April 19, 2019

Nantucket Department of Public Works
c/o Robert D. McNeil III, PE, MPA
Director
188 Madaket Road
Nantucket, MA 02554

RE: Madaket Culverts Evaluation
Final Letter Report

Dear Mr. McNeil:

Fuss & O'Neill has completed a study of several municipally-owned culverts on the Long Pond/Madaket Harbor estuary system in the Madaket section of Nantucket. The objective of the project was to evaluate and provide recommendations for potential culvert replacements or upgrades that would address structural deficiencies, flooding, and degraded water quality in Long Pond. This letter report is the final deliverable for the "Madaket Culverts Evaluation" project, as described in the Scope of Services in our Agreement with the Town of Nantucket dated May 23, 2018.

1. Project Background

The Madaket Harbor/Long Pond estuary is a complex, tidally-influenced system located on the western end of Nantucket Island (Figure 1). Tides from Nantucket Sound propagate from Madaket Harbor into Hither Creek up through a series of culverts and a man-made channel (Madaket Ditch) before reaching Long Pond. Water quality in Long Pond (a brackish 70-acre pond) has been degraded, which is believed to be the result of excessive nitrogen loadings from septic systems, the Nantucket Landfill located on the eastern edge of the pond, fertilizers in runoff from lawns, stormwater runoff from impervious surfaces, and nutrient-rich bottom sediments in Long Pond. Previous studies and monitoring of environmental conditions in the estuarine system has documented nutrient enrichment, periodic extreme decreases in dissolved oxygen, periodic algae blooms, elevated levels of fecal indicator bacteria, and altered benthic community structure within Long Pond.[1] The poor water quality of Hither Creek is also partially dependent on the nitrogen load from Long Pond via Madaket Ditch during ebb tides.[2]

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www.fando.com

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Connecticut
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Massachusetts
New Hampshire
Rhode Island
Vermont

[1] Final Madaket Harbor and Long Pond Estuarine System Total Maximum Daily Loads For Total Nitrogen (CN - 283.0), Massachusetts Department of Environmental Protection, June 2015.

[2] Technical Memorandum: Water Quality Monitoring and Assessment of the Nantucket Island-Wide Estuaries and Salt Ponds, Update 2017, Brian Howes Ph.D. and Roland Samimy Ph.D., Coastal Systems Program, School of Marine Science and Technology (SMAST) University of Massachusetts-Dartmouth, February 28, 2018.

Figure 1. Project area – Madaket Harbor/Long Pond Estuary.

The Town's management of the landfill (i.e., construction of modern landfill liner systems as well as mining of the original unlined landfill and other ongoing improvements) appears to be reducing the nitrogen load from the landfill.[3] The most recent water quality monitoring results indicate some reduction in nitrogen levels in Long Pond, consistent with the landfill improvements. Even with these recent improvements and the recent downward trend in nitrogen levels, Long Pond remains "impaired" since it does not meet State water quality standards for certain designated uses such as contact recreation and aquatic habitat.[4]

Tidal exchange between Madaket Harbor and Long Pond is insufficient to keep up with the nutrient loads entering the pond, which contributes to the water quality issues in Long Pond. Previous studies (2010 Massachusetts Estuaries Project) identified two culverts along Madaket Road as restrictions to tidal exchange that may contribute to degraded water quality in Long Pond.[5]

[3] Technical Memorandum: Water Quality Monitoring and Assessment of the Nantucket Island-Wide Estuaries and Salt Ponds, Update 2017, Brian Howes Ph.D. and Roland Samimy Ph.D., Coastal Systems Program, School of Marine Science and Technology (SMAST) University of Massachusetts-Dartmouth, February 28, 2018.

[4] Massachusetts Year 2016 Integrated List of Waters, Massachusetts Department of Environmental Protection, June 2017.

[5] Massachusetts Estuaries Project, Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Madaket Harbor and Long Pond Estuarine System, Town of Nantucket, MA, University of Massachusetts Dartmouth School of Marine Science and Technology and Massachusetts Department of Environmental Protection, November 2010.

The culverts may also influence flooding within the estuarine system during large storms, as the roads and other infrastructure in the Madaket area are vulnerable to impacts from storm surge and projected sea level rise.[6]

2. Scope of Work

The Town of Nantucket, through the Nantucket Department of Public Works, contracted with Fuss & O'Neill to evaluate the need to replace the study culverts based on consideration of water quality, flooding, and structural condition. The following culverts were included in the evaluation (Figure 2):

- Madaket Road over Long Pond (Culvert #1) – corrugated aluminum box culvert (50 inches high, 9 feet wide, and 50 feet long) connecting Long Pond to North Head Long Pond.
- Madaket Road over Madaket Ditch/Long Pond (Culvert #2) – corrugated aluminum culvert (60 inches high, 16 feet wide, and 60 feet long) connecting the upstream end of Madaket Ditch to Long Pond.
- North Cambridge Street over Madaket Ditch (Culvert #3) - multi-plate steel corrugated culvert (7 feet tall, 50 feet long, with tapered ends) connecting the downstream end of Madaket Ditch to Hither Creek.

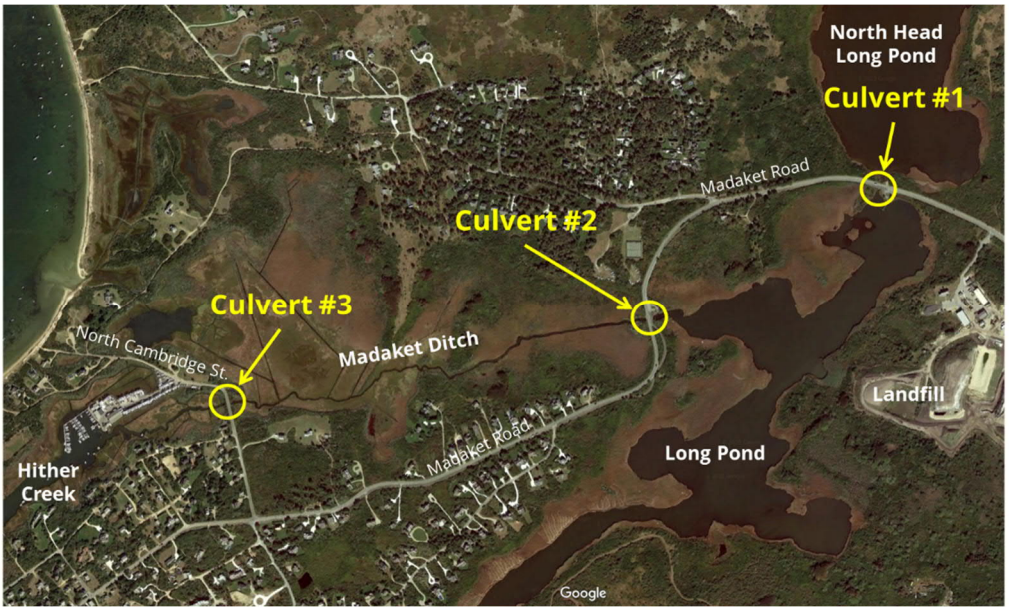

Figure 2. Study culverts.

[6] Massachusetts Sea Level Rise and Coastal Flooding Viewer, https://www.mass.gov/service-details/massachusetts-sea-level-rise-and-coastal-flooding-viewer, accessed on March 19, 2019.

The scope of work for this project consisted of the following tasks, which are described further in the sections below:

1. Structural Condition Assessment
2. Hydrologic and Hydraulic Modeling
3. Alternatives Evaluation

3. Summary of Findings

3.1. Structural Condition Assessment

Fuss & O'Neill conducted structural condition inspections of the study culverts on September 17, 2018.[7] The Madaket Road culvert located at the upstream end of Madaket Ditch (Culvert #2) was last inspected by the Massachusetts Department of Transportation (MassDOT) in 2017. The 2017 inspection report identified "heavy marine growth throughout" but provided no other information on the condition of the metal culvert. No information was available regarding the condition of the other two culverts (Culvert #1 and Culvert #3).

The structural condition inspections were performed by Fuss & O'Neill and Childs Engineering Corporation. The inspections were conducted in accordance with MassDOT and Federal Highway Administration "National Bridge Inspection Standards." The underwater inspections consisted of a visual and limited tactile examination of the accessible interior surfaces of the structures. The portions of the culverts above the waterline and the Massasoit Bridge superstructure were visually inspected at the same time as the underwater inspections. The methods and results of the structural condition assessment are described in a November 29, 2018 letter report, which is provided as Appendix A. The assessment findings are summarized as follows:

- Culvert #1 (Madaket Road between Long Pond and North Head Long Pond) was found to be in good condition, with some buildup of sand and marine growth (2 to 5 inches thick), and a minor sinkhole observed at the top of the headwall.
- Culvert #2 (Madaket Road at upstream end of Madaket Ditch) and Culvert #3 (North Cambridge Street at downstream end of Madaket Ditch) were both rated in satisfactory condition. Culvert #2 had minor deformation of the eastern headwall and some buildup of sand and marine growth (2 inches or less).

[7] The Massasoit Bridge over Long Pond at South Cambridge Street was also inspected although the bridge was not a focus of the overall evaluation given its relatively large hydraulic opening. A 2015 MassDOT inspection report for Massasoit Bridge provided an assessment of the condition of the piles and abutments (the pile bracing was decaying and the fasteners were heavily rusted), but it did not address the timber superstructure.

- Minor corrosion of the plate walls and connections was observed at Culvert #3 and the original protective coating was in poor condition.

Overall, the three study culverts were observed to be in good to satisfactory structural condition and did not appear to require any immediate action. Continued monitoring of their condition and overall sediment buildup is recommended.

3.2. Hydrologic and Hydraulic Modeling

Fuss & O'Neill contracted with Woods Hole Group to conduct a Hydrologic and Hydraulic (H&H) assessment of the Madaket Harbor/Long Pond estuarine system. The H&H assessment was conducted to determine the optimal culvert sizing and invert elevations that would improve water quality in Long Pond by reducing its residence time through increased tidal exchange between the harbor and Long Pond and limit adverse flooding impacts during storms.

The H&H assessment consisted of field data collection to document existing conditions in the estuarine system, development of an Estuarine Culvert Model to simulate tidal exchange and water levels under existing and potential future conditions, and evaluation of alternatives to examine the potential effects of system improvements on water quality and flooding. Field data collection consisted of continuous measurement of water level, temperature, and salinity at 5 locations between October 24 and November 28, 2018, as well as bathymetry survey throughout the estuarine system and survey of key elevations at the study culverts.

The Estuarine Culvert Model was developed to simulate existing tidal flows originating at Madaket Harbor, propagating through the Hither Creek/Madaket Ditch channel, and into the Long Pond system. The Madaket ECM uses the topography and bathymetry of the individual reaches that comprise the system, the geometry of the structures connecting each of the basins, together with the tidal boundary conditions at Madaket Harbor to simulate water levels throughout the estuary. In addition to simulating typical tides, Woods Hole Group also applied the model to assess the effects of the 1%-annual-chance (100-year) storm surge and rainfall events, as well as projected sea level rise, on the Madaket estuarine system. The details of the model development and application are described in a Woods Hole Group memorandum (Madaket Harbor, Hither Creek, and Long Pond, Nantucket, MA–Hydrologic & Hydraulic Assessment of the Madaket Estuarine System) dated March 20, 2019 (Appendix B).

The major findings from the existing conditions model are:

- Based on the 38-day field measurement program, the primary tidal restriction was shown to occur within Madaket Ditch between North Cambridge Street and Madaket Road. Further investigation of the channel elevations and field

observations indicate that the tidal dampening is likely due to the combined effects of the natural sinuosity of the channel and flow restrictions caused by the asymmetric bed elevations at the channel bends.

- With the existing Madaket Ditch channel and current-day tides, the study culverts are not restrictive and are sufficiently sized to convey flow in the upper reach of the Madaket estuary.
- In a 100-year coastal storm event, the culverts within the system and the Madaket Ditch channel would attenuate the surge peak from 7.4 in the harbor to 4.7 feet in Long Pond. The Madaket Ditch channel is shown to restrict drainage of the upstream basins resulting in a 4-day drainage period. With projected 4.3 feet of sea level rise in 2070, the culvert at North Cambridge Street would start to restrict tidal flow to Madaket Ditch and the culvert under Madaket Road connecting Madaket Ditch to Long Pond would slightly restrict tides in Long Pond.
- The North Cambridge Street and Madaket Road crossings would be inundated in a 100-year coastal storm event and in typical tides with 4.3 feet of sea level rise.

3.3. Alternatives Evaluation

The existing conditions model results indicate that, under normal tidal conditions, the Madaket Ditch is the primary tidal restriction rather than the study culverts. In order to develop a greater understanding of the system dynamics, a series of model simulations were conducted using an improved channel in Madaket Ditch (i.e., dredging of the channel) as an initial alternative for increasing tidal exchange and optimizing drainage within the system.

The proposed alternative channel configuration included dredging of shoaled areas along the main channel to effectively double the cross-sectional flow area and reduce the channel friction coefficient. The channel improvements were assumed in a 465-foot section of the channel that was modeled as a restriction. It was assumed the natural sinuosity of the channel would remain unchanged. The combined effects of the increased cross-sectional flow area and the reduced friction were then assessed by conducting the same model simulations of typical tides with and without an increased sea level as well as extreme storm events.

The major findings from the proposed conditions model of the Madaket Ditch dredging alternative are:

- The simulated channel improvements will enhance tidal exchange during typical tides with an increased tidal range in Long Pond. The improved channel is also

shown to reduce the time required for the upper reaches of the system to drain following storm events.

- The improved Madaket Ditch channel would not completely alleviate the restriction to tidal exchange. The natural sinuosity and some frictional effects of the channel would still remain, causing reduced tides further upstream. Improving the channel along its entire length and providing a more uniform channel throughout would help to minimize these effects.
- With the improved channel configuration and current-day tides, the culvert under Madaket Road to Long Pond would not significantly affect water levels; however, the culvert to North Head Long Pond would become slightly restrictive. An increased culvert size equivalent to a 15-foot wide by 5-foot high concrete box would be required at this location to alleviate the restriction.
- In a 100-year coastal storm event with an improved channel, surge elevations in the upper reach of Madaket Ditch would be higher and reach up to 5.5 feet NAVD88, which would impact/overtop Madaket Road. The improved Madaket Ditch channel is shown to reduce the drainage period of the upstream Long Pond basins from 4 days to 2 days.
- For typical tides and a projected 4.3 feet of sea level rise in 2070, both the culvert under Madaket Road connecting Madaket Ditch to Long Pond and the culvert to North Head Long Pond would restrict tidal exchange with an improved Madaket Ditch channel.
- In order to not restrict typical tides with a projected 4.3 feet of sea level rise in 2070, the following minimum culvert sizes (or equivalent) would be required. The existing invert elevations could be maintained:
    - 15' wide by 5' high concrete box at Madaket Road to North Head Long Pond (Culvert #1)
    - 16' wide by 10' high concrete box at Madaket Road to Long Pond (Culvert #2)
    - 20' wide by 10' high concrete box at North Cambridge Street (Culvert #3)
- An improved Madaket Ditch is shown to provide water quality benefits for Long Pond, reducing its local residence time by 36% (from 6.1 to 3.9 days).

4. Recommendations

Based on the assessment results, we recommend that the Town of Nantucket initially pursue dredging of Madaket Ditch, which is anticipated to enhance tidal exchange and improve water quality in Long Pond. Replacing the study culverts with larger structures and elevating portions of

the associated roadways should be considered as a longer-term recommendation to increase the resilience of the Madaket area against future sea level rise and coastal storms.

3.4. Madaket Ditch Dredging

As a first step in improving tidal exchange in the system, the stream bed in Madaket Ditch should be leveled at channel bends and any potential obstructions removed, at a minimum. Figure 3 shows areas identified for potential improvements based on collected bathymetry and channel cross-sections. The total length of channel identified for sediment removal is approximately 850 feet.

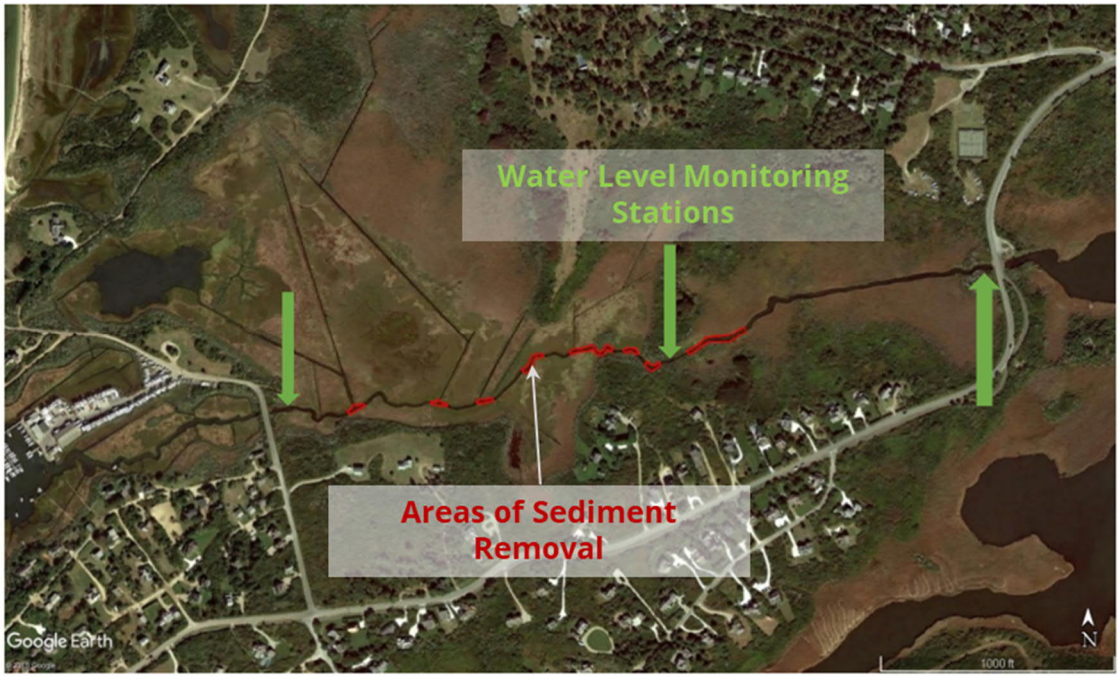

Figure 3. Areas identified for sediment removal (red) and potential locations for post-channel improvement monitoring stations (green arrows).

Following implementation of targeted channel grading, continued monitoring of water levels at three locations in the Madaket Ditch channel would help to assess the immediate effects of the channel improvements and to provide insight into additional maintenance needs/management alternatives for the channel.

Alternately, the Town could pursue a more extensive dredging project, such as dredging the entire length of the channel (approximately 3,500 feet). Improving the channel along its entire length and providing a more uniform channel throughout would further alleviate the restriction to tidal exchange and provide additional water quality benefits. Routine maintenance dredging of the

channel would be required to maintain sufficient tidal exchange in the system over time regardless of the scope of the initial dredging.

Dredging costs will vary depending on the extent of dredging and volume of dredged material, the quality of the dredged sediment and potential disposal/reuse, and other factors such as dredging method and site constraints. Dredging activities within the channel and marsh areas adjacent to Madaket Ditch will also require regulatory review and environmental controls to avoid or minimize impacts to the sensitive coastal environment. Dredging costs could range from $75 to $125 per cubic yards of dredged material. For the targeted dredging scenario described above (improving the cross-sectional flow area along 850 feet of the channel), preliminary planning-level dredging costs could vary from $80,000 to $140,000. Costs associated with dredging of the entire length of the channel (3,500 feet) could range from $350,000 to $600,000.

A dredging feasibility evaluation is recommended to build upon the field data collection and tidal exchange modeling that has already been completed. The feasibility evaluation would include:

- Sediment sampling and analysis for grain size and chemical constituents to identify possible sediment disposal/reuse options and to support subsequent permitting.
- Wetland and resource delineation.
- Supplemental channel survey, as required.
- Refined estimates of dredging volumes.
- Required permits and approvals for the initial dredging and routine maintenance dredging.
- Order-of-magnitude opinion of cost for the design, permitting, and implementation of proposed dredging scenarios (targeted dredging versus dredging of entire length of channel).

The results of the dredging feasibility evaluation would inform the selection of a preferred dredging option and support subsequent design and permitting should the Town choose to move forward with a dredging project for Madaket Ditch.

3.5. Culvert Replacement

The H&H modeling demonstrated that the study culverts do not restrict tidal exchange and are sufficiently sized with the existing Madaket Ditch channel configuration and current-day tides. However, the study culverts are expected to become restrictive to tidal exchange and be inundated in a 100-year coastal storm event and in typical tides with 4.3 feet of projected sea level rise by 2070. With an improved Madaket Ditch, the study culverts are predicted to become more

restrictive to tidal flow and surge elevations in the upper reach of Madaket Ditch would be higher, which would impact/overtop Madaket Road.

Therefore, the Town should consider replacing the study culverts with larger structures as they reach their useful life, which would help to maintain tidal exchange with future sea level rise. Continued monitoring of the structural condition and sediment buildup at each culvert is recommended. The Town should also evaluate the benefits of elevating portions of the roads (and roadway approaches) at the study crossings to avoid or reduce the frequency of inundation/overtopping during coastal storms and future sea level rise. A more detailed parcel-level assessment of potential flooding impacts should also be conducted during subsequent design and permitting if replacing the culverts.

Please contact me should you have any questions regarding our evaluation or recommendations.

Sincerely,

Erik V. Mas, P.E.
Vice President

Appendices: A – Culvert Structural Condition Assessment Letter Report
B – Hydrologic and Hydraulic Assessment Technical Memorandum

Appendix A

Culvert Structural Condition Assessment Letter Report

November 29, 2018

Nantucket Department of Public Works
c/o Robert D. McNeil III, PE, MPA
Director
188 Madaket Road
Nantucket, MA 02554

Re: Madaket Culverts Evaluation
Structural Condition Assessment

Dear Mr. McNeil:

Fuss & O'Neill completed structural condition inspections of four municipally-owned road-stream crossing structures on the Long Pond/Hither Creek estuary system in the Madaket section of Nantucket. The structural condition assessment is Task 2 of the "Madaket Culverts Evaluation" project, as described in the Scope of Services in our Agreement with the Town of Nantucket dated May 23, 2018. The objective of the overall project is to evaluate and provide recommendations for potential culvert replacements or upgrades that would address structural deficiencies, flooding, and degraded water quality in Long Pond.

The following structures were inspected on September 17, 2018:

- South Cambridge Street over Long Pond (Massasoit Bridge)
- Madaket Road over Long Pond (Culvert #1)
- Madaket Road over Madaket Ditch/Long Pond (Culvert #2)
- North Cambridge Street over Madaket Ditch (Culvert #3).

The structure locations are shown on the locus map in *Appendix A*.

The structural condition inspections were performed by Fuss & O'Neill and Childs Engineering Corporation. The inspections were conducted in accordance with Massachusetts Department of Transportation (MassDOT) and Federal Highway Administration (FHWA) "National Bridge Inspection Standards." The underwater inspections consisted of a visual and limited tactile examination of the accessible interior surfaces of the structures. The portions of the culverts above the waterline and the Massasoit Bridge superstructure were visually inspected at the same time as the underwater inspections.

The individual structure inspection reports, in MassDOT bridge inspection format, are provided in *Appendix B*. The inspection findings for each structure are summarized below.

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1. South Cambridge Street over Long Pond (Massasoit Bridge) (N-02-004)

This bridge is an 8-span timber pile bridge with 7 timber pier bents and a north and south abutment soldier pile composed of timber plank backwalls. The 70-foot long by 11-foot wide vehicular bridge is orientated in north-south direction and connects South Cambridge Street to Red Barn Road and Massasoit Bridge Road over Long Pond. The bridge is clearly posted for a 7 ton single unit truck, 13 tons 3S2 Truck, and a 20 ton Type 3-3 truck at the southern approach.

The superstructure on this bridge is in generally good condition, with decking and timber curbing having been recently added to the existing timber stringers. There are extra stringers added to some of the spans, presumably to support the older, now replaced decking.

The abutment timber below the waterline shows dry-rot to the tongue-and-groove planking between support piles. In particular, a gap between planking on the north abutment (photo 4 in the inspection report) is allowing fill material to leak out behind the northern abutment and create a sinkhole (photo 5 in the inspection report) – a condition that will get worse over time. A soldier pile post on the southern abutment has extensive dry-rot and loss of the interior wood for 3 inches in depth.

The bent piles show some minor misalignment, some of which have been shimmed (see photo 9). There is dry-rot of the diagonal bracing and advanced section loss of the hardware at or below the waterline throughout.

2. Madaket Road over Long Pond (No MassDOT Designation)

This 50-inch high by 9-foot wide corrugated aluminum box culvert connects the northern portion of Long Pond north of Madaket Road (also referred to as "North Head Long Pond") to Long Pond south of Madaket Road, carrying the road in an east to west direction. The culvert is approximately 50-feet long and is oriented in a north-south direction. It was found to be in good condition, with no loss of section noted in the walls of the culvert. There is some build-up of sand and marine growth in the northern half of the culvert that somewhat restricts water flow. The sediment/marine growth depths range from 2 to 5 inches.

3. Madaket Road over Madaket Ditch/Long Pond (N-02-005)

This 16-foot wide by approximately 60-inches high corrugated aluminum culvert runs in an east-west direction. The 60-foot long culvert connects Madaket Ditch/Long Pond and carries Madaket Road in a north-south direction. The culvert was nearly submerged in water at the time of the inspection with only a few inches of freeboard between the water surface and the crown of the culvert arch. The culvert showed no loss in aluminum section, with only some fastener loss

resulting in a minor deformation of the eastern headwall noted. Some aggregation of marine and sand debris was noted in the culvert in relation to the mudline at both the inlet and outlet ends.

4. North Cambridge Street over Madaket Ditch (N-02-006)

This culvert is a 7-foot tall multi-plate steel corrugated culvert that runs in an east-west direction over Madaket Ditch, which connects Long Pond to Hither Creek. The 50-foot long culvert carries North Cambridge Street in a north-south direction. There is some minor corrosion of plate walls and connection hardware throughout, with some through-holes concentrated at the ends of the exposed barrel openings. The original protective coating is in poor condition with only some small areas of coating remaining. No deformation of the culvert was observed during the inspection.

5. Findings Summary and Recommendations

From a structural standpoint, only the Massasoit Bridge has some immediate maintenance concerns. In particular, the loss of the tongue-and-groove planking on the northern abutment and the resulting sinkhole from loss of backfill material should be addressed. The substructure elements should be monitored, but require no immediate action.

The three culverts look to be in good to satisfactory structural condition and don't appear to require any immediate action. Continued monitoring of their condition and overall sediment buildup is recommended.

Please contact us with any questions regarding this assessment and findings.

Sincerely,

Dan Whittemore, P.E.
Senior Structural Engineer

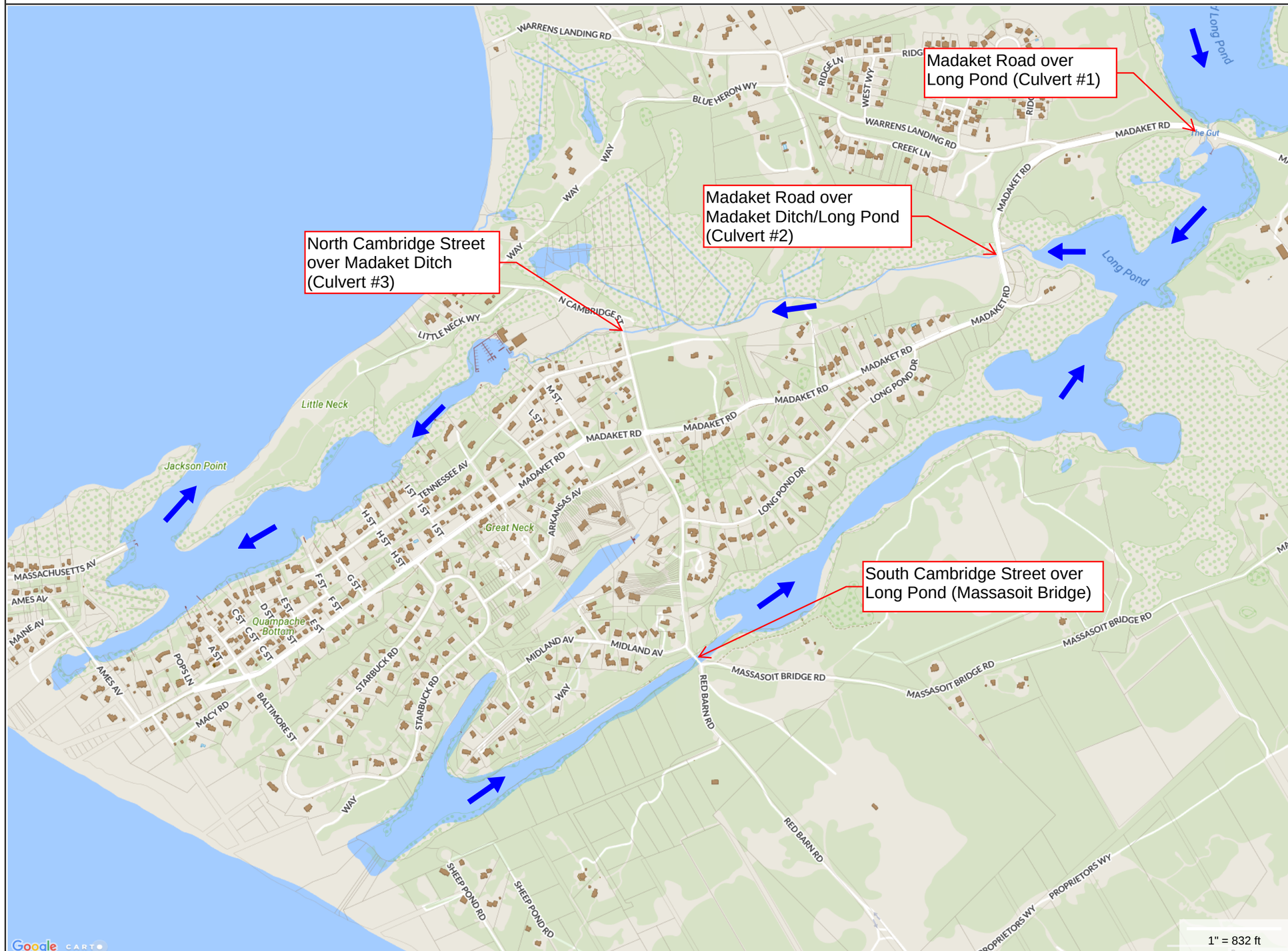
Erik V. Mas, P.E.
Vice President

Appendices: A – Locus Map
B – Structure Inspection Reports

Appendix A

Locus Map

Madaket Culverts



MAP FOR REFERENCE ONLY
NOT A LEGAL DOCUMENT

Town and County of Nantucket, MA makes no claims and no warranties, expressed or implied, concerning the validity or accuracy of the GIS data presented on this map.

Parcels updated December, 2014
Properties updated 01/26/2018

Appendix B

Structure Inspection Reports

MASSACHUSETTS DEPARTMENT OF TRANSPORTATION

UNDERWATER OPERATIONS TEAM
DIVERS ACTIVITY REPORT

2-DIST	B.I.N.	BR. DEPT. NO.
05	443	N-02-004

4-CITY/TOWN	8-STRUCTURE NO.	LEVEL OF INSP.	93b-INSPECTION DATE
NANTUCKET	N-02-004	II	9-17-2018

7-FACILITY CARRIED	ACCESS TO BRIDGE	UNDERWATER OPERATIONS ENGINEER
SOUTH CAMBRIDGE STREET	EMBANKMENT	Charlie Roberts

06-FEATURES INTERSECTED	DEPTH	VISIBILITY	TEAM LEADER (DIVE MASTER)	*Report submitted by:*
WATER LONG POND	6 F	0	Philip Iantosca	Childs Engineering

BOTTOM CONDITION	CURRENT	TEAM MEMBERS
SILT,SAND	slight	Charlie Roberts, Philip Iantosca, Ryan Cavanaugh

ITEM 60 (Underwater) *SUBSTRUCTURE* — 5

		DEF
1. Abutments		
a. Pedestals		
b. Bridge Seats	N	
c. Backwalls	5	M/P
d. Breastwalls	N	
e. Wingwalls	N	
f. Slope Paving/Rip-Rap	7	
g. Pointing	N	
h. Footings	N	
i. Piles	6	M/P
j. Scour	6	
k. Settlement	8	
l.		
2. Piers or Bents		
a. Pedestals		
b. Caps		
c. Columns		
d. Stems/Webs/Pierwalls		
e. Pointing		
f. Footing		
g. Piles		
h. Scour		
i. Settlement		
j.		
k.		
3. Pile Bents		
a. Pile Caps	8	
b. Piles	7	
c. Diagonal Bracing	5	
d. Horizontal Bracing	N	
e. Fasteners	4	M/P

UNDERMINING (Y=Yes / N=No): N

ITEM 61 *CHANNEL & CHANNEL PROTECTION* — 6

		DEF
1. Channel Scour	6	
2. Embankment Erosion	7	
3. Drift	7	
4. Vegetation	5	
5. Utilities	N	
6. Rip-Rap/Slope Protection	6	
7. Aggradation	5	
8. Fender System		
a. Piles		
b. Diagonal Bracing		
c. Horizontal Bracing		
d. Wales		
e. Fasteners		
f. Ladders		

ITEM 59 *SUPERSTRUCTURE* (If any part done by divers.)

ITEM 62 *CULVERTS* — N

		DEF
1. Roof		
2. Floor		
3. Walls		
4. Headwall		
5. Wingwall		
6. Pipe		
7. Protective Coating		
8. Embankment		
9. Wearing Surface		
10. Railing		
11. Sidewalks		
12. Utilities		
13. Member Alignment		
14. Deformation		
15. Scour		
16. Settlement		

UNDERMINING (Y=Yes / N=No)

DEFICIENCY REPORTING GUIDE

DEFICIENCY: A defect in a structure that requires corrective action.

CATEGORIES OF DEFICIENCIES:

M= Minor Deficiency - Deficiencies which are minor in nature, generally do not impact the structural integrity of the bridge and could easily be repaired. Examples include but are not limited to: Spalled concrete, Minor scouring, etc.

S= Severe/Major Deficiency - Deficiencies which are more extensive in nature and need more planning and effort to repair. Examples include but are not limited to: Moderate to major deterioration in concrete, Exposed and corroding rebars, Deteriorated timber piles, Considerable settlement, Considerable scouring or undermining, etc.

C-S= Critical-Structural Deficiency - A deficiency in a structural element of a bridge that poses an extreme unsafe condition due to the failure or imminent failure of the element which will affect the structural integrity of the bridge.

C-H= Critical-Hazard Deficiency - A deficiency in a component or element of a bridge that poses an extreme hazard or unsafe condition to the public, but does not impair the structural integrity of the bridge. Examples include but are not limited to: Any part of piles or fender system which are projecting outward and may become a safety hazard for the navigational traffic, etc.

URGENCY OF REPAIR:

I= Immediate - [Inspector(s) immediately contact District Bridge Inspection Engineer (DBIE) to report the Deficiency and to receive further instruction from him/her].

A= As soon as possible - [Action/Repair should be initiated by District Maintenance Engineer or the Responsible Party (if not a State owned bridge) upon receipt of the Inspection Report].

P= Prioritize - [Shall be prioritized by District Maintenance Engineer or the Responsible Party (if not a State owned bridge) and repairs made when funds and/or manpower is available].

X=UNKNOWN **N=NOT APPLICABLE** **H=HIDDEN/INACCESSIBLE** **R=REMOVED**

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	443	N-02-004	N-02-004	9-17-2018
Remarks & Photos				

GENERAL REMARKS

The bridge is an eight span timber pile bridge with 7 timber pier bents and a north and south abutment soldier pile composed of a timber plank backwalls **(see photos 1 to 3)**. The bridge is orientated in a north to south direction and connects the Massasoit Road to South Cambridge Street over Long Pond. The piers are numbers 1 to 7 with Pier 1 on the north end of the bridge **(see sketch 1)**.

Item 60.1- Abutments

The north and south abutments are composed of 5 equally spaced creosote treated timber soldier piles and horizontally stacked creosote treated tongue and grooved timber planking used to retain the roadway embankment fill material. The height of the backwalls varied along with the number of exposed planks. The north abutment had 8 exposed timber planks that are lag bolted to the adjacent soldier piles. The abutments each have a 16x14 treated timber pile cap. At the time of the inspection bent 7 and the south abutment were in the dry.

Item 60.1.C Backwall

The abutment backwalls are composed of 5 to 8 exposed horizontal tongue and grooved creosoted treated timber planks with 5 treated soldier piles equally spaced across the outshore face of the abutments. The corners and sides of each timber plank have some minor general softness up to ¼” deep.

The south abutment has no visible signs of gaps or dry rot on the exposed planking. The top of the southwest end of the backwall has a 3 inch outshore lean from soldier piles #1 and #2.

The north abutment has 2 existing gaps between timber planks in the backwall. A 3 inch high gap is located 39 inches down and a 6 inch gap is located 50 inches down from the top of the backwall. Both gaps are approximately 7 feet long and centered on soldier pile #4. These gaps have 1.5 foot void behind the headwall and there is a sinkhole noted along the roadway in this area **(see photos 4 and 5).**

Item 60.1.f Slope Paving/ Rip-Rap

The riprap is composed of loosely dumped stones along the northern and southern embankments **(see photo 6).** The vegetation has covered the riprap along the southwest embankment. The reeds along the northeast abutment have been cut back. Both embankments appear to be stable. There were no noted issues with placement of the riprap along both abutment embankments.

Item 60.1.i. Piles
The abutments are constructed with 5 creosoted treated timber soldier piles equally spaced across the front of each abutment. The piles are in fair to poor condition. The piles are typically noted to be 12 inch diameter piles that have some minor softness up to 1 inch deep around the perimeter of the in-water piles at the mudline. The south abutment soldier piles #1 and # 5 and the northern abutment pile #1 each have 2 to 3 feet of dry rot that has hollowed out the pile tops **(see photo 7)**. The northern abutment soldier piles that also support the abutment pile cap are 30% to 50% bearing. Currently there was no crushing of the pile cap or pile tops in the remaining bearing areas. **(see photo 8).**

Item 60.1.j. Scour
There was no noted scour along the abutment. Both the north and south abutments have several feet of soft sediments that can be probed down and under the backwall but the surrounding sediment was built up above the base of the backwall planks. Currently there are eight exposed planks on the north abutment and 5 planks exposed along the south abutment.

Item 60.1.k. Settlement
There was no noted settlement to the north or south abutments. There are some repairs that have been recently made to the south abutments and surrounding pier bents. These repairs include new south abutment pile cap and stringers.

Item 60.3 Pile Bents
There are 7 timber pier bents numbered from pier north to south. The timber bents are composed of two treated timber piles a pile cap and diagonal cross bracing.

Item 60.3.a Pile Caps
The timber pier pile caps are in good condition with some minor checking and splitting on the exposed ends with no major issues. The pile caps on Bent 5, 6, and 7 have been replaced recently. The pile cap on Bent 7 was noted to be notched out 1.5 inches and then shimmed up with 2 bricks on each pier pile **(see photo 9)**.

Item 60.3.b Piles
The creosoted timber pier bent piles are in good condition with no major issues noted. The piles on bent 6 are noted to have double stainless steel band around the tops of the piles**.** The piles at the mudline are noted to have some general softness of less than ¼ inch deep.

Item 60.3.c Diagonal Bracing
Each bent pile has (2) 3 x 10 diagonal timber bracings. These members are noted to be in generally fair to poor condition with the in-water portion of the bracings to have 10 to 30% section loss **(see photo 10).** On Bent 2, the southwest bracing is loose and the fastening hardware has heavy corrosion with reduced section **(see photo 11).**

Item 60.3.e Fasteners
The fasteners range from being in satisfactory to poor condition. The above water fasteners are in good condition with minor coating loss and surface corrosion. The in-water or lower fasteners on the cross bracing have 30 to 100% section loss with heavy corrosion and section loss to the washers and bolt heads (**see photo 12).**

Item 60.3.f Stringers
The stringers are in good condition with some localized deterioration to the edge stringers around the old timber curb fastening holes **(see photo 13).** The new structure has intermediate stringers that have been added adjacent to the 6 main stringers on Bents 5, 6, and 7. The intermediate stringers have been notched out over the pile caps and the two edge stringers have been doubled up and through bolted to the adjacent stringers.

Item 61 CHANNEL & CHANNEL PROTECTION

Item 61.4 Vegetation
The banks are well vegetated with a significant amount of reed build up **(see photos 14 and 15).** The reeds along the southwest and north abutment have been cut back.

Item 61.6. Rip Rap / Slope Protection
The riprap is composed of loosely dumped stones along the northern sides of the bridge of the embankments. The channel runs between bents 3-4 and there is no riprap lining the channel. The vegetation and reeds cover the river embankments with no issues noted.

Item 61.7 Aggradation
Along the south abutment there has been a build-up of sand and sediment from bent 6 to the south abutment **(see sketch 1 and scour chart)**.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	443	N-02-004	N-02-004	9-17-2018
Remarks & Photos				

Scour Chart						
	10/28/1993	9/30/1996	2/19/1999	5/2/2001	5/21/2003	5/18/2005
North Abutment	2.5'/2.5'	1.8'/1.8'	1.5'/1.5'	1.4'/1.8'	1.2'/2.8'	1.1'/2.8'
Bent #1	3.0'/3.5'	2.6'/5.1'	2.9'/4.1'	3.2'/4.1'	3.0'/4.0'	2.7'/4.0'
Bent #2	4.5'/8.5'	4.3'/6.1'	3.8'/8.7'	3.8'/8.1	3.7'/8.7'	3.6'/9.0'
Bent #3	4.8'/8.5'	4.2'/8.8'	4.5'/8.8'	4.6'/8.6'	4.5'/8.9'	4.4'/8.9'
Bent #4	4.8'/8.5'	4.2'/8.8'	4.1'/8.7'	3.8'/9.0'	4.5'/8.4'	4.0'/8.3'
Bent #5	3.8'/10.1'	3.3'/5.3'	2.2'/4.8'	2.6'/3.1'	2.2'/5.2'	2.2'/5.5'
Bent #6	0.5'/0.5'	1.2'/1.2'	0.3'/0.3'	0.6'/0.6'	0.4'/0.4'	0.4'/0.4'
Bent #7	+0.5'/+0.5'	+0.5'/+0.5'	DRY	DRY	DRY	+0.9'/+0.9'
South Abutment	+0.5'/+0.5'	+0.5'/+0.5'	DRY	DRY	DRY	+0.9'/+0.9'
Y	1.8'	1.8'	2.1'	2.4'	2.4'	2.2'
Correction Factor	-	-	-0.3'	-0.6'	+0.6'	+0.4'

Scour Chart						
	5/23/2007	5/19/2009	5/19/2011	5/1/2013	5/20/2015	9/17/2018
North Abutment	1.0'/1.8'	0.5'/0.5'	4.8'/5.3'	3.4'/4.6'	3.2'/4.2'	1.3'/5.3'
Bent #1	2.1'/4.1'	2.5'/2.6'	6.6'/7.8'	5.4'/7.4'	4.6'/7.5'	2.2/6.7'
Bent #2	3.5'/7.8'	3.6'/7.6'	6.6'/8.8'	6.5'/8.8'	5.5'/8.7'	3.3/7.3'
Bent #3	4.2'/8.8'	3.7'/8.1'	6.6'/8.2'	7.9'/9.3'	6.3'/8.9'	4.1'/7.6'
Bent #4	3.6'/8.3'	2.8'/5.5'	5.7'/6.4'	6.1'/8.6'	5.4'/8.6'	4.2'/6.2'
Bent #5	2.2'/3.2'	1.9'/3.1'	5.4'/6.5'	4.4'/6.5'	3.9'/6.2'	3.2/7.2'
Bent #6	0.4'/0.4'	0.3'/0.3'	0.8'/0.8'	0.6'/0.6'	0.6'/0.6'	0.7'/4.7'
Bent #7	+0.3'+0.3'	+0.6'/+0.6'	+0.4'/+0.4'	-0.1'/-0.1'	+0.2'	+0.2'/2.5'
South Abutment	+0.9'/+0.9'	+0.1'/+0.1'	+0.9'/+0.9'	+0.7'/+0.7'	+0.5'	+0.9'/4.9'
Y	2.2'	2.4'	1.7'	2.2'	2.3'	2.8'
Correction Factor	+0.4'	+0.6'	-0.1"	+0.4'	+0.5'	+1.0'

Notes:

1.WATERLINE TO BOTTOM OF BENT CAP AT DOWNSTREAM (EAST) END OF BENT #4, Y=1.8' (10/28/93)

2. SOUNDINGS ARE ADJUSTED TO 10/28/93 WATERLINE WITH CORRECTION FACTOR.

3. TOP NUMBER IS TOP OF SILT TO WATERLINE, BOTTOM NUMBER IS TO REFUSAL.

CHART 1: SCOUR MONITORING CHART - UPSTREAM END (WEST)

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	443	N-02-004	N-02-004	9-17-2018
Remarks & Photos				

Photo 1, North Abutment, Timber soldier piles and timber planking backwall.

Photo 2, Timber bent #4, south face.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	443	N-02-004	N-02-004	9-17-2018
Remarks & Photos				

Photo 3, Bridge deck, looking north.

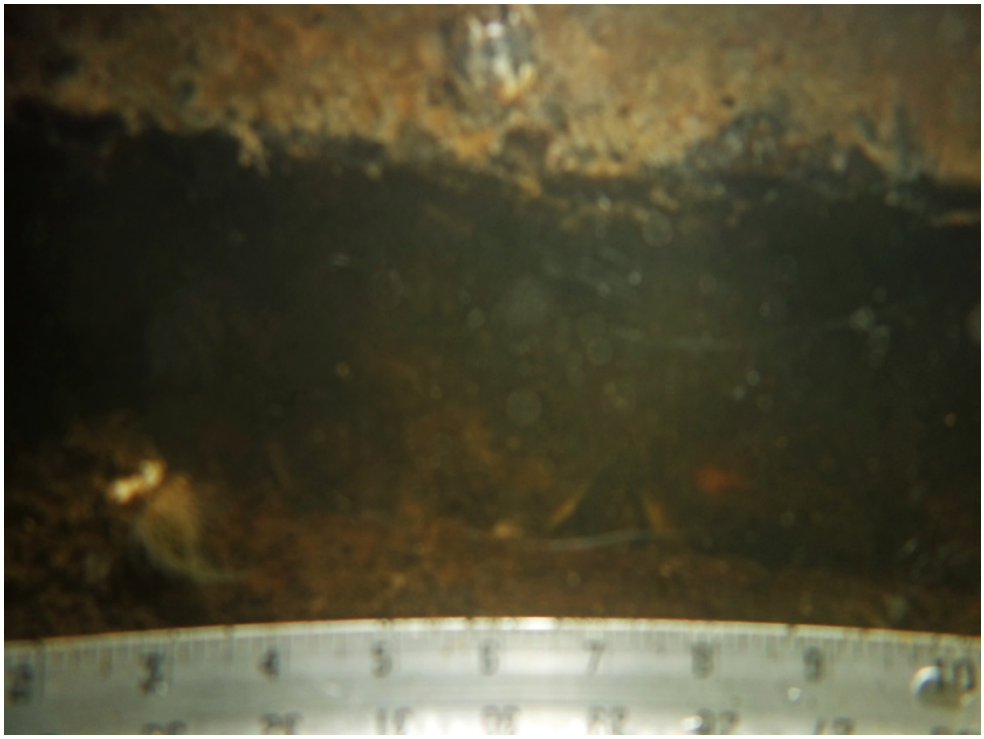


Photo 4, North Abutment, at pile #4, 50 inches down gap between planking.

Photo 5, Sinkhole behind North Abutment timber backwall.

Photo 6, Northeast embankment with loosely dumped riprap stones.

Photo 7, South Abutment, soldier pile #5, 3 feet of dry rot to top of pile.

Photo 8, North Abutment, Pile #3, partially bearing on pile cap.

Photo 9, Bent 7, Pile cap notched and shimmed with bricks.

Photo 10, Bent 4, southeast side with deterioration to in-water portion for bracing.

Photo 11, Bent 2, Southwest side, gap between bracing and pile.

Photo 12, Bent 3, Diagonal bracing with heavily corroded hardware and dry rot to bottom 2 feet.

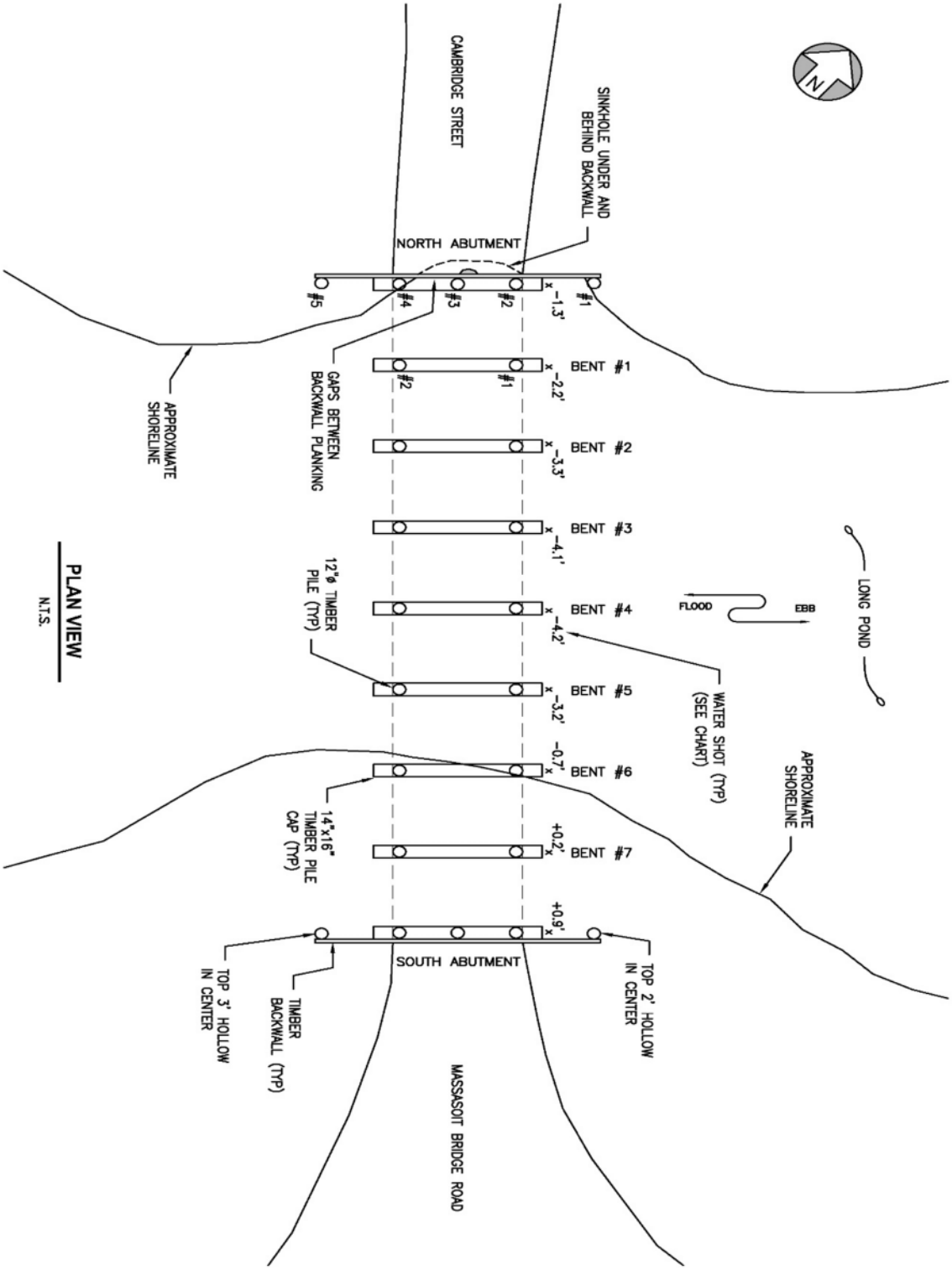
Photo 13, Edge stringer with typical dry rot at old timber curb connection hole.

Photo 14, View of the east downstream end.

Photo 15, View of the west upstream end.

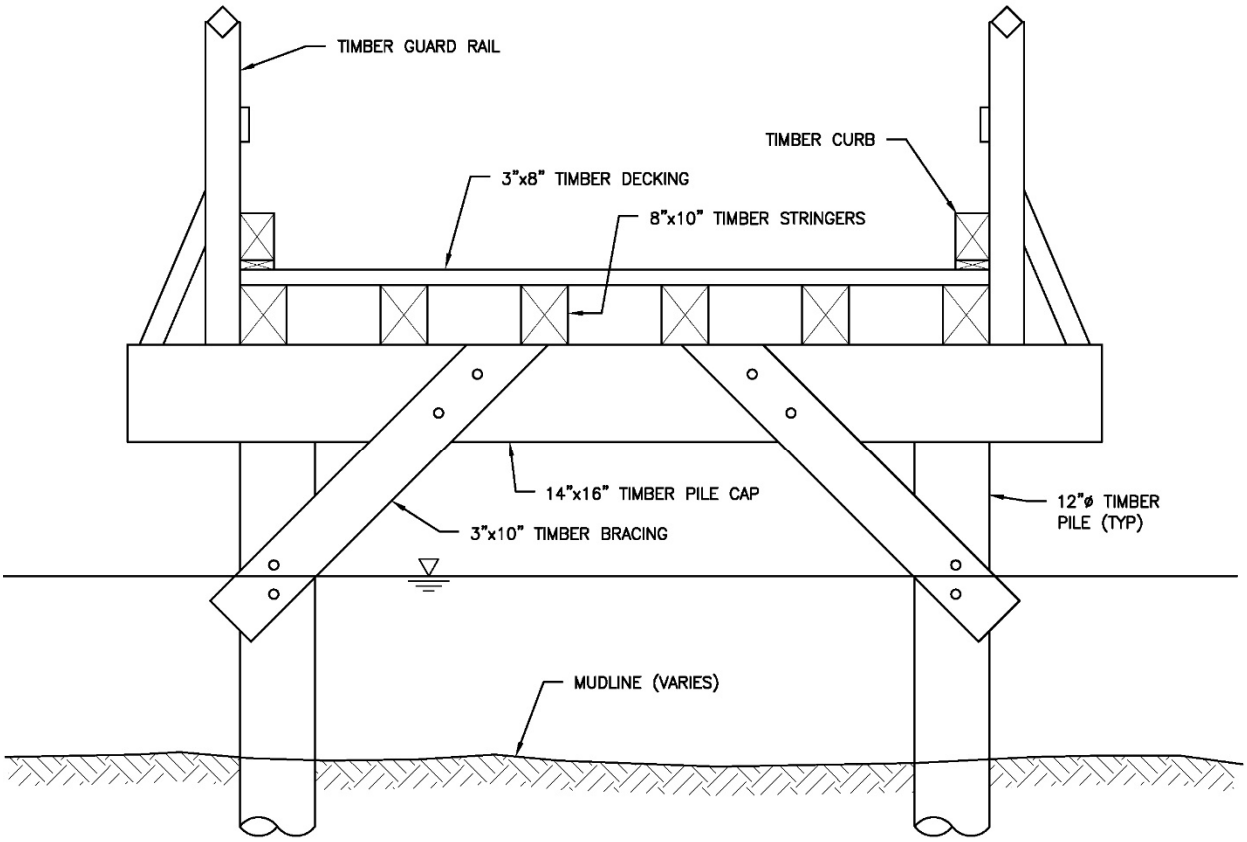
City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	443	N-02-004	N-02-004	9-17-2018
Remarks & Photos				

Sketch 1



City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	443	N-02-004	N-02-004	9-17-2018
Remarks & Photos				

Sketch 2



TYPICAL SECTION

N.T.S.

MASSACHUSETTS DEPARTMENT OF TRANSPORTATION

2-DIST	B.I.N.
05	

UNDERWATER OPERATIONS TEAM
DIVERS ACTIVITY REPORT

BR. DEPT. NO.

4-CITY/TOWN	8-STRUCTURE NO.	LEVEL OF INSP.	93b-INSPECTION DATE
NANTUCKET	Culvert 1	II	9-17-18

7-FACILITY CARRIED	ACCESS TO BRIDGE	UNDERWATER OPERATIONS ENGINEER
MADAKET ROAD WITH BIKE PATH	EMBANKMENT	Charlie Roberts

06-FEATURES INTERSECTED	DEPTH	VISIBILITY	TEAM LEADER (DIVE MASTER)	*Report submitted by:*
LONG POND/ Madaket Road Culvert	4'	0	Philip Iantosca	CHILDS ENGINEERING

BOTTOM CONDITION	CURRENT	TEAM MEMBERS
SHELLS, SILT, GRAVEL	TIDAL, NONE	Charlie Roberts, Philip Iantosca, Ryan Cavanaugh

ITEM 60 (Underwater) *SUBSTRUCTURE* — N

		DEF
1. Abutments		
a. Pedestals		
b. Bridge Seats		
c. Backwalls		
d. Breastwalls		
e. Wingwalls		
f. Slope Paving/Rip-Rap		
g. Pointing		
h. Footings		
i. Piles		
j. Scour		
k. Settlement		
l.		
2. Piers or Bents		
a. Pedestals		
b. Caps		
c. Columns		
d. Stems/Webs/Pierwalls		
e. Pointing		
f. Footing		
g. Piles		
h. Scour		
i. Settlement		
j.		
k.		
3. Pile Bents		
a. Pile Caps		
b. Piles		
c. Diagonal Bracing		
d. Horizontal Bracing		
e. Fasteners		

UNDERMINING (Y=Yes / N=No) | |

ITEM 61 *CHANNEL & CHANNEL PROTECTION* — 6

		DEF
1. Channel Scour	6	
2. Embankment Erosion	6	
3. Drift	6	
4. Vegetation	6	
5. Utilities	N	
6. Rip-Rap/Slope Protection	N	
7. Aggradation	6	
8. Fender System	N	
a. Piles		
b. Diagonal Bracing		
c. Horizontal Bracing		
d. Wales		
e. Fasteners		
f. Ladders		

ITEM 59 *SUPERSTRUCTURE* (If any part done by divers.)

ITEM 62 *CULVERTS* — 7

		DEF
1. Roof	7	
2. Floor	7	
3. Walls	7	
4. Headwall	7	
5. Wingwall	N	
6. Pipe	N	
7. Protective Coating	N	
8. Embankment	6	
9. Wearing Surface	N	
10. Railing	N	
11. Sidewalks	N	
12. Utilities	N	
13. Member Alignment	7	
14. Deformation	7	
15. Scour	7	
16. Settlement	7	
17. Corr. Alum. Plate	7	
	N	

UNDERMINING (Y=Yes / N=No) | N

DEFICIENCY REPORTING GUIDE

DEFICIENCY: A defect in a structure that requires corrective action.

CATEGORIES OF DEFICIENCIES: M/P=Minor Deficiency/Prioritize

M= Minor Deficiency - Deficiencies which are minor in nature, generally do not impact the structural integrity of the bridge and could easily be repaired. Examples include but are not limited to: Spalled concrete, Minor scouring, etc.

S= Severe/Major Deficiency - Deficiencies which are more extensive in nature and need more planning and effort to repair. Examples include but are not limited to: Moderate to major deterioration in concrete, Exposed and corroding rebars, Deteriorated timber piles, Considerable settlement, Considerable scouring or undermining, etc.

C-S= Critical-Structural Deficiency - A deficiency in a structural element of a bridge that poses an extreme unsafe condition due to the failure or imminent failure of the element which will affect the structural integrity of the bridge.

C-H= Critical-Hazard Deficiency - A deficiency in a component or element of a bridge that poses an extreme hazard or unsafe condition to the public, but does not impair the structural integrity of the bridge. Examples include but are not limited to: Any part of piles or fender system which are projecting outward and may become a safety hazard for the navigational traffic, etc.

URGENCY OF REPAIR:

I= Immediate - [Inspector(s) immediately contact District Bridge Inspection Engineer (DBIE) to report the Deficiency and to receive further instruction from him/her].

A= As soon as possible - [Action/Repair should be initiated by District Maintenance Engineer or the Responsible Party (if not a State owned bridge) upon receipt of the Inspection Report].

P= Prioritize - [Shall be prioritized by District Maintenance Engineer or the Responsible Party (if not a State owned bridge) and repairs made when funds and/or manpower is available].

X=UNKNOWN **N=NOT APPLICABLE** **H=HIDDEN/INACCESSIBLE** **R=REMOVED**

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

GENERAL REMARKS

Culvert 1 is orientated in a north to south direction and connects North Head Long Pond to Long Pond and carries Madaket Road in an east to west direction. Culvert 1is an aluminum box culvert that is 50 feet long from barrel opening to barrel opening and is 9 feet wide at each barrel opening.

Item 61 CHANNEL & CHANNEL PROTECTION

Item 61.2 Embankment Erosion

There is some minor erosion of the embankment adjacent to the southeast barrel opening **(see photos 1 and 2).**

Item 61.5 Vegetation

The vegetation is composed of marsh type grasses and some reeds around the edges of the culvert head walls **(see photo 3).**

Item 61.7 Aggradation

There is some minor aggradation that has deposited 2 to 5 inches of fine sand material throughout the full of the culvert.

Item 62 CULVERTS

The Aluminum box culvert is in overall good condition with some minor aggradation of loose sand throughout the culvert. The normal waterline is located 18 to 20 inches below the apex of the culvert. The inside walls of the Aluminum corrugated culvert below the water are covered with 1 inch of light marine growth and silt that get thicker toward the northern half of the culvert. The mudline is composed of sand with some silt and shells. The water heights ranged from 25 inches to 30 inches. The bottom of the box culveret was uncovered at the midpoint of the culvert and the invert height of the culvert was recorded at 50 inches. The sediments buillt up ranged from 2 to 5 inches throughout the lenght of the culvert. Measurements form the mudline to the waterline and from the waterline to the apex of the culvert were taken at 10 foot intervals **(see sketches 1 and 2)**

Item 62.1 Roof

The normal water line appears to be approximately 18 inches below the top of the apex of the culvert. There were no noted issues with the roof.

Item 62.2 Floor

The floor is in good condition with no noted issues. The elevation of the existing floor was recorded as 50 inches below the apex of the culvert. There was roughly 2 to 5 inches of sand built-up with some shells and silt throughout the culvert **(see photo 4)**. The sediment build up was loosely packed and easily removed to expose the floor.

Item 62.3 Walls
The walls remain in good condition with light marine growth of mussel shells and silt **(see photo 5).**

Item 62.4 Headwall
The headwall were noted to be in satisfactory condition. The headwall is constructed with corrugated aluminum that was used to construct the walls and roof. The headwall has one D-shaped horizontal wale that is located half way down on the exposed portion of the headwall. The headwalls remain in good condition with no noted defects **(see photos 6 and 7).**

A sinkhole was noted adjacent to the apex of the north headwall **(see photo 8).** The sand and fill material appears to be leaching out at the corrugated headwall roof line.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

Photo 1, Southwest bank, erosion of the river bank.

Photo 2, Erosion of the south east river bank with some slumping.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

Photo 3, Well vegetated river banks to the north of the culvert.

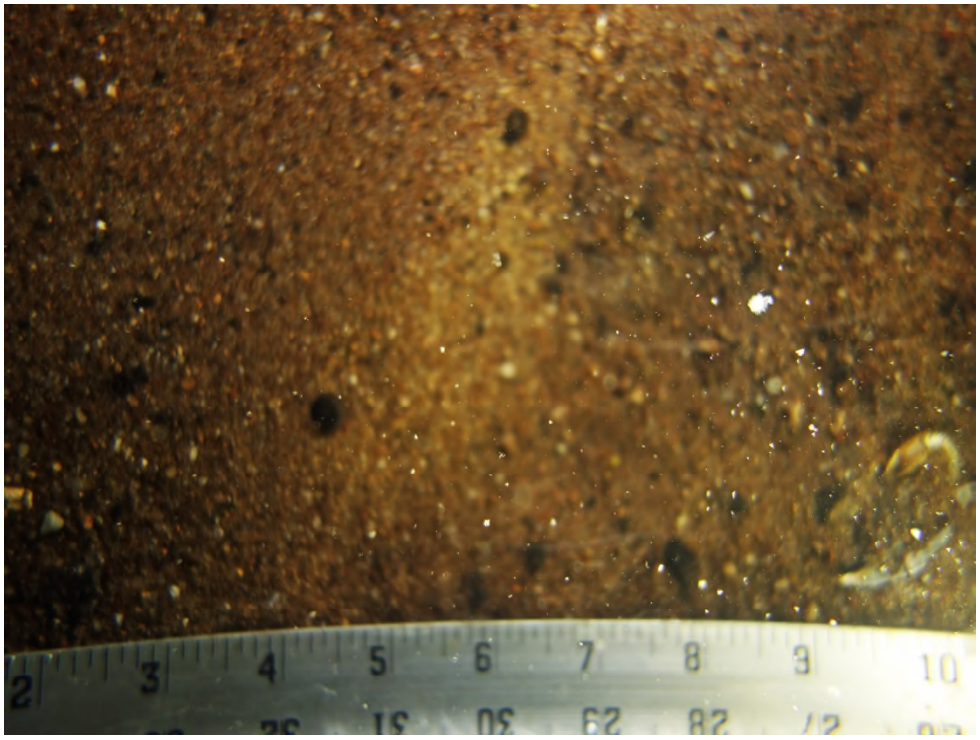


Photo 4, Sand deposited throughout the culvert.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

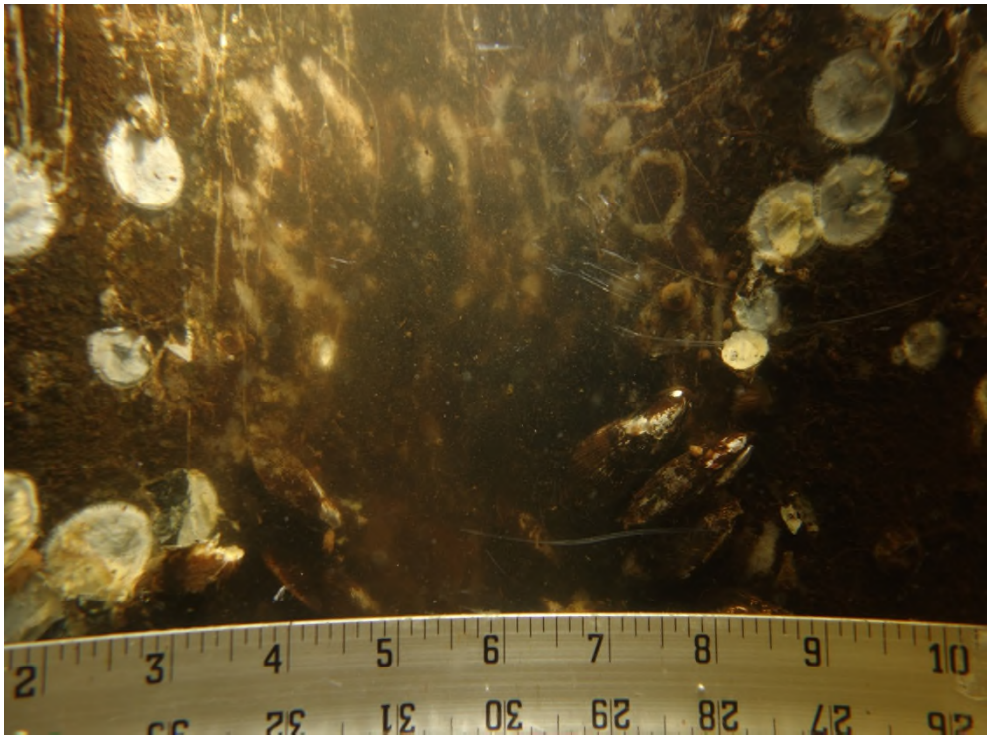


Photo 5, Underwater cleaning at station 0+20.

Photo 6, South headwall.

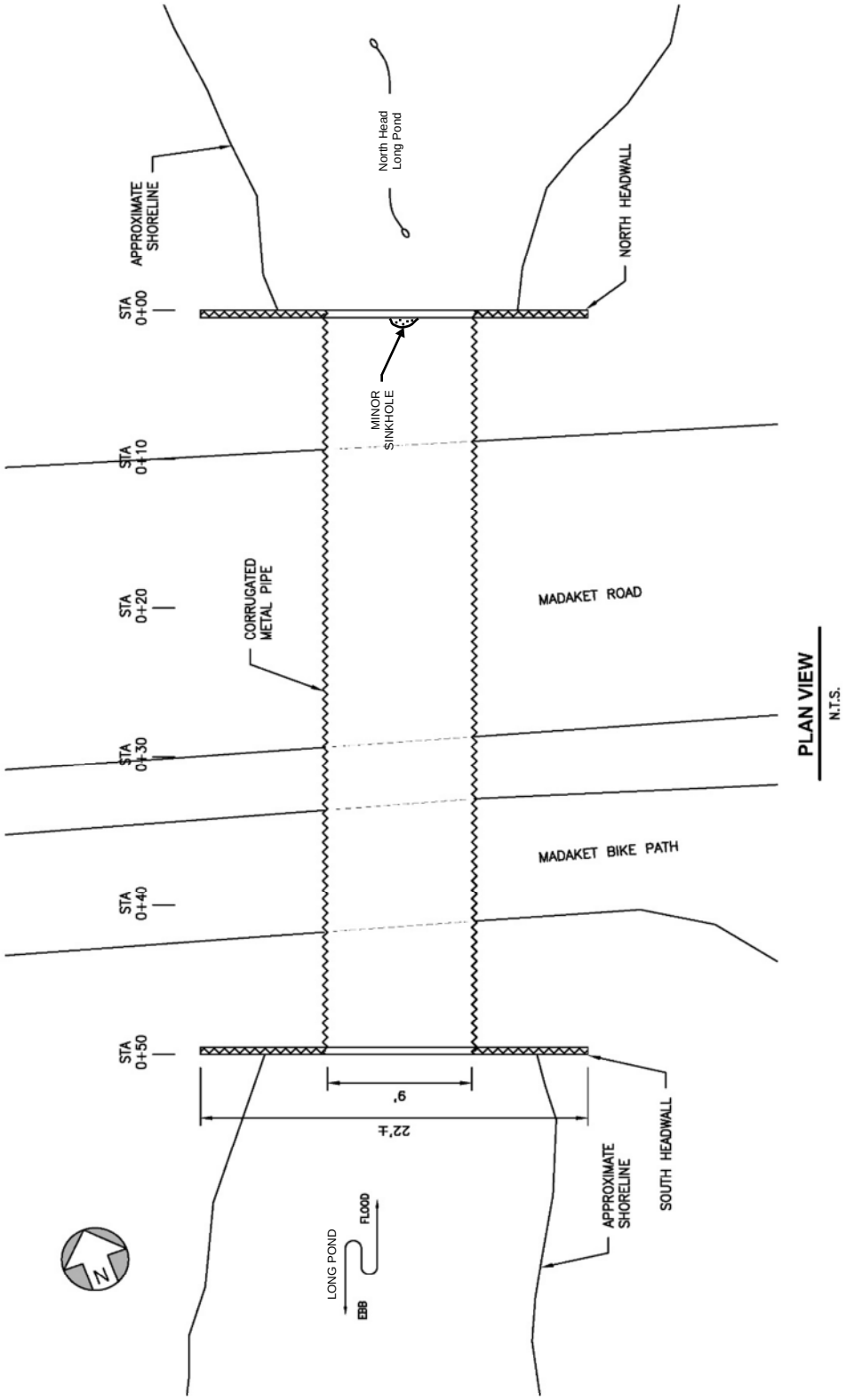
City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

Photo 7, North headwall.

Photo 8, North headwall minor sinkhole located above the apex of the culvert.

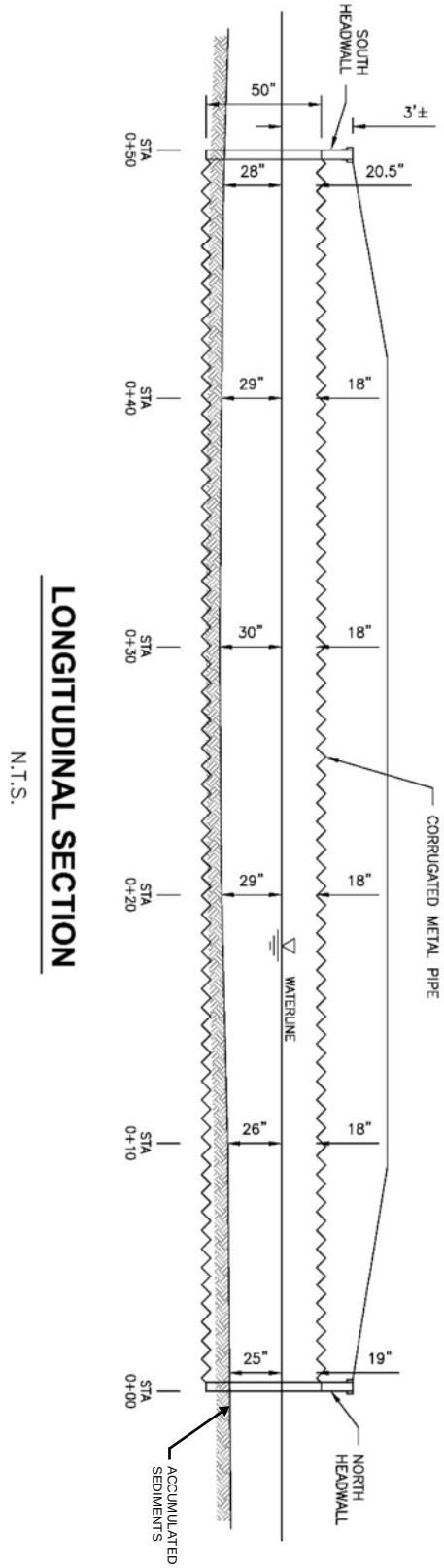
City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

Sketch 1



City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET			Culvert 1	9-17-2018
Remarks & Photos				

Sketch 2



LONGITUDINAL SECTION

N.T.S.

MASSACHUSETTS DEPARTMENT OF TRANSPORTATION

UNDERWATER OPERATIONS TEAM
DIVERS ACTIVITY REPORT

2-DIST	B.I.N.	BR. DEPT. NO.
05		N-02-005

4-CITY/TOWN	8-STRUCTURE NO.	LEVEL OF INSP.	93b-INSPECTION DATE
NANTUCKET	Culvert 2	II	9-17-18

7-FACILITY CARRIED	ACCESS TO BRIDGE	UNDERWATER OPERATIONS ENGINEER
MADAKET ROAD WITH BIKE PATH	EMBANKMENT	Charlie Roberts

06-FEATURES INTERSECTED	DEPTH	VISIBILITY	TEAM LEADER (DIVE MASTER)	*Report submitted by:*
Madaket Ditch /Long Pond Culvert	4'	0	Philip Iantosca	CHILDS ENGINEERING

BOTTOM CONDITION	CURRENT	TEAM MEMBERS
SHELLS, SILT, GRAVEL	TIDAL, NONE	Charlie Roberts, Philip Iantosca, Ryan Cavanaugh

ITEM 60 (Underwater) *SUBSTRUCTURE* — N

		DEF
1. Abutments		
a. Pedestals		
b. Bridge Seats		
c. Backwalls		
d. Breastwalls		
e. Wingwalls		
f. Slope Paving/Rip-Rap		
g. Pointing		
h. Footings		
i. Piles		
j. Scour		
k. Settlement		
l.		
2. Piers or Bents		
a. Pedestals		
b. Caps		
c. Columns		
d. Stems/Webs/Pierwalls		
e. Pointing		
f. Footing		
g. Piles		
h. Scour		
i. Settlement		
j.		
k.		
3. Pile Bents		
a. Pile Caps		
b. Piles		
c. Diagonal Bracing		
d. Horizontal Bracing		
e. Fasteners		

UNDERMINING (Y=Yes / N=No) | |

ITEM 61 *CHANNEL & CHANNEL PROTECTION* — 6

		DEF
1. Channel Scour	6	
2. Embankment Erosion	6	
3. Drift	6	
4. Vegetation	6	
5. Utilities	N	
6. Rip-Rap/Slope Protection	N	
7. Aggradation	5	
8. Fender System	N	
a. Piles		
b. Diagonal Bracing		
c. Horizontal Bracing		
d. Wales		
e. Fasteners		
f. Ladders		

ITEM 59 *SUPERSTRUCTURE* (If any part done by divers.)

ITEM 62 *CULVERTS* — 6

		DEF
1. Roof	6	
2. Floor	6	
3. Walls	6	
4. Headwall	6	
5. Wingwall	N	
6. Pipe	N	
7. Protective Coating	N	
8. Embankment	6	
9. Wearing Surface	N	
10. Railing	N	
11. Sidewalks	N	
12. Utilities	N	
13. Member Alignment	6	
14. Deformation	6	
15. Scour	6	
16. Settlement	6	
17. Corr. Alum. Plate	6	
	N	

UNDERMINING (Y=Yes / N=No) | N

DEFICIENCY REPORTING GUIDE

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CATEGORIES OF DEFICIENCIES: M/P=Minor Deficiency/Prioritize

M= Minor Deficiency - Deficiencies which are minor in nature, generally do not impact the structural integrity of the bridge and could easily be repaired. Examples include but are not limited to: Spalled concrete, Minor scouring, etc.

S= Severe/Major Deficiency - Deficiencies which are more extensive in nature and need more planning and effort to repair. Examples include but are not limited to: Moderate to major deterioration in concrete, Exposed and corroding rebars, Deteriorated timber piles, Considerable settlement, Considerable scouring or undermining, etc.

C-S= Critical-Structural Deficiency - A deficiency in a structural element of a bridge that poses an extreme unsafe condition due to the failure or imminent failure of the element which will affect the structural integrity of the bridge.

C-H= Critical-Hazard Deficiency - A deficiency in a component or element of a bridge that poses an extreme hazard or unsafe condition to the public, but does not impair the structural integrity of the bridge. Examples include but are not limited to: Any part of piles or fender system which are projecting outward and may become a safety hazard for the navigational traffic, etc.

URGENCY OF REPAIR:

I= Immediate - [Inspector(s) immediately contact District Bridge Inspection Engineer (DBIE) to report the Deficiency and to receive further instruction from him/her].

A= As soon as possible - [Action/Repair should be initiated by District Maintenance Engineer or the Responsible Party (if not a State owned bridge) upon receipt of the Inspection Report].

P= Prioritize - [Shall be prioritized by District Maintenance Engineer or the Responsible Party (if not a State owned bridge) and repairs made when funds and/or manpower is available].

X=UNKNOWN **N=NOT APPLICABLE** **H=HIDDEN/INACCESSIBLE** **R=REMOVED**

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				

GENERAL REMARKS

Culvert 2 is orientated in an east to west direction and connects Madaket Ditch / Long Pond and carries Madaket Road in a north to south direction. Culvert 2 is an aluminum box culvert that is 60 feet long from barrel opening to barrel opening and is approximately 16 feet wide at each barrel opening **(see sketch 1).**

Item 61 CHANNEL & CHANNEL PROTECTION

Item 61.2 Embankment Erosion

There is some minor erosion of the embankment adjacent to the eastern headwall and some minor slumping of the river banks.

Item 61.5 Vegetation

The vegetation is composed of marsh type grasses and some reed around the edges of the culvert head walls **(see photos 1 and 2).**

Item 61.7 Aggradation

There is a large amount of deposited shells, silt, and small stone in the culvert. The deposited material is well packed and refusal was found to be 2 inches or less over the full length of the culvert**.** The aggradation starts approximately 15 feet from both barrel openings and continues to increase to the midpoint of the culvert. The sediment buildup is one foot higher at each barrel opening out to a radius of 15 feet from headwalls where the mudline start to drop down (**see sketch 2).**

Item 62 CULVERTS

The Aluminum box culvert is in overall satisfactory condition. At the time of the inspection, the waterline was within 6 to 7 inches of the apex of the culvert**.** The inside of the Aluminum corrugated culvert was covered with 2 inches of marine growth and silt**.** The mudline is hard packed and composed of shells covered by silt and sand with some small stones. The bottom of the box culvert could not be uncovered or located due to the large amount of sediment that has been deposited throughout the culvert. The sediment is noted to be hard packed with 1 to 2 inches of penetration to refusal. Measurements from the mudline to the waterline and from the waterline to the apex of the culvert were taken at 10 foot intervals from the north headwall to the south headwall**.**

Item 62.1 Roof

The roof is constructed out of aluminum corrugated. The water line was approximately 6 to 7 inches below the apex of the culvert. There were no issues noted with the roof.

Item 62.2 Floor

The elevation of the existing floor could not be seen or uncovered due to the large amount of slit, sand, shell, and small stones deposited throughout the full length of the culvert **(see photo 3)**. The sediment build up was well packed and would require shovels to uncover the floor. The existing mudline to top of waterline is 4 feet 2 inches throughout the length of the culvert **(see sketch 2)**.

Item 62.3 Walls
The walls are constructed of a corrugated aluminum. The walls remain in satisfactory condition with moderate to heavy marine growth including mussel shells and silt **(see photo 4).**

Item 62.4 Headwall
The headwall is constructed with corrugated aluminum **(see photos 5 and 6 and sketch 3)**. The headwall has a D-shaped horizontal wale that is located just below the normal waterline or roughly 1 foot below the top of the headwall **(see photo 7)**. The headwalls remain in good condition with only one minor defect noted on eastern headwall at the apex of the culvert were a fastener to pull through and is allowing the fastening ring to deflected **(see photo 8).**

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				

Photo 1, View of the riverbanks east of the culvert.

Photo 2, View of the river west of the culvert.

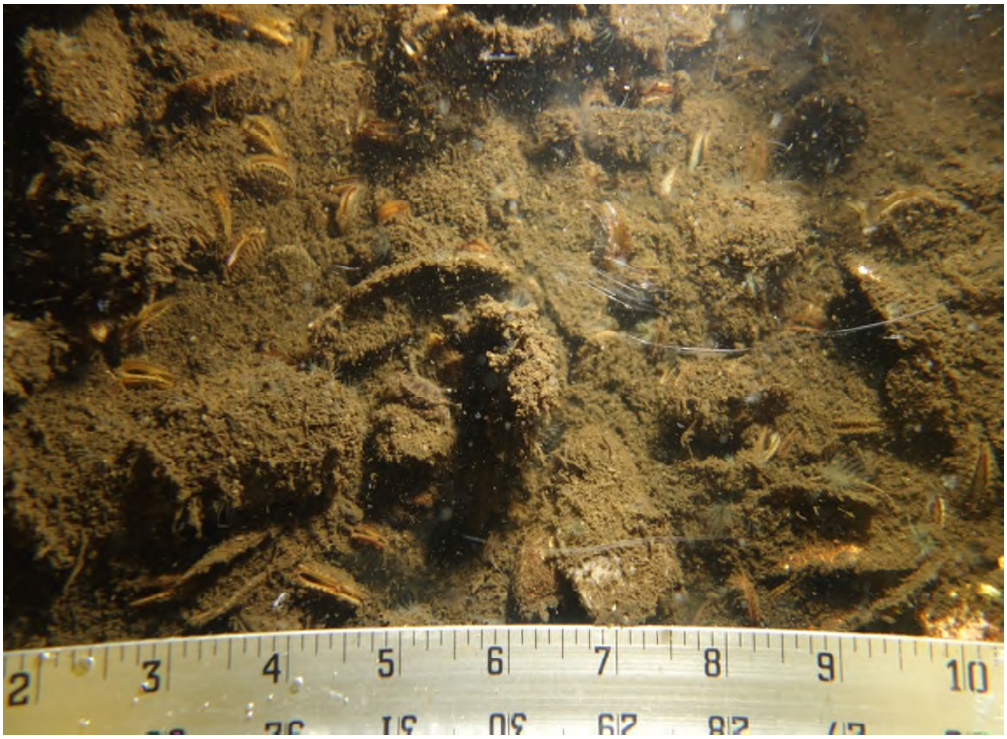


Photo 3, Mudline conditions with heavy build-up of silt, sand, and shells with some stones.

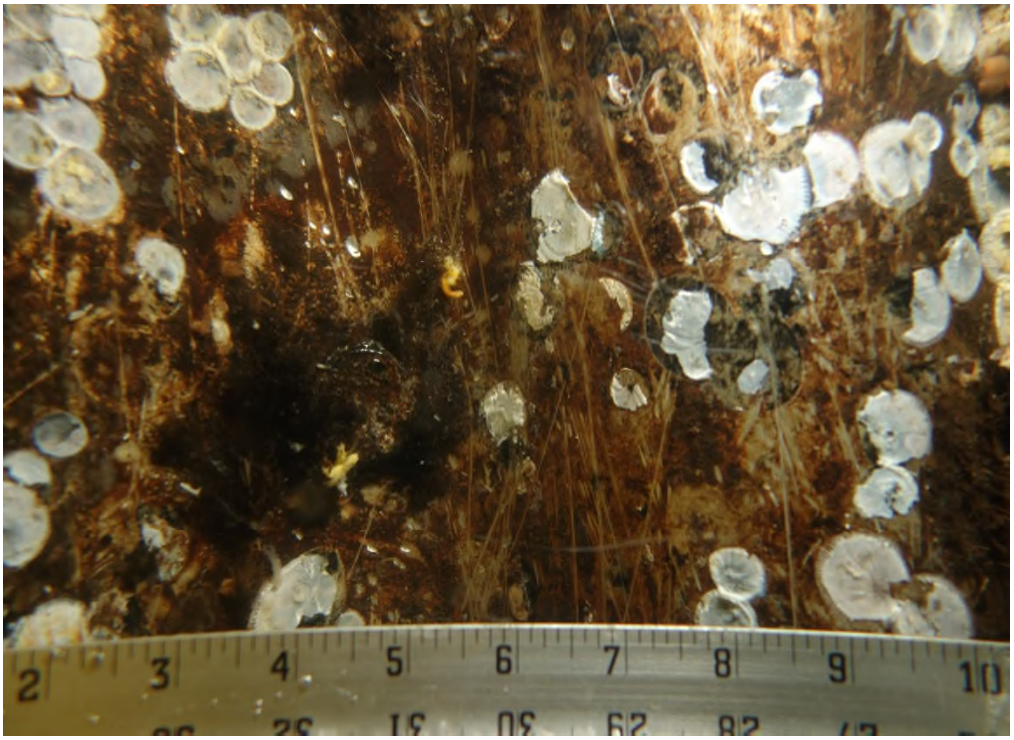


Photo 4, Southeast wall, below water cleaning at station 0+10.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				

Photo 5, East headwall, with normal waterline within 6 inches of apex of culvert.

Photo 6, West headwall, with normal waterline within 6 inches of apex of culvert.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				

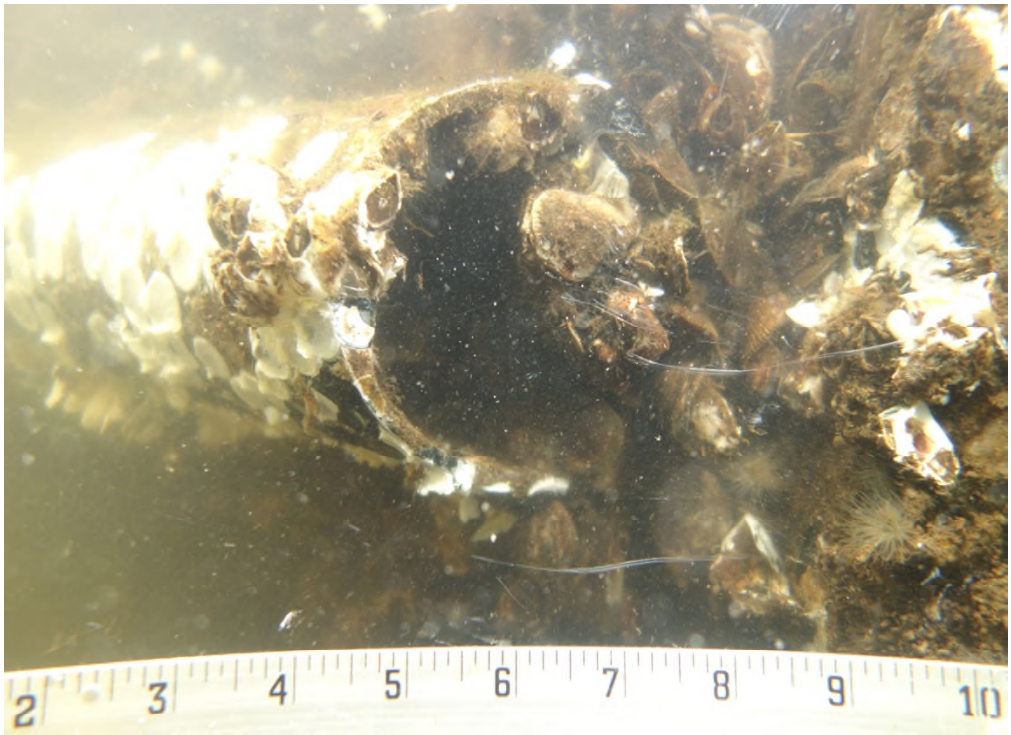
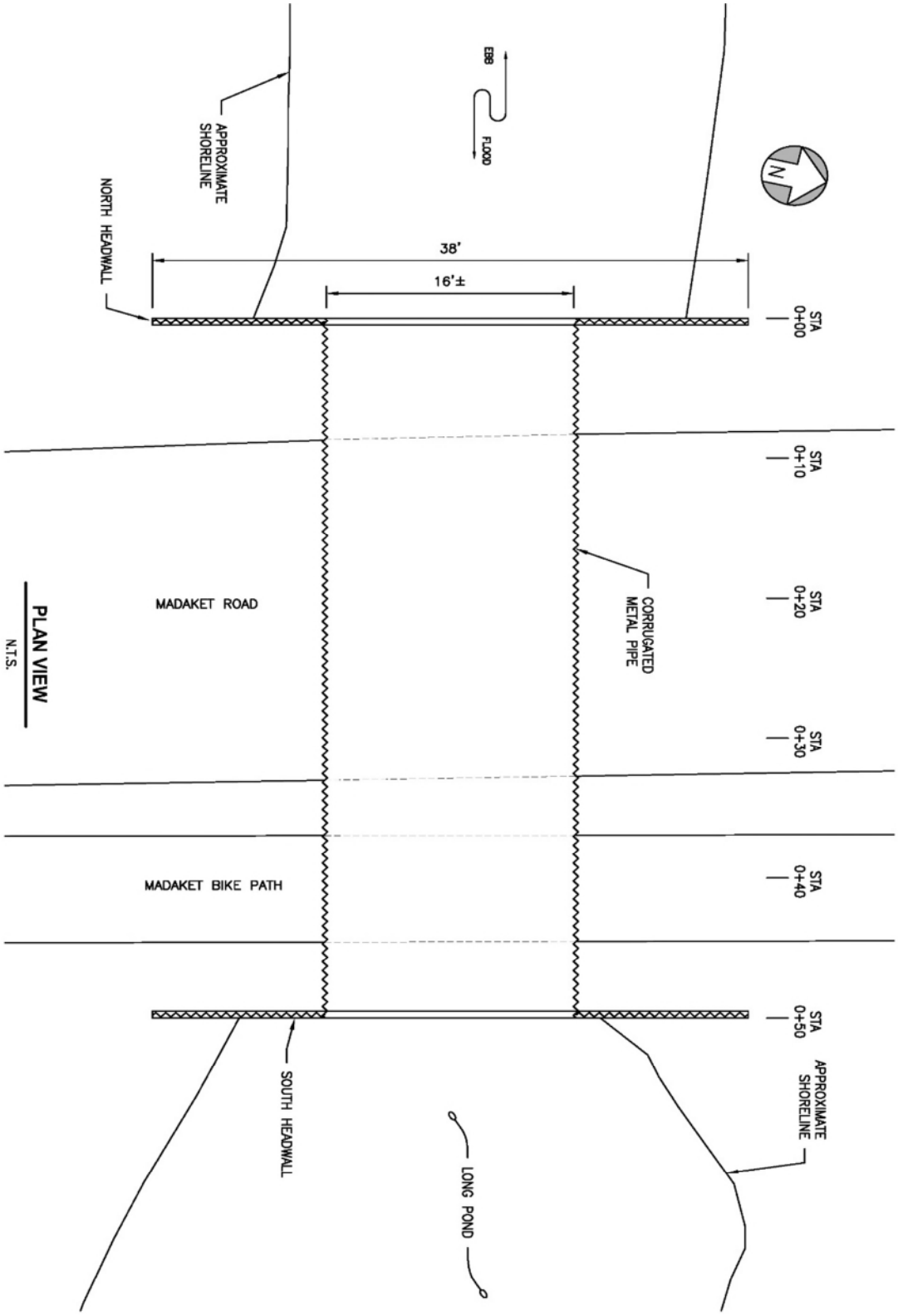


Photo 7, Headwall d- shaped horizontal wale.

Photo 8, Eastern headwall with bolt that pulled through allowing stiffener ring to deflect.

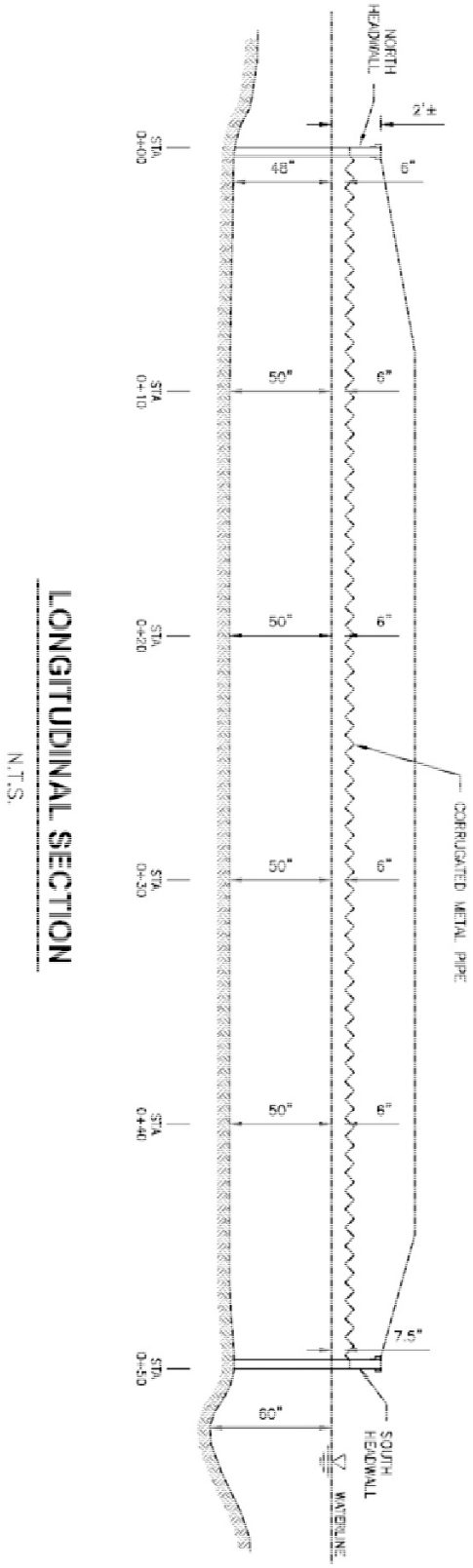
City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				

Sketch 1



Sketch 2

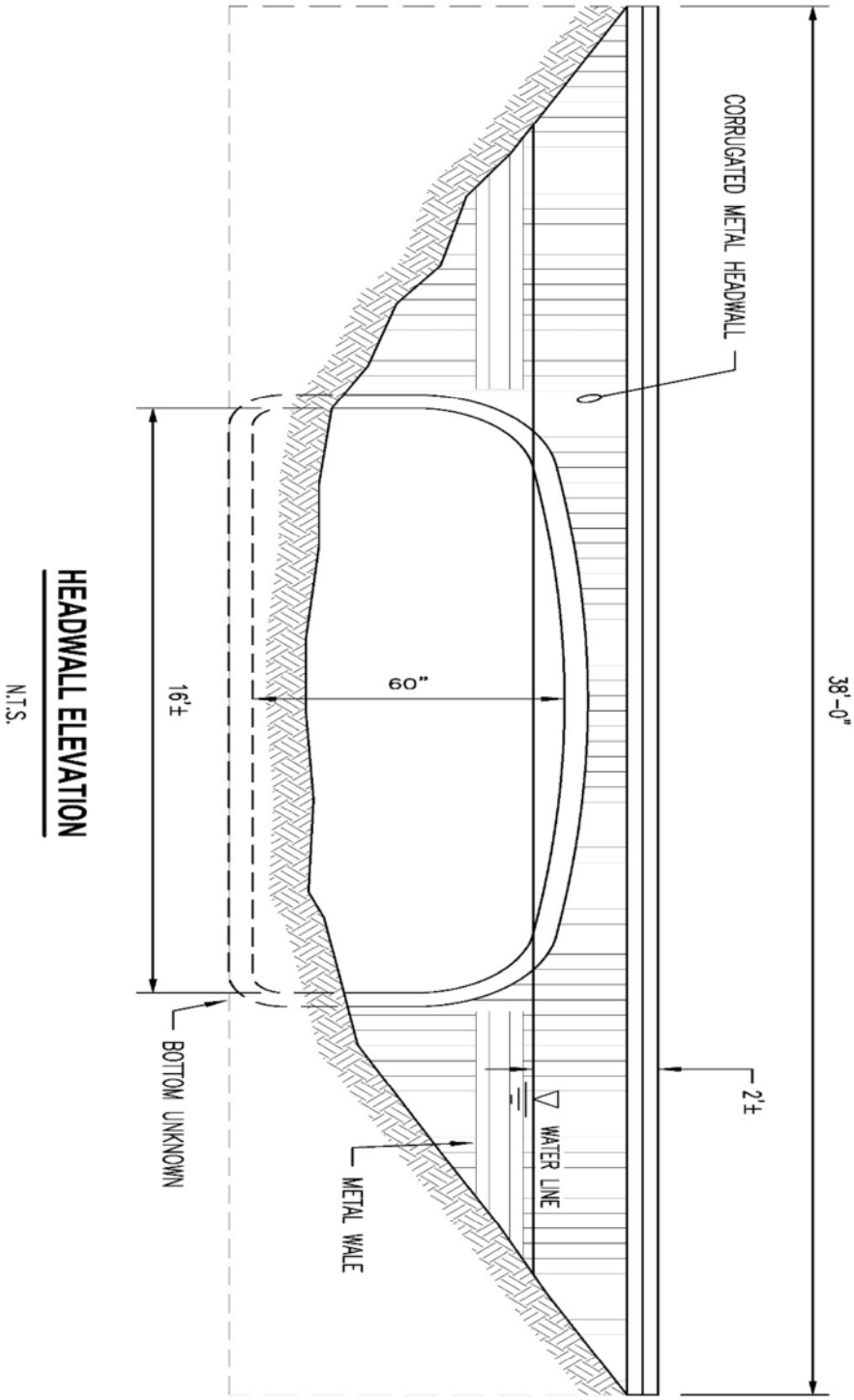
City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				



Sketch 2

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET		N-02-005	Culvert 2	9-17-2018
Remarks & Photos				

Sketch 3



MASSACHUSETTS DEPARTMENT OF TRANSPORTATION

UNDERWATER OPERATIONS TEAM
DIVERS ACTIVITY REPORT

2-DIST	B.I.N.	BR. DEPT. NO.
05	9K7	N-02-006

4-CITY/TOWN	8-STRUCTURE NO.	LEVEL OF INSP.	93b-INSPECTION DATE
NANTUCKET	Culvert 3	II	9-17-18

7-FACILITY CARRIED	ACCESS TO BRIDGE	UNDERWATER OPERATIONS ENGINEER
NORTH CAMBRIDGE STREET	EMBANKMENT	Charlie Roberts

06-FEATURES INTERSECTED	DEPTH	VISIBILITY	TEAM LEADER (DIVE MASTER)	*Report submitted by:*
MADAKET DITCH	4	0	Philip Iantosca	CHILDS ENGINEERING

BOTTOM CONDITION	CURRENT	TEAM MEMBERS
SILT& SHELLS	TIDAL	Charlie Roberts, Philip Iantosca, Ryan Cavanaugh

ITEM 60 (Underwater) *SUBSTRUCTURE* — N

		DEF
1. Abutments		
a. Pedestals		
b. Bridge Seats		
c. Backwalls		
d. Breastwalls		
e. Wingwalls		
f. Slope Paving/Rip-Rap		
g. Pointing		
h. Footings		
i. Piles		
j. Scour		
k. Settlement		
l.		
2. Piers or Bents		
a. Pedestals		
b. Caps		
c. Columns		
d. Stems/Webs/Pierwalls		
e. Pointing		
f. Footing		
g. Piles		
h. Scour		
i. Settlement		
j.		
k.		
3. Pile Bents		
a. Pile Caps		
b. Piles		
c. Diagonal Bracing		
d. Horizontal Bracing		
e. Fasteners		

UNDERMINING (Y=Yes / N=No) | |

ITEM 61 *CHANNEL & CHANNEL PROTECTION* — 6

		DEF
1. Channel Scour	6	
2. Embankment Erosion	6	
3. Drift	7	
4. Vegetation	7	
5. Utilities	N	
6. Rip-Rap/Slope Protection	N	
7. Aggradation	6	
8. Fender System	N	
a. Piles		
b. Diagonal Bracing		
c. Horizontal Bracing		
d. Wales		
e. Fasteners		
f. Ladders		

ITEM 59 *SUPERSTRUCTURE* (If any part done by divers.)

ITEM 62 *CULVERTS* — 6

		DEF
1. Roof	N	
2. Floor	N	
3. Walls	N	
4. Headwall	N	
5. Wingwall	N	
6. Pipe	5	
7. Protective Coating	4	
8. Embankment	6	
9. Wearing Surface	N	
10. Railing	N	
11. Sidewalks	N	
12. Utilities	N	
13. Member Alignment	7	
14. Deformation	7	
15. Scour	6	
16. Settlement	7	
	N	

UNDERMINING (Y=Yes / N=No) | N

DEFICIENCY REPORTING GUIDE

DEFICIENCY: A defect in a structure that requires corrective action.

CATEGORIES OF DEFICIENCIES: M/P=Minor Deficiency/Prioritize

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City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

GENERAL REMARKS

Culvert 3 is a multiplate steel corrugated culvert oriented in an east to west direction over Madaket Ditch, which connects Long Pond to Hither Creek Harbor. The culvert carries North Cambridge Street that runs in a north to south direction. The culvert is approximately 50 feet long and has a tapered barrel opening on the east and west ends. The culvert was stationed from the east to the west end.

Item 61 CHANNEL & CHANNEL PROTECTION

Item 61.2 Embankment Erosion

There is 2 to 4 feet area of erosion adjacent to the west and east barrel openings.

Item 61.5 Vegetation 7

The river banks are well vegetated. The vegetation is composed of marsh type grasses and reed around the edges of the culvert **(see photos 1 and 2).**

Item 61.7 Aggradation

There is 8 to 12 inches of built-up of loose sand and sediment along the full length of the culvert.

Item 62 CULVERTS

Item 62.6 Pipe

The Culvert is in overall satisfactory condition. There is a 3 foot band located 2 to 5 feet above the floor of the culvert and runs the full length of both walls that has minor to moderate corrosion. The wall corrosion and scale increase at each barrel opening were the walls are noted to have thick corrosion, heavy scale, and corrosion holes **(see photos 3 to 6).** Below the 2 feet waterline the corrugated steel plates are covered with light marine growth with some light corrosion and pitting **(see photo 7).** The mudline is composed of loose sand and silt sediment with some shells **(see photo 8).** Measurements were taken from the west end station 0+00 to the east end 0+60 along the inside of the culvert. The measurements were from the bottom of culvert to the waterline and from the waterline to the top of the inside of the culvert (see sketch 1 and scour chart).

Item 62.7 Protective Coating

The protective coating is in poor condition with only small areas of localized coating remaining **(see photo 9).** The barrel openings have heavy scale and corrosion and in the areas of the cleanings the steel was noted to be thin.

Item 62.8 Embankment

The embankments have some minor slump along the water edge but remain stable at this time.

Item 62.13 Member Alignment
There were no issues with the alignment. Measurements were taken from the top of water to the inside apex of the culvert which did not differ more than 2 inches over 60 feet.

Item 62.14 Deformation
There is no deformation of the corrugated walls, ceiling or floor on the culvert.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

Photo 1, Western (downstream) end of culvert with well vegetated banks.

Photo 2, Eastern (upstream) end of culvert with well vegetated banks.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

Photo 3, Eastern opening, with 3 foot heavy corrosion band from the normal water line down.

Photo 4, Eastern opening, northeast wall exhibits thick corrosion with heavy section loss to the wall material. Only minor areas of coating still remain.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

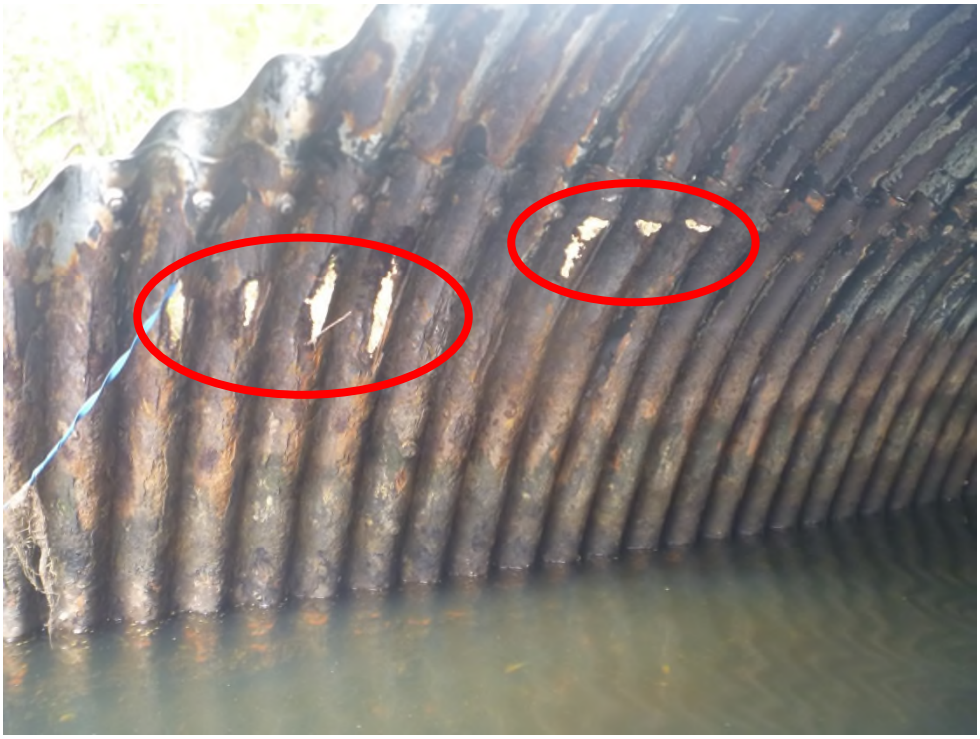


Photo 5, West barrel opening, northwest wall with heavy scale and corrosion holes.

Photo 6, West opening, southwest wall with heavy section loss and corrosion holes below the waterline.

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

Photo 7, Eastern opening, below water view of the southeast wall with corrosion, scale and pitting, 1 foot below the waterline.

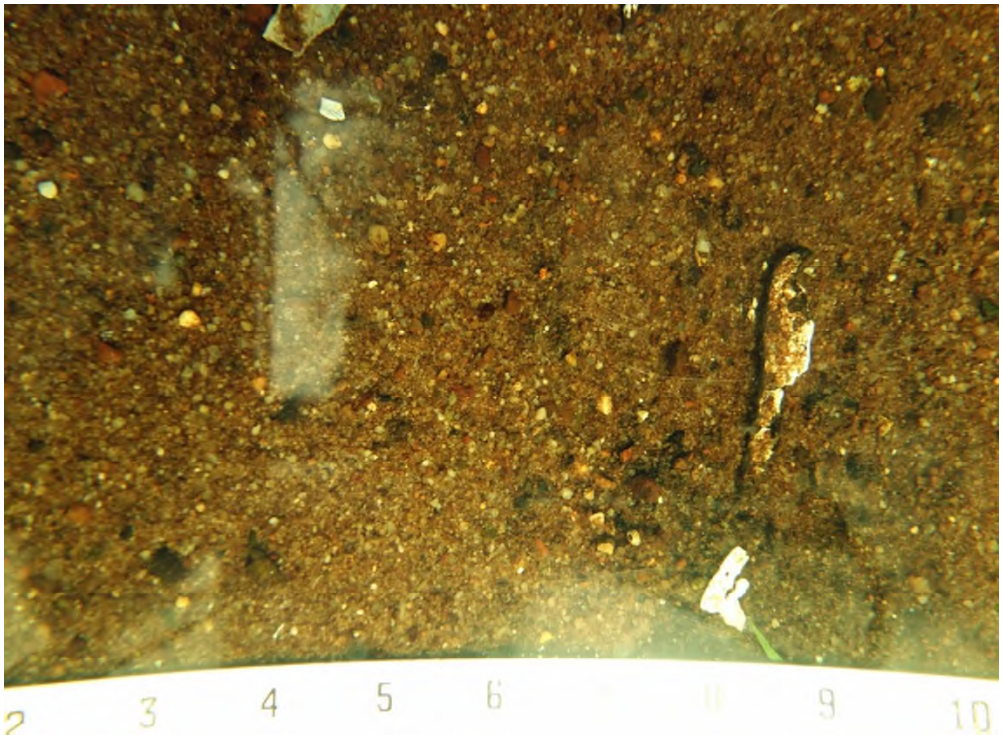


Photo 8, Mudline composed of loose sand with some shells.

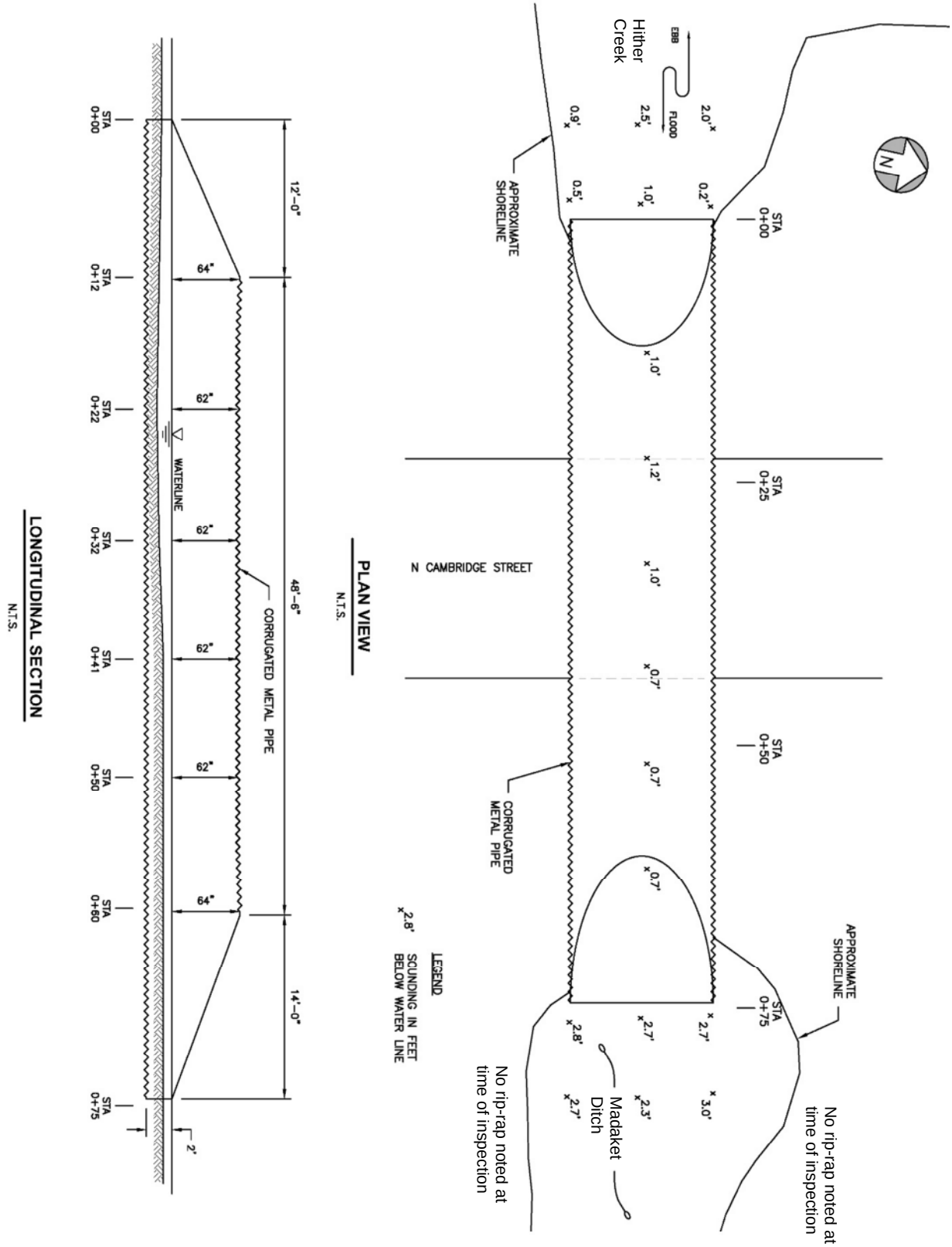
City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

Photo 9, Station 30 looking west at north wall, with localized areas of coating and corrosion from the normal waterline.

Culvert #3 Scour Chart			
Station starts at west end	Sediment build-up	bottom of culvert to waterline	Waterline to apex of culvert
0+00	12	30	
0+12	12	30	64
0+22	14	30	62
0+32	12	30	62
0+41	8	30	62
0+50	8	30	62
0+60	8	30	64
0+75	32	30	

City/Town	B.I.N.	Br. Dept. No.	8 – Structure No.	90 – Inspection Date
NANTUCKET	9K7	N-02-006	Culvert 3	9-17-2018
Remarks & Photos				

Sketch 1



Appendix B

Hydrologic and Hydraulic Assessment Technical Memorandum

MEMORANDUM

DATE March 20, 2019

TO Erik Mas, PE
Fuss & O'Neill, Inc.
1550 Main Street, Suite 400
Springfield, MA 01103

FROM Arden Herrin, Matt Shultz, PE
Woods Hole Group
107 Waterhouse Road
Bourne, MA 02532
Direct Phone: (508) 495-6271

Madaket Harbor, Hither Creek, and Long Pond, Nantucket, MA– Hydrologic & Hydraulic Assessment of the Madaket Estuarine System

1. Introduction

The Madaket-Long Pond estuary is a complex, tidally influenced system located on the western side of Nantucket Island. Tides from Nantucket Sound propagate from Madaket Harbor into Hither Creek up though a series of culverts and channels before reaching Long Pond and terminating at the North Head of Long Pond. Woods Hole Group conducted a Hydrologic and Hydraulic (H&H) assessment of the system in support of Fuss & O'Neill and the Town of Nantucket's efforts to: 1) improve water quality in Long Pond by reducing its residence time through increased tidal exchange between the harbor and Long Pond; and 2) ensure the existing culverts are sufficiently sized to achieve maximum drainage from the upstream reaches of Long Pond. Increased tidal exchange and drainage in the Madaket-Long Pond estuary would likely help to improve water quality, mitigating the effects of nitrogen loading in the system and restoring the system to a more natural state. Previous studies (2010 Massachusetts Estuary Project) identified the culverts as being tidally restrictive. Our assessment was conducted to determine the optimal culvert sizing and inverts that will allow for increased tidal flushing and facilitate drainage while limiting any adverse flooding impacts.

This memorandum is divided into the following sections:

2. Field Data Measurements of Existing Conditions,
3. Estuarine Culvert Model Development of Existing Conditions,
4. Alternative Evaluation and Effects on the Madaket-Long Pond Estuary,
5. Summary of Findings and Recommendations.

2. Field Data Measurements of Existing Conditions

In support of this assessment, Woods Hole Group deployed a system of five (5) AquaTroll data loggers to continuously measure temperature, salinity, and water level at key locations throughout the Madaket-Long Pond estuarine system. The AquaTrolls collected data from October 24, 2018 through November 28, 2018 and were deployed at the locations shown in Figure 1. The instrument designated MH1 was deployed at the F Street boat dock. The instrument designated as MH2 was deployed on the upstream side of the N. Cambridge Street culvert which connects Hither Creek to Madaket Ditch. Instruments MH3 and MH4 were deployed on the downstream and upstream sides of the Madaket Road culvert connecting Madaket Ditch to Long Pond, respectively. Instrument MH5 was deployed on the upstream side of the Madaket Road culvert connecting Long Pond to North Head Long Pond.

In addition, Woods Hole Group collected updated bathymetry data throughout the entire Madaket-Long Pond Estuarine system. The survey was performed using a 200-kHz survey-grade single-beam echosounder, Real Time Kinematic Global Positioning System (RTK GPS) navigation, HYPACK data acquisition software, and a surveyed water level gauge to establish reference to the NAVD88 vertical datum. All survey data were post-processed for QA/QC, to remove any influences of tides or varying water levels during the survey. This data is further detailed in section 3.

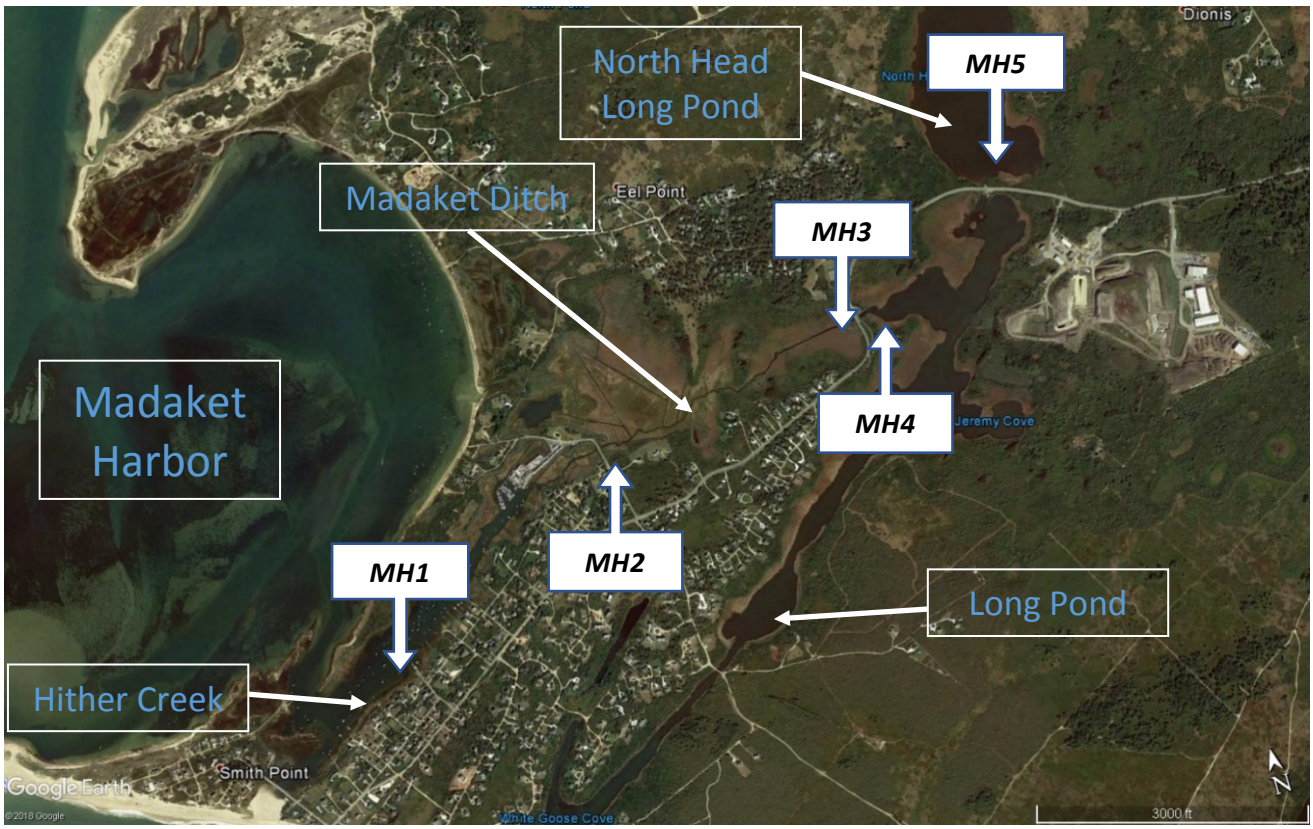


Figure 1. Locus map of the Madaket-Long Pond estuarine system. Arrows indicate the different reaches of the system and approximate locations of the AquaTROLL data loggers deployed in support of this study.

2.1 Water Levels in Madaket Estuarine System

The measured water levels in the estuarine system from the 38-day deployment period (October 24 to November 28, 2018) are shown in Figure 2. The upper panel of the figure compares time series of water levels in Hither Creek (MH1), Madaket Ditch lower (MH2), and Madaket Ditch upper (MH3), while the lower panel compares water levels between Madaket Ditch upper (MH3), Long Pond (MH4), and North Head Long Pond (MH5). The water levels in the upper panel indicate there is minimal tidal attenuation between Hither Creek (red line) and Madaket Ditch lower (blue line), however tides are significantly dampened between Madaket Ditch lower and Madaket Ditch upper (green line). Conversely, in the lower panel, the water levels at Madaket Ditch upper (green), Long Pond (cyan), and North Head Long Pond (black dotted line) exhibit minimal differences between the three observation stations in the upper section of the system.

The minimal tidal attenuation between Hither Creek and Madaket Ditch lower indicates the culvert at N. Cambridge Street is currently not restricting tidal flow. Instead, the large reduction in tidal range between Madaket Ditch lower and Madaket Ditch upper indicates that the largest contributor inhibiting tidal exchange and drainage from the upper ponds is the channel within the Madaket Ditch reach.

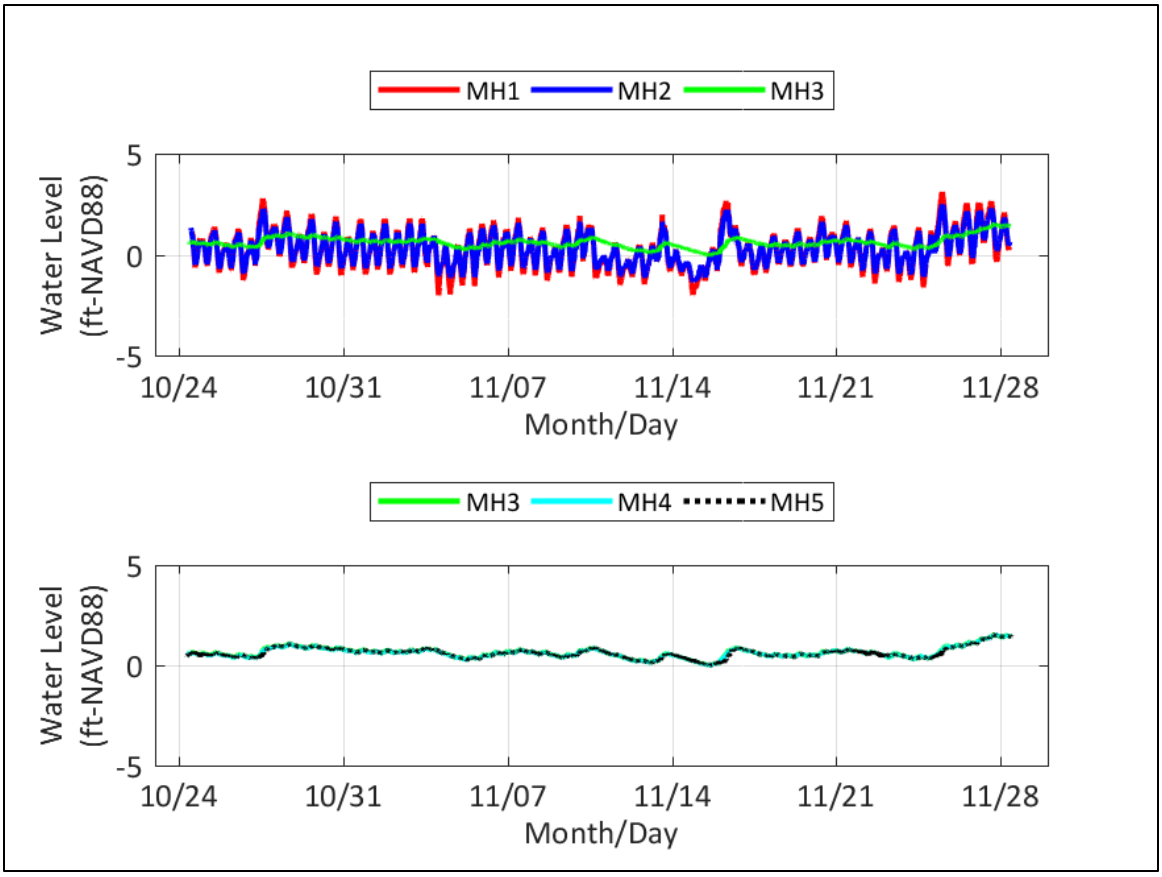


Figure 2. Observed water levels in the Madaket-Long Pond estuary from October 24, 2018 through November 28, 2018.

2.2 Salinity in the Madaket Estuarine System

Time series of measured salinity in the Madaket-Long Pond estuary are shown in Figure 3. The measured salinity in the harbor is shown in the upper panel as a red line along with the Madaket Ditch lower and Madaket Ditch time series as blue and green lines respectively. The lower panel of the figure shows a comparison of the salinity in Madaket Ditch upper (green), Long Pond (cyan), and North Head Long Pond (dotted black line). Salinity in Hither Creek (MH1) is consistently higher than salinities in the upper reaches of the system. Typically, during flood tides, the salinity in Madaket Ditch (MH2 and MH3) increases, and the salinity decreases during ebb tides, likely as freshwater from the upstream reaches and from groundwater inflow provide a higher degree of influence. In the lower panel, the salinities observed on both sides of the Madaket Road culvert separating Madaket Ditch (MH3), and Long Pond (MH4) are very similar. In the uppermost reach of the system at the North Head of Long Pond (MH5), the influence of higher salinity inflows from the harbor are generally negligible with minor fluctuations in salinity corresponding with higher spring or storm-driven tides.

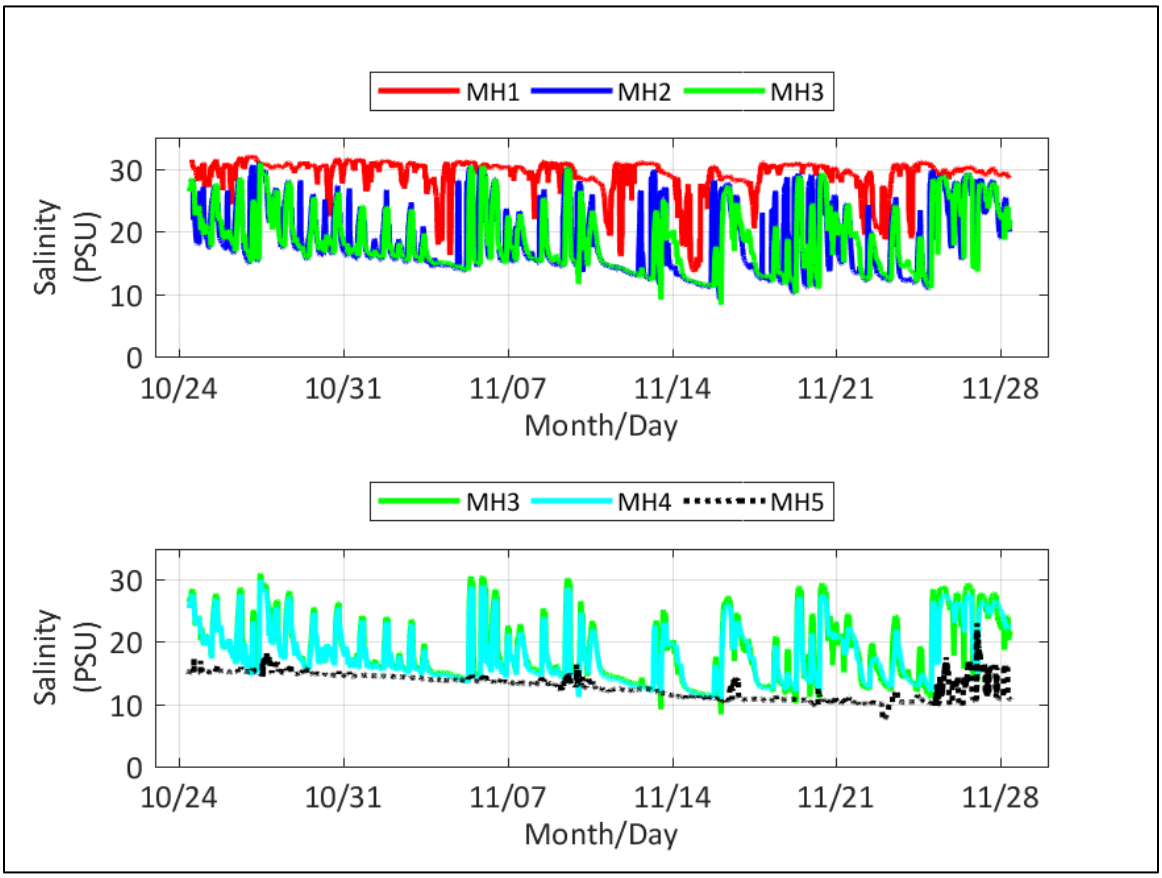


Figure 3. Observed salinities in the Madaket-Long Pond estuary from October 24, 2018 through November 28, 2018.

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T: +1 508.540.8080 **F**: +1 508.540.1001

3. Estuarine Culvert Model Development of Existing Conditions

The Madaket-Long Pond system was evaluated using the Estuarine Culvert Model (ECM) to simulate tidal flows originating at Madaket Harbor, propagating through the Hither Creek/Madaket Ditch channel, and into the Long Pond system. In addition to simulating typical tides, Woods Hole Group also applied the Madaket ECM to assess the effects of the 1%-annual-chance (100-year) surge and rainfall events on the Madaket estuarine system. The Madaket ECM uses the topography and bathymetry of the individual reaches that comprise the system, the geometry of the structures connecting each of the basins, together with the tidal boundary conditions at Madaket Harbor to simulate water levels throughout the estuary. The model is based on conservation of mass principles in propagating water fluxes through flow-control structures into basins described by their hypsometry (the relationship between the elevation and the surface area). Hypsometric analysis describes the elevation distribution across an area of land surface. It is an important tool to evaluate areas flooded and volumes of water with respect to specific water levels. The ECM is a proprietary model developed by Woods Hole Group.

The technical approach utilized by the ECM hypsometric model involves a simple procedure for calculating the tidal response in a marsh connected to the ocean by a fully or partially full opening. The assumptions are that the sea level in the marsh is independent of position, and that the flow through the culvert is described by a standard hydraulic head-loss relationship, depending on the type of flow control structure and depth of flow. Given the assumption of a horizontal sea surface within the marsh, the conservation-of-mass equation for the water in the marsh is

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

$$Q_{culvert} = -au \quad (2)$$

where t is time; h_{marsh} (t) is the time-varying elevation of the water level in the marsh (NAVD88 feet); A is the surface area of the marsh, which 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). Q_{gw} and Q_{rain} are volumetric flow rates into the marsh resulting from groundwater input and surface water runoff, respectively. For circular pipe culverts, it is straightforward to calculate the relevant geometric parameters required to determine the velocity (cross-sectional area a, the wetted perimeter P, and hydraulic diameter $d_h = 4a/P$).

The quadratic head-loss relationship for the flow through a circular pipe culvert(s) is:

$$h_{marsh} - h_{ocean} = \left(K_{entrance} + K_{exit} + \frac{fl}{d_h}\right)\frac{u|u|}{2g} \quad (3)$$

where g is the acceleration due to gravity, entrance K and exit K are the dimensionless head-loss coefficients for the entrance and exit to the culvert, respectively, *l* is the length of the culvert, d_h is the hydraulic diameter, and f is the empirical Darcy-Weisbach friction factor. The solution of (3) for the velocity u is

$$u = 2g\left(\frac{|h_{marsh} - h_{ocean}|}{K_{entrance} + K_{exit} + \frac{fL}{d_h}}\right)^{1/2} \frac{(h_{marsh} - h_{ocean})}{|h_{marsh} - h_{ocean}|} \qquad (4)$$

The friction factor, f varies depending on roughness and flow velocity in the pipe and is calculated iteratively using the Manning's n equation. The above equations are solved in time by means of standard first-order finite difference approach. Results of the computations include the water level time series in the marsh, time dependent water surface area in the marsh, and discharge volume through the culvert.

To account for potential overtopping of channel banks that separate the Madaket Ditch basins in the model, an additional overtopping flow can be specified in the model once a certain water elevation is reached. This flow is incorporated into the model using the broad crested weir equation (Equations 5 and 6).

$$Q_{weir} = CLH^{\frac{3}{2}} \quad (5)$$

$$C = \frac{2^{\frac{3}{2}}}{3} g^{\frac{1}{2}} \qquad (6)$$

Where Q_{weir} is the flow over the barrier, L is the length of the road section over which water is flowing, H is the head difference between the water and the road, and g is the force of gravity.

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3.1. Model Configuration

The Madaket ECM was developed using tides measured in Hither Creek as a boundary, or forcing condition for four (4) interconnected basins, as shown in Figure 4. Hither Creek is directly connected to Madaket Ditch lower via the corrugated metal culvert under N. Cambridge Street. The Madaket Ditch lower basin is connected to Madaket Ditch upper via an earthen channel. Madaket Ditch upper is connected with Long Pond via the second of two culverts under Madaket Road. North Head Long Pond is connected to Long Pond by the first culvert under Madaket Road.

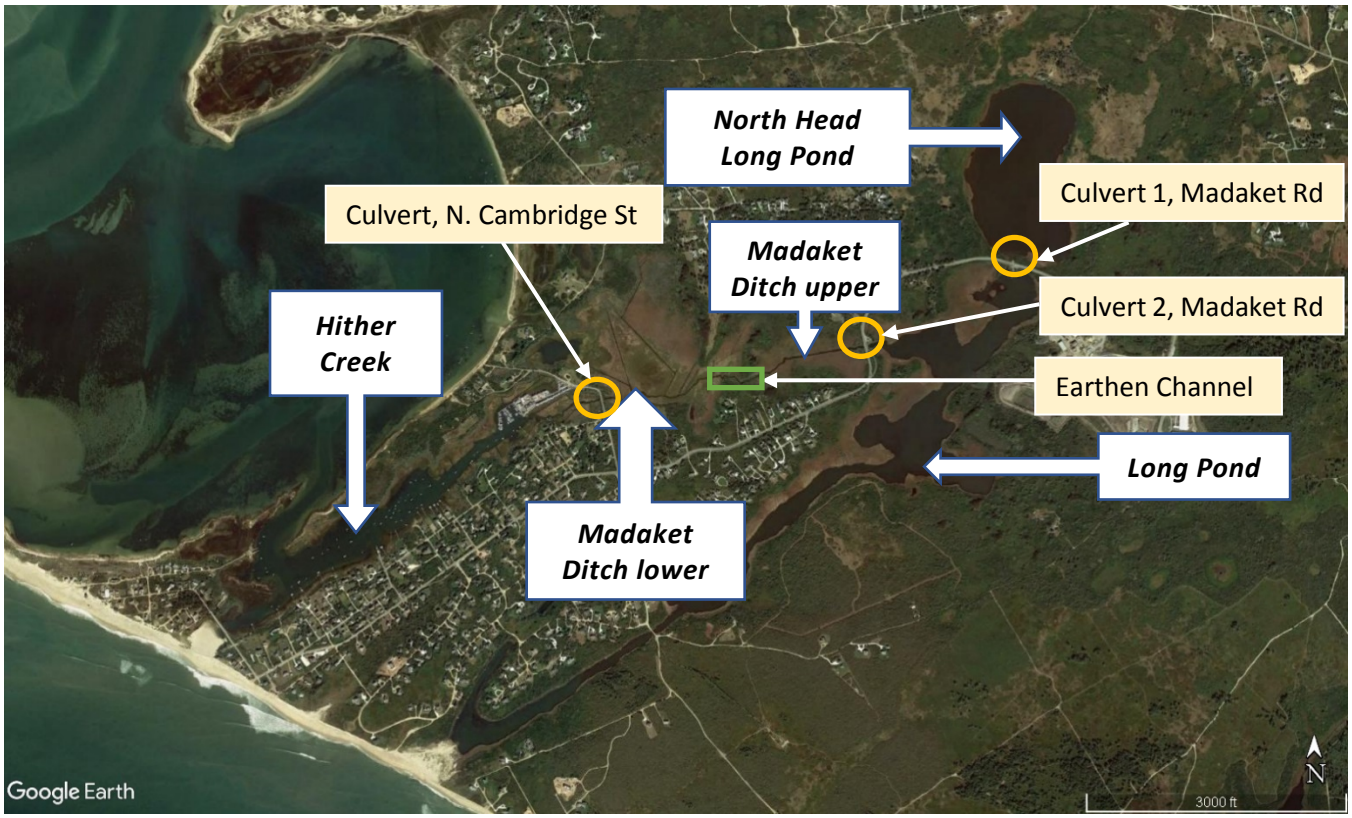

Figure 4. Aerial view of the Madaket-Long Pond estuarine system showing Hither Creek where the tidal boundary was specified, the flow-control structures, and each of the four (4) upstream basins used in the Madaket ECM.

3.1.1. Topography/Bathymetry

The Madaket estuary was subdivided into the 4 (four) marsh basins shown in Figure 4. The basin elevations were derived from the 2016 NOAA topobathy LiDAR for Nantucket and Martha's Vineyard supplemented with Real Time Kinematic (RTK) bathymetry survey data collected by Woods Hole Group in support of this study. The LiDAR dataset (Figure 5) was used to primarily inform the topography outside of the channels and ponds within the yellow square. The bathymetry survey data collected by Woods Hole Group (Figure 6) were combined with the LiDAR, and the combined elevations were used to develop hypsometric curves for each of the basins.

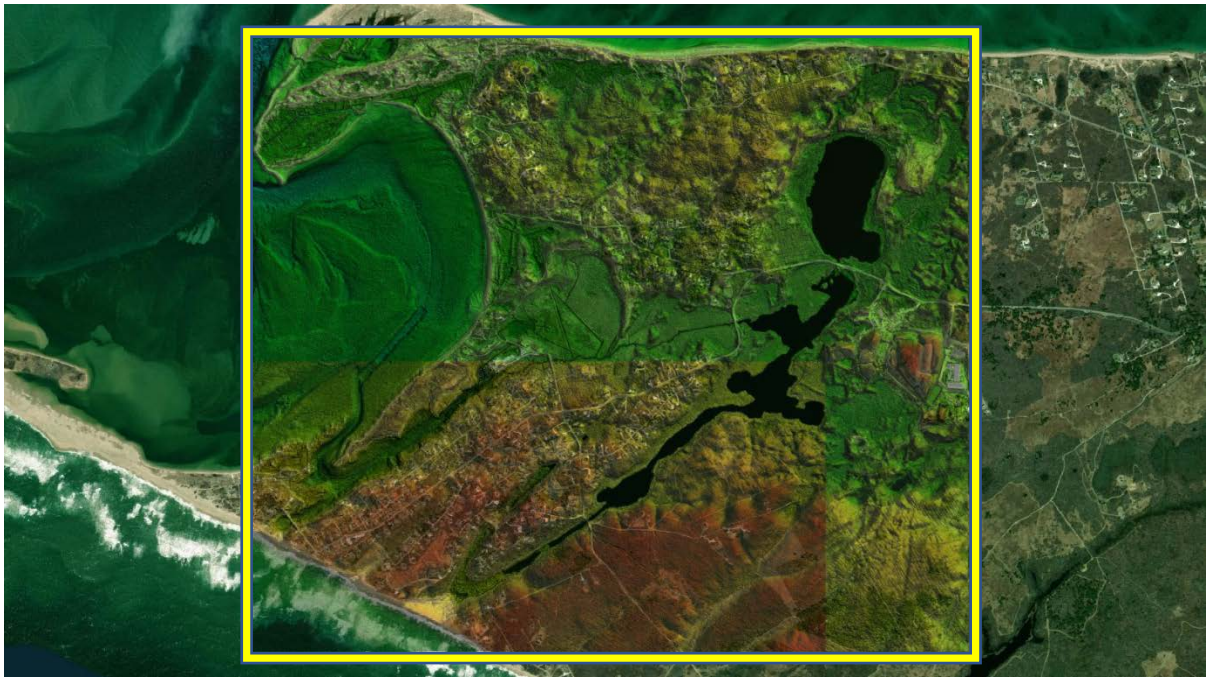

Figure 5. Aerial showing the extents of the NOAA LiDAR dataset coverage used in developing the basin hypsometry for the Madaket ECM. LiDAR is shown as colored contours within the yellow box overlaying the aerial image.

Figure 6. Aerial showing the extents of RTK bathymetry survey data collected in Autumn 2018. The RTK survey data is shown as colored survey points reflecting the measured elevations.

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The combined elevation datasets for the Madaket ECM were used to generate a computational grid framework for each separate basin. Figure 7 shows the contours of elevation used to define the first basin, designated as Madaket Ditch lower in this study. The northern extent of the basin was defined by Blue Heron Way. Similarly, N. Cambridge Street and Madaket Road were used to define the western and southern extents of the Madaket Ditch lower basin. The hummock approximately halfway between N. Cambridge St. and Madaket Road was used as the eastern extent of the Madaket Ditch lower basin. The hypsometric curve defining the relationship between the elevation and the surface area is shown as an inset on Figure 7. The Madaket Ditch lower basin covers 92.5 acres, of which approximately 55 acres are between 1 ft-NAVD88 and 3 ft-NAVD88.

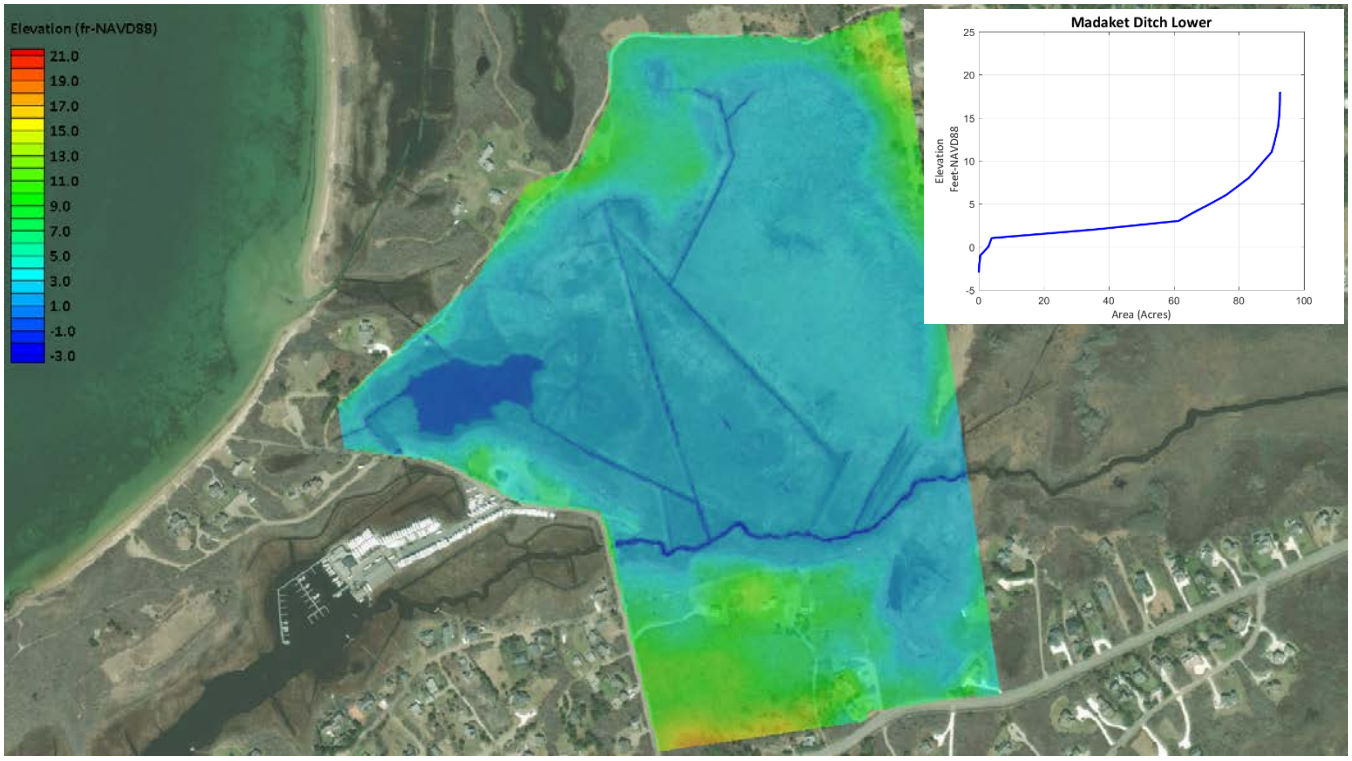

Figure 7. Computational grid of the Madaket Ditch lower basin using the combined LiDAR and RTK data. Inset shows the hypsometric curve for the basin.

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Figure 8 shows the elevation contours for the Madaket Ditch upper basin with the hypsometric curve shown as an inset. The hummock located at approximately the midpoint of Madaket Ditch was used as the western extent of the upper basin. The northern extent of this basin was delineated using higher elevations just north of Warrens Landing Road, while Madaket Road delineated the eastern and southern extents of the Madaket Ditch upper basin. In total, the Madaket Ditch upper basin covers approximately 83 acres, of which approximately 28 acres are at an elevation of 3 ft-NAVD88 or lower.

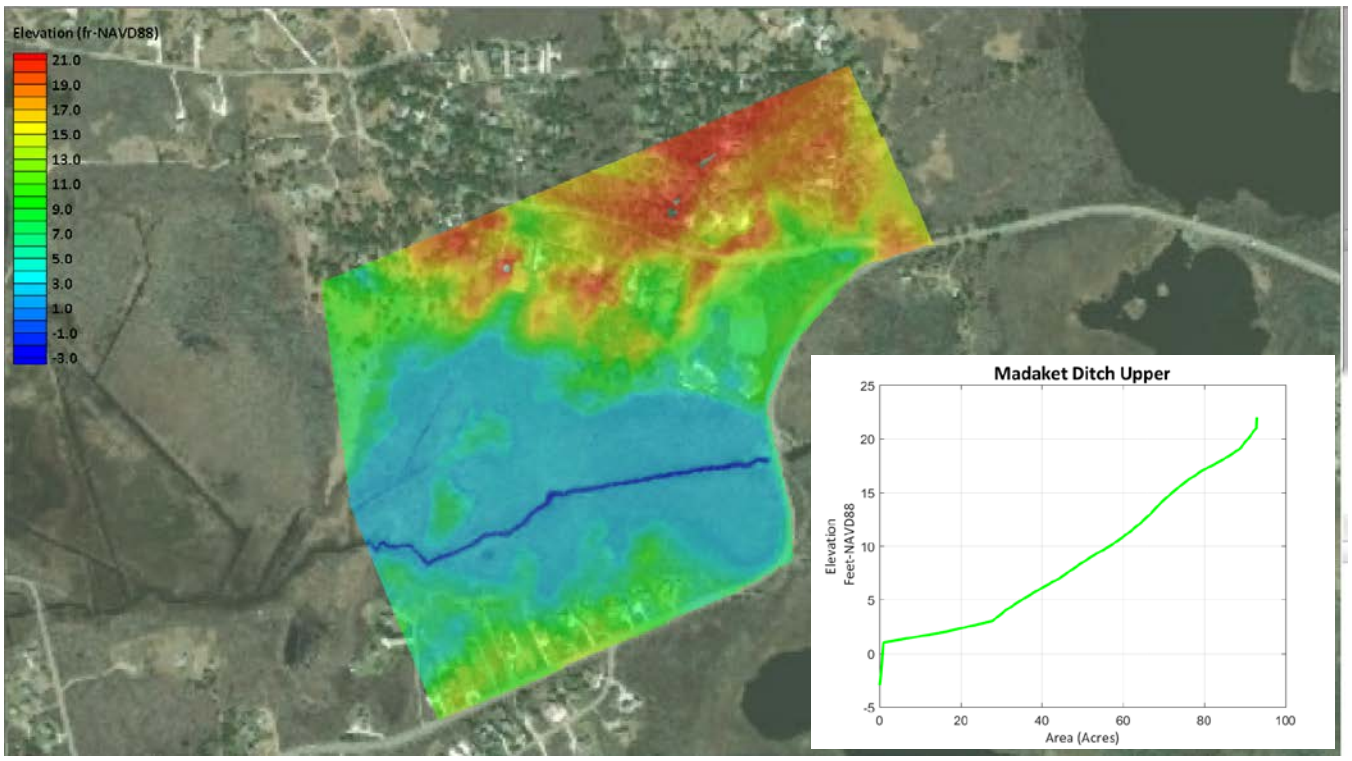

Figure 8 Computational grid of the Madaket Ditch upper basin using the combined LiDAR and RTK data. Inset shows the hypsometric curve for the basin.

Figure 9 shows elevations used to define the hypsometry for the Long Pond basin in the Madaket ECM. Color contoured elevations are shown with the hypsometric curve line shown as an inset on the Figure. Of the basins, Long Pond comprises the largest total area (375 acres). The basin is separated from Madaket Ditch and North Head Long Pond basins to the east and west by Madaket Road, while the upland areas of higher elevation defined the eastern extent of the basin. Of the 375 acres comprising the Long Pond basin, 70.2 acres are at or below 1 ft-NAVD88 and comprise the surface area of the pond during most observed tidal conditions.

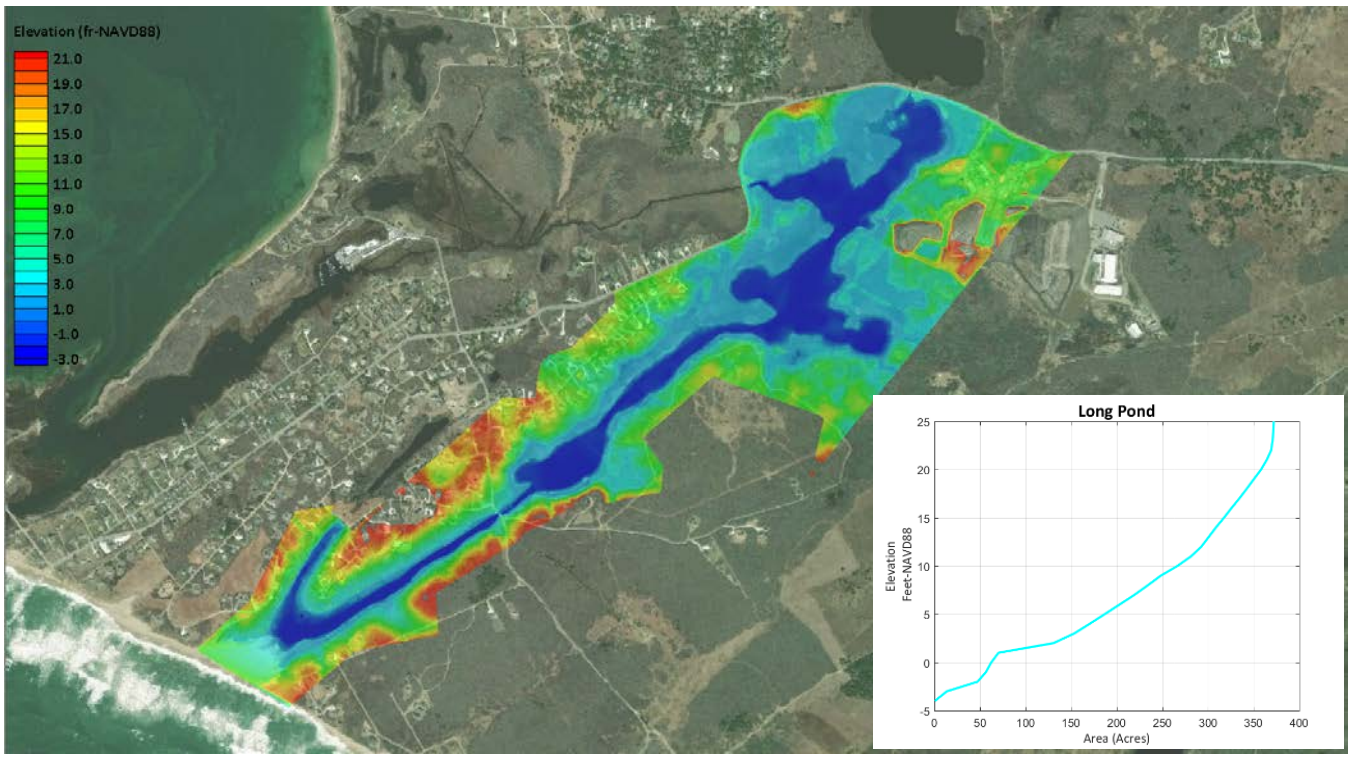

Figure 9. Computational grid of the Long Pond basin using the combined LiDAR and RTK data. Inset shows the hypsometric curve for the basin.

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The final basin, North Head Long Pond, represents the upstream terminus of tidally influenced flows in the system. The elevation data used to define the North Head basin are shown as contours in Figure 10. The hypsometric curve for the North Head basin is shown as the dotted line on the inset panel in Figure 10. The North Head basin is separated from the Long Pond to the south by Madaket Road, while the higher elevations surrounding the pond define the extent in the other directions. The North Head Long Pond basin consists of 181.9 acres, of which 45 acres are at or below 1 ft-NAVD88 and define the surface of the pond under normal tidal conditions.

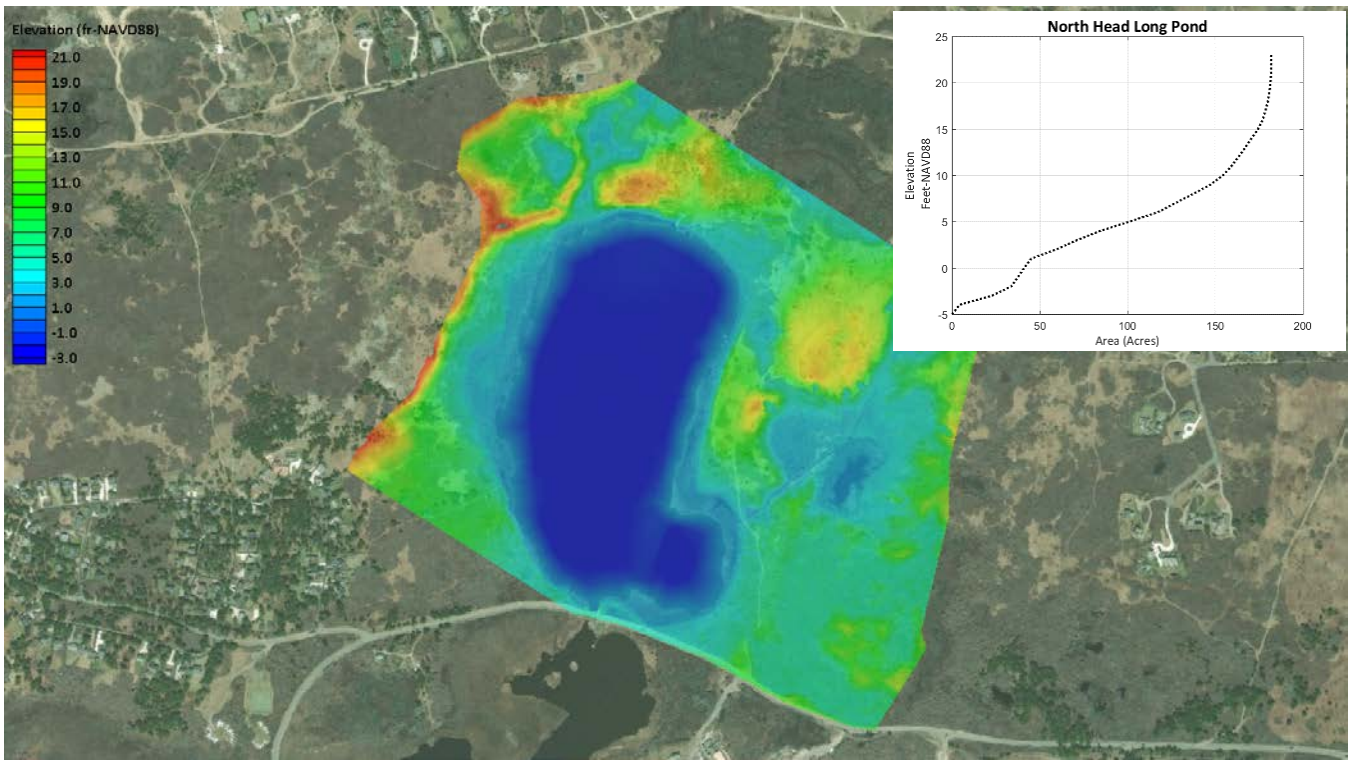

Figure 10. Computational grid of the North Head Long Pond basin using the combined LiDAR and RTK data. Inset shows the hypsometric curve for the basin.

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The hypsometric curves for all four basins used in the Madaket ECM model are shown in Figure 11. Both of the downstream basins, Madaket Ditch lower (blue line) and Madaket Ditch upper (green line), have small surface areas at elevations below 1 ft-NAVD88, and are largely defined by the channels in each of the basins. Both Long Pond (cyan line) and North Head Long Pond (dotted black line) have significantly larger surface areas at the same elevation, which is representative of the larger storage volumes available within the ponds during typical tidal conditions.

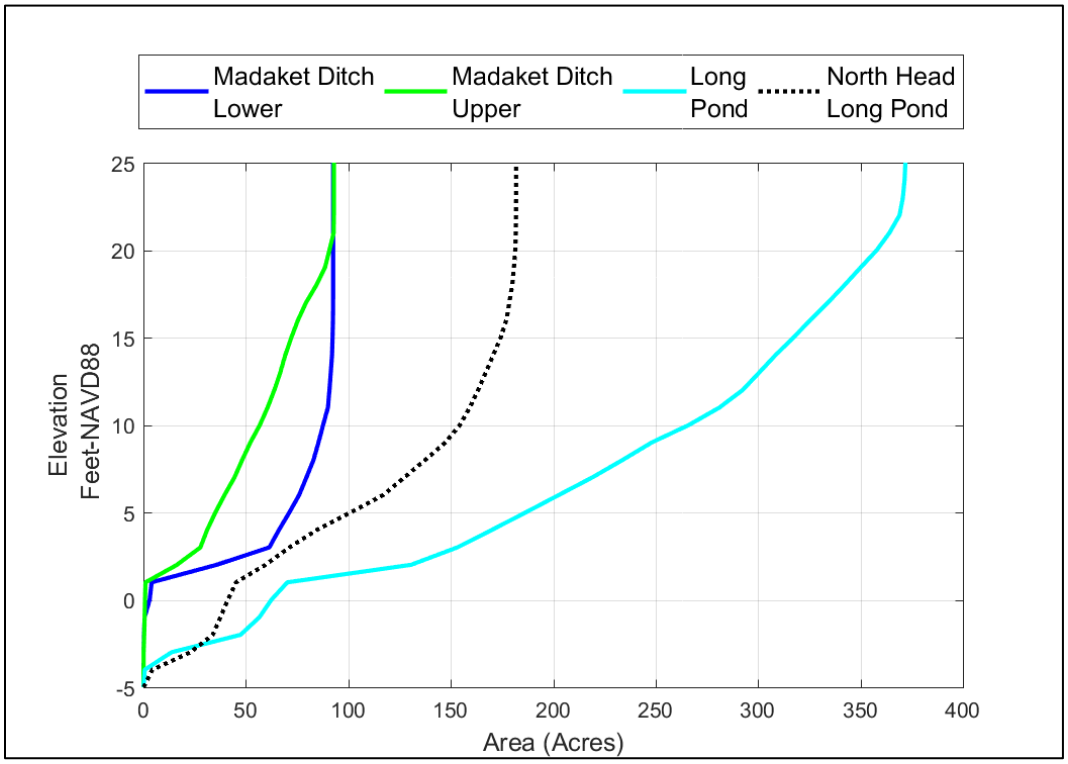

Figure 11. Hypsometric curves for each of the upstream basins comprising the Madaket ECM model.

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3.1.2.Boundary Conditions

Woods Hole Group developed boundary conditions for Hither Creek to provide tidal and coastal storm forcing in the model simulations of both existing and proposed conditions. These boundary conditions consisted of: 1) typical tides developed from observed data, 2) projected sea level rise for the years 2070 and 2100 superimposed with typical tides, and 3) a 1%-annual-chance (100-year) coastal storm surge event. Additionally, an upstream inflow boundary condition was defined for a 1%-annual-chance (100-year) rainfall event.

3.1.2.1. Typical Tides

Observed water levels from Hither Creek, discussed in section 2.1, were used as the tidal boundary condition for the Madaket ECM. From the 38 days of collected data, two separate ten (10) day periods were selected to provide a range of typical tidal conditions. The first 10-day period, November 05, 2018 through November 15, 2018 (hereafter referred to as calibration period) includes both spring tides occurring at the start and neap tides as you get closer to November 15th. A second 10-day period from November 15 through November 25 (hereafter referred to as validation period) includes neap tidal cycles during the first 5 days and then transitions to spring tidal cycles towards the end of the period. The validation period includes the occurrence of two coastal storm driven tides, one on November 15th and another on November 24th when measured water levels exceeded 2 feet NAVD88. Figure 12 shows the calibration period (top) and validation period (bottom) which are representative of typical tides in Hither Creek. The yellow bars indicate periods of rainfall based on data collected at Nantucket Memorial Airport.

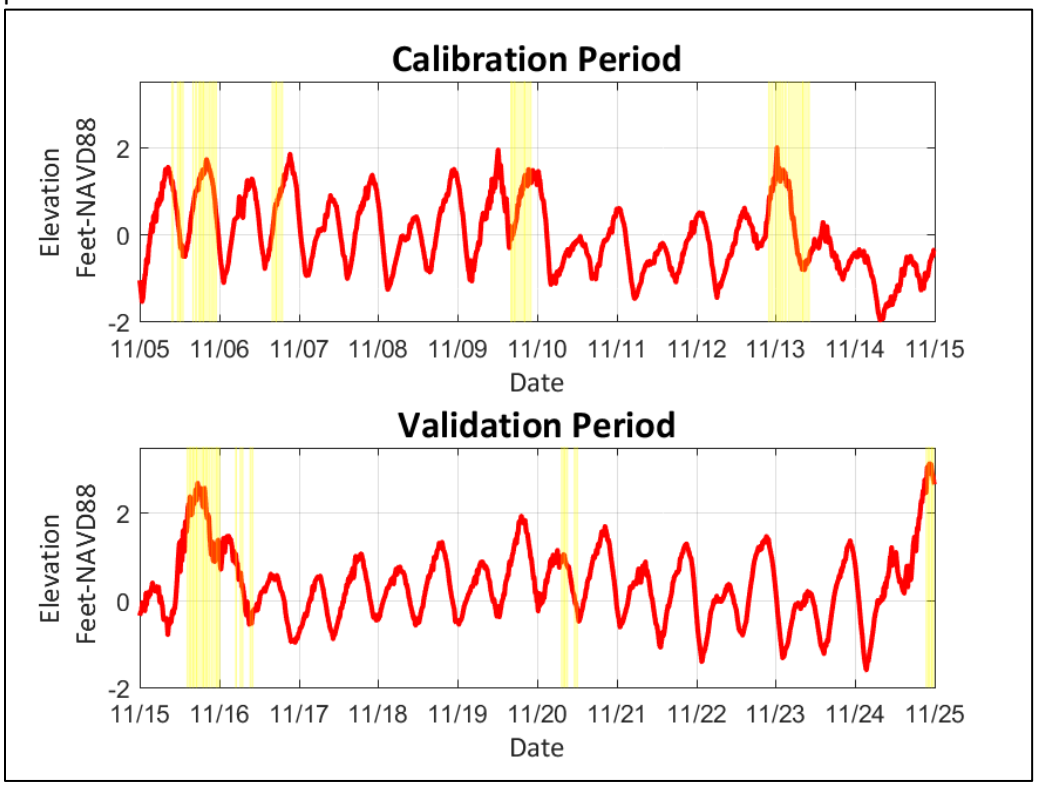

Figure 12. Tide measurements from the Hither Creek gauge (MH1) used as model forcing for typical tidal conditions.

3.1.2.2. Typical Tides with Sea Level Rise

In order to evaluate potential future conditions with projected increases in sea level, tidal boundary conditions were developed for different sea level rise (SLR) scenarios. As this study is assessing the need for replacing culvert structures, SLR scenarios were selected based on a typical culvert design life of 50 to 75 years. As such, the first SLR scenario used was the high-emission scenario for year 2070 which gives a predicted increase of 4.3 feet (Deconto & Kopp, 2017). The 10-day validation period was used as the basis for the SLR model simulations and Figure 13 shows the typical tidal conditions accounting for SLR in 2070.

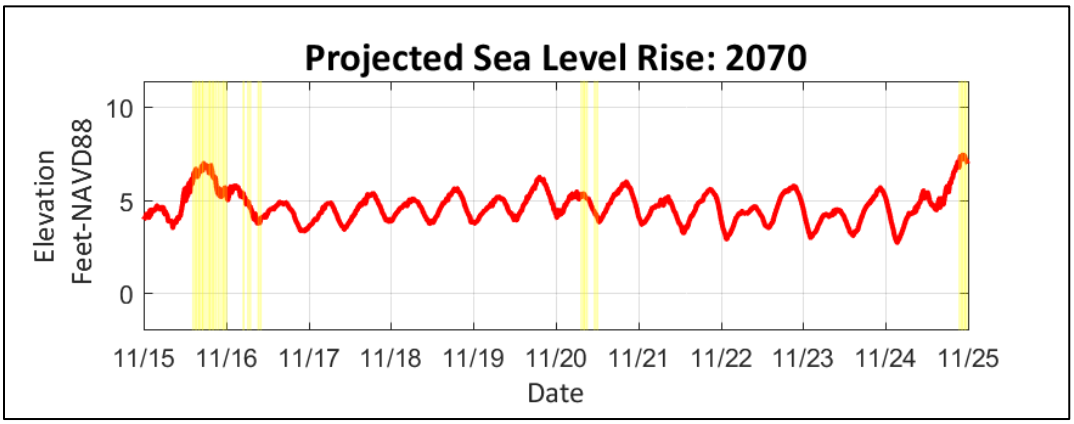

Figure 13. Tidal conditions for Hither Creek with projected sea level rise superimposed on the tidal forcing. The 2070 scenario includes a sea level rise of 4.3 feet.

3.1.2.3. Coastal Storm Surge Event

Boundary conditions were also developed for model simulations of coastal storm surge events at the 1%-annual-chance (100-year) level. The extreme storm surge elevation used in this study of 7.4 ft-NAVD88 is from the effective Flood Insurance Study for Nantucket County (FEMA, 2014). This peak water level was used to develop a synthetic storm surge hydrograph using methods detailed in the 2004 Federal Highway Administration Hydraulic Engineering Circular No. 25. The storm surge hydrograph developed using this procedure for a 100-year storm event occurring over 36 hours is shown in Figure 14.

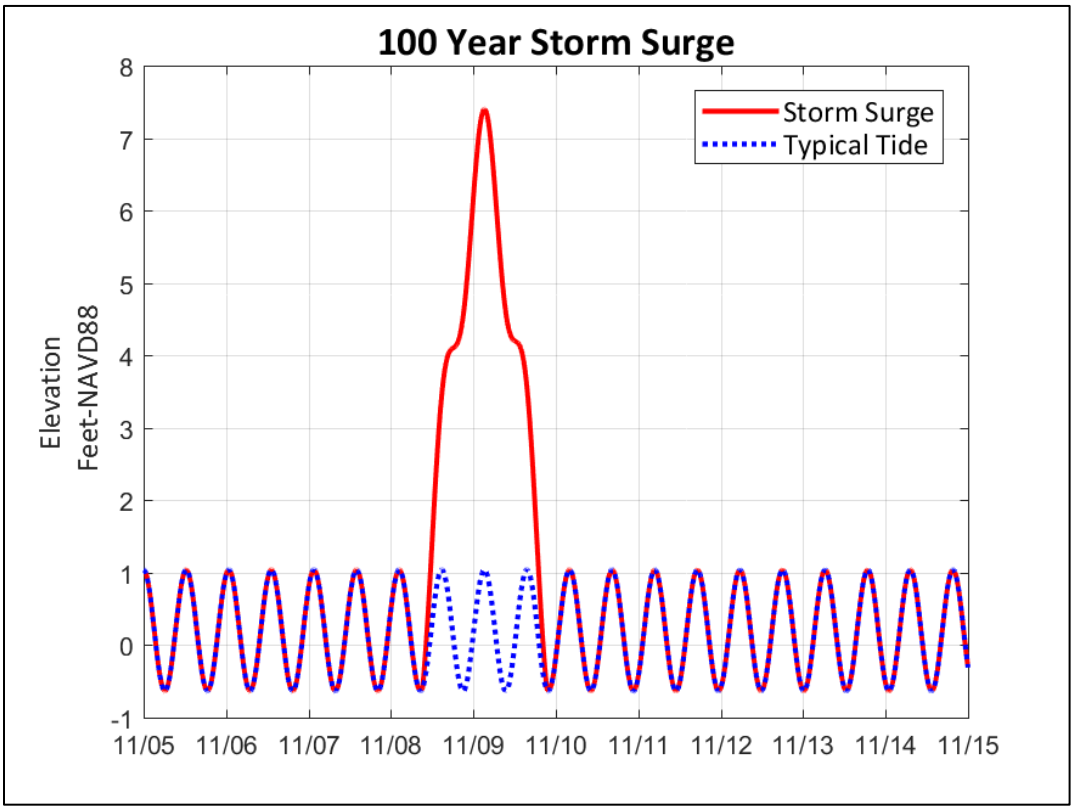

Figure 14. Synthetic storm surge hydrograph for the 1%-annual-chance event.

3.1.2.4. Upstream Boundary Condition

The next step in developing model boundary conditions was to determine the upstream input condition attributed to groundwater inflow applied at the North Head Long Pond basin, and surface water runoff from rainfall during the observed time period for each of the basins. The upstream boundary condition was specified as an input flow or discharge representing combined contributions from a constant groundwater volumetric flow of 4.62 ft^3/s (Howes, et al., 2010) and surface water runoff feeding the upstream basins.

To develop the upstream inflows associated with surface water runoff which occurred during the calibration and validation periods, hourly rainfall data were collected from Nantucket Airport. The established rational method was then used to establish the surface water discharge, *Q*, using the following equation:

$$Q = C_R i A \qquad (7)$$

where C_R is a dimensionless runoff coefficient, *i* is the rainfall intensity, and *A* is the area of the watershed. Inspection of the aerial photography of each of the basins in the Madaket ECM were used to develop the runoff coefficients for each basin as listed in Table 1. Also listed in the table is the surface area for each of the basins. Surface areas were defined as the maximum surface area from the basin hypsometry as discussed in prior sections, while the value of the runoff coefficient used was for unimproved areas (Chin, 2006).

Table 1. Surface areas and runoff coefficients used in the Madaket Estuarine Culvert Model to determine the contribution of surface water runoff during precipitation events.

Basin	Surface Area (Acres)	Runoff Coefficient (C_R)
Madaket Ditch lower	92.6	0.10
Madaket Ditch upper	92.9	0.10
Long Pond	375.5	0.10
North Head Long Pond	181.9	0.10

Woods Hole Group also created a boundary condition for a synthetic rainfall storm event based on the 100-year, 24-hour duration rainfall of 6.82 inches (NOAA, 2015). The 24-hour event was transformed into a rainfall hyetograph using the USGS Type III rainfall distribution, from which flow rates were defined using the rational method as described above. Figure 15 shows the volumetric flow rates developed for the 100-year rainfall event.

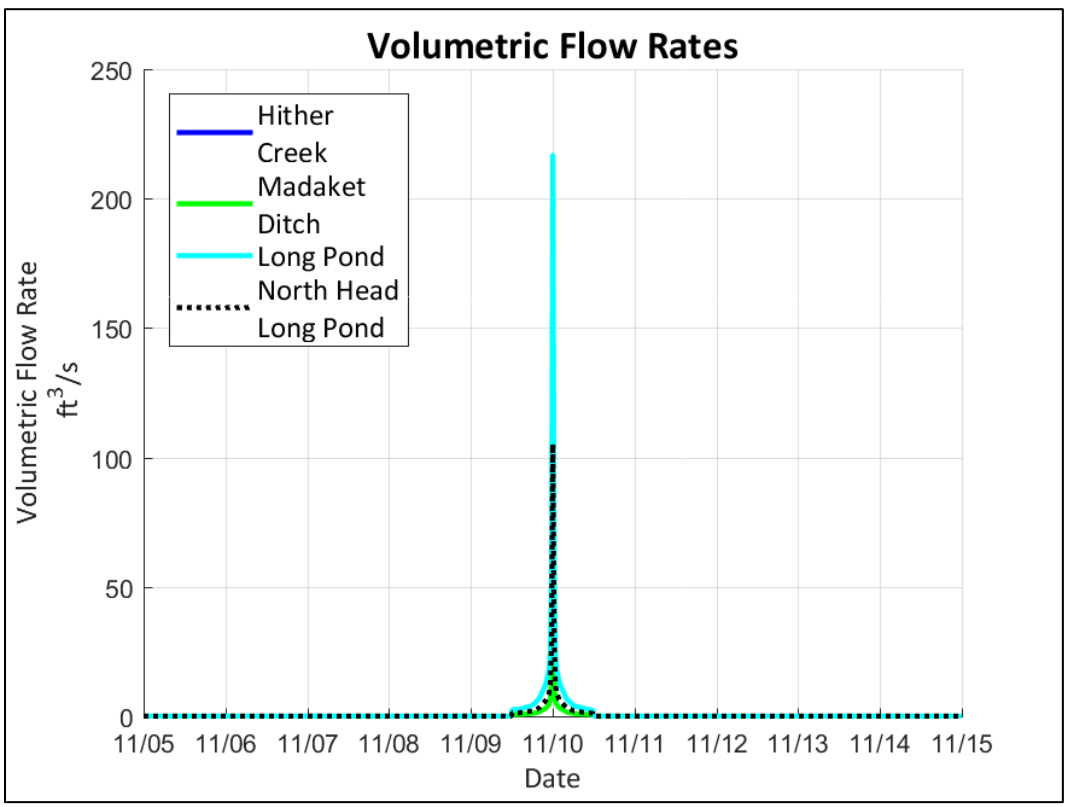

Figure 15. Volumetric flow rates developed for the 100-year rainfall event in each of the Madaket ECM basins using the rational method.

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3.2 Model Calibration and Validation – Typical Tides

Model calibration refers to a comparison of model results with measured data, and refining the model parameters within reasonable values to improve the model skill and minimize uncertainties in the model results. To quantify model performance or the level of accuracy, error statistics are often computed. In evaluating the Madaket ECM, two 'goodness of fit" statistics, bias and Root Mean Square Error (RMSE), were calculated using the model results at each basin within the system. This was done for multiple simulations of the calibration period until the model results and measurements were within reasonable agreement, and error statistics were minimal. After calibrating the model, the validation period was simulated to determine the efficacy of the model to replicate observed results under similar, but differing conditions.

The calibration and validation simulations resulted in using the geometric variables listed in Table 2 for each of the culvert/channel connections between individual basins. Culvert geometries were primarily derived from a combination of Wood Hole Group survey data and the 2018 Culvert Structural Condition Assessment provided by Fuss & O'Neill (Whittemore & Mas, 2018). The culvert at N. Cambridge Street was modeled as an 8 ft diameter circular corrugated metal culvert measuring 48.5 feet in length and having a Manning's n frictional coefficient of 0.025.

The results of the Madaket ECM and comparisons with measured data for the calibration period are shown in Figures 16 and 18 through 20 where the black line is the modeled water level and the observed values are shown in red. Yellow areas on the graphs indicate time periods with measured rainfall.

Figure 16 shows the comparison within the Madaket Ditch lower basin and the model compares well with the observed water levels. The model bias is less than ¼ inch, with a RMSE of less than an inch over the entire 10-day simulation.

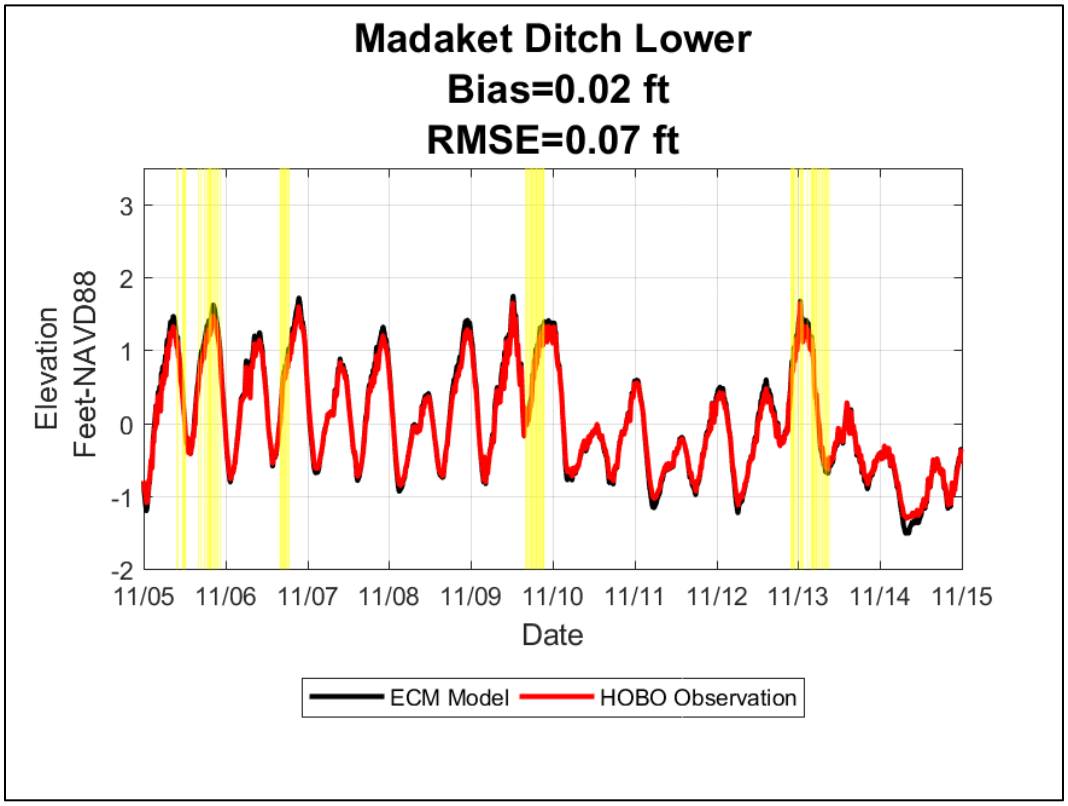

Figure 16. Comparison of the Madaket ECM model results to the AquaTROLL observations over the calibration period at the Madaket Ditch lower basin, gauge (MH2).

As discussed in Section 2.1, measured water levels at the Madaket Ditch lower and upper basins indicated there was significant tidal dampening, or reduction in the tide range between the two basins. This was an area of focus during the model calibration and further field investigation of Madaket Ditch was conducted to identify whether there were significant obstructions or significant shoaling within the channel that may be restricting tidal flow to the upper basin. During this field investigation, additional survey data were acquired within the Madaket channel including the deepest point along the channel and cross-sections. The investigation did not identify any significant obvious obstructions within the channel, but did show how the channel with its sinuosity, has naturally shoaled to a point in certain locations that is restrictive to tidal flow.

In order to represent this restriction in the model, the connection between the two Madaket Ditch basins was specified as a 465-ft long natural channel having a triangular shape which is similar to the v-shaped cross sections observed at shoaled areas in the channel bends. This portion of the channel was selected based on field observations of changes in wetland vegetation and presence of channel shoals. The channel top width was set to 20 feet for the entirety of the channel, with a top of bank elevation of 1.1 ft-NAVD88. Overbank flows were modeled using the broad-crested weir equations with an overbank width of 13 feet which was measured at the narrowest point between the hummocks. Bed elevation of the channel was set to -2.5 ft-NAVD88, and a composite Manning's n value of 0.046 was used to account for channel material, vegetation, sinuosity, and potential obstructions (Chow, 1959).

Figure 17. Portion of Madaket Ditch modeled as a triangular channel between the lower and upper basins

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Figure 18 shows the model calibration results for the Madaket Ditch upper basin. The time series comparison shows the channel restriction is well represented in the ECM model and captures the reduction in tidal range at the upper basin. The model bias and RMSE are minimal at this location being less than an inch and 1.1 inches, respectively.

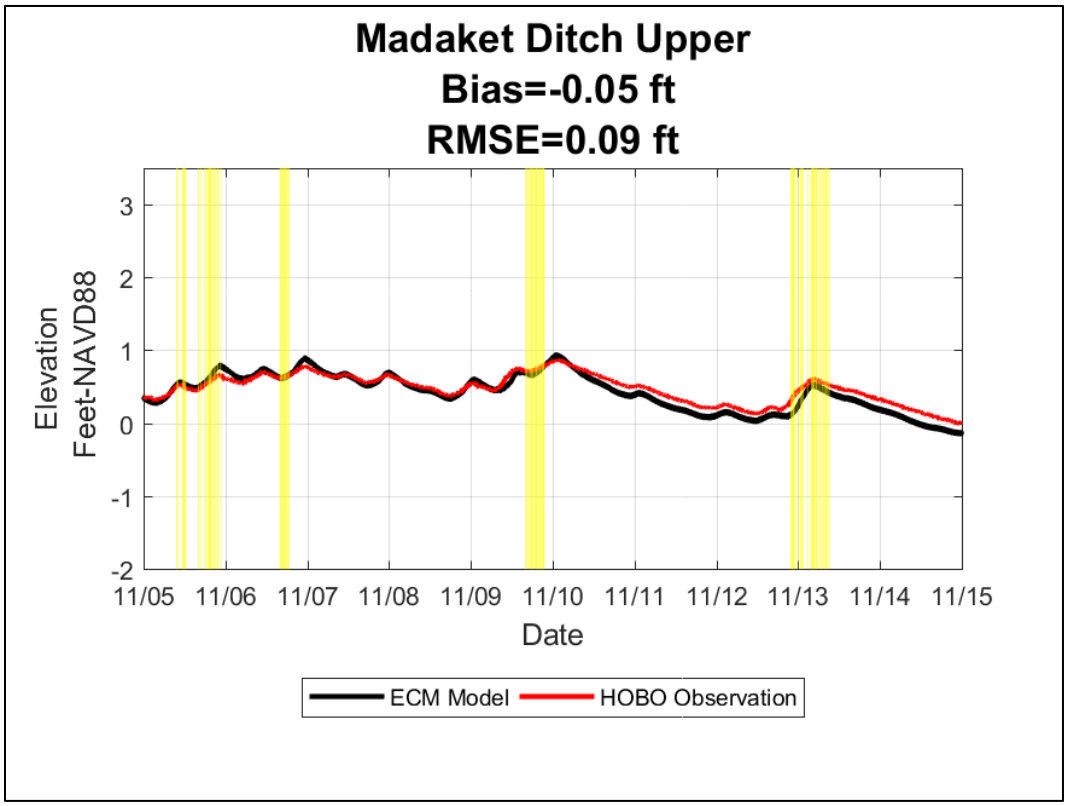

Figure 18. Comparison of the Madaket ECM model results to the AquaTROLL observations over the calibration period at the Madaket Ditch upper basin, gauge (MH3).

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The second of three culverts in the Madaket-Long Pond system is located under Madaket Road and connects Madaket Ditch upper to Long Pond. This culvert was modelled as a corrugated metal box culvert 60 feet in length, with a width of 16 feet and a height of 5 feet. The Manning's n used for the culvert was set to 0.030 to account for both the roughness of the pipe, and secondary roughness contributions related to marine growth and aging of the culvert. Because the culvert is not a true box and has an element of curvature, especially on the roof of the culvert, a secondary coefficient, K, 0.95 was used to account for additional entrance and exit losses due to the disparity in culvert shape. Figure 19 shows the results of the calibration simulation for the Long Pond basin. Similar to the results for the Madaket Ditch upper basin, the modeled water levels closely match observed values and there is a slight negative bias of 0.5 inches, with an RMSE of 1.1 inches.

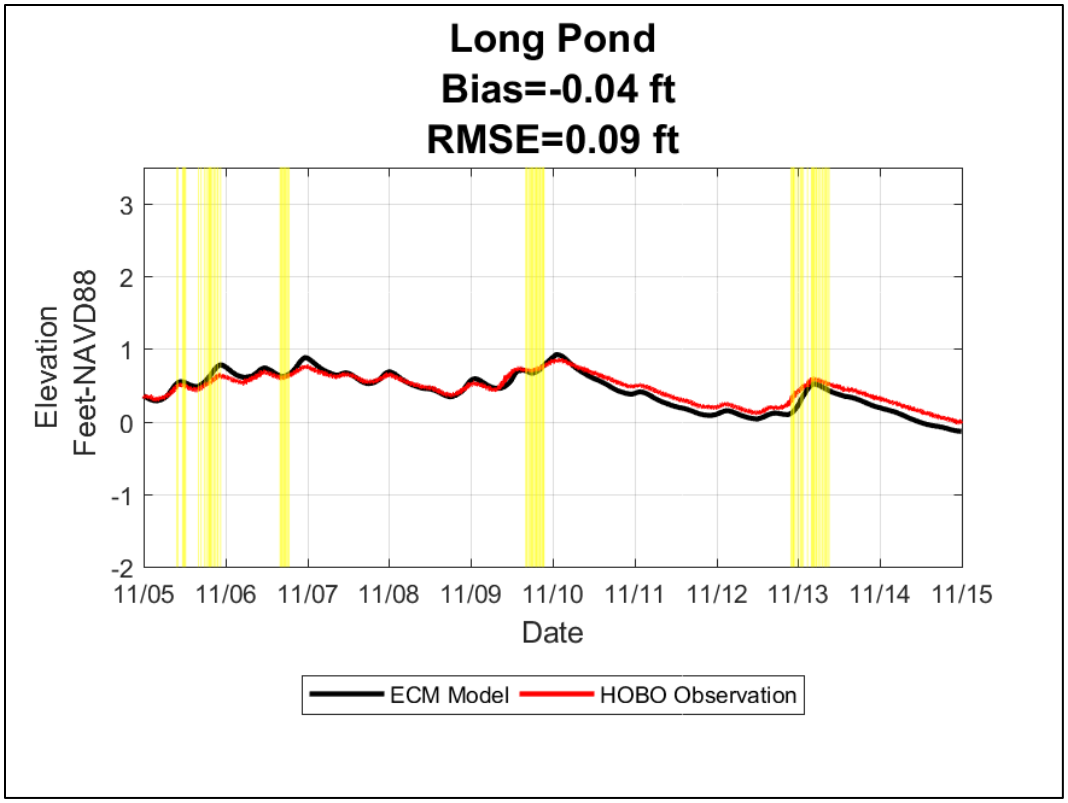

Figure 19. Comparison of the Madaket ECM model results to the AquaTROLL observations over the calibration period at the Long Pond basin, gauge (MH4).

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The final culvert in the Madaket-Long Pond system running under Madaket Road and connecting Long Pond to North Head Long Pond was also modelled as a corrugated metal box culvert. A length of 50 feet, width of 9 feet and height of 4.2 feet (50 inches) were used in specifying the culvert geometry. The Manning's n used for the culvert was also set to 0.030 for similar reasons given for the other Madaket Road culvert. Again, a secondary coefficient, K, set to 0.95 was used to account for any additional entrance and exit losses due to the disparity in culvert shape. Figure 20 shows the results of the calibration simulation in the North Head Long Pond basin. The water levels and comparisons are almost identical to the comparisons made for the Long Pond basin, indicating the culvert currently does not have a significant effect on flow between the basins during typical tides.

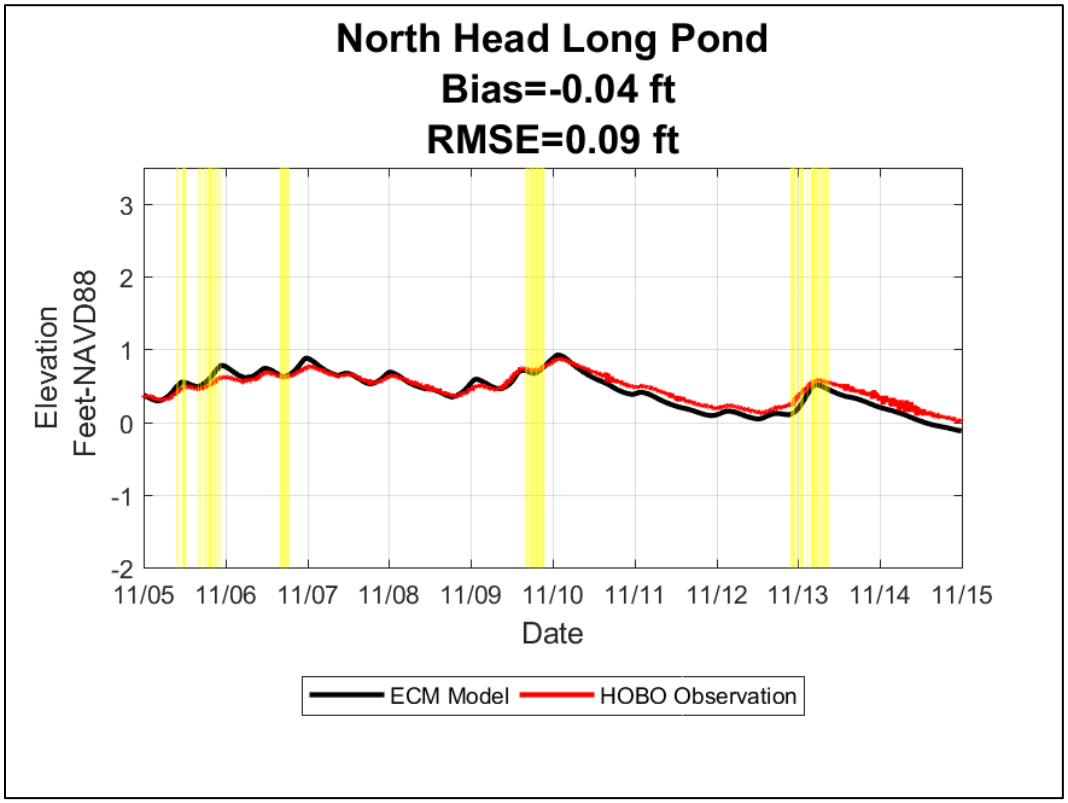

Figure 20. Comparison of the Madaket ECM model results to the AquaTROLL observations over the calibration period at the North Head basin, gauge (MH5).

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Figure 21 shows the results of the ECM simulation in each of the basins during the 10-day model validation period from November 15, 2018 through November 25, 2018. ECM results are shown in each of the panels as black lines, while the observations for the same time period are shown in red. Madaket Ditch lower is shown in panel A, and has similar accuracy to the calibration run with a bias of 0.5 inches and a RSME of 1.1 inches. Madaket Ditch upper (panel B) had a minor negative bias of 0.1 inches, and a 0.7-inch RMSE. Long Pond (panel C) and North Head Long pond (panel D) showed similar small bias and RMSE values.

Overall from the calibration and validation simulations, the model shows good skill in predicting water levels within the different basins of the Madaket-Long Pond estuarine system and is a valid tool to assess different scenarios and alternatives.

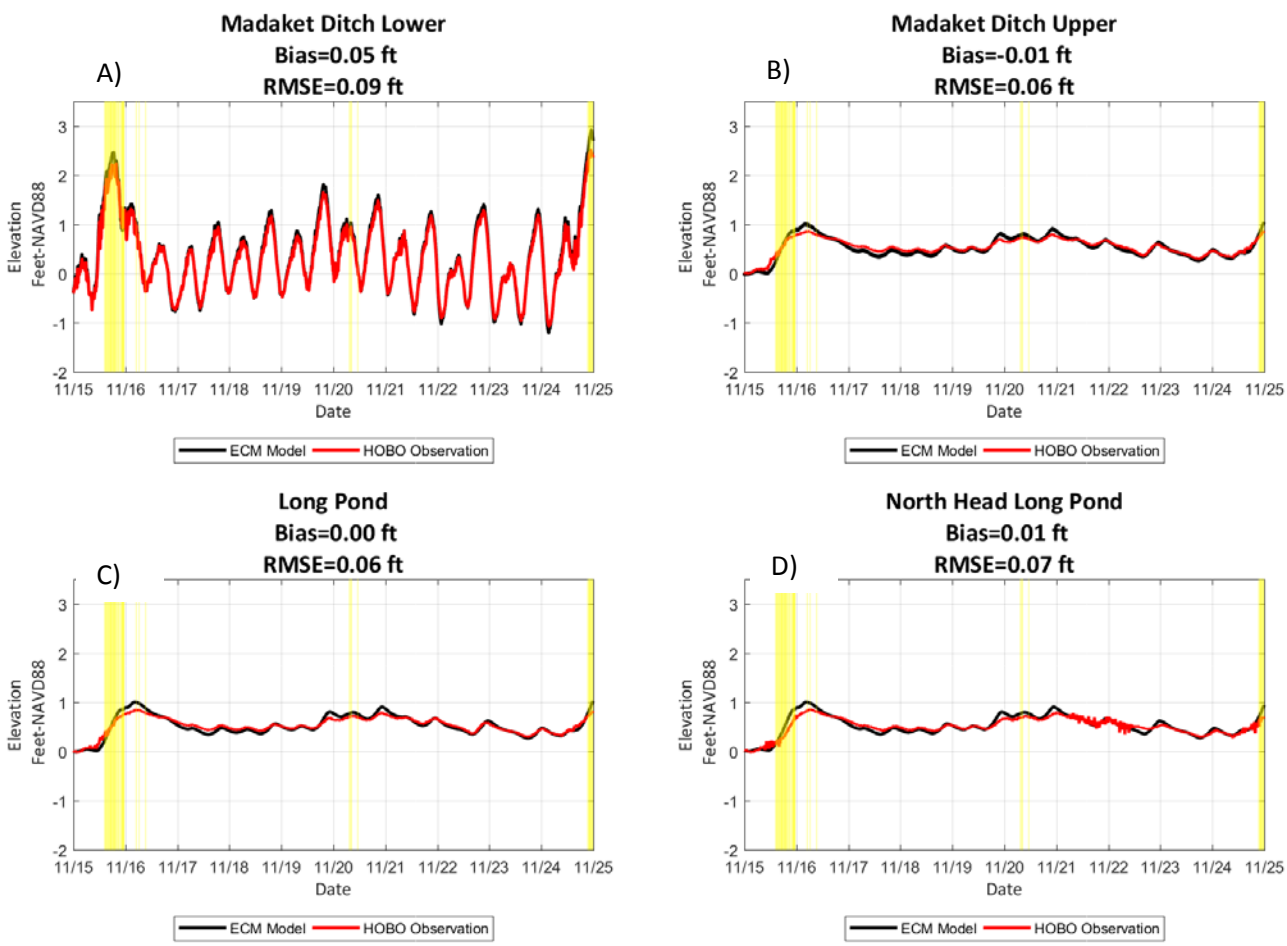

Figure 21. Madaket Harbor ECM results for the model validation period from November 15, 2018 through November 25, 20018. Clockwise from top: A) Madaket Ditch lower, B) Madaket Ditch upper, C) Long Pond, and D) North Head Long Pond.

Table 2. Connection type, and geometric attributes of each of the basin connections modelled in the Madaket ECM for existing conditions

Basin	Connection Type	Length (ft)	Width (ft)	Height (ft)	Cross-sectional Area (ft^2)	Downstream Invert Elevation (ft-NAVD88)	Upstream Invert Elevation (ft-NAVD88)	Entrance Coefficient	Manning's n
Madaket Ditch lower	Pipe Culvert	48.5	8	8	50.3	-3.389	-2.939	1	0.025
Madaket Ditch upper	Triangular Channel	465	20	3.6	36.0	-2.5	-2.5	1	0.046
Long Pond	Box Culvert	60	16	5	80.0	-4.11	-3.386	0.95	0.03
North Head	Box Culvert	50	9	4.17	37.5	-1.141	-1.541	0.95	0.03

Table 3. Connection type, and geometric attributes of each of the basin connections modelled in the Madaket ECM for improved channel

Basin	Connection Type	Length (ft)	Width (ft)	Height (ft)	Cross-sectional Area (ft^2)	Downstream Invert Elevation (ft-NAVD88)	Upstream Invert Elevation (ft-NAVD88)	Entrance Coefficient	Manning's n
Madaket Ditch lower	Pipe Culvert	48.5	8	8	50.3	-3.389	-2.939	1	0.025
Madaket Ditch upper	Rectangular Channel	465	20	3.6	72.0	-2.5	-2.5	1	0.024
Long Pond	Box Culvert	60	16	5	80.0	-4.11	-3.386	0.95	0.03
North Head	Box Culvert	50	9	4.17	37.5	-1.141	-1.541	0.95	0.03

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3.3 Additional Simulations of Existing Conditions

After the Madaket ECM was calibrated and validated for typical tides, simulations of existing conditions were conducted during both 100-year storm surge and 100-year rainfall events. Additional simulations were also conducted to assess the effects of sea level rise for the year 2070. **For these model simulations of extreme storms and SLR, the roadway at North Cambridge Street and Madaket Road were raised to elevations sufficient to prevent overtopping and maintain estuarine flows through the existing culverts. Both roadways have minimum elevations less than 5.4 ft-NAVD88 and would otherwise be expected to be inundated during both a 100-year storm and high tides in 2070 with the projected increase in sea level.**

3.3.1. Projected Sea Level Rise in 2070

Figure 22 shows water levels within each Madaket-Long Pond basin under typical tides with projected 4.3 feet of sea level rise in 2070. The SLR model results are shown (black line) together with current-day water levels (red line). In the upper right panel A, tides in the Madaket Ditch lower basin with SLR have a slightly reduced range in comparison to current-day tides, and there is the obvious vertical offset reflecting the increase in mean sea level. Moving upstream into the system, tides in the Madaket Ditch upper basin (panel B) with SLR closely match the tides in Madaket Ditch lower. Continuing upstream from Madaket Ditch upper into Long Pond basin (panel C), the tidal signal is still evident, with some attenuation due to the culvert between the two basins. Finally, in panel D of Figure 22, tides in North Head Long Pond under this SLR scenario closely match those in Long Pond.

The model simulations of the existing culverts under typical tides with SLR indicate the culvert at N. Cambridge Street starts to restrict tidal flow to Madaket Ditch. Additionally, the culvert under Madaket Road connecting Madaket Ditch to Long Pond slightly restricts tides in Long Pond under this SLR scenario. The Madaket Ditch channel is no longer a restriction with this increase in sea level as the marsh is inundated during ALL tidal cycles.

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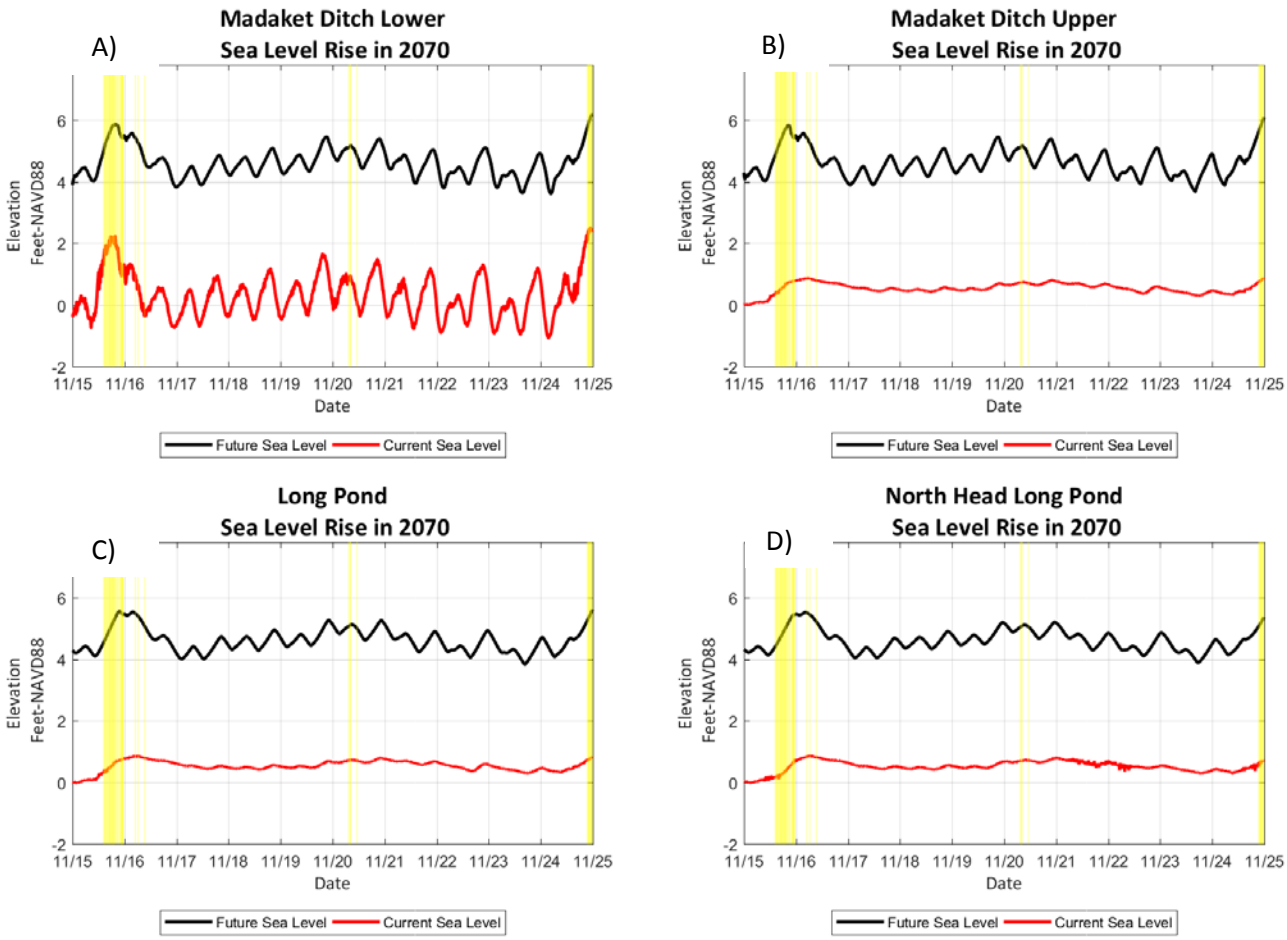

Figure 22. Time series of water levels throughout the Madaket-Long Pond Estuary for existing conditions/typical tides with the current-day sea level (red), and with a projected sea level increase of 4.3 feet in 2070 (black).

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3.3.2. 100-Year Storm Events

Modeled water levels within the Madaket-Long Pond estuary during a 100-year coastal storm surge event are shown in Figure 23 as a black line in each of the panels. The red lines in the Figure are typical (predicted) tides, shown as a basis for comparison. The peak storm surge in Hither Creek is 7.4 feet which includes both the wind-driven storm surge and the local effect of wave setup at Madaket Harbor (FEMA, 2014). The culvert under North Cambridge Street attenuates the peak surge from 7.4 ft-NAVD88 in the harbor to a maximum of 5.8 feet in the Madaket Ditch lower basin (Panel A). Similarly, peak water levels in the Madaket Ditch upper basin (Panel B) are further reduced to a maximum of 5.0 ft-NAVD88, while Long Pond and North Head Long Pond have maxima of 4.7 and 4.6 ft-NAVD88 respectively. **Overall, drainage of Long Pond after the peak is shown to occur over a 4-day period with the existing culvert configuration.**

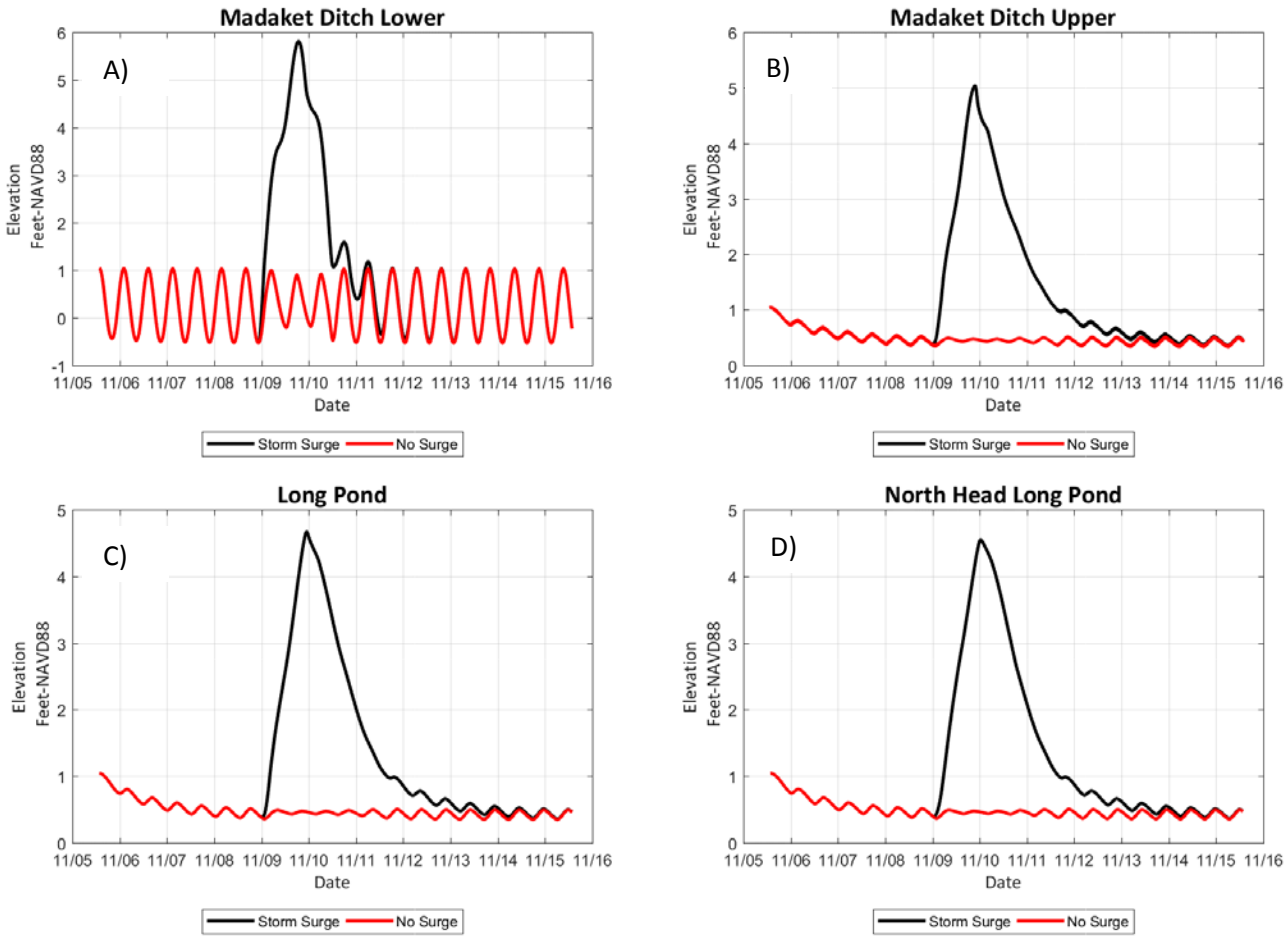

Figure 23. The 100-year storm surge event in Madaket-Long Pond Estuary for existing conditions

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Figure 24 shows the effect of the 24-hour duration 100-year rainfall event in the Madaket-Long Pond Estuarine system. In each panel, the black line shows the modeled water level with the contribution of the 100-year rainfall induced flow, while the red line shows the ECM modelled water level without any contribution from rain. The yellow band in each of the panels shows the time period during the model simulation over which the precipitation occurred. In Madaket Ditch lower (Panel A), the precipitation event has negligible effect on the modelled water levels. In panel B, showing Madaket Ditch upper, the inflow from rainfall contributes to a slight increase in water level after approximately 12 hours of rain, which then drains over approximately two days until returning to the tide-induced water levels. **This trend is also shown to occur in both Long pond (panel C) and North Head Long Pond (Panel D), again indicating the channel connecting Madaket Ditch upper and Madaket Ditch lower is the largest restriction to flow/drainage in the system.**

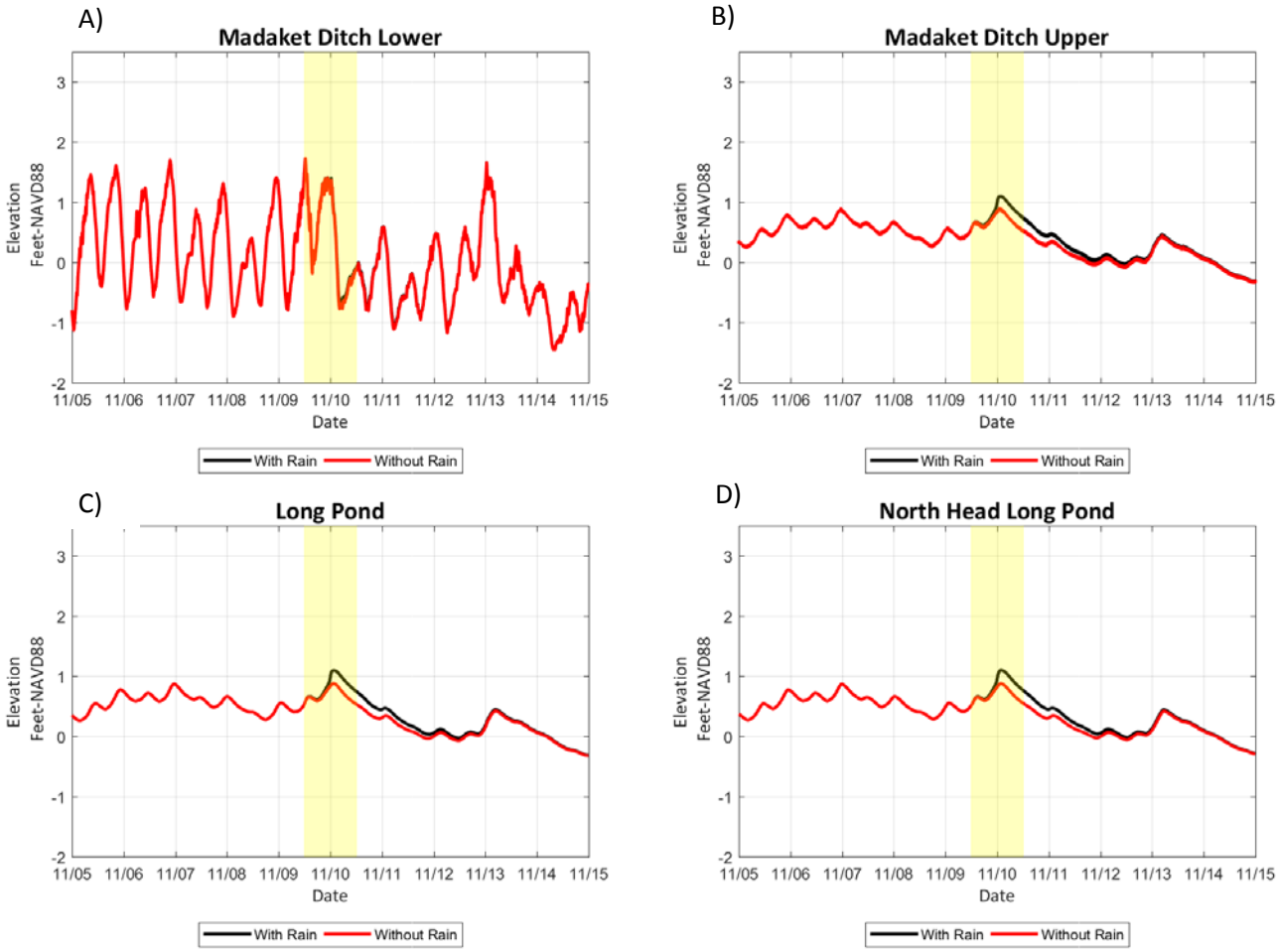

Figure 24. The 100-year rainfall event in Madaket-Long Pond Estuary for existing conditions.

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4 Alternatives Evaluation and Effects on the Madaket-Long Pond Estuary

The measured water levels collected during October and November of 2018 indicate the reduced tides in the upstream basins was primarily due to the hydraulics of the main channel connecting the Madaket Ditch lower and Madaket Ditch upper basins. There is minimal tidal attenuation between Madaket Ditch upper, Long Pond, and ultimately North Head Long Pond indicating that, with the current channel geometries, both culverts under Madaket Road are of sufficient size. In order to develop a greater understanding of the system dynamics, and to optimize the drainage in both basins of Long Pond, a series of simulations were conducted using an improved channel in Madaket Ditch.

The proposed alternative channel configuration included **improving the main channel (i.e. dredging of shoaled areas) so that the channel geometry would be rectangular (20 feet wide by 3.6 feet deep)**. This was done in the 465-foot section of the channel that was modeled as a restriction (see Figure 17). It was assumed the natural sinuosity of the channel would remain unchanged, however the **overall effect of channel improvements** would help to **reduce the Manning's n friction coefficient from 0.046 to 0.024**. The combined effects of the **increased cross-sectional flow area and the reduced friction were then assessed by conducting the same model simulations** of typical tides with and without an increased sea level as well as extreme storm events.

4.1 Typical Tides

Woods Hole Group used the 10-day calibration period to assess the effects of channel improvements on the Madaket-Long Pond estuary in typical tidal conditions. The modelled water levels with an enhanced channel are shown in Figure 25 as black lines. For comparison, the model results for the existing channel configuration are also shown (red lines). Starting at the basin farthest downstream, Madaket Ditch lower in panel A, at high tide elevations there is little change between the proposed and existing conditions. During low tides, however, the increased drainage capacity from the upper basins results in an increase in water level during low tides. Moving upstream from Madaket Ditch lower into the Madaket Ditch upper basin, shown in panel B, the increased exchange between the two basins is evident in both an increase in high tide levels, and increased outflows with lower low tide levels. **The improved Madaket Ditch channel still slightly restricts tides in the upper basin, however.** Moving farther upstream into Long Pond, panel C, and North Head Long Pond, panel D, the increased tidal exchange and drainage capacity of Madaket Ditch is evident in both basins. The culvert under Madaket Road to Long Pond does not significantly affect water levels, **however the culvert to North Head Long Pond becomes slightly restrictive**.

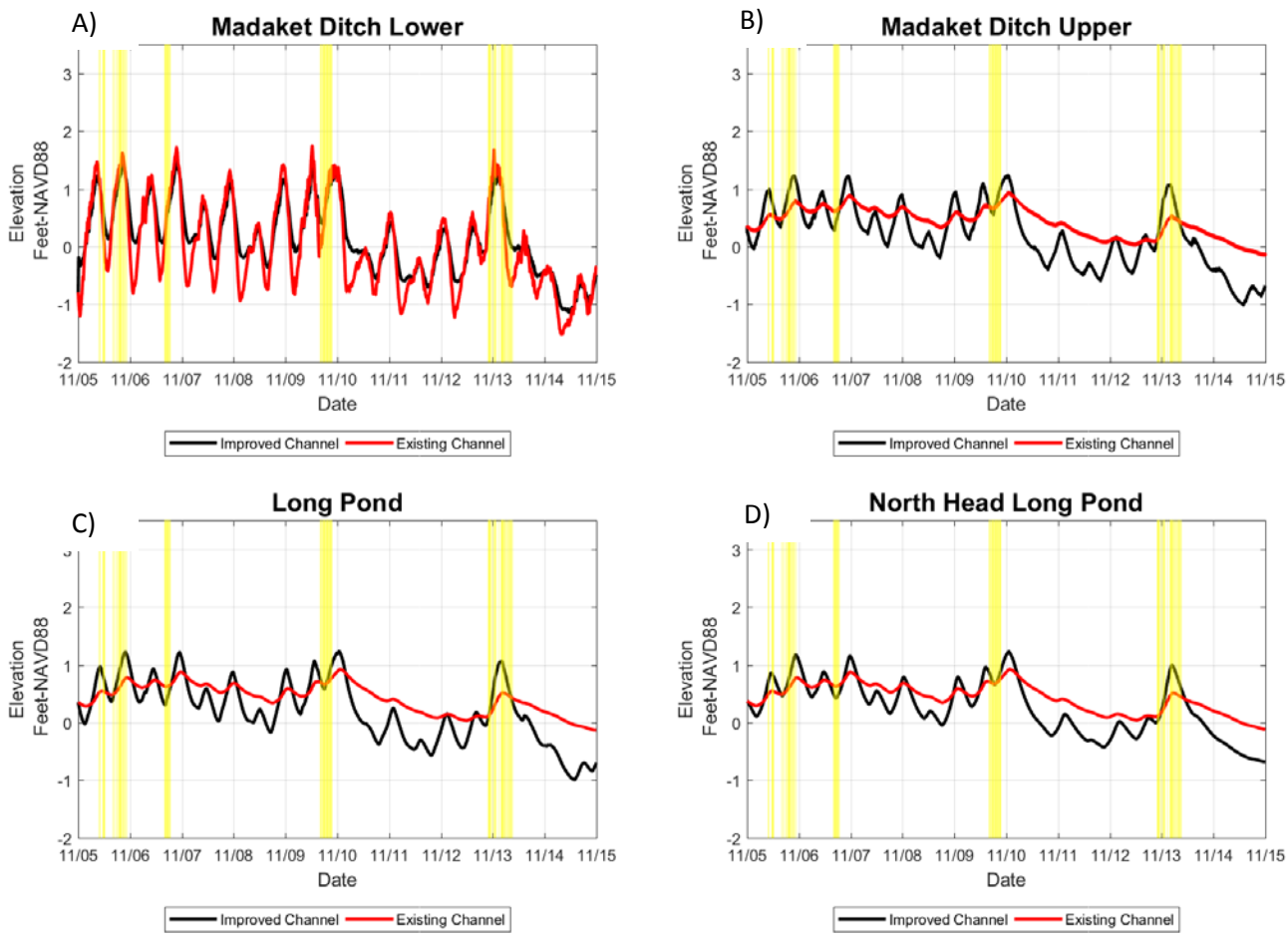

Figure 25. Effects of channel improvements in Madaket Ditch on tidal exchange and drainage in the estuary during typical tides.

4.2 Sea Level Rise and the 100-Year Storm Events

After assessing the effects of channel improvements for typical tides and the current-day sea level, additional simulations were conducted including: 1) typical tides in 2070, 2) a 100-year coastal storm surge event, and 3) a 100-year rainfall event. **Again, it was assumed that the roadway elevations of N. Cambridge Street and at the Madaket Road culverts were increased to a height sufficient to prevent overtopping.**

4.2.1. Projected Sea Level Rise in 2070

Figure 26 shows the effects of channel improvements in Madaket Ditch on water levels throughout the Madaket-Long Pond estuarine system with projected 4.3 feet of sea level rise in the year 2070. Water levels with the proposed channel improvements are shown in black, while the water levels in 2070 with the existing channel geometry is shown in red. With the exception of the ebb tides near the end of the simulation in Madaket Ditch upper (panel B), the water levels are indistinguishable between current and proposed conditions. Additionally, there is minimal tidal attenuation between Madaket Ditch lower (panel A), and the farthest upstream basin shown in panel D for North Head Long Pond.

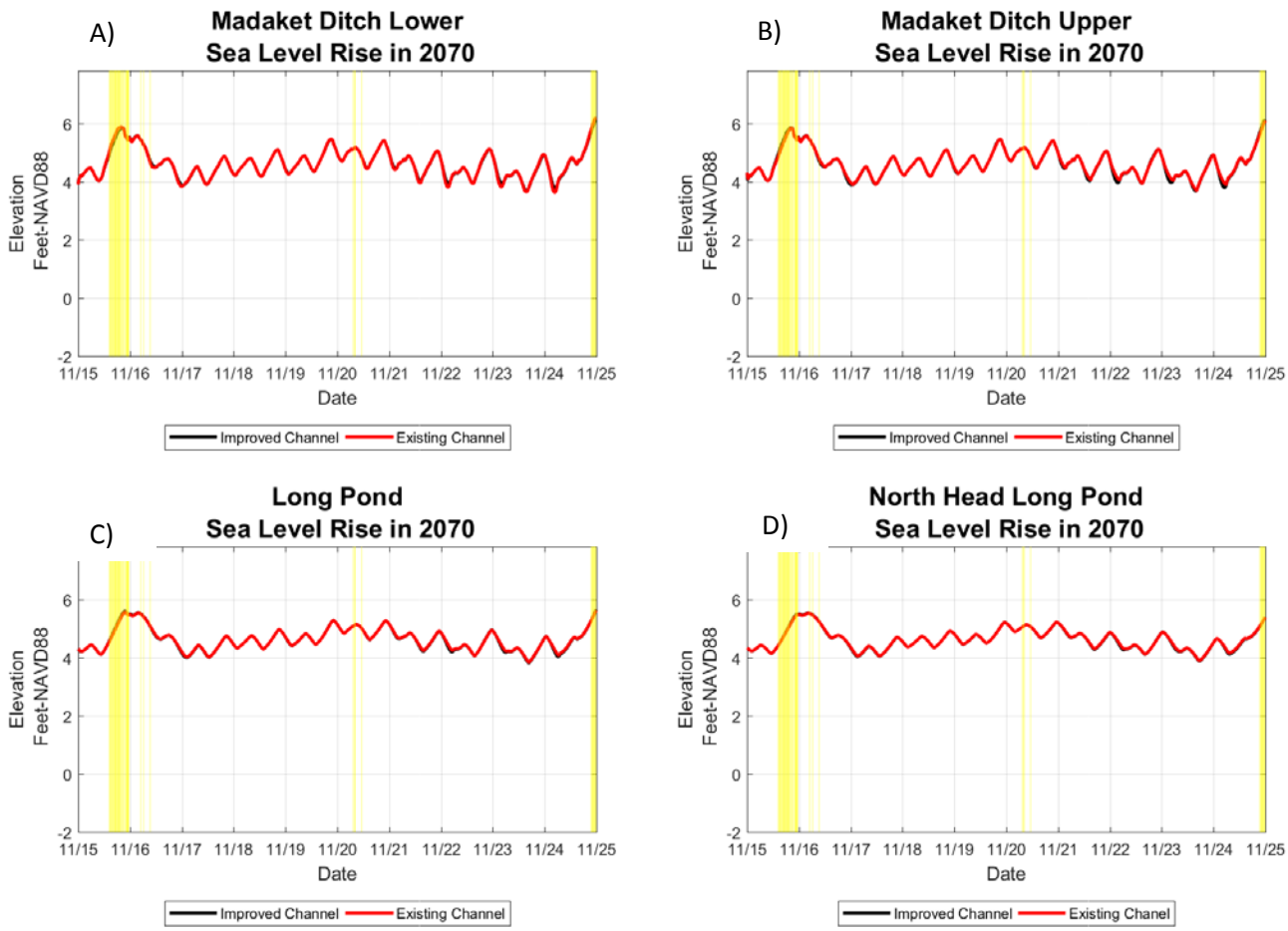

Figure 26. Effects of channel improvements in Madaket Ditch on tidal exchange and drainage in the estuary during typical tides with sea level rise in 2070.

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4.2.2. 100-Year Storm Events

The 1%-annual-chance (100-year) storm surge event was simulated with the **alternative channel improvements** in Madaket Ditch and the resulting water levels are shown as black lines in Figure 27 for each of the four sub-basins. For comparison, the water levels with the existing channel configuration are shown as red lines in the figure. Starting at Madaket Ditch lower (panel A) there is a small reduction in peak surge and in drainage out of the basin as there is more flow exchange with the upstream basins. **Moving upstream into Madaket Ditch upper (panel B), the channel improvements allow for more flow during the tides preceding the storm, and there is a small increase in the peak surge. The amount of time required for the system to drain following the storm event is reduced by 50% in comparison to existing conditions, however, from approximately 4 days to 2 days.** A similar response is seen in the upper two basins, Long Pond (panel C) and North Head Long Pond (panel D).

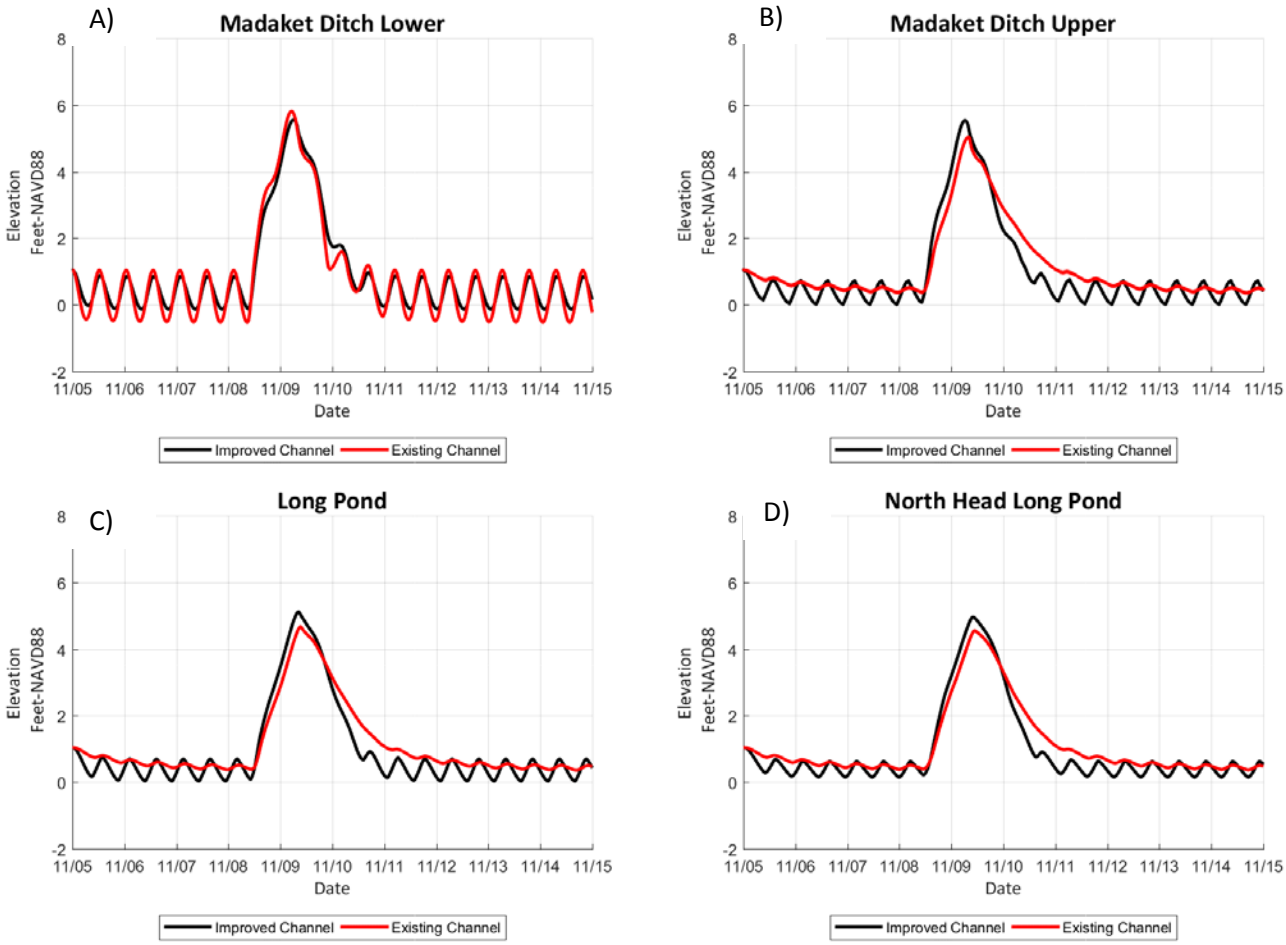

Figure 27. Effects of channel improvements in Madaket Ditch during a 100-year level storm surge event.

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In addition to the 1%-annual-chance storm surge event, a simulation was conducted for the 100-year precipitation event. The results from the extreme rainfall event simulation are shown in Figure 28. The yellow band in each of the panels shows the time period during the model simulation over which the precipitation occurred. Following the precipitation event, the water in the upstream basins drains at both a faster pace, and to a lower level than with the existing channel. In Long Pond (panel C) and North Head Long Pond (panel D), the Madaket Ditch channel improvements also result in lower water levels during ebb tides following the rainfall event.

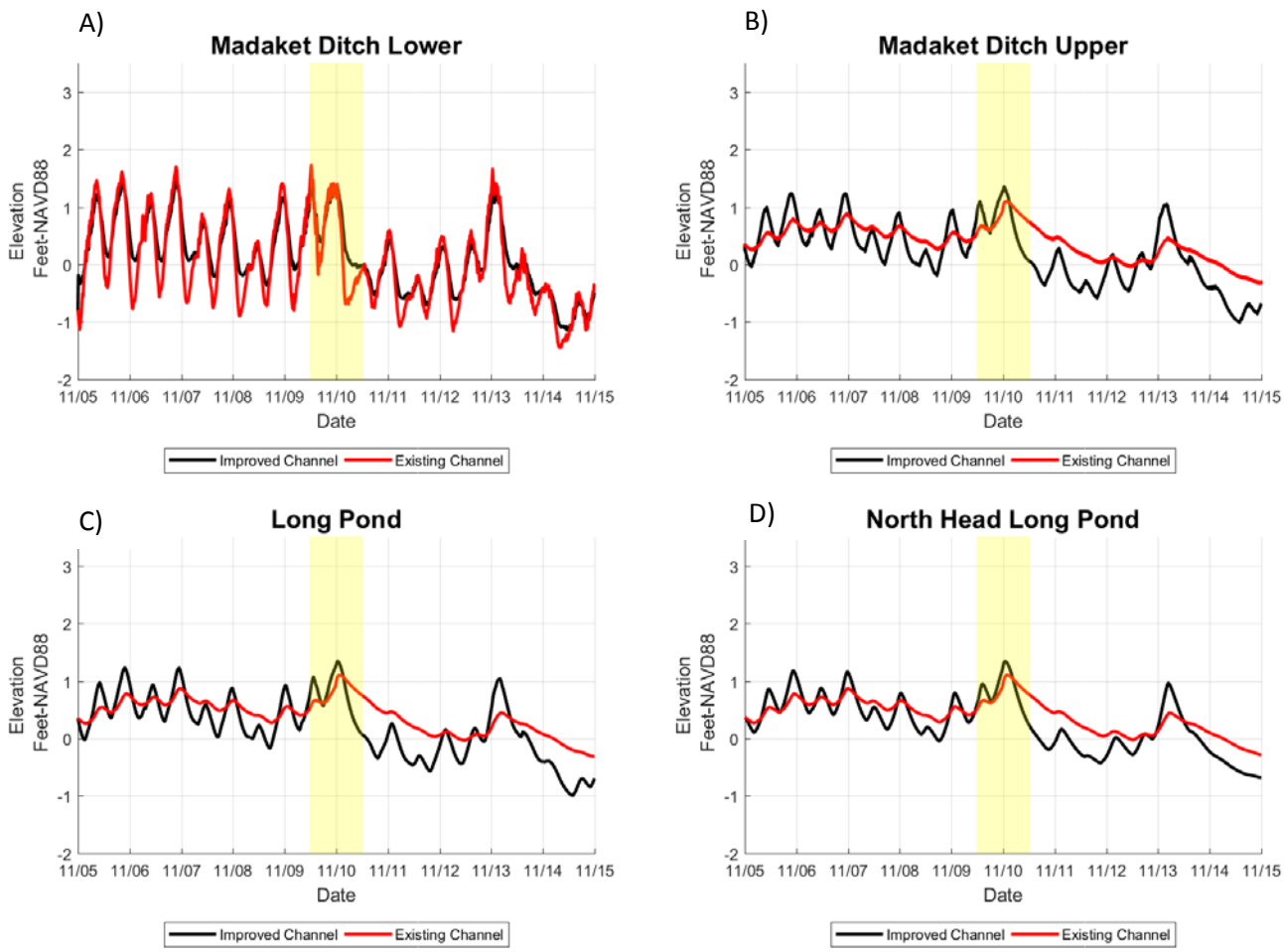

Figure 28. Effects of channel improvements in Madaket Ditch on drainage in the estuary during the 100-year level rain event.

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*Table 4. Maximum water elevations (feet, NAVD88) in each of the basins for existing conditions and **with an improved channel***

	100 Year Surge		2070 SLR	
Estuary Basin	**Existing Conditions**	**Improved Channel**	**Existing Conditions**	**Improved Channel**
Madaket Harbor	7.4	7.4	7.4	7.4
Madaket Ditch lower	5.8	5.6	6.2	6.1
Madaket Ditch upper	5.0	5.5	6.1	6.1
Long Pond	4.7	5.1	5.6	5.6
North Head Long Pond	4.6	5.0	5.5	5.5

Peak water levels within each basin were extracted from the model simulations of a 100-year storm surge event and typical tides with SLR, as these produced the highest water levels within the estuary. These elevations are compared with the minimum roadway elevations at each of the culverts:

- 5.7 feet NAVD88 at N. Cambridge Street
- 5.0 feet NAVD88 at Madaket Rd. to Long Pond (Culvert 2)
- 3.8 feet NAVD88 at Madaket Rd. to North Head Long Pond (Culvert 1)

These comparisons show that each roadway section **would need to be elevated** in order to prevent overtopping/inundation during a 100-year event and normal tidal cycles in 2070. Compared to existing conditions, an improved Madaket Ditch channel would increase the 100-year peak water levels in Madaket Ditch upper and Long Pond to 5.5 and 5.1 feet, respectively.

Table 5 lists the **minimum recommended roadway elevations based on the modeling conducted**, however, a more comprehensive assessment is required to look at elevations of surrounding roadways within the Madaket area, what roadway elevations are feasible, primary and alternate access routes, prioritization of improvements, and recommended timing through cost-benefit analysis. This would be more readily done once the statewide probabilistic flood maps for current-day and future climate conditions become available later this year (currently in development by Woods Hole Group for MassDOT).

*Table 5. **Minimum** recommended roadway elevations (feet, NAVD88).*

Roadway	***Minimum Recommended Elevation (ft, NAVD88)****
N. Cambridge St	8.5
Madaket Road	8.0

***Assumes approximately 1-foot of freeboard**

4.3 Improved Flushing within Long Pond

Residence times for each of the Long Pond basins were computed for existing conditions and for an improved Madaket Ditch channel. **Residence time quantifies the flushing rate within an estuary and is a first order evaluation of water quality. Short residence times generally correspond to higher water quality; however, residence times may be misleading depending upon the pollutant/nutrient loading rates and the overall quality of the harbor water. Both the rate of nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with the residence times to better assess water quality effects.**

Residence time is defined as the average time required for a parcel of water to be flushed out of an estuarine system (or sub-basin). The residence times for each basin provided herein are valuable to determine the relative improvements in water quality based on the changes to the system.

For this study, residence time is computed using the following formula:

$$Residence\ Time\ = \frac{Volume\ (mean\ tide\ level)}{Tidal\ \ Prism_{flood}} \times\ T_{M_2}$$

where T_{M2} is the period of the tidal cycle (12.42 hours). Table 6 shows the computed local residence times based on the typical tidal cycles that were simulated in the ECM model. The improved Madaket Ditch channel results in decreases in residence time of 2.2 days for all of Long Pond (including North Head), and 3 days for North Head Long Pond alone.

Table 6. Computed local residence times for existing conditions and with an improved Madaket Ditch channel.

	Local Residence Time (days)		**Reduction in Local Residence Time with improvements**
Basin	*Existing Conditions*	*Improved Madaket Ditch*	
Long Pond	6.1	3.9	**36%**
North Head Long Pond	7.8	4.8	**38%**

5 Summary of Findings and Recommendations

As currently configured, the Madaket-Long Pond estuarine system has **significant** tidal dampening between the open harbor and the uppermost reaches. During a 38-day field measurement program in which water levels and salinity were acquired at five (5) locations in the system, the primary tidal restriction was shown to occur within Madaket Ditch between N. Cambridge Street and Madaket Road. Further investigation of the channel elevations and field observations indicate that the tidal dampening is likely due to the combined effects of the natural sinuosity of the channel and flow restrictions caused by the asymmetric bed elevations at the channel bends. Some of the other relevant results from the Hydrologic and Hydraulic study of existing conditions are:

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1. The primary tidal restriction was shown to occur within Madaket Ditch between N. Cambridge Street and Madaket Road.
2. With the existing Madaket Ditch channel and current-day tides, the culverts under Madaket Road connecting Long Pong and North Head Long Pond are not restrictive and are sufficiently sized to convey flow in the upper reach of the Madaket estuary.
3. In a 100-year coastal storm event, the culverts within the system and the Madaket Ditch channel attenuate the surge peak from 7.4 in the harbor to 4.7 feet in Long Pond. The Madaket Ditch channel is shown to restrict drainage of the upstream basins resulting in a 4-day drainage period.
4. With projected 4.3 feet of sea level rise in 2070, the culvert at N. Cambridge Street starts to restrict tidal flow to Madaket Ditch and the culvert under Madaket Road connecting Madaket Ditch to Long Pond slightly restricts tides in Long Pond.
5. Both N. Cambridge Street and Madaket Road crossings are inundated in a 100-year coastal storm event **AND** in typical tides with 4.3 feet of sea level rise.

A suite of simulations was conducted to assess the effects of an improved Madaket Ditch channel as an initial alternative for increasing tidal exchange and optimizing drainage within the system. Simulating the Madaket Ditch channel with an increased cross-sectional area and reduced friction indicates that channel improvements will enhance tidal exchange during typical tides with an increased tidal range in Long Pond. The improved channel is also shown to reduce the time required for the upper reaches of the system to drain following storm events. Other relevant results include:

- The improved Madaket Ditch channel does not completely alleviate the restriction to tidal exchange. The natural sinuosity and some frictional effects of the channel would still remain, causing reduced tides further upstream. Improving the channel along its entire length and providing a more uniform channel throughout would help to minimize these effects.

- With the improved channel configuration and current-day tides, the culvert under Madaket Road to Long Pond does not significantly affect water levels, however the culvert to North Head Long Pond becomes slightly restrictive. **An increased culvert size equivalent to a 15-foot wide by 5-foot high concrete box would be required at this location to alleviate the restriction.**

- In a 100-year coastal storm event with an improved channel, surge elevations in the upper reach of Madaket Ditch are higher and reach up to 5.5 feet NAVD88 which would impact/overtop Madaket Road. The improved Madaket Ditch channel is shown to reduce the drainage period of the upstream Long Pond basins from 4 days to 2 days.

- For typical tides and a projected 4.3 feet of sea level rise in 2070, both the culvert under Madaket Road connecting Madaket Ditch to Long Pond and the culvert to North Head Long Pond restrict tidal exchange with an improved Madaket Ditch channel.

- In order to not restrict typical tides with a projected 4.3 feet of sea level rise in 2070, the following minimum culvert sizes (or equivalent) would be required. The existing invert elevations could be maintained.

20'w x 10'h concrete box at N. Cambridge Street
16'w x 10'h concrete box at Madaket Rd. to Long Pond (Culvert 2)
15'w x 5'h concrete box at Madaket Rd. to North Head Long Pond (Culvert 1)

- A more detailed parcel-level assessment of potential flooding impacts should be conducted in subsequent design phases if replacing the culvert(s).
- An improved Madaket Ditch is shown to provide water quality benefits for Long Pond reducing its local residence time by 36% (from 6.1 to 3.9 days)

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As a first step in improving the system, it is recommended that at a minimum, the stream bed in Madaket Ditch should be leveled at channel bends, and any potential obstructions removed. Figure 29 shows areas identified for potential improvements based on collected bathymetry and channel cross-sections. **The total length of channel identified for sediment removal is approximately 850 feet** (Note that 465 feet of the channel was identified as the reach dividing the upper and lower Madaket Ditch basins where there is a reduced cross-section contributing to the restriction, while 850 feet is the length where any shoaling was identified and would allow for a more uniform channel throughout). Following implementation of channel grading, continued monitoring of water levels at three locations in the Madaket Ditch reach of the system would help to assess the immediate effects of the channel improvements and to provide insight into additional maintenance needs/management alternatives for the channel.

Figure 29. Locus map showing areas identified for sediment removal (red) and potential locations for post-channel-improvement monitoring stations. Green arrows point to provisional gauge locations.

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