December 15, 2023

Mr. John Riehl
Natural Resources Advisory Board
Wellfleet, MA 02667

Report on Wellfleet Harbor and Mayo Creek Sediment Analysis

Dear Mr. Riehl:

Woods Hole Group is pleased to report on the project entitled, "Wellfleet Harbor and Mayo Creek Sediment Analysis," funded by the Town of Wellfleet and conducted in communication with you. The concern is fine sediment, termed "black custard", which accumulates in Wellfleet Harbor in the North Access Channel and near the L Pier (Figures 1 and 2). The project is structured around key points:

- The potential exists to mobilize black custard and mitigate its buildup near the Town Pier by restoring the flowrate between Wellfleet Harbor and Mayo Creek.
- The potential dual benefits are marsh restoration and reduction of dredging requirements.
- Motivation is provided by the observation that Duck Creek (Figure 1) is free of black custard.
- The Woods Hole Group effort is a pilot study to produce a preliminary impacts assessment and recommended next steps.
- The study builds on the 2011 and 2016 Woods Hole Group hydrodynamic study and alternatives analysis for the Mayo Creek Salt Marsh.
- The study supports and benefits from the ongoing two-phase restoration of the Mayo Creek Salt Marsh by the Town of Wellfleet.

Figure 1. Google Earth image showing the Mayo Creek salt marsh, Duck Creek, Commercial Street, the North Access Channel, the Town Pier, the L Pier, and Wellfleet Harbor.

Figure 2. Thicknesses of black custard layer near Town Pier. Reproduced from the 2020 Center for Coastal Studies report (see reference list in Appendix).

The following presents existing information (Section 1), a hydrodynamic and sediment transport analysis (Section 2), an alternatives analysis (Section 3), recommendations (Section 4), and references (Section 5).

1. Existing information

This section reviews existing sediment data, tide data, and hydrodynamic model results. The sources are the 2011 and 2016 reports by Woods Hole Group, the 2020 report by the Center for Coastal Studies, and dredge information and visual observations provided by John Riehl.

Woods Hole Group (2011) used a box model of the Mayo Creek Salt Marsh. The model was forced by precipitation and the water surface elevation in Wellfleet Harbor, and it was calibrated and validated against measurements of water surface elevation in the Creek. An objective was to limit the water surface elevation over the Marsh during spring tides to 3.0 feet above the North American Vertical Datum of 1988 (NAVD88), which does not produce upland flooding and is below all surveyed upland infrastructure elevations as provided by the Town of Wellfleet (Woods Hole Group, 2011, page 3). The analysis addressed normal tides, projected sea level rise, and storm events, including rainfall and storm surge. The cases considered and the corresponding results are:

- Existing 24” culvert with duck bill valve in place. The intertidal area over the Marsh is minimal. Sea level rise will cause an increase in the mean water surface elevation and a reduction of the tidal range. The water surface elevation during storms is dominated by precipitation. The time required to drain the marsh after a storm is long (approximately 17 days).
- Existing culvert with duck bill valve removed. Under normal tides, relative to the existing configuration, the mean water level over the marsh increases by approximately 2.0 feet, and the intertidal area increases to approximately 20 acres. Under sea level rise, the spring high tide remains below the target of 3.0 feet NAVD88 for the 50-year projection, but it exceeds 3.0 feet

NAVD88 and overtops Commercial Street during the 100-year projection, rendering the culvert inconsequential. Under storms short of overtopping Commercial Street, the water surface elevation over the Marsh is less than 2.0 feet NAVD88. Large storms would overtop Commercial Street and flood the Marsh irrespective of the culvert. Marsh drainage times after storms are roughly halved relative to the condition with the duck bill valve in place.

- 40” culvert without duck bill valve. Under tidal forcing, the mean high water over the Marsh increases by 3.3 feet, the mean tide level increases by 1.2 feet, and the intertidal area increases to nearly 38 acres. The response to sea level rise is like that of the preceding cases. Drainage times after storms decrease significantly.

Woods Hole Group (2016) used the box model described by Woods Hole Group (2011) to evaluate targeted solutions that optimize the tidal range, with limitations on the mean high water to avoid adverse flooding impacts and limitations on the mean tide level to avoid increases in groundwater elevation. A box culvert and an actively controlled tide gate were recommended to achieve the design objectives. For the Marsh, the existing condition (non-excavated) and an enhanced condition (excavated with channel creation) were considered. The excavated Marsh with box culvert and an actively controlled tide gate were found to increase the tidal range by more than two feet compared with the existing channels case and approximately four feet compared with the existing culvert design, resulting in greater inundation without affecting existing infrastructure or increasing the mean tide level.

The key findings listed in the 2020 Center for Coastal Studies report are:

- The fine sediments in Wellfleet Harbor are not “black mayonnaise,” which denotes highly contaminated particles devoid of normal aquatic life. They are instead termed “black custard.”
- The sediments are higher in organic matter and lower in species diversity than sediments at a control station in “The Gut,” a nearby location with stronger flows.
- The layer of black custard varies in thickness between 8 and 12 feet (Figure 2). The black custard is composed of silt-sized particles, which differ from sand-sized particles in The Gut.
- The overall source of the organic material in the black custard is marine.
- Sediments coarsen with depth in the sediment cores, indicating stronger currents when the channels were deeper. Deposition near the Town Pier (Figures 1 and 2) likely results from flocculation of clay- and silt-sized particles.

Table 1 in the 2020 Center for Coastal Studies report indicates that the organic matter content for seafloor samples near the Town Pier is at most 23%, so that the bottom material is mostly sediment. Sediment samples and grainsize analysis (Figure 3) indicate a surficial median diameter of 14.2 microns in the Boat Basin, with larger surficial sediments near the culvert, where localized flows to and from the culvert are likely strong, and at the end of Town Pier, where currents are probably significant because of the exchange between Wellfleet Harbor and Duck Creek. An earlier model study (Giese et al., 1994) indicates that the currents in the inner Wellfleet Harbor are flood dominant, i.e., tending to transport sediments from the Harbor toward Duck Creek.

John Riehl (personal communication) provided information about dredging and observed locations of black custard (Figure 4). According to this information, the Federal Channel and the Federal Anchorage were dredged in late 2020, the North and South Access Channels and the L Pier were dredged in fall 2021, and the South Anchorage is scheduled to be dredged. Visual observations indicate that black custard occurs in the North Access Channel and near the L Pier. The fully dredged depth in the North Access Channel is approximately 5 feet below Mean Low Water, which is in turn 5 feet below the North American Vertical Datum of 1988 (NAVD88; see the 2011 Woods Hole Group Report, page 14, Figure 7).

Figure 3. Sediment sample sites from the 2020 Center for Coastal Studies report. According to Table 3 in that report, the median surficial sizes are 39.0, 14.2, 659.5, 24.4, and 542.5 microns, respectively, at sites 1 through 5.

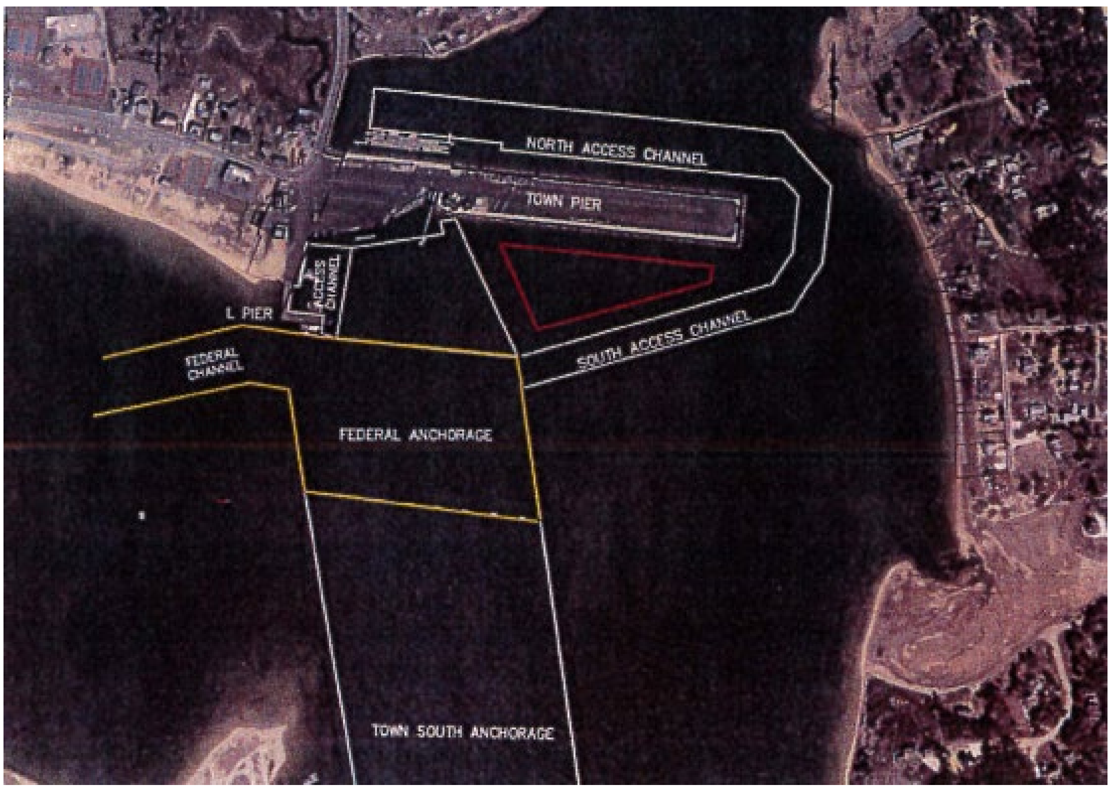

Figure 4. Map showing regions in Wellfleet Harbor. Reproduced from https://www.wellfleet-ma.gov/sites/g/files/vyhlif5166/f/file/file/marina_rules_and_regs_approved_08-27-15.pdf

2. Hydrodynamic and sediment transport assessment

This section presents calculations of tidal inundation in the Mayo Creek marsh and the corresponding currents and sediment transport in the North Access Channel. The scenarios considered are:

1. The existing culvert and the North Access Channel dredged to -10 feet NAVD88, approximately 5 feet below Mean Low Water (MLW).
2. A new culvert sized to achieve a maximum water surface elevation of 3.0 feet NAVD88 over the Mayo Creek marsh, the maximum level that does not flood abutting property and infrastructure (Woods Hole Group, 2011, page 5), and the North Access Channel dredged to -10 feet NAVD88.
3. A new culvert sized as in Scenario 2 and the North Access Channel seafloor at -7.5 feet NAVD88, representing reduced dredging or conditions prior to dredging.
4. A new culvert sized to achieve maximum marsh restoration to the full tidal exchange with Wellfleet Harbor and the North Access Channel dredged to -10 feet NAVD88.

In all scenarios, the ocean forcing is a semidiurnal tide with an amplitude of 7.0 feet, corresponding to spring tides (Woods Hole Group, 2011, page 14, Figure 7). The culvert dimensions for Scenario 1 are chosen so that the maximum water surface elevation over the Mayo Creek salt marsh is approximately consistent with spring tide observations (Woods Hole Group, 2011, page 21, Figure 15). These dimensions do not coincide with the actual existing culvert dimensions, and they represent effective values that account for the existing duck bill valve and likely flow blockage. The culvert dimensions for Scenarios 2 through 4 are chosen to achieve the desired maximum water surface elevations over the Mayo Creek salt marsh, and they do not constitute design recommendations. Table 1 summarizes the culvert dimensions and the dredged depth of the North Access Channel for the scenarios considered.

The calculations are based on standard equations for hydrodynamics and sediment transport, using approximations that are suited to the present application. The water surface elevation over the Mayo Creek salt marsh is assumed to be horizontal. The flowrate through the culvert is determined as a function of the water surface elevations in the North Access Channel and over the marsh by the hydrodynamic equations for a culvert flowing full or partially full (e.g., Henderson, 1966). The time rate of change of volume over the Mayo Creek salt marsh is equal to the volume flowrate through the culvert. The surface elevation over the Mayo Creek salt marsh is determined as a function of the volume over the marsh by using the hypsometry (area vs elevation) in Figures 11 and 12 in the 2011 Woods Hole Group report. The velocity and the tidal excursion in the North Access Channel are determined by using the computed flowrates through the culvert and the continuity equation. The maximum seabed sediment grain size that can be set in motion by the current in the North Access Channel is determined by the Shields criterion (e.g., Henderson, 1966), and the maximum sediment grain size that is transportable in suspension is determined by the Stokes settling law (e.g., Batchelor, 2000).

Table 1 presents the four scenarios with the results of the hydrodynamic and sediment calculations. In Scenario 1, the median-diameter surficial seabed sediments in the North Access Channel are not transported. In Scenarios 2 through 4, these sediments are transported, and the tidal excursion is comparable to the Pier length (approximately 1400 ft), so that some of the mobile suspended sediments would be carried past the Pier end and into the main channel connecting Wellfleet Harbor and Duck Creek, where they could be further dispersed. Under Scenarios 2 through 4, the flow velocity in the culvert is ebb dominant, meaning that the strength is greater in the ebb direction than in the flood direction, which means that Mayo Creek would tend to export fine sediments to the North Access

Channel, remaining free of black custard, as in Duck Creek. The calculations indicate greater flow speeds, sediment sizes, and tidal excursions in Scenario 3 than Scenario 2, suggesting that as the North Access Channel accumulates fine sediments and shoals, the system becomes more effective at transporting and dispersing sediments, thus potentially accumulation of black custard in the Channel.

Table 1. Scenario descriptions and results of hydrodynamic and sediment transport analysis.

Statistic	Scenario			
	1	2	3	4
	Existing condition	Max tidal exchange without flooding; full dredge depth	Max tidal exchange without flooding; shallow dredge depth	Full tidal exchange; full dredge depth
Culvert span (ft)	0.5	8.0	8.0	32.0
Culvert rise (ft)	0.5	3.0	3.0	9.5
Culvert invert elevation (ft NAVD88)	-2.5	-2.5	-2.5	-2.5
North Access Channel seafloor elevation (ft NAVD88)	-10.0	-10.0	-7.5	-10.0
Mayo Creek maximum water surface elevation (ft NAVD88)	0.1	3.0	3.0	6.9
Mayo Creek minimum water surface elevation (ft NAVD88)	-2.5	-2.5	-2.5	-2.5
Mayo Creek marsh maximum inundation (acres)	7	40	40	60
North Access Channel maximum flow speed (ft/s)	0.0	0.2	1.4	0.5
North Access Channel maximum sediment size transported (microns)	0	16	48	27
North Access Channel seaward tidal excursion (ft)	0	1100	3500	1400

A natural tendency for fine sediments to accumulate in the North Access Channel might exist even in the natural (pre-road) condition, implying that accumulation in the North Access Channel would be lessened but not eliminated under Scenarios 2 through 4 in Table 1. Because of its broad, channelized geometry, Duck Creek is likely ebb-dominant (e.g., Friedrichs, 2010), so Duck Creek exports sediment to Wellfleet

Harbor. Similarly, Mayo Creek likely exported sediment to Wellfleet Harbor because of its geometry. Giese et al. (2010) reported model calculations indicating that currents in the inner Wellfleet Harbor are flood-dominant, i.e., tending to transport sediment landward toward Duck Creek and Mayo Creek. Together, this information suggests that the sediment transport converges where Duck and Mayo Creeks enter Wellfleet Harbor, so that sediment accumulates there. These processes are like those that form turbidity maxima in estuaries (e.g., Geyer et al., 1993, Burchard et al. 2004, and references therein). A possible natural tendency for sediment to accumulate is likely exacerbated by the Town Pier and the culvert beneath Commercial Street, which create a stagnant zone that facilitates sediment deposition in the North Access Channel.

The above considerations of a natural tendency for sediment accumulation suggest that modifying the culvert to increase the tidal exchange between Wellfleet Harbor and Mayo Creek will lessen, but not eliminate, the accumulation of black custard in the North Access Channel. A very rough estimate based on existing information is that the accumulation rate might lessen under Scenarios 2 and 3 by a factor on the order of two, indicating a reduction in the required dredging frequency from the present approximately ten-year intervals (personal communication, John Riehl) to some 20 years. However, quantitative calculations of accumulation rates will not be carried out until the finalized hydrodynamic and engineering design study (see Recommendation 1 in Section 4, below), and it must be recognized that predictions of sediment transport processes on decadal timescales are exceedingly uncertain.

Figure 5, using LIDAR elevation data, shows the extent of inundation under Scenarios 2 and 3, with a water surface elevation of 3.0 ft NAVD88 over Mayo Creek and the marsh.

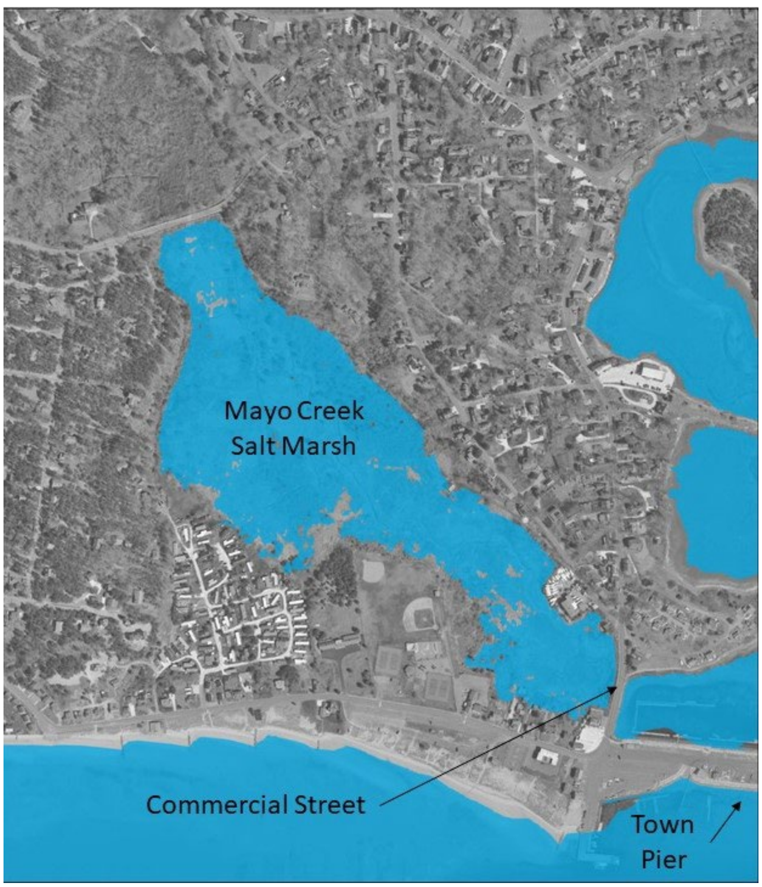

Figure 5. Extent of inundation with a water surface elevation of 3.0 ft NAVD88.

3. Alternatives analysis

The alternatives considered are:

1. No action.
2. Resize the culvert to achieve the maximum tidal exchange between Wellfleet Harbor and Mayo Creek that does not cause tidal flooding of property and infrastructure abutting the Mayo Creek salt marsh (Scenarios 2 and 3).
3. Resize the culvert to achieve the full tidal exchange between Wellfleet Harbor and Mayo Creek (Scenario 4).

These alternatives are evaluated against the following objectives:

1. Do not cause flooding of property and infrastructure adjacent to the Mayo Creek salt marsh during spring tides.
2. Reduce the buildup of black custard in the North Access Channel.
3. Do not cause accumulation of black custard in Mayo Creek and the marsh.

Co-benefits considered are:

1. Increase tidal exchange between Wellfleet Harbor and Mayo Creek.
2. Speed drainage of Mayo Creek salt marsh after storm surge or rainfall flooding event (identified as a concern in the 2011 and 2016 Woods Hole Group reports; not analyzed quantitatively here).

The results are summarized in Table 2. The only alternative that satisfies all objectives is Alternative 2.

Table 2. Alternatives analysis.

Objective or co-benefit	**Alternative**		
	1	2	3
	No action	Resize culvert to achieve maximum tidal exchange without flooding	Resize culvert to achieve full tidal exchange
Does not cause tidal flooding of property & infrastructure abutting Mayo Creek Salt marsh	Yes	Yes	No
Reduces buildup of black custard in North Access Channel	No	Yes	Yes
Does not cause accumulation of black custard in Mayo Creek and marsh	Yes	Yes	Yes
Increases tidal exchange between Wellfleet Harbor and Mayo Creek	No	Yes	Yes
Speeds drainage of Mayo Creek salt marsh after storm surge or rainfall flooding event	No	Yes	Yes

A related consideration is a tide gate. A tide gate is not required to achieve the results in Table 1 and the alternatives analysis in Table 2, which address regularly occurring flooding by the astronomical tide. However, a tide gate would be useful to protect property and infrastructure abutting the Mayo Creek salt marsh from episodic flooding caused by ocean storm surge. The design of a tide gate and development of a protocol for its operation are included in the recommendations.

4. Recommendations

The recommendations are:

1. Undertake a finalized hydrodynamic and engineering design study for the restoration of Mayo Creek.
    a. The design would resize the culvert to achieve the maximum tidal exchange without flooding the adjacent property and infrastructure (Alternative 2).
    b. The project would include finalized modeling, culvert sizing, engineering design, consideration of tidal control measures, and (if desired) permitting.
    c. The rights and concerns of the residents who own property and infrastructure abutting the Marsh must be understood and respected.
2. Enhance the resilience of Town Pier considering sea level rise projections.
    a. At some future time, the existing pier will be underwater at many high tides and will need to be raised.
    b. The opportunity could be taken to improve the circulation in the North Access Channel to reduce the buildup of black custard.

5. References

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