Road and private properties bordering Mill Pond
- Minimize vulnerability of bordering private properties to increased tides

Ecological Restoration

- Maximize aquatic passage and ecological restoration
- Maximize potential sediment transport
- Increase tidal flushing and enhancement of bordering salt marsh areas
- Enhance shellfish habitat
- Improve water quality

Emergency Response

- Minimize impacts to emergency response vehicles for private properties on Mill Pond Road and public recreation within Mill Pond

Recreation

- Maximize recreational passage for paddlecraft and motorcraft users
- Maximize safety for recreational boating
- Maximize passive recreation opportunities (e.g., birdwatching, etc.)

6.1.2 Construction Phase Criteria

The following construction phase criteria were considered in assessing each alternative.

Minimize Construction Cost

- Minimize the overall cost for construction

Minimize Construction Duration

- Minimize the duration of construction

6.1.3 Long-Term Operation and Maintenance

The following long-term operations criteria were considered in assessing each alternative.

Minimize Operation/ Maintenance Costs

- Minimize repair or future replacement costs.
- Minimize the overall cost for future operation and maintenance

Maximize Resiliency to Climate Change

- Maximize adaptability to climate change and sea level rise

6.2 Alternatives Assessment and Recommended Alternative

Comparative criteria evaluation matrices have been developed addressing considerations, advantages and disadvantages for each alternative in relation to respective criterion, based on our project's team's assessments to date. Respective matrices reflect weighted and unweighted criteria based on initial evaluations by the engineering assessment, with weighted criteria subject to revision based upon input received from the Town and project partners.

Within each matrix, brief descriptions of assessment results and relative numeric scores are provided for each alternative/criterion. Scores as based on a scale of 1 to 5, with 5 being most advantageous and 1 being most disadvantageous, with respect to other alternatives. Scores for each alternative are aggregated across all criteria to identify an overall score representing relative rankings with respect to other alternatives.

It is noted that the matrices are intended as a decision-making tool to facilitate aggregation of multiple layers of information within a single document, thus providing a clearly documented and transparent mechanism to communicate assessment results within a project team. Its value is in providing a collaborative platform to inform decision-making where multiple, and sometimes conflicting considerations, present a complex environment from which to advance subsequent project development with the support of all interested parties.

The weighted and unweighted assessment matrices developed through project evaluations and consultations with project partners are included in Attachment H, and a summary of overall scores is provided below in Table 4.

Table 4
Overall Alternatives Assessment Matrix Scores

Conceptual Alternative	Unweighted Evaluation Matrix Score	Weighted Evaluation Matrix Score
Culvert Alternative No. 1	2.67	2.66
Culvert Alternative No. 2	2.67	2.69
Breach Alternative No. 1	3.78	3.80
Breach Alternative No. 2	3.67	3.74

Based on the results of above evaluations, Breach Alternative 1 has been identified as the preferred alternative. Further investigations, hydraulic modeling, and design evaluations, and consultations with the Town of Truro and project partners are recommended to confirm and refine this determination.

Mill Pond Restoration
Conceptual Design Report
Truro, Massachusetts

June 22, 2022

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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.

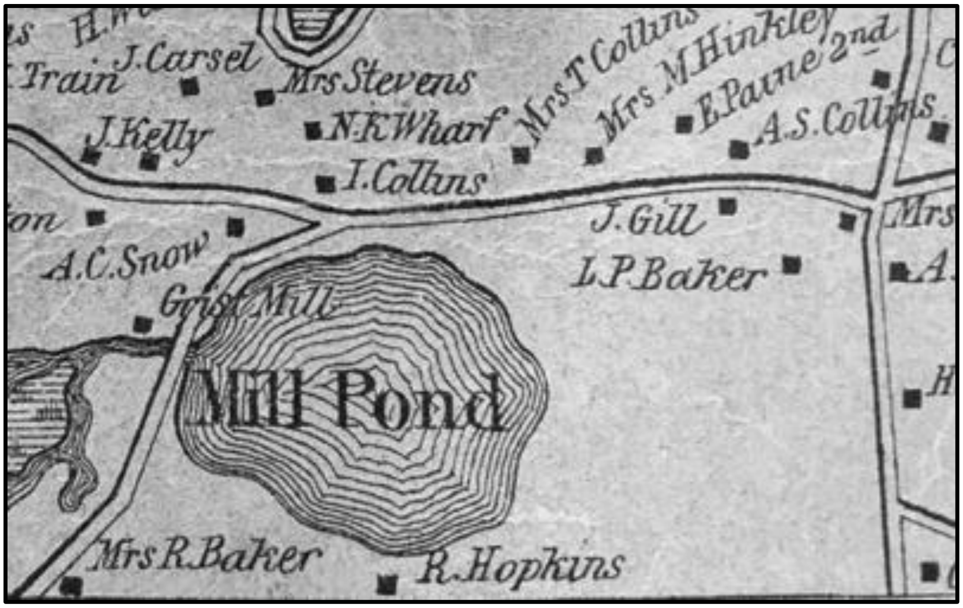

Figure 2. Historic 1858 Map of Mill Pond (Richards, 2021).

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

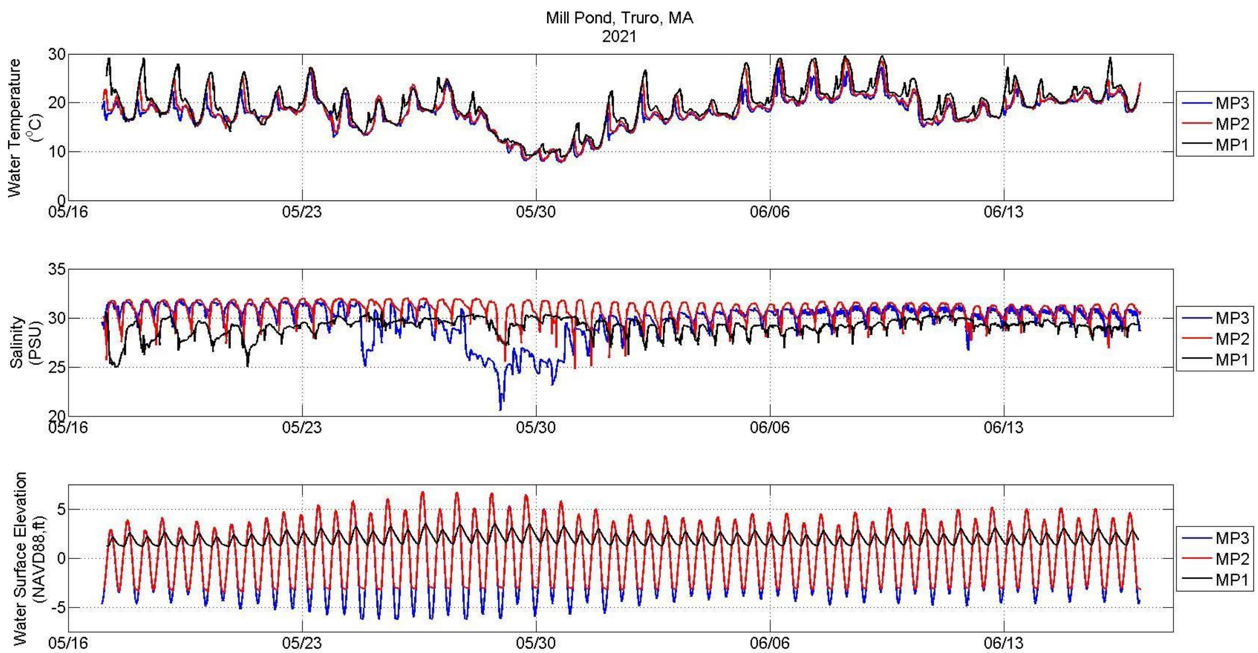

Figure 3. Time series of the data collected by the CTD instruments. From top to bottom: Water temperature, Salinity, and water surface elevation. MP1 is in Mill Pond, MP2 in the middle basin, and MP3 in the harbor. Note that a rainstorm at the end of May decreased salinity for several days.

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.

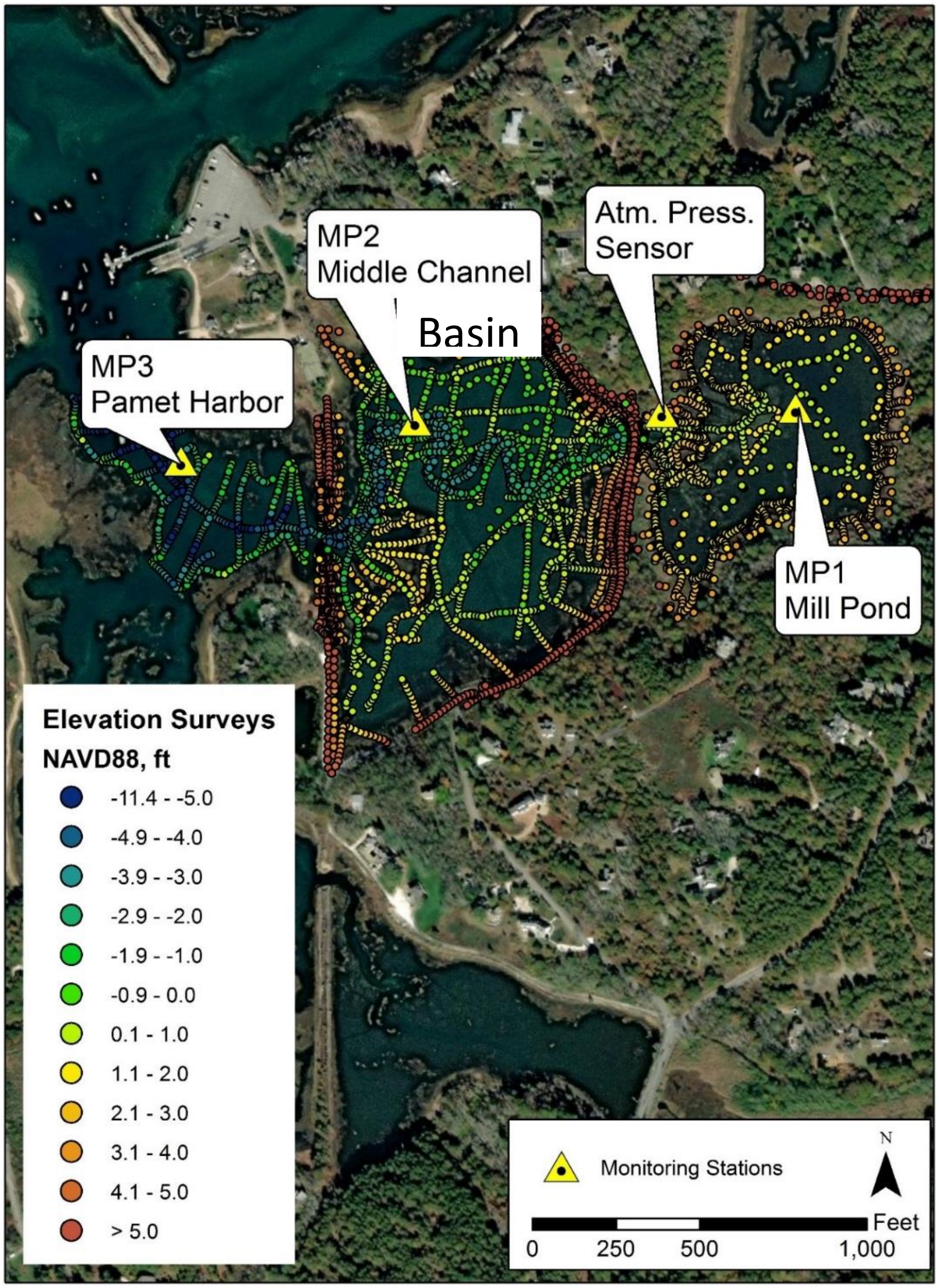

Figure 4. Map showing the locations of the CTD instruments deployed for the tide study and coverage of the topographic and bathymetric surveys in 2021.

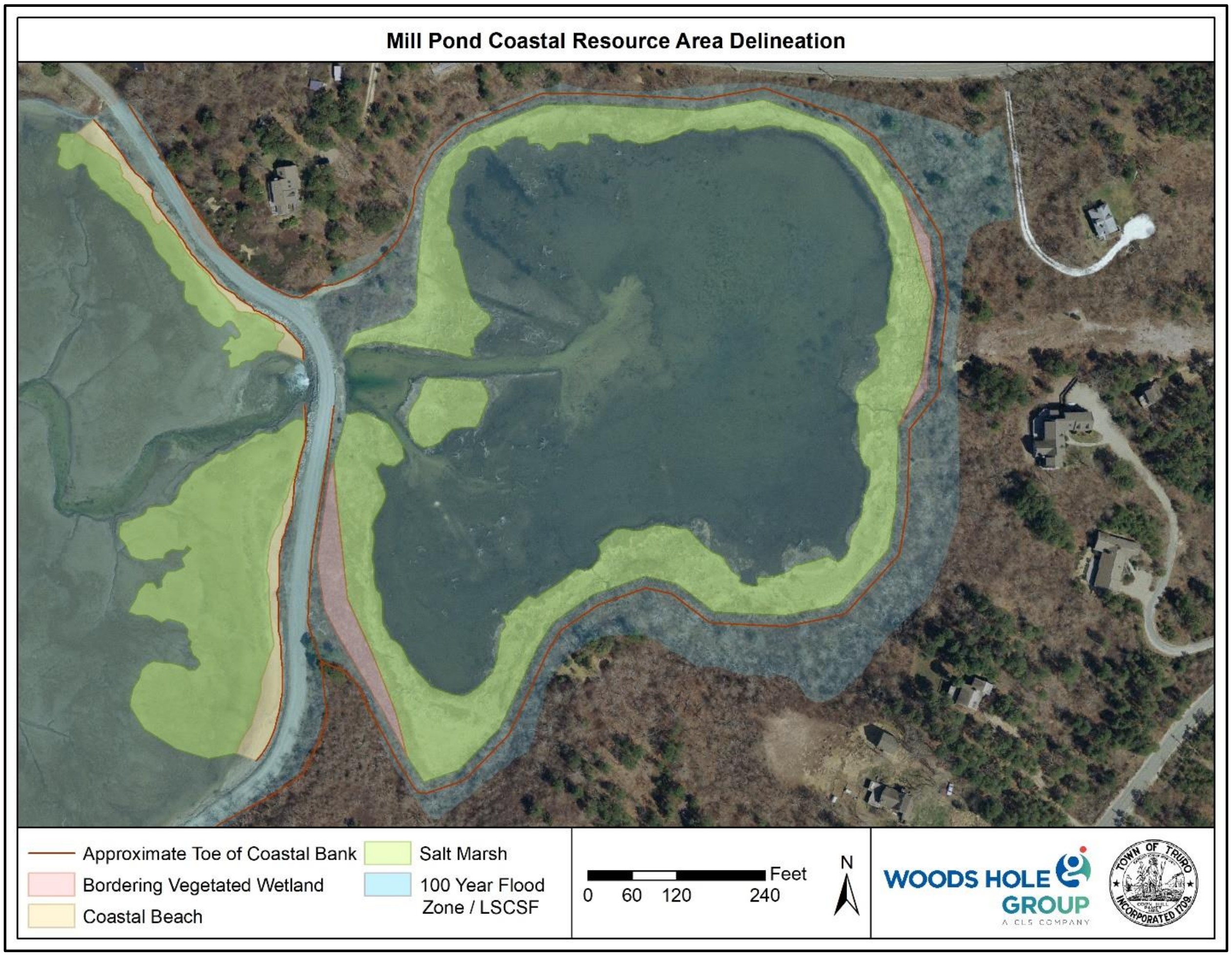

Figure 5. Coastal resource areas delineated in 2021 along Mill Pond Road and Mill Pond basin.

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.

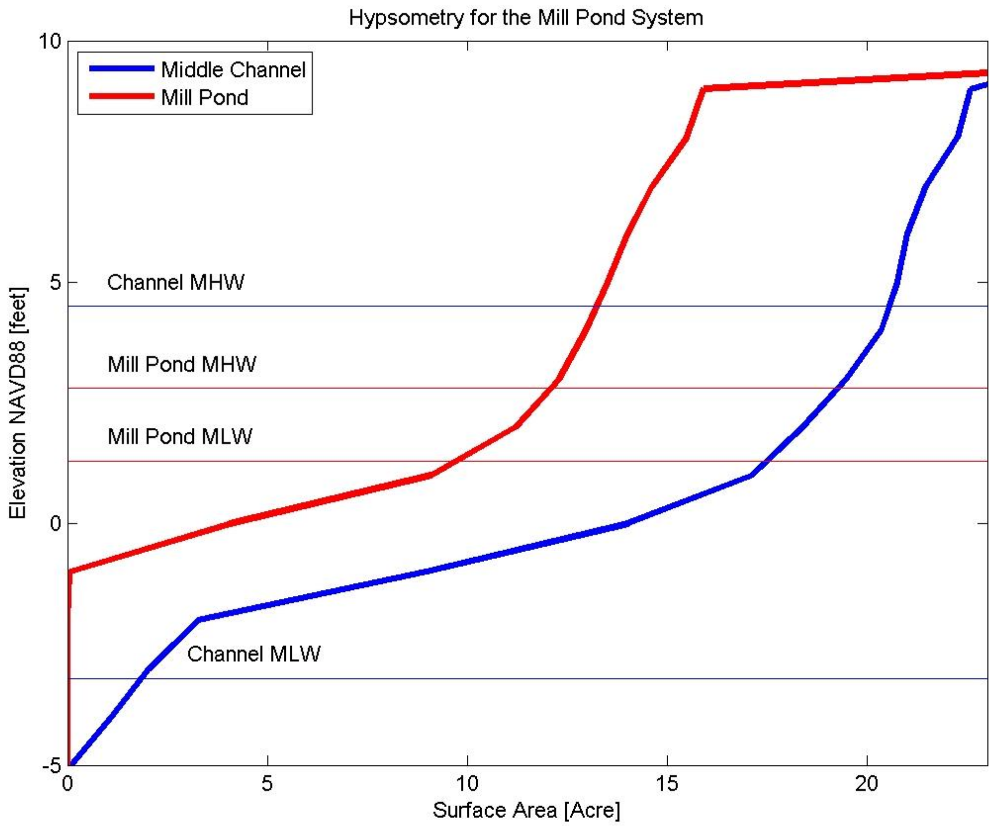

Figure 6. Hypsometric curves for Mill Pond and the downstream Middle Basin plotted with their respective MLW and MHW tidal datums.

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

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

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

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:

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

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

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

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

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

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

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

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

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.

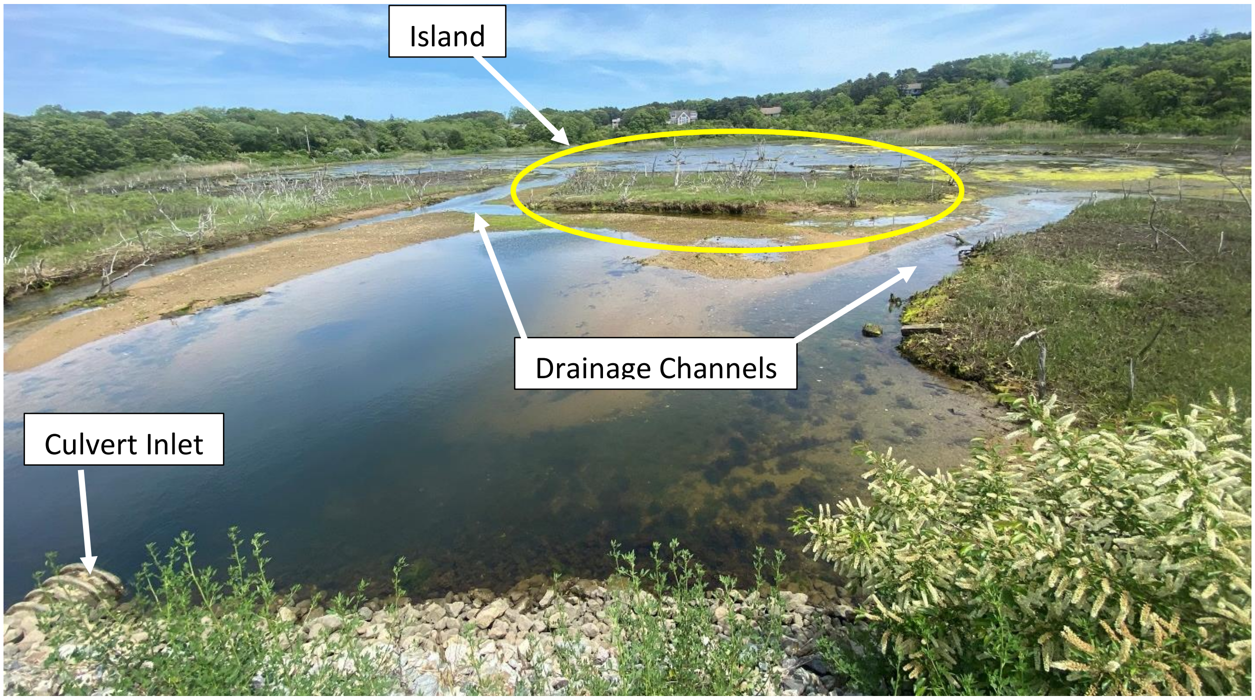

Figure 7. Photo of the Mill Pond culvert inlet (bottom left), the island (yellow circle) that acts as a weir, and the drainage channels around it.

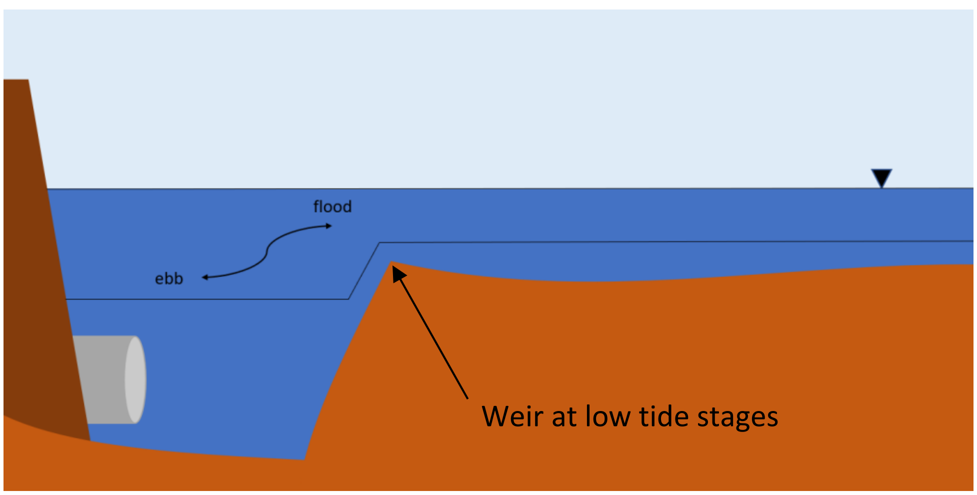

Figure 8. Sketch of the culvert through the embankment and into Mill Pond, the invert is at a lower elevation than the bed of the pond, which causes a weir effect over the island and into the scour pit that impedes full drainage. Note the graphic is not to scale.

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.

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

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

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.

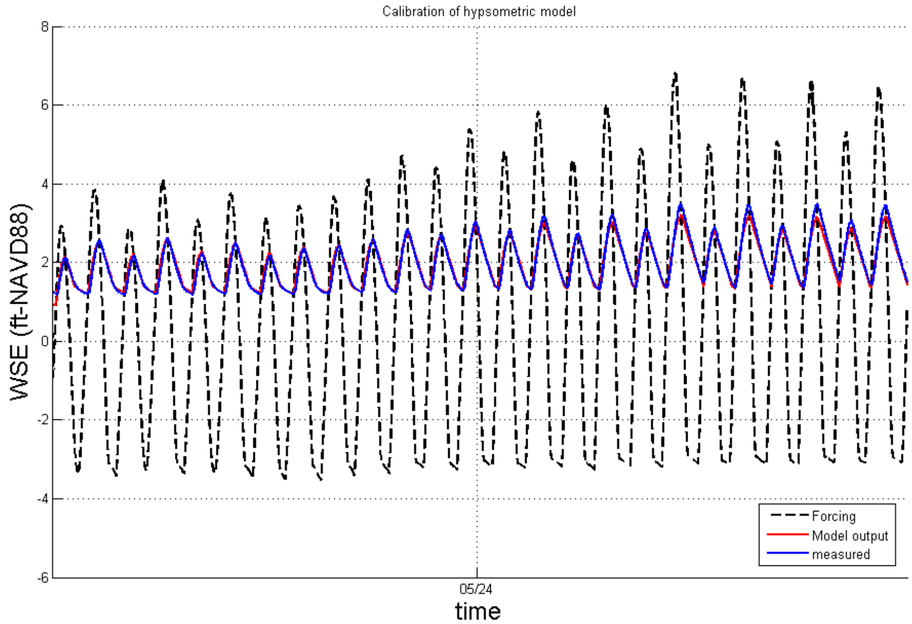

Figure 9. Boundary conditions at Pamet Harbor compared to measured and modeled water levels in Mill Pond based on the hypsometric model.

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.

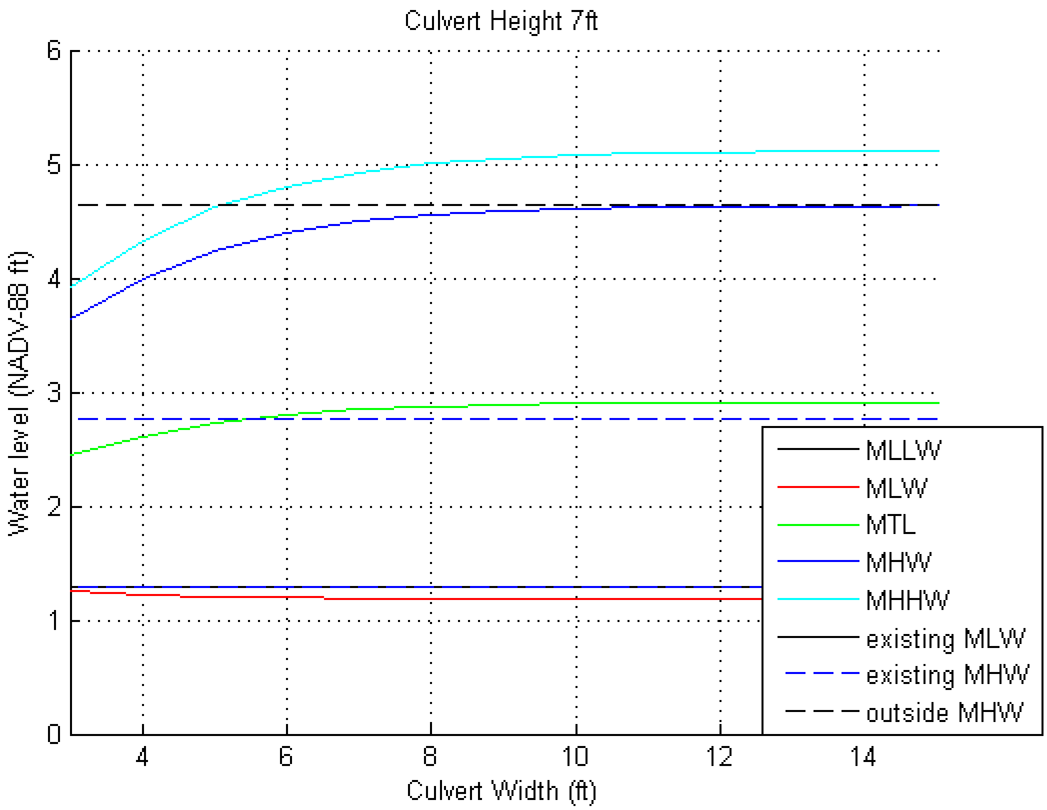

Figure 10. **Hypsometric model results for tidal datums in Mill Pond corresponding to various alternative culvert widths.**

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.

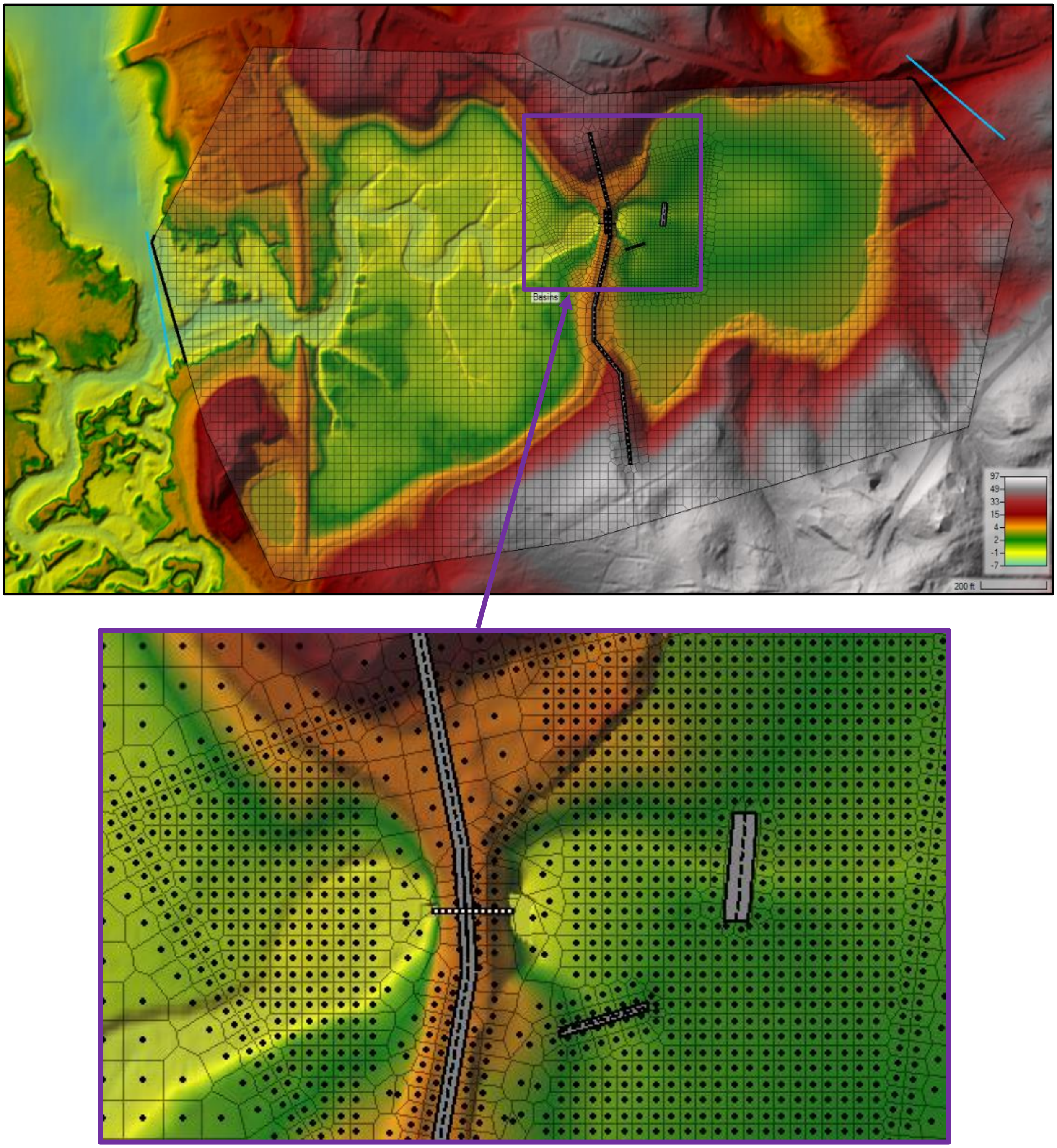

Figure 11. HEC-RAS 2D model grid domain (top) for the Mill Pond system and the refinement region in the 2D model around the road, culvert and the weirs symbolized as grey rectangles with dashed lines (bottom).

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.

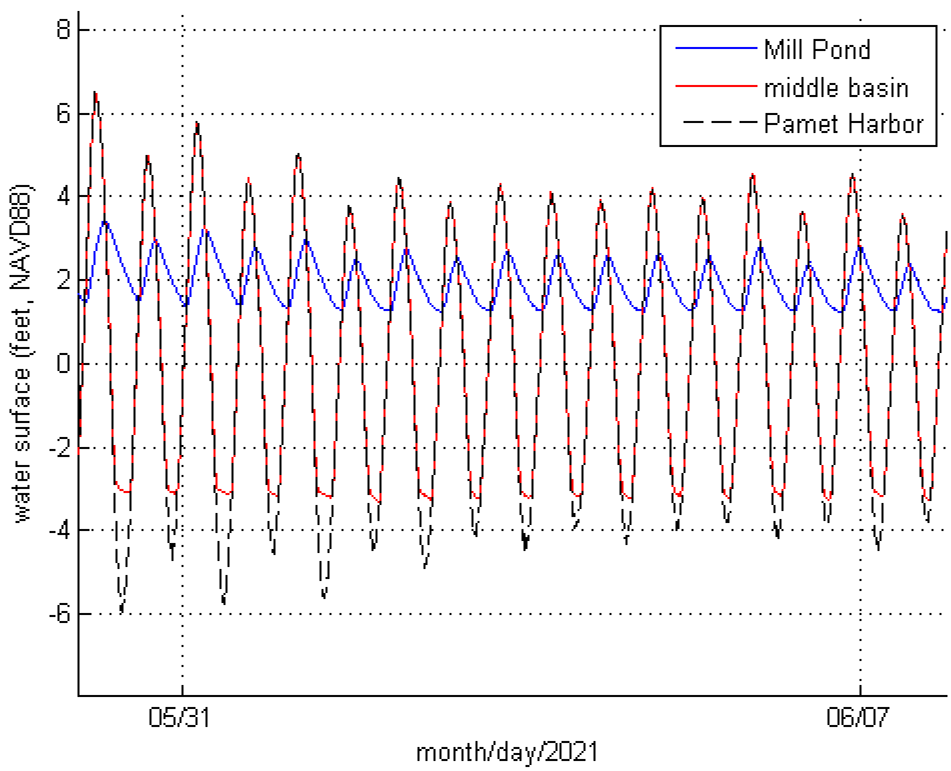

Figure 12. Time series of the observed water levels measured at three CTD instrument locations.

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

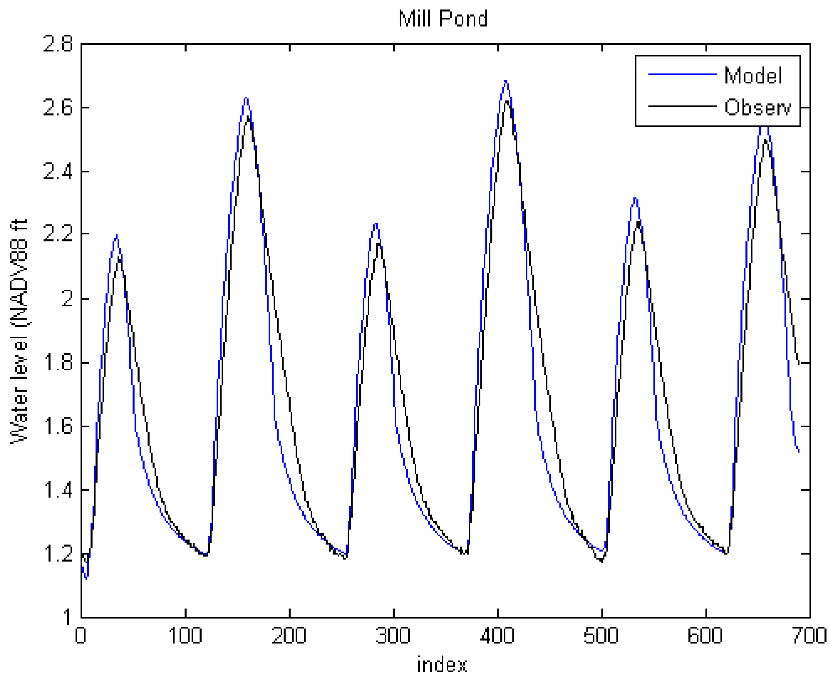

Figure 13. Comparison of the 2D modeled vs observed water surface elevations in Mill Pond.

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

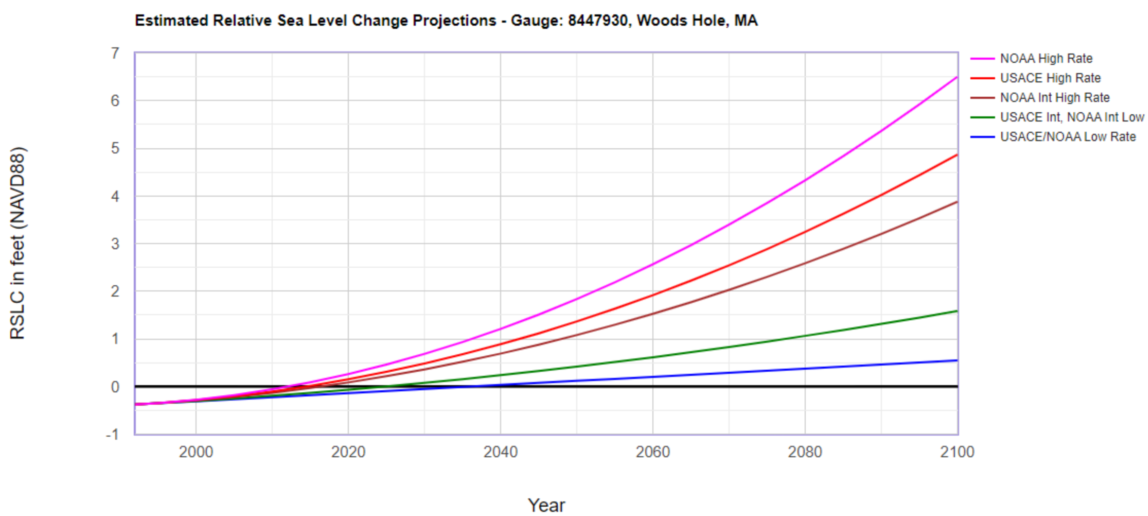

Figure 14. USACE/NOAA sea level rise projection curves. *(Sea-Level Curve Calculator (army.mil))*.

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

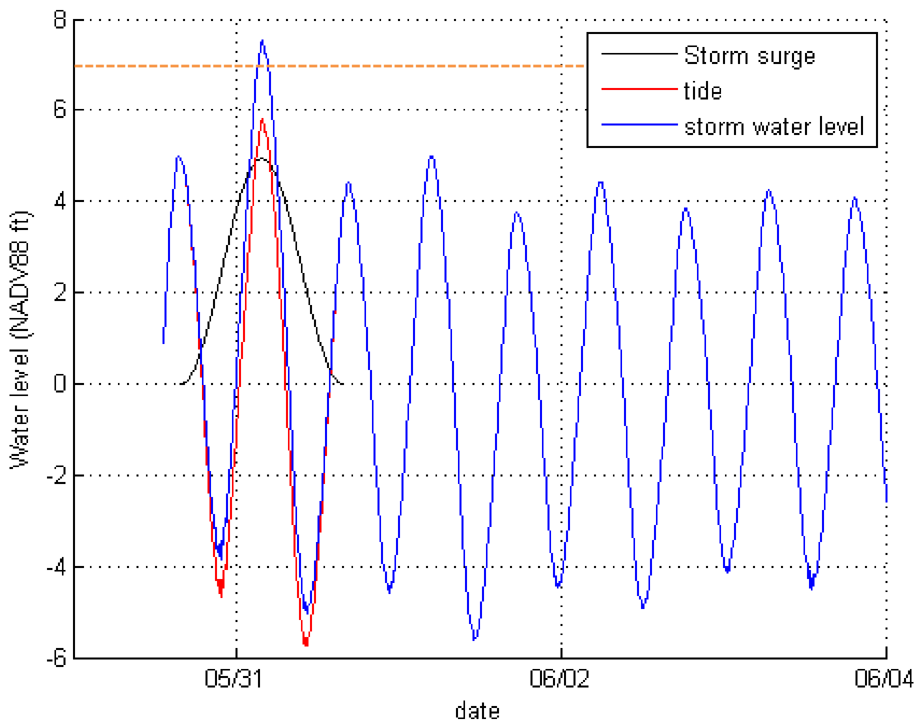

Figure 15. Storm boundary condition (in Pamet Harbor) for the 20-year storm. Mill Pond Roadway elevation shown approximately by the orange dashed line.

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

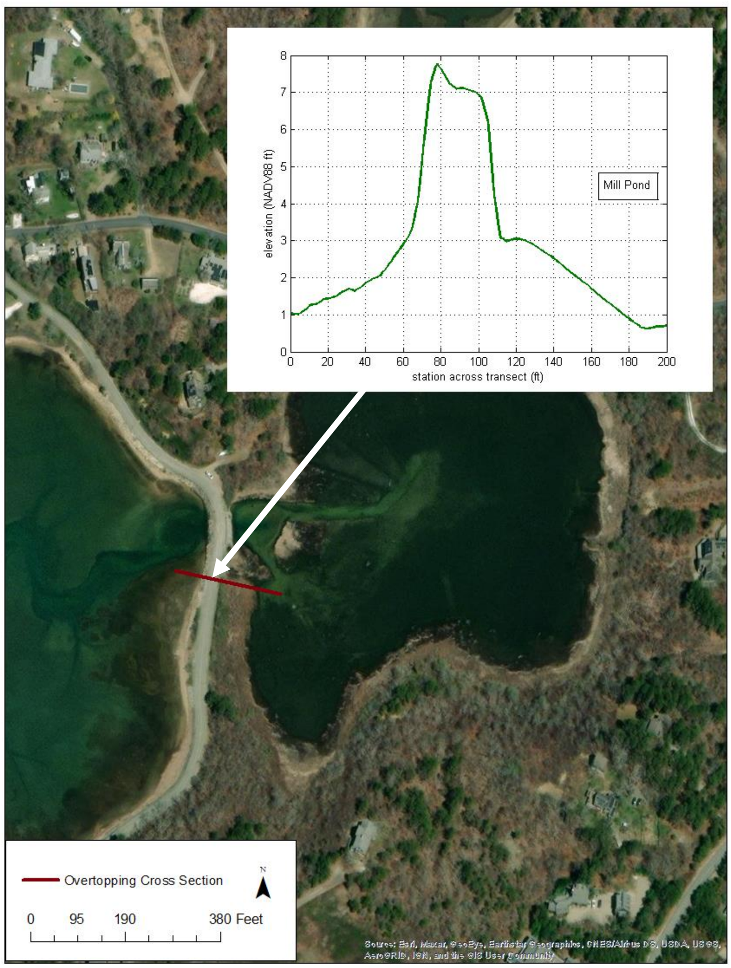

Figure 16 Cross section of the lowest point of Mill Pond Road used to determine overtopping or wetting of the road. Note that the Mill Pond (upstream) side of the culvert is at a lower elevation than the downstream side.

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.

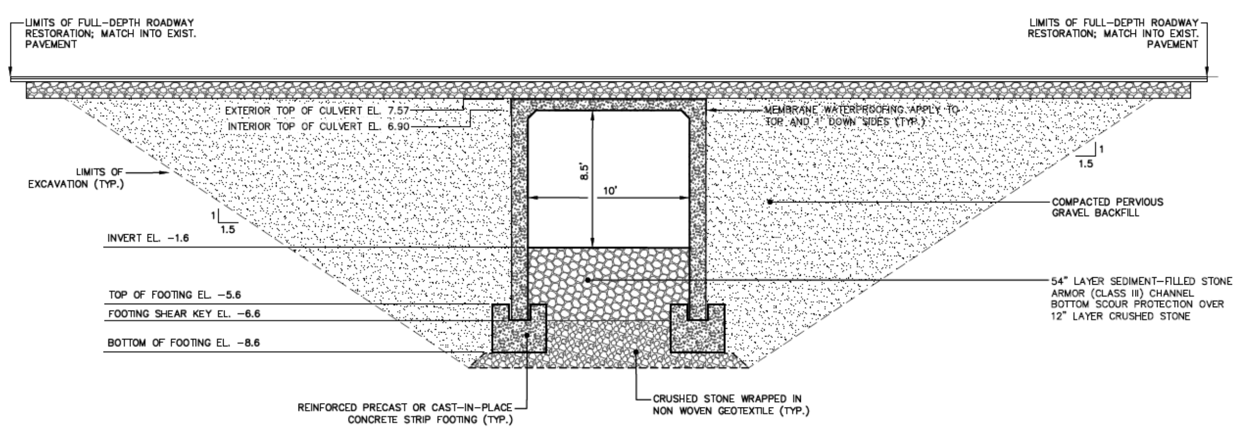

Figure 17. Alternative 1: 10 foot width by 8.5 foot high open bottom culvert.

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).

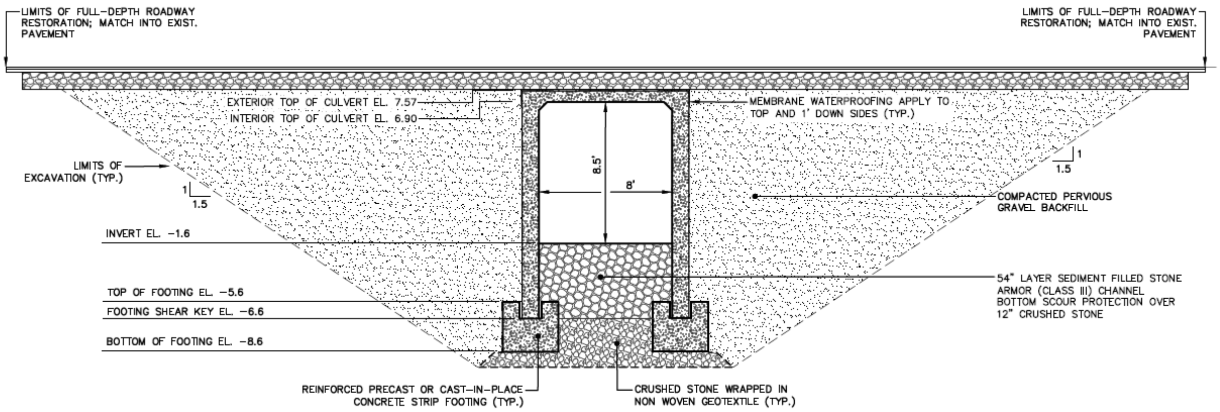

Figure 18. Alternative 2: 8 foot wide by 8.5 foot high open bottom culvert.

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.

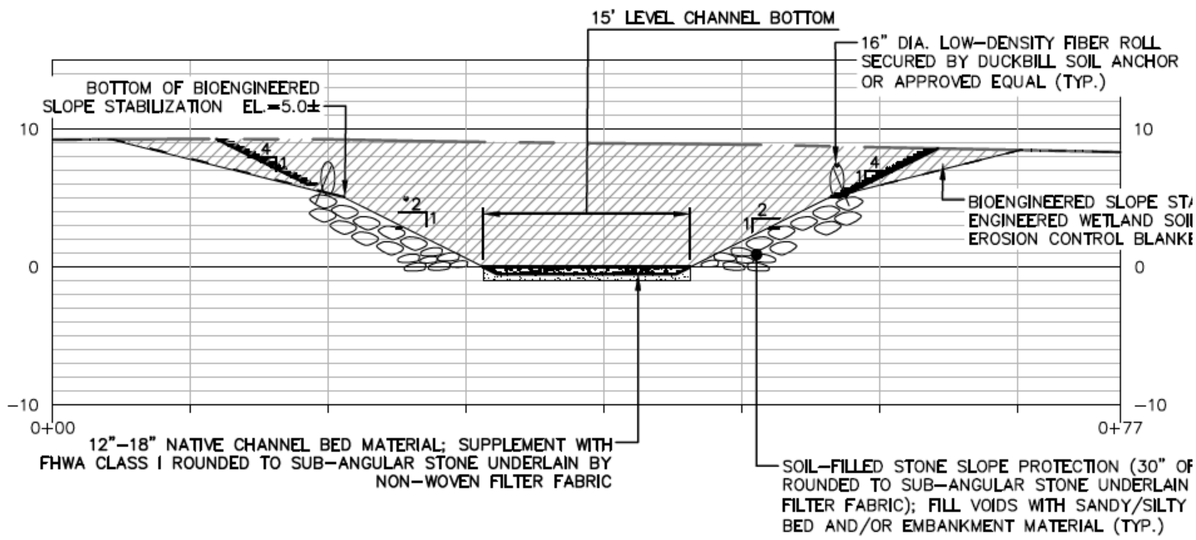

Figure 19. Alternative 3: 15-foot width open channel breach with no roadway overtop.

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.

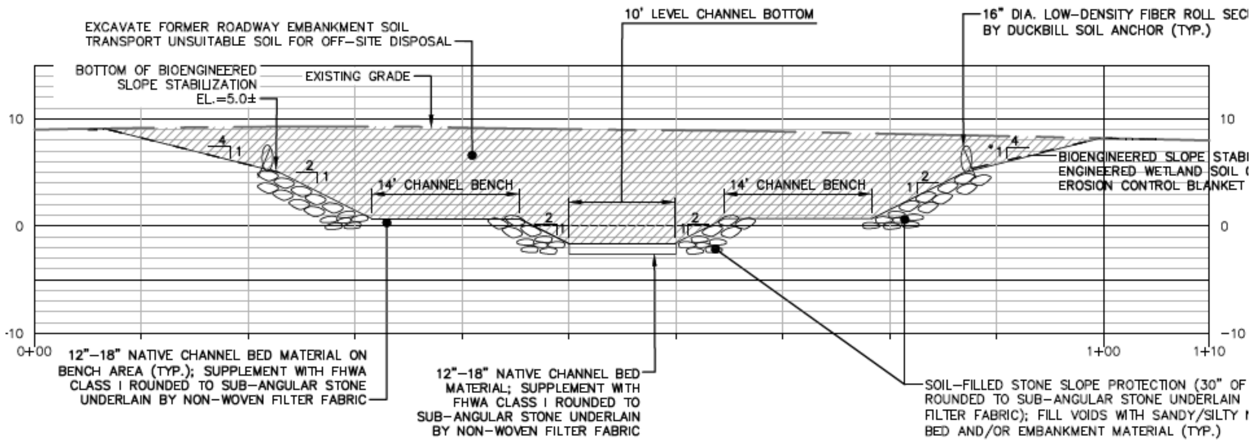

Figure 20. **Alternative 4: The ~95-foot-wide breach with a 10-foot-wide inner channel and 14-foto wide saltmarsh benches. No roadway remains overtop.**

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.

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

$$D_{50\,riprap} = \frac{K_r\, y_0}{(S_g - 1)}\left(\frac{V_{ac}^2}{g y_0}\right)^{0.33}$$ 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 (Ψ_{cr}) to determine if sediment initiation occurs at each point of interest. The critical value of ψ for the initiation of sediment motion is found by using a methodology to determine the threshold Shields' Criterion, ψ_{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

ω_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)
υ 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.

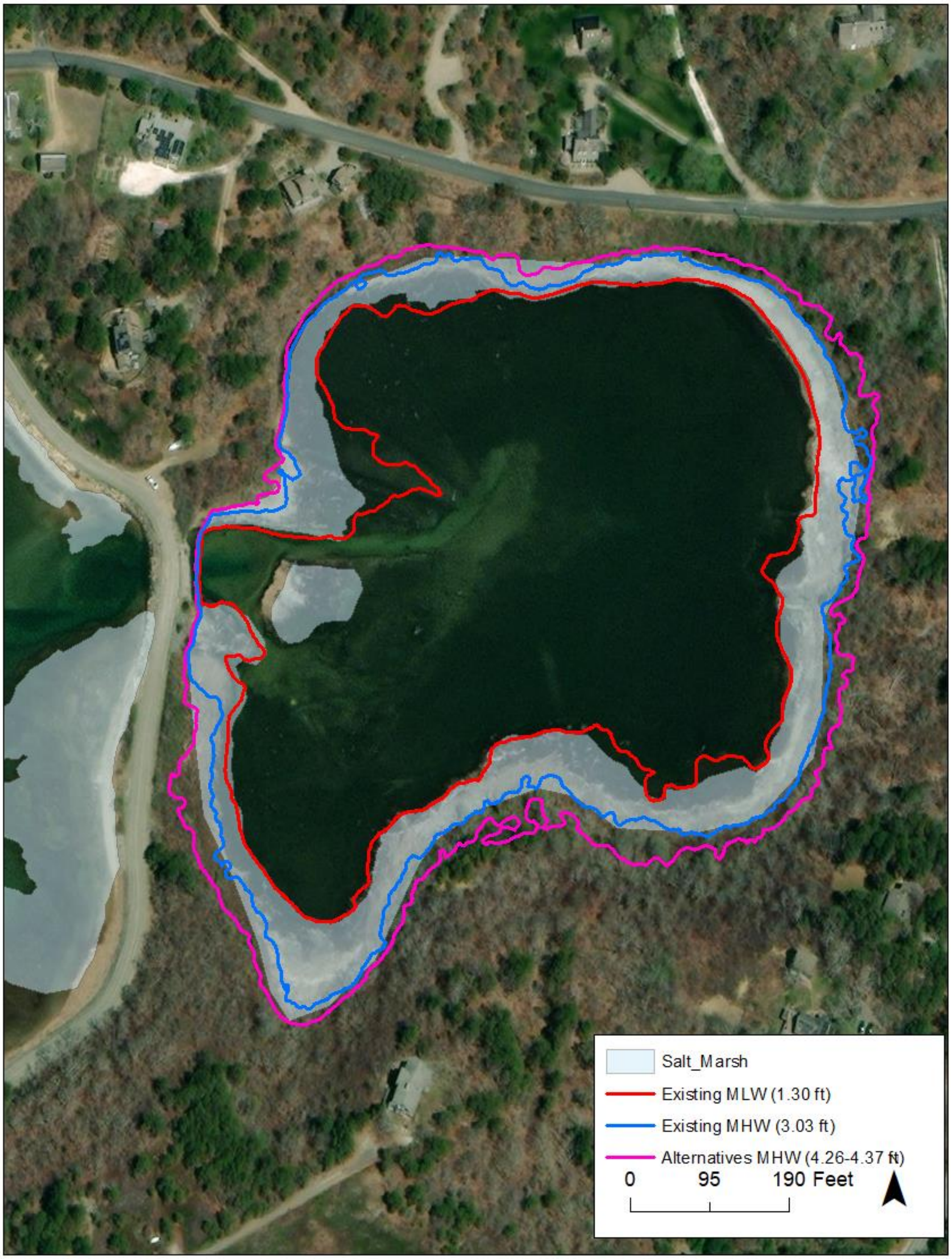

Figure 21. **Comparison of the extent of existing salt marsh relative to MLW and MHW levels for existing conditions (red/blue) and the alternatives (pink).**

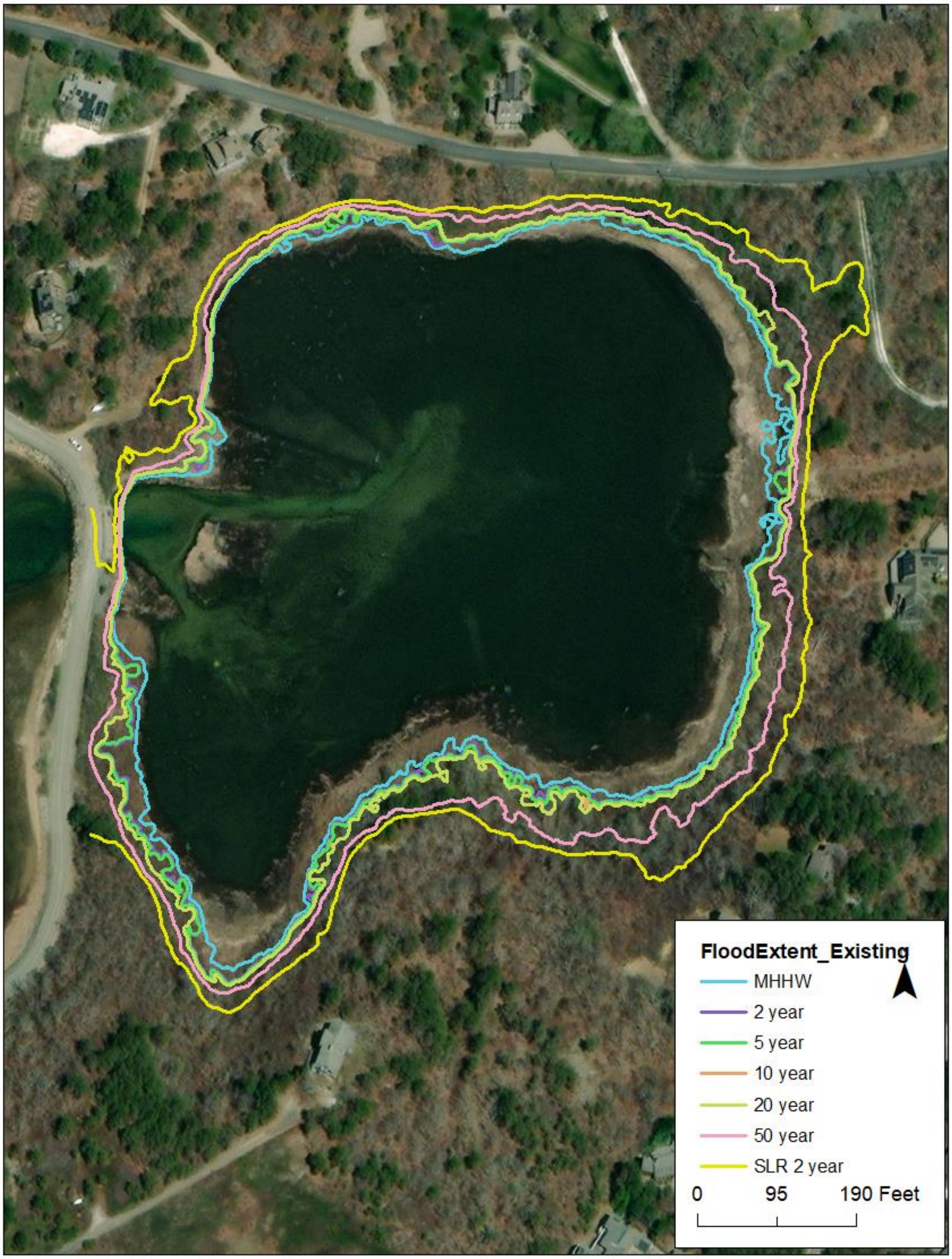

Figure 22. Comparison of the extent of existing salt marsh relative to return period storms with and without sea level rise (SLR) for existing conditions modeling.

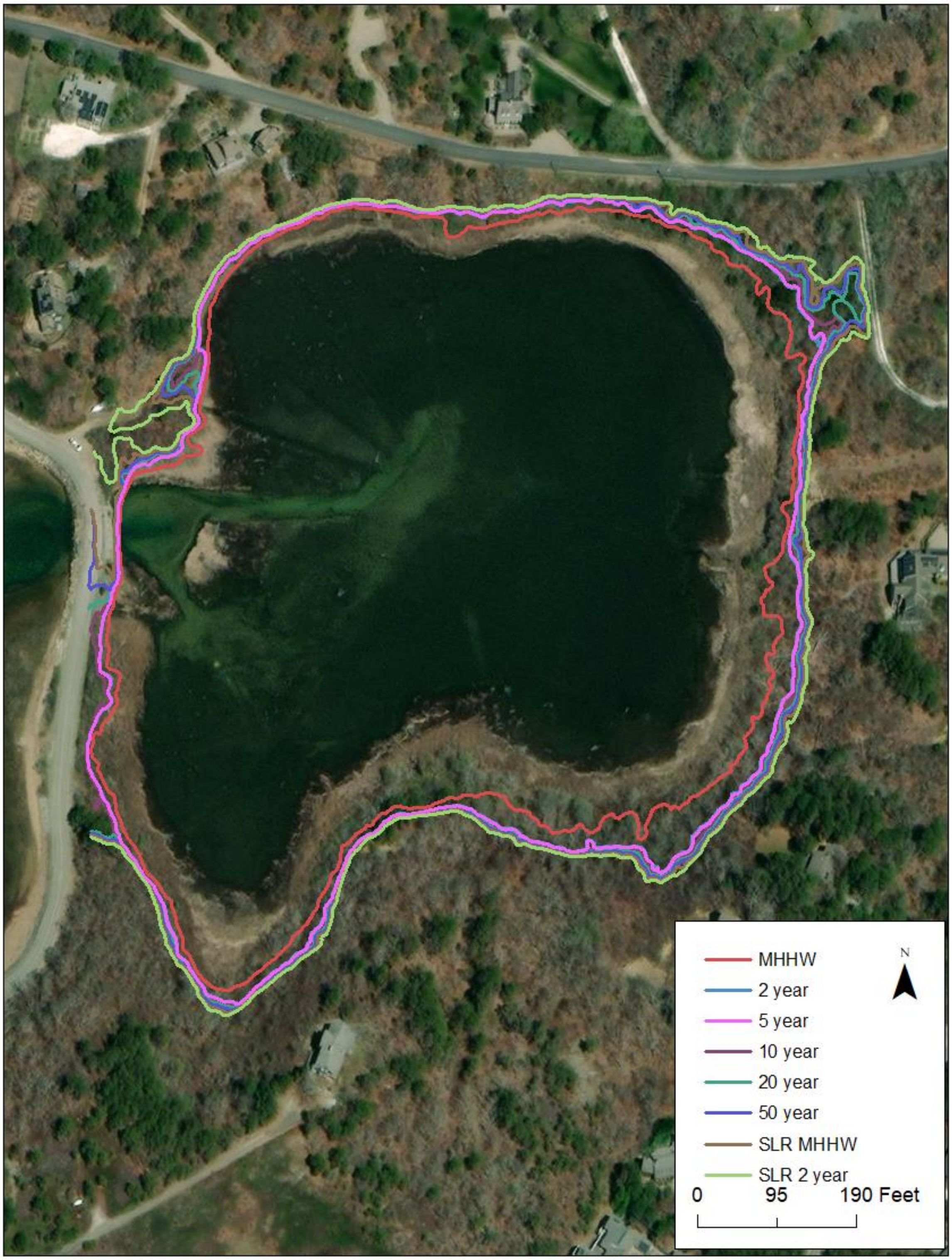

Figure 23. **Comparison of the extent of existing salt marsh relative to MHHW and return period storms with and without sea level rise (SLR) for the alternatives modeling.**

- **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.

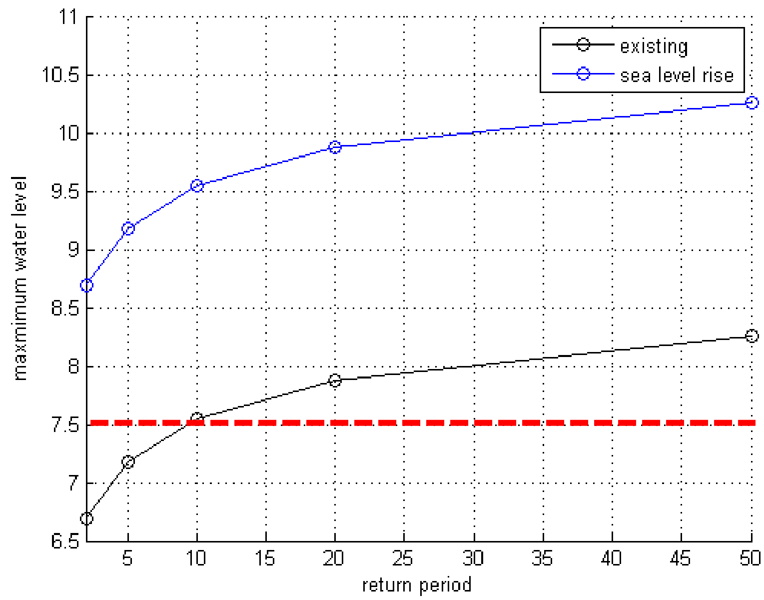

Figure 24 **Maximum water levels at the middle basin side of Mill Pond Road (feet-NAVD) for each return period up to 50-years. Current lowest roadway point is 7.5 feet NAVD as shown by the red line.**

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

Location Map Not to Scale

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Date	Revisions
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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

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18-0189_SEPTICS5.DWG

Attachment B – Fuss & O'Neill Conceptual Design Report